CONVR 2018

Evolving Construction: Towards a technological revolution

Proceedings of the 18th International Conference on Construction Applications of Virtual Reality

22 – 23 November 2018
Auckland, New Zealand

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
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CONVR History

The International Conference on Construction Applications of Virtual Reality was initiated by Prof. Nashwan Dawood. The first CONVR was held in Teesside, Middlesbrough, UK in 2000. The conference focuses on the fields of Virtual Reality (VR) and Augmented Reality (AR) which are forward-looking technologies that enable considerable benefits in all stages of the Architecture, Engineering and Construction (AEC) process, from initial planning and conceptual design to facility management and operations. Over the last 18 years the conference has been held all around the globe and sponsored by major software and engineering companies:

- CONVR2017 (as part of JC3) in Crete, Greece
- CONVR2016 in Hong Kong, China
- CONVR2015 in Banff, Alberta, Canada
- CONVR2014 in Sharjah, UAE
- CONVR 2013 in London, UK
- CONVR 2012 in Taipei, Taiwan
- CONVR 2011 in Weimar, Germany
- CONVR 2010 in Sendai, Japan
- CONVR 2009 in Sydney, Australia
- CONVR 2008 in Kuala Lumpur, Malaysia
- CONVR 2007 in Pennsylvania, USA
- CONVR 2006 in Orlando, USA
- CONVR 2005 in Durham, UK
- CONVR 2004 in Lisbon, Portugal
- CONVR 2003 in Blacksburg, USA
- CONVR 2001 in Chalmers, Sweden
- CONVR 2000 in Teesside, UK

CONVR2018 Keynote Speakers

Prof John Messner, Penn State University, USA
John Messner is a professor of architectural engineering. He has special research interests in advanced visualisation technologies for construction design. He is the director of the Computer Integrated Construction (CIC) Research Program at Penn State

Prof Nashwan Dawood, Teeside University, UK
Nash is the Director of the Technology Futures Institute, through which the engineering, science and technology research at Teesside University in UK is structured and supported. His research and consultancy has ranged from sustainable construction to 4 & 5D modelling and VR

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A TRANSFER LEARNING METHOD FOR DEEP NEURAL NETWORK ANNOTATION OF CONSTRUCTION SITE IMAGERY

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ABSTRACT: *Digital images are extensively used to increase the accuracy and timeliness of progress reports, safety training, RFIs, productivity monitoring, and claims and litigation. While these images can be sorted using date/time tags, the task of searching an image dataset for specific visual content is not as trivial. In pattern recognition, generating metadata tags describing image contents (objects, scenes) or appearance (colors, context) is referred to as multi-label image annotation. Given the large number of construction imagery, it is desirable to generate image tags automatically. Previous work has applied pattern matching to synthetic images or images obtained from constrained settings. In this paper, we present a deep learning (particularly, transfer learning) algorithm to annotate construction imagery from unconstrained real-world settings with high fidelity. We propose a convolutional neural network (CNN) which takes RGB values as input and outputs the labels of detected objects. This CNN is pre-trained on the ImageNet dataset, and re-trained using construction images retrieved with web mining techniques and labeled by human annotators. Testing the trained model on previously unseen photos yields an accuracy of >90%, indicating the high sensitivity and specificity of the designed methodology in reliably identifying the contents of construction imagery.*

KEYWORDS: *Deep Learning, Transfer Learning, Convolutional Neural Networks, Construction Photos, Image Annotation, Web Mining, Object Recognition.*

STREAM: *Sensing and AI (Stream 2).*

1. INTRODUCTION

Construction site imagery is valuable for creating progress reports, request for information (RFI), and safety training, productivity monitoring, and claims and litigation. In the advent of digital cameras and, in recent days, drones, digital images can be readily captured from the construction site and used to increase accuracy and timeliness of those reports. However, most often, the images are large in number and contain only date/time and, in some cases, geolocation tags. Therefore, retrieving a particular set of images, from a larger collection, based on specific visual contents is a non-trivial task. Only if the images are stored in a structured and organized way, for instance, with metadata tags describing the contents (e.g., objects, scenes) and/or the appearance (e.g., color, context), the time and complexity of retrieval become significantly reduced. However, given a large number of construction site images, manual tagging is time-consuming and effortful, rendering the automatic generation of metadata an appealing solution.

In pattern recognition, generating metadata tags is referred to as multi-label image annotation. Recent studies have made a significant progress in annotating image, i.e., recognizing objects from digital images (Krizhevsky et al. 2012; Simonyan and Zisserman 2014). However, the majority of the studies aimed at recognizing everyday objects/animals, particularly, because of the large number of publicly available datasets. On contrary, there is a limited number of publicly available dataset that contains useful construction site images. Despites, there are studies that designed and tested methodologies for recognizing construction equipment, e.g., excavators (Zou and Kim 2007), and materials (Brilakis and Soibelman 2008) in digital images. However, while these methodologies follow an extensively careful design of features, only a few studies utilized deep-learning based automatic feature extraction methods using real-world data (Ding et al. 2018; Kolar et al. 2018; Siddula et al. 2016). Although deep learning methods have achieved significantly promising results in image recognition for the larger dataset, transfer learning is more convenient when dealing with smaller datasets. In this approach, a model pre-trained with a larger dataset with different labels (but from the similar domain) is retrained with some constraints for a new (generally, smaller) dataset (Oquab et al. 2014). Despite potential differences with respect to the image input space and the final class labels, this approach, generally, yields a better result (Oquab et al. 2014). Therefore, in this paper, a deep and transfer learning-based methodology is proposed that can annotate construction imagery from unconstrained real-world settings with high fidelity. Particularly, a convolutional neural network (CNN) is proposed which takes RGB values of an image as input and outputs the detected object. The CNN is trained using construction images that are automatically retrieved using web mining techniques and labeled by human annotators. Finally, the CNN model is tested on unseen photos through a validation framework.

2. LITERATURE REVIEW

With the increase in quantity and quality of photos and videos taken from construction sites, more attention is being drawn to streamlining the process of automatically extracting content from digital imagery through object/material detection. For example, Zou and Kim (Zou and Kim 2007) utilized HSV (hue, saturation, and value) color space of images to identify excavators in construction photos. In particular, they used the threshold of saturation as a feature to distinguish a relatively colorful excavator object from the dark soil or white snow background. Brilakis et al. (Brilakis et al. 2005), and Brilakis and Soibelman (Brilakis and Soibelman 2008) proposed a method to detect shapes in an image, and identify corresponding material types (e.g., steel or concrete) within the texture of the detected shape region. Wu et al. (2009) employed Canny edge detection and watershed transformation methods to detect the edges of an object (e.g., columns in an image), and applied object reconstruction to locate and quantify objects (e.g., number of columns). Kim et al. (2016) used scene-parsing and label transfer to match a target image with a number of labeled images, find candidate images that match more closely, and transfer labels from candidate images to the target image.

Recent work has also utilized machine learning (ML) algorithms to automate the process of object recognition in construction site imagery. For example, Chi and Caldas (Chi and Caldas 2011) used Naïve Bayes (NB), and neural network (NN) classifiers to detect workers, loaders, and backhoes. Son et al. (2014) used a voting-based ensemble classifier combining several base classifiers such as support vector machine (SVM), NN, NB, decision tree, logistic regression, and k-nearest neighbor (KNN), to identify construction materials (e.g., concrete, steel, and wood) in an image. Dimitrov and Golparvar-Fard (Dimitrov and Golparvar-Fard 2014), and Han and Golparvar-Fard (Han and Golparvar-Fard 2015) used one-vs-all multi-class SVM to classify major construction materials (around 20 types).

The majority of the aforementioned methodologies, however, requires the extraction of handcrafted image features that are particularly relevant to the given classes (Kolar et al. 2018). However, for content-rich imagery such as construction photos that contain a large number of highly diverse objects or cover a large visual field under a variety of environmental conditions (e.g., lighting, landscape, etc.), automatic feature extraction methods such as convolutional neural network (CNN) and histogram of oriented gradients (HOG) are more advantageous because of their ability to self-learn features from a given dataset (Kolar et al. 2018). Particularly, CNN has achieved outstanding results in image classification by overcoming the challenge of enormous computational power demanded by traditional NN (LeCun et al. 1998). A good example of CNN can be found in LeCun et al. (LeCun et al. 1998) which involves recognizing handwritten digits in an image. Other recent studies include but are not limited to classifying 1.2 million images (ImageNet dataset) into 1,000 different classes (various everyday objects/animals such as French fries, printer, umbrella, dog) (Krizhevsky et al. 2012; Simonyan and Zisserman 2014).

Within the construction domain, there are several studies that have used CNN for visual analysis of images and videos, mostly for construction safety. For example, Kolar et al. (Kolar et al. 2018) used CNN to detect safety guardrails in site photos. Siddula et al. (Siddula et al. 2016) combined the Gaussian mixture model (GMM) with CNN to detect objects of interest in images taken from roof construction sites. Ding et al. (Ding et al. 2018) integrated the long short-term memory (LSTM) model with CNN to recognize unsafe behaviors of construction workers (e.g., climbing a ladder) in video frames. However, to date, there is a limited number of studies that have investigated the potential of CNN in classifying common construction objects for general applications. Therefore, this research aims at developing a CNN-based methodology to annotate construction site imagery with predefined labels (e.g., building, construction equipment, and construction worker).

3. CONVOLUTIONAL NEURAL NETWORK (CNN) AND TRANSFER LEARNING

Similar to the traditional NN, CNN consists of a series of layers (i.e., input, hidden, and output layers). However, in CNN, the first few hidden layers are convolutional layers where convolution and pooling operations take place (LeCun et al. 2015). Each convolution operation outputs a numerical value by applying a filter (i.e., a matrix of weights) to a sub-region of an image (Kolar et al. 2018). A sample convolution operation involving a 3×3 filter is shown in Fig. 1(a). A pooling operation, on the other hand, is performed to merge semantically similar features into one, thus reducing the size of the image (a.k.a., sub-sampling) (LeCun et al. 2015). Fig. 1(b) illustrates max-pooling, one of the most commonly used pooling operations, where a 2D image is divided into fixed-sized sub-regions (i.e., kernels) and the maximum value in each sub-region is passed to the next layer. The remaining hidden layers are fully-connected layers that are similar to traditional NN. Of note, while working with small training data, to prevent overfitting, some hidden units are often randomly turned off (a.k.a., dropout) (Hinton et al. 2012).

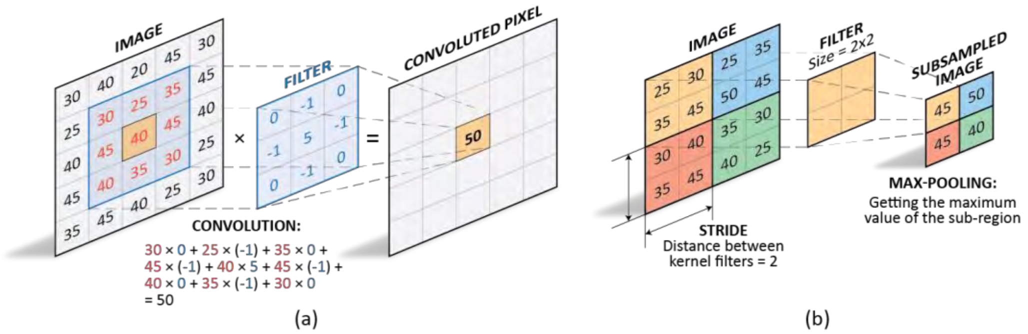

Fig. 1: Example of (a) convolution operation performed with 3 × 3 filter and (b) max-pooling operation performed with a 2 × 2 filter.

For a particular dataset, a CNN model can be trained from scratch. However, to achieve optimal results, a large amount of training data coupled with the proper selection of optimal hyperparameters (e.g., number of layers, number of nodes in each layer, filter size, number of epochs, learning rate, and dropout) is required which might take substantial amount of time for training (Kolar et al. 2018). One way to overcome this challenge is to perform transfer learning, i.e., using a CNN model (e.g., GoogleNet, AlexNet, VGG-16) that is pre-trained with a different but related dataset, and re-training some parts of the model with the desired dataset. Building upon previous studies that have found significantly better and consistent performance using transfer learning (Oquab et al. 2014; Shin et al. 2016), in this research, the authors have used a pre-trained model, i.e., VGG-16, which is trained on ImageNet dataset (Simonyan and Zisserman 2014).

4. METHODOLOGY

The overall framework of the designed methodology is shown in Fig. 2 and discussed at length in this Sections.

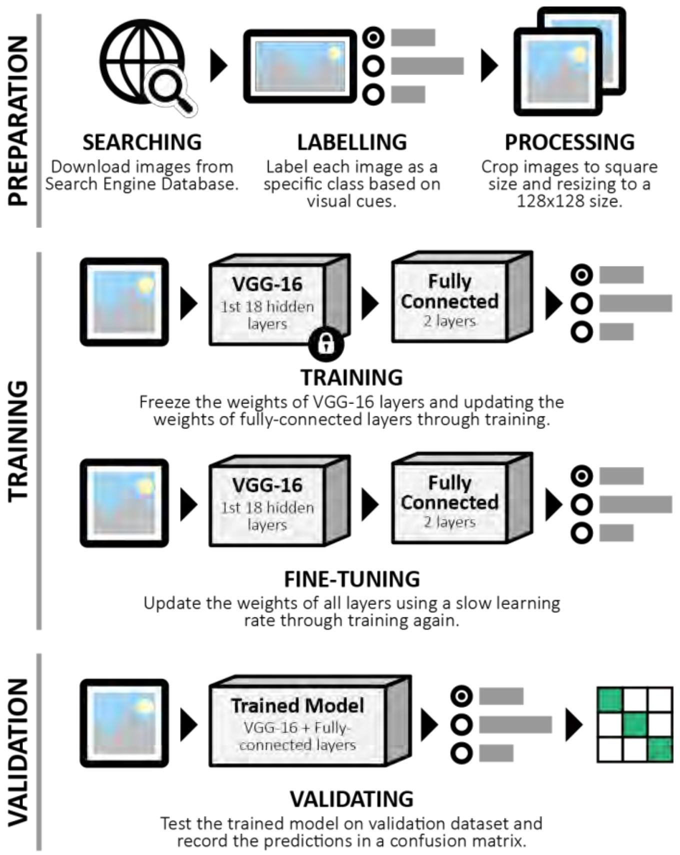

Fig. 2: Overall framework of the methodology.

4.1 Image collection and labelling

To obtain sufficient training data for the classifier model, a substantial number of images that contain specific visual contents need to be acquired. One of the most effective tools to achieve this goal is publicly available image search engines which contain a large number of images corresponding to one or more keywords (Fergus et al. 2005). The Google image search database is of particular interest to this research as it contains a relatively large number of images (Deng et al. 2009), and can provide more relevant images with higher ranks (Fergus et al. 2005). In this work, the following keywords are used when searching for mages in Google: 1) building under construction, 2) construction equipment, 3) construction worker.

When an image is retrieved, Labelbox ("Labelbox" n.d.) is used to label it as containing one of the three possible classes, namely "building", "equipment", or "worker". It must be noted that some of the retrieved images could be visually unrelated (Fergus et al. 2005), or manipulated (e.g., the background of construction equipment is removed). In order to obtain a clean image dataset, such irrelevant and manipulated images are labelled as "irrelevant" during the labeling process, and disregarded when preparing, training, and testing the dataset.

For the VGG-16 model, the input image must be of a square size. Therefore, any rectangular image is further cropped into a group of square images that cover the entire visual field of the original image while being equidistantly distributed along the longer dimension of the original image. An example is shown in Fig. 3 where a portrait rectangular image is cropped into three square images. The number of cropped images is determined based on the smallest integer number greater than or equal to (i.e., ceiling of) the ratio between the longer and shorter dimensions of the original image. Next, all cropped images are resized to 128×128 images using the bicubic interpolation method (Zhang et al. 2011).

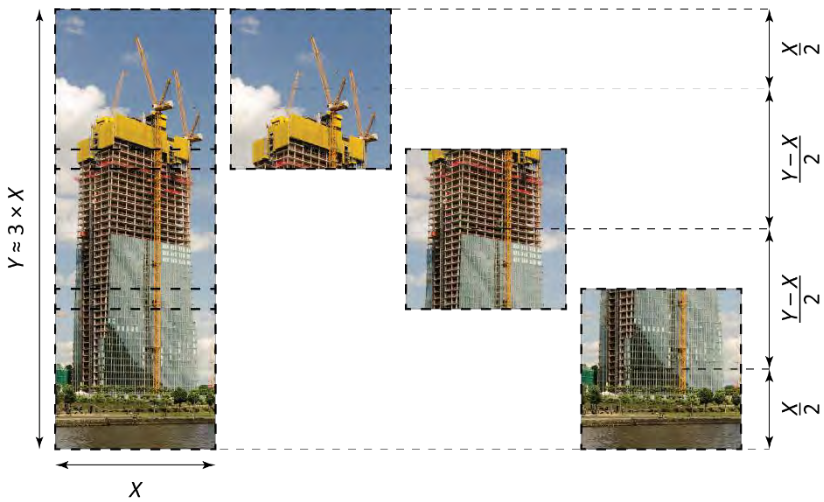

Fig. 3: Example of cropping a rectangular image into a group of square-sized images.

4.2 Architecture of the CNN

The designed CNN consists of one input layer (i.e., 128×128 images), 18 VGG-16 layers, 2 fully-connected layers, and one output layer (e.g., labels or tags) as shown in Fig. 4. The VGG-16 layers are comprised of a series of convolutional and max-pooling layers with a total number of 14,714,688 pre-trained weights. In the convolutional layers, convolution is performed using a 3×3 filter with a stride of 1 pixel that preserves the size of the image. However, in the pooling layers, max-pooling is performed using a 2×2 filter with a stride of 2 pixels that reduces the size of the image by half in each direction. The outputs of the last VGG-16 layer are connected to a flattened layer consisting of 8,192 nodes, which is fully-connected to the next layer of 256 nodes (the number of nodes in the layer is selected based on empirical observations). In this layer, a dropout operation is performed with 50% probability, i.e., during each iteration of the training session, 50% of the nodes are randomly excluded from weight updating. Together, the two fully-connected layers contain 2,097,408 (i.e., 8192×256) weights. The last hidden-layer is connected to the output layer which yields a vector represented as "one-hot encoding" (Marinai et al. 2005). In this encoding, each element of the vector represents one class and can have a value of either 1 (i.e., the input image belongs to that class) or 0 (i.e., the input image does not belong to that class). Finally, the rectified linear unit (ReLU) non-linear activation function is applied to the output of each hidden layer, both convolutional and fully-connected layers, to accelerate the convergence (Krizhevsky et al. 2012).

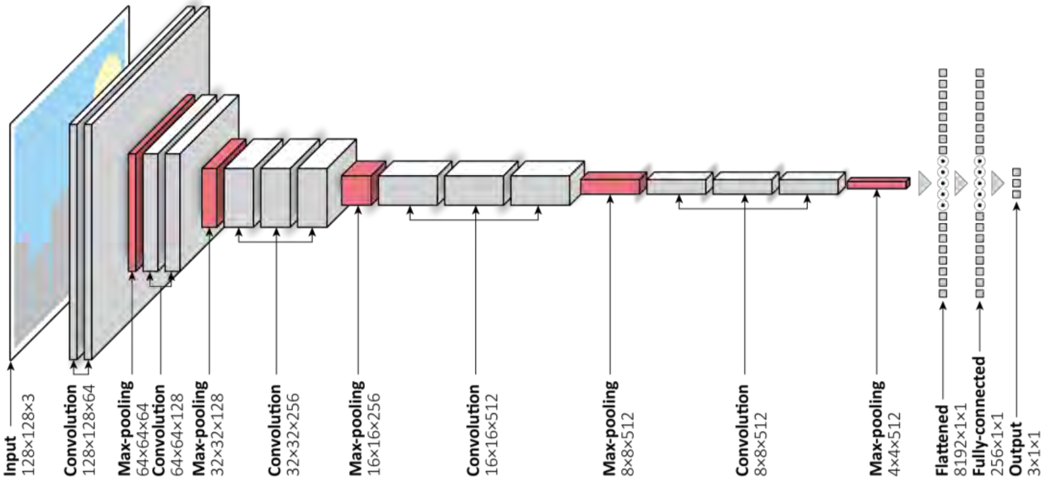

Fig. 4: Architecture of the CNN model.

4.3 Training and validation of the model

In this study, ~80% of the collected images is randomly selected for training the model, and the remaining ~20% is set aside to validate the trained model. The training phase is performed in two steps. First, all weights of the VGG-16 layers are frozen from updating, and only the weights of the fully-connected layers are updated using the training dataset. This step allows the CNN model to learn to classify the new set of classes without forgetting the filters learned from the pre-trained dataset. In this step, weights are optimized using the RMSprop optimization algorithm (Tieleman and Hinton 2012). Next, the training dataset is fed to the model again and weight values of the last three convolutional layers and two fully-connected layers are updated using the stochastic gradient descent (SGD) algorithm (Bottou 2010) with a slow-learning rate (the hyper-parameters, e.g., learning rate = 10^{-4}, and momentum = 0.9, are empirically selected). This step is referred to as "fine-tuning" and allows the previously frozen layers to adapt to the new dataset without drastically changing their weights. Finally, for model validation, the validation dataset is tested on the trained model, and the model performance is measured using accuracy, precision, and recall.

5. DATA DESCRIPTION

From a total of 2,686 images that are initially retrieved from Google, 2,103 most relevant images are chosen for training and testing the designed CNN. These relevant images are cropped into a total of 4,144 square-sized images following the technique previously laid out. From these images, 3,392 images (~80%) are used for training and 752 images (~20%) are used for validation. As described earlier, the image dataset contains three labels: 1) building (building under construction), 2) equipment (various construction equipment such as excavator, truck, bulldozer, loader, dozer, and crane), and 3) worker (construction worker). The distribution of the number of samples per class label is shown in Fig. 5. As shown in the Figure, 1,575 images contain the "building" label, 1,426 images contain the "equipment" label, and 1,143 images contain the "worker" label.

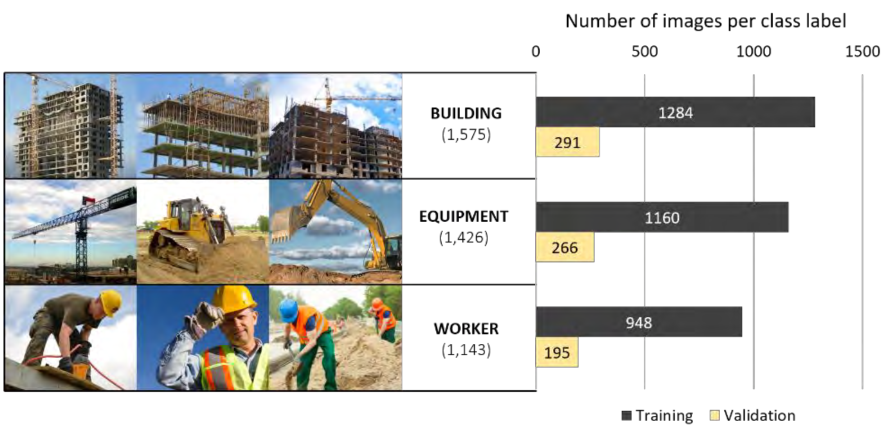

Fig. 5: Distribution of the number of samples per class label.

6. RESULTS AND DISCUSSION

The proposed CNN model takes an RGB image as input, generates intermediate features through a series of convolution and max-pooling operations, passes the features to the fully-connected layer, and outputs the probabilities of the image to belong to each class. The intermediate features for a randomly selected image labelled as “building” are shown in Fig. 6. The figure shows that the model finds background sky and edges of the building useful features to detect the building with high probability. The performance of the proposed model on the test dataset is summarized in Table 1. Also, classification rates of the proposed model are demonstrated in the confusion matrix of Fig. 7. Table 1 shows that all classes are predicted with ~90% accuracy by the proposed model. Also, the average accuracy, precision, and recall (both weighted and unweighted) are all >90%. However, the precision of recognizing buildings (i.e., 89.1%) is slightly lower than the other two labels, an indication that there is a relatively lower chance that an image recognized as building by the model actually contains building(s). Similarly, the recall of recognizing a worker (i.e., 88.7%) is relatively lower than the other two labels, i.e., the model has relatively higher tendency to misclassify an image containing worker as one containing building or equipment. To establish a baseline for results, the authors also conducted a parallel investigation in which a CNN model was built following a similar architecture as CifarNet (Shin et al. 2016) and trained from scratch using an identical dataset as described earlier in this paper. This model (referred to as “baseline model” in Table 1) yielded an accuracy of ~83%, which is ~8% lower than what was ultimately achieved using a pre-trained model (i.e., transfer learning).

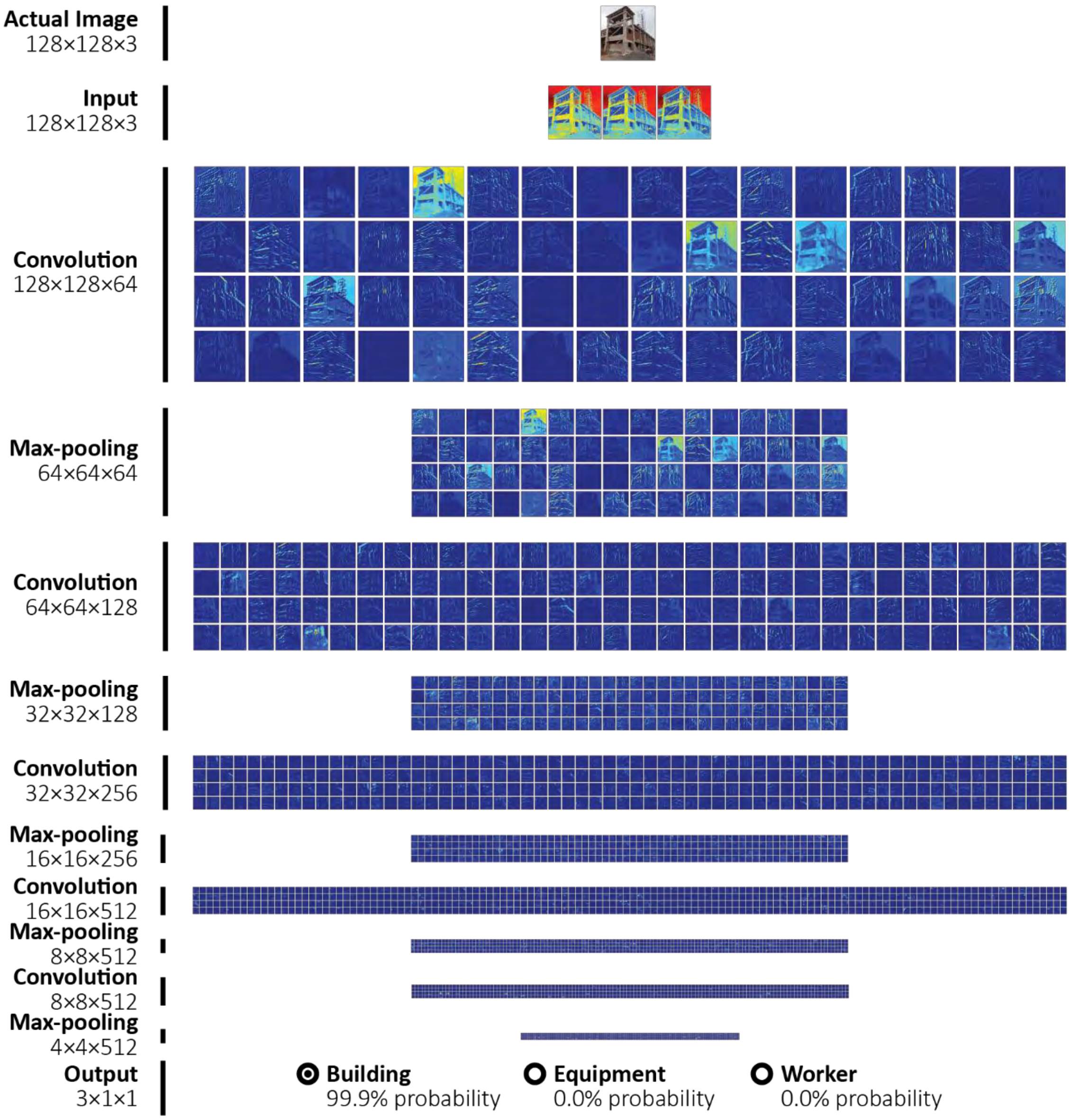

Fig. 6: Visualization of intermediate features.

Table 1: Performance metrics of the trained CNN model.

	Proposed Model [a]			Baseline Model [b]		
Class	**Accuracy**	**Precision**	**Recall**	**Accuracy**	**Precision**	**Recall**
Building	95.2%	89.1%	95.2%	95.5%	78.3%	95.5%
Equipment	89.5%	92.6%	89.5%	77.4%	87.7%	77.4%
Worker	88.7%	94.0%	88.7%	73.8%	88.9%	73.8%
Unweighted Average	91.1%	91.9%	91.1%	82.3%	85.0%	82.3%
Weighted Average	91.2%	91.3%	91.2%	83.2%	84.1%	83.2%

[a] VGG-16 fine-tuned on target data, with two fully-connected layers.

[b] CifarNet trained from scratch on target data.

Prediction

Actual	Building	Equipment	Worker
Building	277	9	5
Equipment	22	238	6
Worker	12	10	173

Fig. 7: Confusion matrix of the labels predicted by the proposed model.

The reasons behind the proposed model's misclassifications can be better understood from Fig. 8, where the confusion matrix is shown with a few randomly selected sample images. First, it can be seen that most of the misclassified images contain multiple visual cues. Particularly, some that are detected as "building" also contain equipment or worker (or both) in the foreground, obscuring the building in the background. However, the model detects the object in the background that occupies major proportion of the field of vision, rather than the equipment/worker in the foreground, not complying with the labelers' subjective judgement who had labeled those images as "equipment" or "worker". This justifies the reason behind lower precision in detecting buildings in the image dataset.

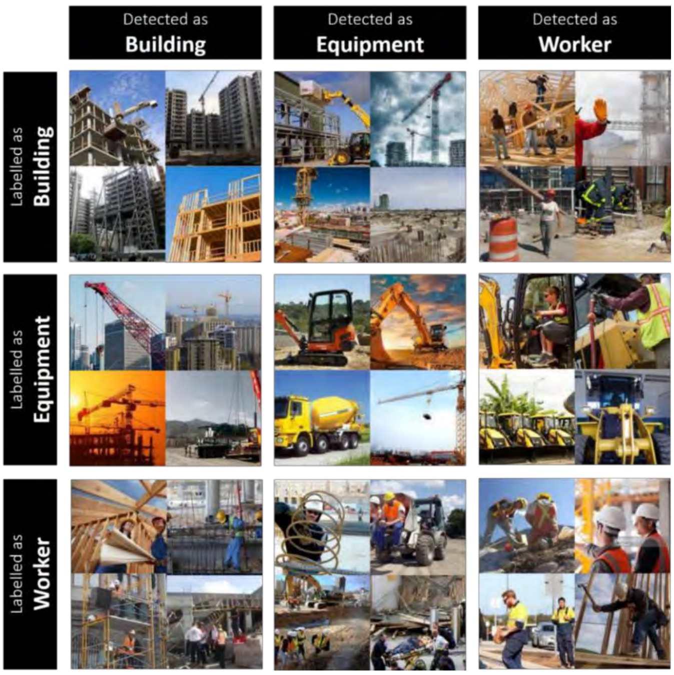

Fig. 8: Visualization of the confused labels.

On the other hand, construction workers are omnipresent and constantly in move in construction sites especially in the vicinity of buildings or equipment (or both). Therefore, some of the images labelled as "worker" may also contain building and/or equipment. Moreover, the visual footprint of a worker (portion of the image occupied by a worker) is relatively much smaller than buildings or equipment (e.g., truck, dozer). Thus, the model, having higher tendency to detect objects with larger visual footprints, may inadvertently mislabel such images as "building" or "equipment", reducing the recall of detecting workers.

Despite these issues, the performance of the designed CNN model is still very comparable with the state-of-the-art methodologies. For example, Kolar et al. (Kolar et al. 2018)'s CNN model detects safety guardrails in images with 86% accuracy (precision = 94.9%, recall = 76.1%). Siddula et al. (Siddula et al. 2016)'s combined GMM+CNN model detects objects with 96.67% accuracy from roof construction site imagery. Ding et al. (Ding et al. 2018)'s CNN+LSTM hybrid model recognizes unsafe climbing of workers with 97% and 92% accuracy, while classifying the behavior with two and four labels, respectively. Son et al. (2014)'s SVM model identifies construction materials with 91.68% accuracy. Han and Golparvar-Fard (Han and Golparvar-Fard 2015)'s multi-class SVM can classify different construction materials with 92.4% accuracy on average.

Of note, the accuracy of a CNN model and the computational time are in hyperbolic relationship, i.e., a slight increase in the accuracy will cost a significant amount of computational burden (Canziani et al. 2016). For example, while the average precision of VGG-16 is 2 times higher than HOG model, the latter processes 872 times more pixels per second than the former (Suleiman et al. 2017). However, recent research on optimizing hardware to accelerate CNN-based algorithms promises that with specialized hardware CNN models can be applied with similar computational complexity as hand-crafted feature-based algorithms (e.g., HOG) (Suleiman et al. 2017).

7. CONCLUSIONS AND FUTURE WORK

In this paper, a deep learning-based method is proposed which can automatically recognize scenes (e.g., building under construction) and objects (e.g., construction equipment, construction worker) from RGB images. The image dataset is automatically retrieved from Google image search database using web-mining technique and manually labeled by human annotators. Then, a transfer leaning method is used where a CNN model, VGG-16, is utilized which is pre-trained with 1.2 million images containing 1,000 class labels. Two fully-connected layers are added with the VGG-16's convolutional layers and weights are updated through training and fine-tuning the model with construction image dataset. The CNN model is tested on unseen photos and it recognizes the class labels with 91.1% accuracy (91.9% precision, and 91.1% recall). Also, it was found that most of the misclassified image contained multiple objects.

The performance of the proposed method is comparable with the contemporary methods of recognizing construction objects and materials. The proposed method can be applied to automatically generate tags for construction site imagery which would be helpful to readily retrieve particular images based on visual cues. In the future, the dataset will be expanded to generate more class labels (e.g., different equipment types). Also, multi-task learning algorithms will be applied to the dataset to detect multiple objects in a single image. Moreover, the annotation algorithm will be further improved to automatically generate natural language-based tags (a.k.a., captions) describing the scene contained within each image.

8. ACKNOWLEDGMENTS

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AR FOR DATA INTENSIVE WORKFLOWS

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ABSTRACT: *This paper reports on research investigating how new and emerging technology disrupt the design and making processes. This project uses the Microsoft Hololens platform to offer new opportunities for overlaying virtual data on real-world components during construction processes. This project explores both automated robotic construction, automatic recognition of building components and overlay of additional, relevant data. The use of data and knowledge-bases to assist with decision making is well documented. We are in an increasingly data intensive world, however benefits are only possible if pertinent data can be drawn upon and meaningfully visualized. Data, is not benign, what, where and how data is presented is key to positively (or negatively) impacting a process or decision. Composite materials present an interesting test case in that they can look perfect but contain hidden structural imperfections. Previous research has created technology demonstrators to gather structural data on composite panels. This phase of the research explores novels techniques for panel recognition and data visualization within the design and construction process. During this phase of the research we design and robotically assist construction of an 'igloo' structure from composite panels. We investigate novel techniques for panel handling, recognition and data visualization within the design and construction process.*

KEYWORDS: *Hololens, Augmented Reality, Digital Fabrication, Design, Data, Visualization*

1. INTRODUCTION

Using data to help shape the built environment is not a new phenomenon, the use of environmental information to inform building decisions can be found in Vitruvius' 'The Ten Books of Architecture' in the first century BC (Pollio and Morgan, 1960; McEwen, 2003). However, we currently find ourselves in a maelstrom of data, thanks to the Internet of Things (IoT) and the proliferation of digital infrastructure and connected devices. Virtually everything we do on mobile devices can be tied to a place and time. A google search will reveal dozens of city 'dashboards,' which store and stream data from sensors deployed across the world. If we consider data and its connectedness a utility, like many new utilities, it is initially ad-hoc with different often uncoordinated providers (Graham, 2002) and the infrastructure that sits behind it is thus contested. Some initiatives are driven from the top-down, funded by multinational corporations focused on monetizing the infrastructure (Romm, 2015). Others are bottom-up community initiatives like The Thing Networks, creating community sponsored infrastructure. In different ways both are interested in the creation of new value through data, something that Speed and Oberlander are interrogating through Design Informatics (Speed and Oberlander, 2016). Although there is a history of using information to inform decision making in regard to the built environment, I suggest we are entering a profoundly different epoch. One where the quantity, quality and granularity of information available on the built environment is unprecedented in human history. The challenge is not necessarily finding data, it is the creation, encoding and reproduction (or visualization) of data at a time and place which is meaningful and useful. The construction process has, historically, been resistant to innovation and new technology, and it is reported that approximately 80% of technology implementations and innovations do not persist beyond trials within the construction environment (Peansupap and Walker, 2005; McMeel, 2009). It is suggested this is because the construction environment is — partially at least — highly dynamic if not chaotic (McMeel and Coyne, 2004; McMeel, Coyne and Lee, 2005). It is contingent on weather, it is necessarily dirty and dusty, both of which are highly problematic for technology.

However, the use of technology and data in architecture and construction is not a new challenge or innovation. It can be traced back to the 1400's when the Architect and Artist Alberti was pioneering numeric encoding of graphical information (Carpo, 2011, p. 54). Alberti was primarily attempting to facilitate the reproduction of his complex and detailed map of Rome, the 'Discriptio Urbis Romae' (Carpo *et al.*, 2007). Alberti realized there was value in enabling and allowing the sharing of his map. Thus, he created a device and a numerical annotation system that would allow anyone to accurately locate key locations within Rome on a surface. This would make it considerably easier to accurate locate points and create an accurate scaled visualization that was geometrically superior to anything currently in existence. Returning to the subject of this paper what we have in Vitruvius and Alberti is part of a historical continuum that recognizes the value of data as well as the development of technology and machines for its encoding and visualization.

Augmented Reality (AR) is part of this continuum of innovation and presents new possibilities for sharing, reproducing and visualizing data. Research elsewhere has been exploring the potential for AR using iPads to augment construction drawings and navigate virtual spaces (Amor *et al.*, 2012; McMeel and Amor, 2013). But data and the infrastructures through which it flows has come under scrutiny from various geographers, economists and theorists that claim it influences our decision-making (Schön, 1979; Massey, 1994; Thrift, 2005). The challenge becomes how to use it in a meaningful way. Buildings, during their construction and operational lifecycle generate copious amounts of data (Burry, Burry and Davis, 2011). Although the software systems are often closed which significantly limits data sharing and innovation (McMeel and Amor, 2012).

The research covered in the following sections documents the robotically assisted construction of an 'igloo' structure from composite panels. The project is a collaboration between the Centre for Advanced Composite Material and the Faculty of Creative Arts and Industry, both located within the University of Auckland in New Zealand. During the construction process we want to visualize structural data onto the real-world composite components before they are fixed in place. The aim of the research is to investigate techniques for inserting valuable data in complex assembly processes to help improve decision making and reduce error within those processes.

2. BACKGROUND

The construction industry has a checkered past with regards to productivity. When compared to improvements in the manufacturing and finance sectors, construction appears relativity unchanged in the past 30 years (Ruddock, 2006; Bock and Linner, 2009; McMeel, 2009). There have been various attempts to address this, in the UK alone two major reports influenced revisions to construction procurement practice in 1990's (Latham, 1994; Egan, 1998). The results were mixed, some selective implementation of the recommendations did solve a number of preexisting problems. However, the changes to procurement most notably the introduction of PPP (Public Private Partnerships), created new problems with quality and lifecycle maintenance (Bresnen and Marshall, 2000; Hill, 2001). Currently the UK has established the BIM Task Group, aimed at implementing BIM, in an attempt to again improve the design and construction process.

Construction continues to come under criticism, in particular because it generates a remarkable amount of waste (Bossink and Brouwers, 1996). It also causes significant disruption particularly when construction is in an urban or suburban area. This is particularly relevant in Auckland, New Zealand where a housing shortage and a new regulatory plan have dramatically increased construction in these areas. It is becoming apparent through academic studies and reports in the popular press that traditional construction logistics and timeframes have a significant impact on surrounding residents quality of life (Barton, 2014; Gordon, 2015; Priestley, 2015). Increasingly, construction is not on ‘green field’ sites, it is in urban or suburban environment. As such there continues to be a need to identify ways in which construction can evolve into a faster more efficient process.

There have, of course, been innovations and improvements to building construction. There has been steady progress in methodologies for off-site construction such as panelized and volumetric approaches to building. Cladding systems have widely adopted a panelized approach, although much commercial construction remains an on-site activity. The evolution of prefabrication—now widely accepted—was not without early implementation problems. Initially it suffered from quality issues and occasional structural failures (Pearson and Delatte, 2005) and by the 1980's it was becoming synonymous with socio-economic problems (McLeod, 1983). Currently off-site construction is much more reliable and associated with quality; it is the core of companies like Lindbacks and HUF-haus. These companies’ on-site activities are best described as ‘assembly’ rather than ‘construction,’ which is faster and produces less waste. Other companies such as FACIT Homes take a different innovative approach. They move shipping containers onto site, fitted internally with a computer numerical controlled (CNC) router. On site bespoke plywood boxes are manufactured, which interlock becoming the primary structure of the building; it is analogous to the process of assembling Lego. However, because the construction sector is largely made up of small to medium sized enterprises (SME's), much building work remains traditional. The investment need to facilitate the transition to modern methods of construction such as prefabrication mean it is out of reach for approximately 90% of the construction sector that is comprised of SME’s (McMeel and Sweet, 2016).

Currently automated construction is only one of a series of ongoing initiatives intended to produce productivity and quality improvements in the construction sector. Most developed nations also have BIM (Building Information Modelling) initiatives as well as working groups researching Lean Construction and Integrated Design and Delivery (IDD). This reflects the growing concern that construction is in need of dramatic change on many fronts. In order to find a meaningful way forward this research turns towards the marine composite material manufacturing sector. In many ways it is very similar to the construction sector; it builds big things, which are highly engineered and involve a lot of specialist collaboration. A key point of difference is that they are more advanced in their use of automated fabrication, testing and computer simulation. By looking at this sector we gain valuable insights into possible ways for the construction sector to evolve and what immediate research might produce results.

2.1 The Composite sector: challenges and opportunities

The composite manufacturing sector is currently facing challenges that are relevant to the construction industry. This provides a useful lens through which to look at the construction industry; it also might point to areas of focus for research within the construction sector. Specifically, composite construction is like building construction in at least two ways. (1) It relies on individuals and their expertise, but test data can be difficult to access by these experts in a hands-on manufacturing/on-site environment. There is interest exploring how test data can be visualized and made available to experts during fabrication to assist their decision-making. (2) They are faced with the problem of how to use these sophisticated fabrication machines when the thing being fabricated–parts of a yacht (or building)–is bigger than the machine can make? In this project we were presented with the opportunity to investigate these two aspects.

2.2 The research aims

The research had two specific aims: (1) To create a technology demonstrator using general purpose manufacturing robots that could be moved around a construction process and continue to assemble an object from any location. Thus being able to assemble something much bigger than where the robot is fixed in place. (2) To visualize and reintroduce structural component data into this construction process. The project does not seek to address or report on any specific Health and Safety aspects of AR as these are well reported elsewhere (Wang and Dunston, 2007; Sulankivi *et al.*, 2010).

3. THE DIGITAL IGLOO PROJECT

To address the two aims we undertook a research project to design and assemble a ‘digital igloo’ (Fig. 1). The project had four distinct parts (1) automated fabrication and robotic assembly of unique composite panels into an igloo structure (2) visual augmentation of individual composite panels with data obtained from specialized structural testing (3) implementation of a parametric design system for the automatic generation of panel CNC cutting files and robot instructions for assembly (4) visual tracking system to monitor robot location.

Fig. 1: The Digital Igloo.

3.1 The research problems

The research was addressing two problems that are common to composite manufacture and assembly but are also applicable to other industries such as construction. First, composite manufacture continues to be largely a manual process. It relies heavily on individuals with expertise and knowledge of the process, which limits the industry as a whole from scaling their market and customer-base. There is significant interest in exploring how and where processes might be automated. Second, flaws within the inside of a composite panel cannot be seen but can be identified through various structural tests. If a machine or manual fabrication process has a fault this most often within the hidden interior layers of the composite panel and not visible to the naked eye.

To fully understand the structural data is must be viewed in parallel with the panel. This is necessary because anomalies in the data can result from a change in panel thickness or shape. Results can also be affected if a panel has a penetration designed into it or has another material inserted. The result of this is that accessing a panel and its numerical data is a highly specialized process. The data is not fully understood by the fabricator and vise-versa the panel construction is not fully understood by the Finite Element Analysis expert. In addition, these panels may need specialist equipment or be brought to a specialist location to obtain the structural data. All of which disrupts the manufacturing process, leaving expertise and data scattered across various disciplines, locations and formats. Some recent research has used affordable sensors in combination with innovate sonic testing techniques to gather data data quickly and easily from panel in the assembly environment and visualize it on a laptop. This novel innovation solves some of the problems of gathering and visualizing data without major disruption of the manufacturing process. However, laptops are cumbersome and the data remained abstracted in a simple 2D graphic environment. We hypothesize if we are able to combine a more sophisticated visualization of the data and the physical panel then decision making can be improved while the manufacturing process can remain undisrupted.

3.2 The solution

The specifics of the automated fabrication and assembly part of the research will be documented elsewhere. This paper focuses on the AR component of the research. Within this context the Microsoft Hololens was the hardware solution chosen for several reasons: it is widely available; has a mature development kit; and is quick to learn. The Hololens is also wireless, this is critical within the research to maintain maximum mobility for users. Finally, it is hands free, worn like glasses or a headset and once turned on can be controlled with gestures. Thus there is no need to touch the device to interact with it. This was desirable within a manufacturing environment where dirt and moisture are present and protective clothing including gloves need to be worn.

4. EXECUTION AND ANALYSIS

This section will first explain how the four individual parts of the project merged together into a three day robotically assisted build of a 'digital igloo' by two research assistants. It will then turn specifically to analyzing the AR component of the project.

4.1 Execution

The project was executed in an Optitrack suite, which is a room fitted with high definition cameras around the perimeter. The position of an object fitted with special markers can then be tracked within the space with sub-millimeter accuracy. This technology is most commonly usually used to motion-track people for special effect in movies. In this case we placed special markers on our general-purpose ABB IRB120 robot, thus enabling us to track its precise location within the room (Fig. 2).

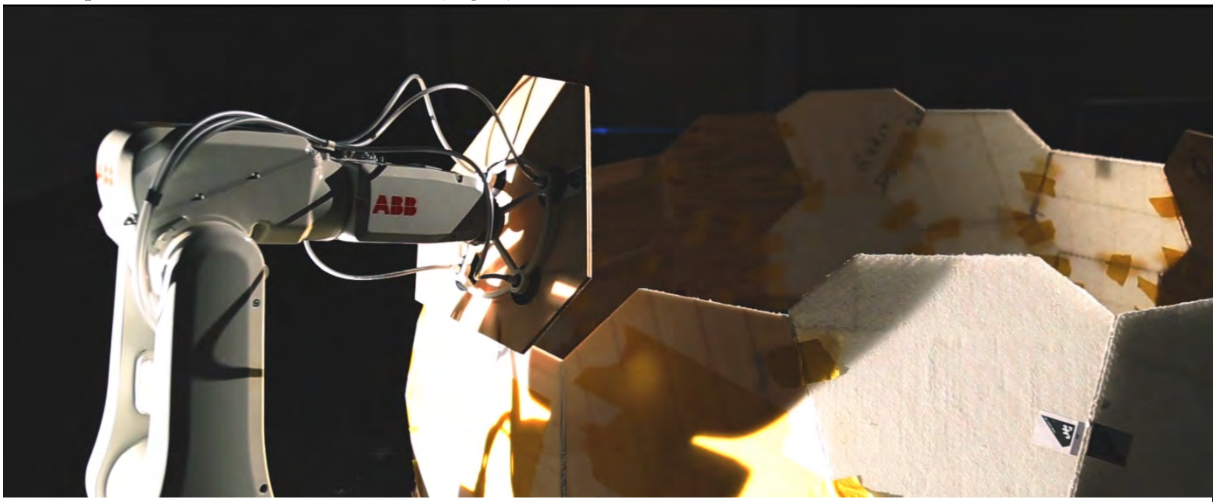

Fig. 2: Automated robotic assembly process.

In parallel a sophisticated parametric design system was created using the Rhino 3D design software and the Grasshopper parametric software. This system was designed to:

1. Enable the design and modification of an igloo structure approximately 1.5 meters in diameter.

2. Automatically extrapolate and export individual panel geometry for cutting on a computer numerical controlled (CNC) router.

3. Automatically generate instructions to enable the robot to pick up and position a specific subset of panel in a specified sequence for assembly.

4. Automatically create undated instructions every time the robot was repositioned to enable easy and quick continued assembly from the new position.

A special base was created for the robot with an integrated 'jig.' This was a feature to hold each panel is a precise and known position, critical to ensuring the system can pick up and position panels accurately.

With the robot in a given position, a researcher manually determined the number of panels that could be positioned from that specific location. These panels were programmed in order, positioned on the robots' jig sequentially and the instructions sent to the robot. From any one position the robot could position between two to four panels, then the robot was relocated to a new position. The new location was determined by the researchers using their expert knowledge of the process and what was or was not possible. The Optitrack position tracking technology combined with the parametric software system enabled automatic regeneration of the robot instruction set, which is what makes this innovation possible (**Error! Reference source not found.**).

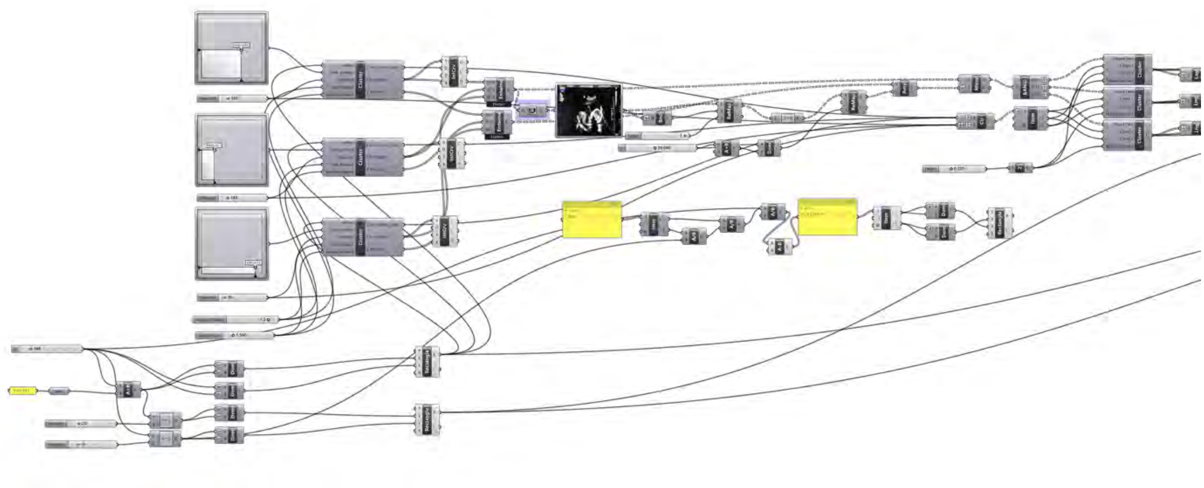

Fig. 3: Parametric design system, created in Grasshopper.

The innovation here was enabling the ad-hoc and improvised repositioning of the robot. Traditionally robots are fixed in position and objects they interact with have their positioned accurately calibrated. This is an important process that is very time consuming. As a result, robots are rarely moved and their operations are thus limited to an area they can reach.

It is useful to compare this processes with the previous phase of the research which explored the implementation of the parametric design system with a fixed—not mobile—robot. In this case the maximum size of the igloo was limited by several factors including, how far the robot could reach, what mechanism was used to pick up the panels and where the robot was fixed in relation to the igloo. The same robot was used, an ABB IRB120 robot, and during the first phase of the research the maximum size of the igloo was 120mm (Error! Reference source not found.). In this second phase of the research where the robot was mobile the diameter possible was 1200mm; an increase of 1000 percent.

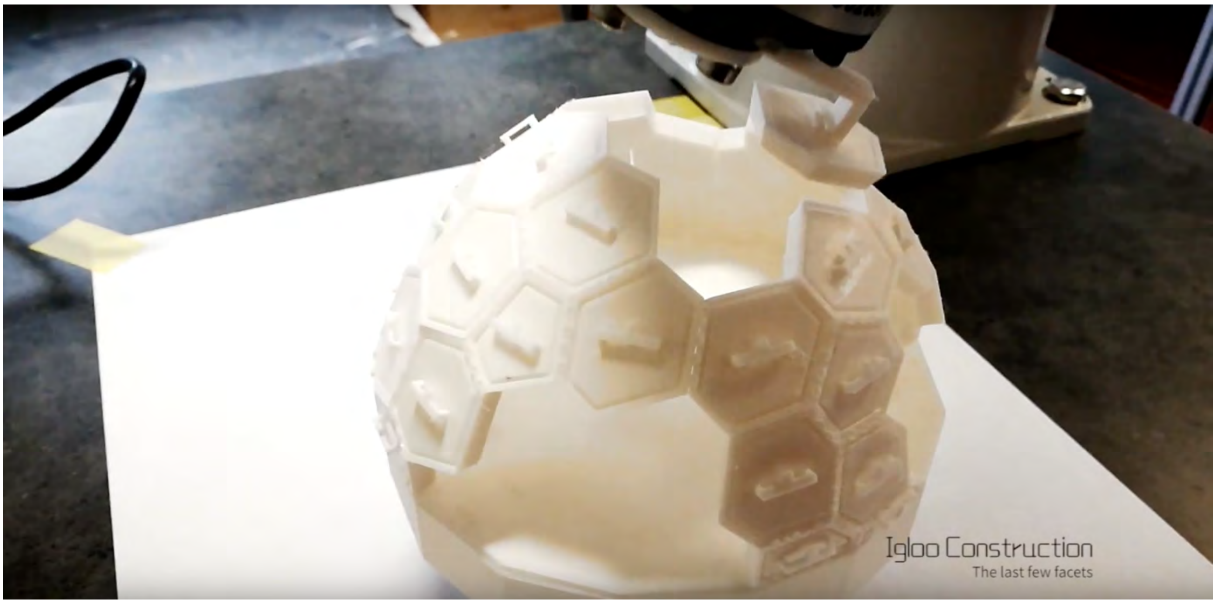

Fig. 4: Digital igloo, assembled from a fixed robot position. Image by Xi Shao

4.2 Augmented Reality Implementation

The AR concept for the project was first to implement a technique that would allow for the recognition of individual panels in the work space. Then to visualize the structural data for that panel within the Hololens and make it appear overlaid on the panel in the real world through the Hololens.

To recognize the individual panel several vison systems were investigated, the most reliable system used unique markers fixed to each panel. To visualize the structural data two data sources had to be combined. Firstly, the shape of each panel had to be imported from the parametric design system. Then the structural data was imported from a Comma Separated Variable (CSV) file. A mesh surface was created from these two pieces of data with the height of the surface at any given point representing a key piece of structural data. If this variable increases in value the height and color of the mesh changes (**Error! Reference source not found.**) to visually represent the data.

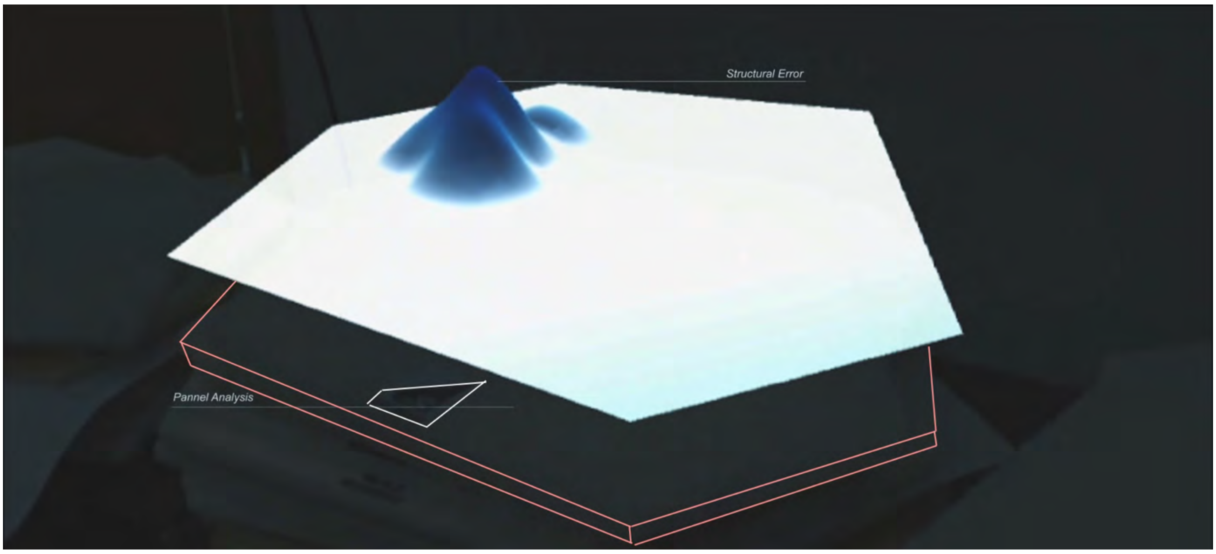

Fig. 5: AR environment with physical panel and overlaid data.

The unique markers served a second function, the AR system uses the markers as reference points to overlay the mesh. As the user moves around the panel the mesh automatically reorients itself. This can be seen in action in the following video https://youtu.be/GpnkNORIP9M. The panels and the markers can be clearly seen in Figure 1.

Within the Hololens environment a user would see a large white polygon, which is the visualization of the structural data in mesh form (**Error! Reference source not found.**); the blue peak on that polygon is a structural anomaly. Beneath the mesh, for the benefit of the reader, the panel has been outlined and the small polygon is where the unique identification marker is located. Even in the dark environment in which this the assembly took place the marker identification and position system worked remarkably well.

4.3 Analysis

The analysis will be discussed under two themes (1) problematics of automation and (2) the need for co-production. First the research supports the supposition that it is problematic to automate everything. Recent reports of Tesla removing robots from their factory and replacing them with people add increased support to this position (Maynard, 2014; Gibbs, 2018). When assembling the igloo, the researchers intervened regularly, mainly because certain tasks required judgment or improvisation. It was more efficient to do tasks like applying jointing glue manually. This resulted in users' hands getting dirty, but this did not inhibit their ability to call and overlay data using the Hololens gesture interface.

In parallel, the robotic assisted assembly, was helpful where time was required to make a judgment call. The robots could be paused, holding the panel in its precise position while a problem was discussed, or data was called up in the Hololens and overlaid on the panel in real time. Due to time constraints it was not possible to test this system with industry users to assess benefits and legibility of data. However this will be an important aspect to study in the next phase of research.

The second theme that emerged, related to the first, was co-production. The researchers and the robot were working together to assemble the structure. Each doing things that the other were not easily capable of. Framed like this, in any given process, it will be likely people will need hands free to control additional machinery. In this respect it becomes important to analyze and understand the processes and roles of construction in terms of the extent to which their characteristics involve repetition or improvisation. This will help future research target meaningful areas for automation.

5. CONCLUSIONS AND FUTURE WORK

The process revealed a number of areas that require further investigation. Firstly, in the same way we automatically recognized the position of the robot–it is also necessary to implement technology to accurately locate the build platform. This project used a plywood ring to fix the igloo in place (Fig. 1), the ring was manually measured and positioned. A small rotational error of approximately 3 degrees was not apparent as the first and second panel were fixed because it was visually insignificant. However, as the third and fourth base panel were positioned the rotational problem became obvious as the panels were not aligning with the base. Although the base was repositioned correctly, the panels already fixed were now out of position; this caused ongoing issues as the assembly progressed. A valuable piece of additional research would be automatic recognition of fixed objects in space to which the assembly must relate. A second area for future work would be simulating the assembly process. This innovation, potentially using the HoloLens, would also help identify any anomalies in the positioning and calibration of the system.

Within the context of construction, deviations and errors or 1-2 millimeters or degrees are acceptable. Within the context of automation, it is not. As these errors compound and result in inaccuracy that calls into question the claimed precision and quality benefits of automation. Thus, this presents cultural issues for construction to change what is and is not deemed acceptable. Certainly with robotics and AR our expectations are often informed by both science fiction and with cutting edge research. Recent reports of robots building IKEA furniture and robotic promotional videos from Institute of Computational Design Zurich make robotic assembly look effortless. They do not necessarily fully convey the complexity, diversity and man-hours of the teams that bring these robotic concepts into reality. The aim of this research was to deepen our understanding of the opportunities and obstacles for robotics and AR in an automated construction environment.

In summary although the technology demonstrator proved proof-of-concept it brought several other factors to center stage. Firstly, at every stage of set up there were potential deviations that added small calibration errors. Although these were small, perhaps a 1-2 mm deviation or 3-degree rotation deviation. These compounded each other resulting in a maximum error of approximately 20mm during construction. The room in which this build took place also suffers from significant solar gain at key points of the day. Temperature is known to affect the Optitrack capture data but to what extent it influenced accuracy is not known. Secondly, not everything could be automated and the degree to which a task or role requires judgement or improvisation related directly to how simple or complex it is to automate that process. Immediate future opportunities for robotics are then most likely to succeed within processes and practices where there is some–but limited–judgement or personalization required. The Augmented Reality aspect of the research also suggests potential in displaying and combining disparate information. However some mutual understanding of the data and objects from the disparate domains is critical for the data to be useful in specialist contexts such as these.

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IMPROVING STUDENT UNDERSTANDING OF CONSTRUCTION TERMS AND TECHNIQUES USING ANNOTATED DIGITAL MODELS

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ABSTRACT: *This project sought to determine whether digital models with embedded element descriptions could solve a problem observed whereby students experienced difficulties identifying and understanding residential timber frame systems, their specific timber members and published definitions. The project establishes that digital resources are more engaging media for students learning timber frame design than just verbal annotation, and also very effective as a learning resource augmenting written texts especially for English additional language students. This study shows students find digital models useful towards achieving tangible learning outcomes by encouraging engagement with the model. Results indicate that students enjoy model interaction and realise the benefits of their use. Methodology was centred around a case study of two cohorts studying timber frame design in a construction course. Preparation included creation of a timber frame model with member names labelled from a local building standard thus aligning with current terms and assisting students with up to date timber member identification using a free model viewer. Resources provided to students included a class demonstration covering downloading the viewer, how to view various elements and also the embedded definitions. Students from two different semesters were surveyed and the tutor interviewed informally collating a range of evidence on the model's benefits which were found to be overwhelmingly positive. Results confirm students enjoy using digital BIM models which enhance their learning and assist them in achieving better assignment outcomes. This research is important because it demonstrates one approach to solving a problem experienced by many students especially English additional language who can often struggle with the technical jargon of discipline text books and legislation. BIM models are shown here to help bridge learning gaps and the teaching approach is viable for application in both other areas of construction and jurisdictions beyond New Zealand.*

KEYWORDS: *BIM, Learning, Definitions, Teaching, Models*

1. INTRODUCTION

This research seeks to solve a problem observed where many students experienced difficulties comprehending the principles of residential timber frame design. The investigation also addresses issues where students struggled with element identification e.g. piles, nogs, dwangs etc and the parts played by language capabilities and terminology in contributing to student's lack of understanding. Although the focus in this research was on residential timber frame systems, their specific timber members and published definitions, such problems are not confined to teaching timber frame design. The aim of our study is mainly to aid identification of system elements and context meaning this generic approach would work also for steel and concrete design despite the inherent material and detail differences. Using a 3D digital model to try to bridge perceived learning gaps could equally be employed in teaching these systems. This is especially true where the model used as a learning resource is not intended to show in detail how distinct construction system components are fixed together.

Differences in detailing, fixing and terminology can be addressed by embedding information into objects as in our model where names, terms and definitions follow the New Zealand Building Code residential timber frame design acceptable solution NZS3604:2011. Similar information embedded into models can be region or system specific meaning this proposed approach is not limited by such constraints and can work across residential and commercial construction contexts.

The study group in this project were Architectural Technology students across two different semesters, one late 2017 and the other early 2018 taking the level 5 Construction for Small Buildings paper of the New Zealand Diploma at Unitec, New Zealand. This course is common across options of the diploma qualification offered at Unitec including Quantity Surveying, Construction Management and Architectural Technology and is a core paper in the overall award. Course content focuses on Timber Frame residential design to NZS3604:2011 the most important design guide on this topic in New Zealand. Definitions provided in this standard can be challenging for new students and many for whom English is an additional language. This project investigates whether using BIM models can make learning a simpler and more engaging process. The overarching intention seeks to solve identified issues by enhancing student engagement in course content and augmenting their learning via the BIM model.

The digital model provided to students was intended to encourage them to engage with it and the other resources made available to them on the course online learning platform Moodle. The complete model is shown in Figure 1.

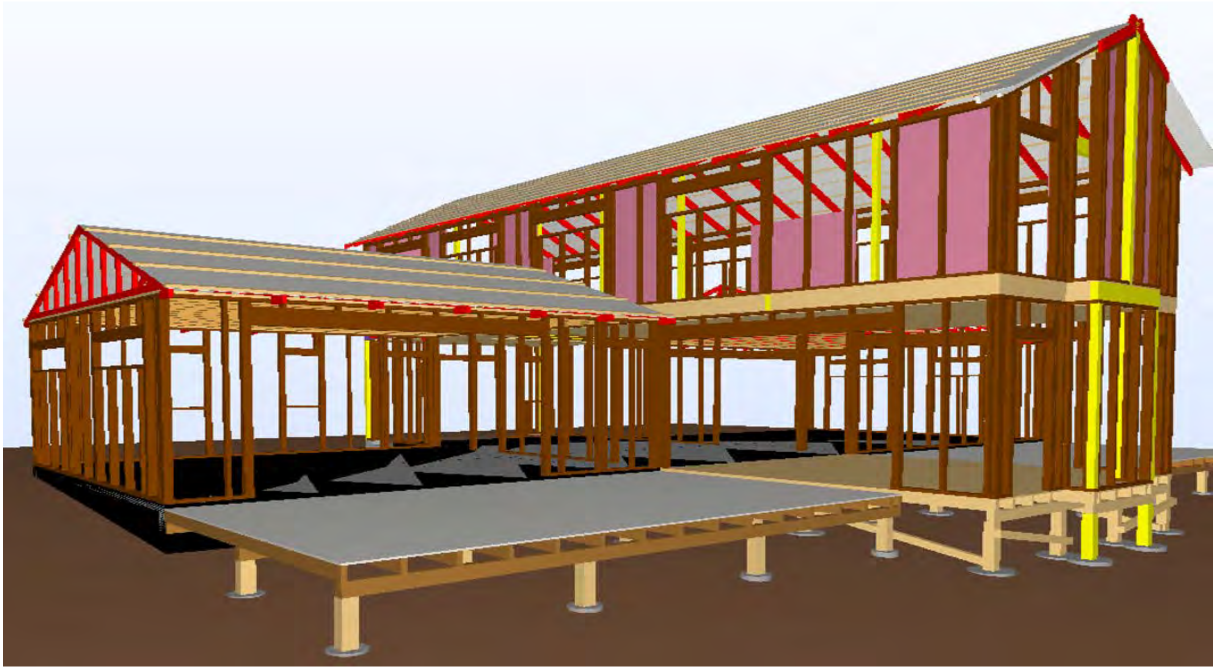

Fig. 1: IFC model of timber framed house designed to NZS3604:2011

2. LITERATURE REVIEW.

2.1: Learning BIM software to meet the needs of industry.

The importance of enabling students to become comfortable in the use of BIM technologies is highlighted frequently along with keeping learning aligned with industry requirements(Azhar, Sattineni, & Hein, 2010). Students should be taught how to engage with BIM models so that they can perform their jobs more efficiently.(Shelbourn, Macdonald, McCuen, & Lee, 2017):(Ibrahim, 2007). Ibrahim considers an ever-present learning curve to acquiring sufficient software skills to perform even straightforward tasks noting students need support at these formative stages. He states also that students must feel empowered to encourage further engagement with software applications. The importance of engaging with the digital model files is also widely stated(Azhar et al., 2010):(Barison & Santos, 2013):(Ibrahim,2007).

2.2: How models were used in research projects.

The use of model authoring was reported frequently across much of the literature as an approach to teach BIM principles. Students are often tasked with creating and editing a model or sometimes to attempt sophisticated tasks involving programming (Azhar et al., 2010):(Barison & Santos, 2013). This is a common model purpose with many instances requiring a construction sequence BIM use. The aim of this approach is that students utilise information from models to make informed decisions towards successful completion of other tasks(Azhar, Khalfan, & Maqsood, 2012), for example as described by (Kim2012) in creating digital models from 2D drawings and then using this model for a quantities take off.

2.3: Perceived barriers to BIM implementation in courses.

Many BIM implementation barriers were identified in literature including difficulties balancing teaching of required course content and relevant BIM software. Ascertaining which software skills students required in studies and future careers posed issues and some students questioned why they learnt skills such as model authoring when future roles probably required only interrogation of models for data(Shelbourn et al., 2017).This research also highlighted challenges of tutor buy in to new approaches and learning software. One study concluded that few schools were addressing the challenges of preparing students for future BIM focused workplaces.(Ibrahim, 2007).However other studies presented applications of BIM teaching environments that would appear to contradict this opinion(Azhar et al.,2010):(Barison & Santos, 2013):(Kim, 2012).

2.4: Perceived benefits of BIM implementation in courses.

Much consensus was observed highlighting BIM benefits, especially 3D visualization aiding student understanding and this included where paper research aims and objectives varied(Azhar et al., 2012):(Shelbourn et al., 2017). The most common theme identified in literature was the effectiveness of BIM as a learning tool.

2.5 Effectiveness of BIM as a learning tool.

Student perceptions of BIM's value as a learning tool was evaluated in some studies by survey and others by analysis of actual course grades(Azhar et al.,2010):(Kim, 2012). Methods of embedding BIM into curricula varied with students sometimes producing models from 2D drawings supplied (Azhar et al., 2010). Others provided students with physical models from which they generated 2D views before producing BIM models(Kim,2012). This study noted difficulties students had reading 2D drawings and with visualization concluding that traditional lecturing does not help students visualize buildings or construction systems. Shelbourn discusses the importance of scaffolding in supporting learners in early stage development of new skills such as using BIM software. This support can be reduced as learners progress allowing them to achieve course outcomes themselves and providing further learning motivation. This paper references a non-BIM study by Koltich and Dean (1999) which discusses the engaged critical paradigm teaching model. This stresses the importance of student engagement thus developing more profound levels of understanding. Plass et al.,1998 investigated additional language multimedia environments, a study overlapping this paper's intentions. Native English-speaking participants engaged with a resource in German and tests were then carried out assessing comprehension. Two modes of understanding were identified: verbal annotation where students read just text and visual annotation where pictures or video clips denote words. Students were found to remember translated terms better when both visual and verbal annotation were used as opposed to just one method. This finding is still relevant to our research project despite this paper's age.

2.6 Gaps in the literature reviewed.

It was difficult to find literature which aligned very closely with this study's method of using BIM models in teaching. Models are commonly used as vehicles to increase learning and engagement but focus on teaching BIM as a subject rather than exploring the use of a model as a teaching tool for other construction material. Much of the literature focused on BIM as a learning outcome, not use of models to aid student comprehension. No discussions were found on creating teaching resource models only nor what the briefs for these should be compared to models used within industry.

3. METHODOLOGY

The academic context to this research was the Construction for Small Buildings level 5 paper studied as part of an overall New Zealand Diploma in Construction level 6 award. In an international context this award equates to level 5 Higher professional qualifications on the European Qualifications framework. Qualifications are typically 120 ECTS(European Credit Transfer and Accumulation System) and aim to prepare learners for employment (ANQEP, 2016).The methodology includes case studies of 2 student cohorts from 2017 and 2018 taking the paper in their Architectural Technology diploma studies and involved project preparation, survey and a semi structured interview. Initial preparation entailed producing a timber frame BIM house designed to comply with NZS3604:2011 modeled using ARCHICAD to incorporate text definitions from the standard. This involved identifying separate discrete elements making up the dwelling timber frame and labelling each one to align with the NZS3604:2011 definition. Separate layers were set up for individual elements such as timber studs, lintels, rafters, etc. and even steel straps provided as roof bracing. In total some 68 separate layers were required identifying the various elements.

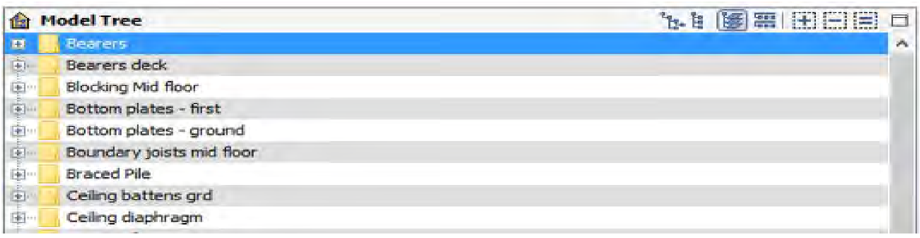

Fig. 2: Element layers named as per NZS3604:2011 definitions.

Figure 2 shows a selection of the layers and naming framework used. This method was utilized with an eye to the future navigation of the model by the students and sought to make the resource less daunting and more user friendly, attractive and engaging. Figure 3 shows a view of the model restricted to a specific sub system allowing students to view only the sub floor framing elements.

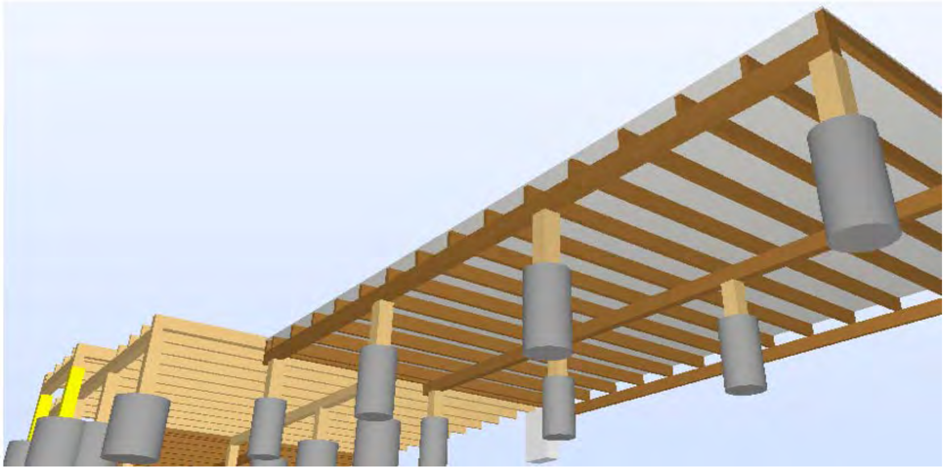

Fig. 3: Model view with a specific sub system selected (sub floor framing).

Following on from this listing and identification exercise was the actual embedding within the 3D elements of their NZS3604:2011 definitions. The final stage was to save the ARCHICAD model as an IFC file that would be available for use with a number of freely available BIM model viewers. The default package used after testing to see that model data came through the file conversion intact was Solibri Model viewer, but the IFC model will open in a range of BIM viewers such as Tekla BIMsight.

Figure 4 presents a view where a student has selected an individual element in Solibri Model Viewer and hovered over its' description in the information window to access the embedded NZS3604:2011 definition.

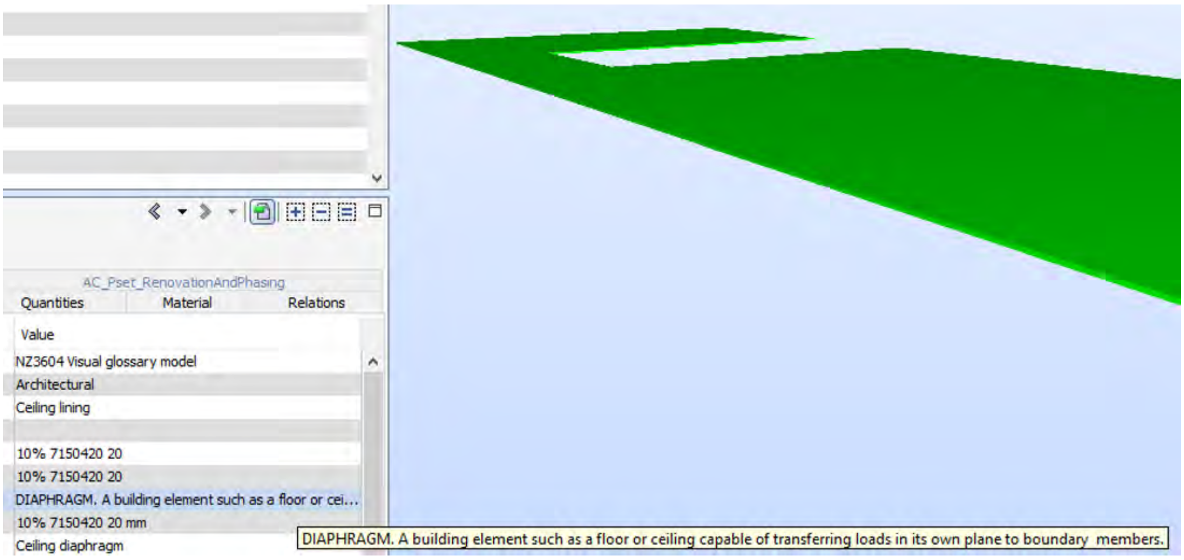

Fig 4. Embedded NZS3604:2011 definition of a diaphragm popping out in Solibri Model Viewer.

The final model was made available on the online learning platform (Moodle) for student download. Various support resources were provided here also such as a demonstration video and a startup user guide for Solibri Model viewer. To encourage students to use the model, some quizzes were set up in Moodle for the 2018 cohort requiring the students to access the BIM model to obtain the answers. These quizzes each focused on specific systems, e.g. Timber Sub Floor, Concrete Slab and Wall framing and were designed so that the first question of each quiz required students to identify and make visible the elements necessary for that specific system from a list provided. The intention was to direct students to a simplified model which would be easier for them to navigate through to locate the elements referred to in the questions.

In order to assess the value of the annotated model resource, student participants were asked to complete an anonymous twenty question survey using Google Docs. The survey is available online using this link. Questions were grouped to gather information across areas such as prior experience with BIM software, ease of accessing software resources provided including model and viewer, model value as a learning aid, student engagement with model and its benefit to English additional language students. Most questions used Likert scales with resources and software queries seeking answers ranging from simple to very difficult. Questions regarding model value as a learning resource asked how strongly students agreed with statements in areas such as aiding understanding and whether students felt their assignments had improved from using the model.

The 2017 student group comprised 99 students and 14 people responded to the request to complete the survey questionnaire. The class in semester 1 2018 was made up of 69 active participants and 42 survey responses were received. A semi structured interview was held with the single course tutor to get his perceptions regarding the value of the BIM model approach as a learning aid. This was to establish from the teacher's perspective whether the BIM model teaching strategy helped resolve the problem previously identified with student learning. Gathering student and staff data sought to help assess the BIM model approach from each side and its tangible value in bridging identified learning gaps.

4. FINDINGS AND DISCUSSION.

4.1 Findings from 2017 semester 2 student cohort.

Despite the small 2017 sample size of 14 students, responses and especially comments provided valuable data towards improving student engagement with the model teaching strategy the following year. A majority of respondents (9/14) stated they already had good experience of BIM model use and 9 also found the class demonstration of value. Half of respondents were neutral about the value of the quickstart Solibri guide and Youtube video but 6 students found them useful and of these 4 very useful. Software navigation and the ability to identify specific system elements was found to be quite easy and students did not have issues selecting individual timber frame elements and accessing relevant information including the NZS3604:2011definitions embedded within the 3-D objects. Table 1. presents the breakdown of responses related to the ease of use of the model viewer.

Table 1: Questions on ease of download and use of BIM viewer.

Question number	**Simple**				**Difficult**
Scale range	**1**	**2**	**3**	**4**	**5**
Q7. How easy was it to access, download and open the IFC BIM model of the timber framed house made available on Moodle?	42.9%	14.3%	14.3%	28.6	0%
Q8. How easy was it to Navigate the Solibri software to view the house model?	21.4%	28.6%	35.7	14.3%	0%
Q9. Was finding the information and definitions embedded in the model elements a simple or difficult process?	14.3%	28.6%	50%	7.1%	0%

Students felt the model helped them identify residential timber frame elements with unanimous agreement on aspects such as identifying individual elements and their forms, the embedded definitions and structural context regarding loads sustained and transferred. All respondents thought the model helped in understanding better an elements place in the overall house framing system and in sub-systems such as Sub floor, Wall, Roof etc.

Table 2 shows students' responses to statements asserting the value of the model. The majority thought the model useful in learning timber frame residential design. Some comments requested more use of models and others reiterated how helpful the class demonstration was. An overriding message however was that more early stage support was required to help students effectively use Solibri and that students wanted to learn and use it more. Nine respondents identified as English additional language students, and stated the model helped overcome language difficulties. Eleven participants said they really enjoyed using the model. None stated a categorical dislike.

Table 2: Questions on how software supported student learning

Question number	Don't agree				Agree strongly
Scale range	**1**	**2**	**3**	**4**	**5**
Q10. How much would you agree with this statement? " The model definitely helped me in identifying the individual elements of the timber frame house"	7.1%	0%	21.4%	57.1%	14.3%
Q11. How much would you agree with this statement? " The model definitely helped me in viewing each element's physical form and shape"	0%	0%	21.4%	64.3%	14.3%
Q12. How much would you agree with this statement? " Engaging with the BIM model definitely helped me understand the element definitions provided in NZS3604 much better than just reading them in the book"	0%	0%	28.6%	57.1%	14.3%
Q13. How much would you agree with this statement? " Engaging with the BIM model definitely helped me see how the elements of a New Zealand timber framed house relate to each other. eg bearers supported on piles, joists supported on bearers and things like rafters onto walls"	0%	0%	21.4%	64.3	14.3
Q14. How much would you agree with this statement? "I liked the way the BIM viewer allowed me to see elements individually and then together with others shown transparent if I wanted "	0%	7.7%	30.8%	23.1%	38.5%
Q15. How much would you agree with this statement? " Using the BIM model definitely helped me learn and understand more easily the way a timber frame system in a house works"	0%	14.3%	21.4%	50%	14.3%
Q16. How much would you agree with this statement? " Using the BIM model definitely helped me improve the quality of the assignment submissions I made to my courses"	0%	14.3%	28.6%	42.9%	14.3%

4.2 Findings from 2018 semester 1 student cohort.

This class consisted of 55 students and from this cohort 42 responses were received.

Table 3: Questions on ease of download and use of BIM viewer.

Question number	Simple				Difficult
Scale range	**1**	**2**	**3**	**4**	**5**
Q7. How easy was it to access, download and open the IFC BIM model of the timber framed house made available on Moodle?	23.8%	40.5%	28.6%	4.8%	2.4%
Q8. How easy was it to Navigate the Solibri software to view the house model?	21.4%	26.2%	38.1%	9.5%	4.8%
Q9. Was finding the information and definitions embedded in the model elements a simple or difficult process?	19%	42.9%	23.8%	11.9%	2.4%

Almost 44% of respondents stated they had never used BIM models previously. Most found the support resources provided very useful with 74% stating they liked the in-class demonstration and 90 % stating the Youtube demo and written quickstart guide were of benefit in getting started with the Solibri model viewer. These student resources were the same across both years. This cohort found model download, its navigation and finding embedded definitions within specific objects all simple tasks. The results summarised in Table 3 show that students found it simple to access the various resources provided and use them to good effect in working with the digital model. The majority of this group also said that the model helped them identify individual system elements. The results presented in Table 4 indicate that the digital model definitely helped students learn more easily and understand better how a residential timber frame works. There is generally strong agreement across the various questions supporting the view that the students found the digital model to be of real value in helping them overcome issues of comprehension and further-more allowing them to apply this knowledge in the course assessment events. Many students also believed that there was an improvement in the quality of the assignments they submitted during the course to provide evidence of learning outcomes. This included an open book examination on NZS3604:2011 in both 2017 and 2018 where students had to refer to the standard to answer questions in the test

Table 4: Questions on how software supported student learning

Question number	**Don't agree**				**Agree strongly**
Scale range	**1**	**2**	**3**	**4**	**5**
Q10. How much would you agree with this statement? " The model definitely helped me in identifying the individual elements of the timber frame house"	0%	4.9%	26.8%	43.9%	24%
Q11. How much would you agree with this statement? " The model definitely helped me in viewing each element's physical form and shape"	0%	4.9%	22%	46.3%	26.8%
Q12. How much would you agree with this statement? " Engaging with the BIM model definitely helped me understand the element definitions provided in NZS3604 much better than just reading them in the book"	2.4%	2.4%	28.6%	42.9%	23.8%
Q13. How much would you agree with this statement? " Engaging with the BIM model definitely helped me see how the elements of a New Zealand timber framed house relate to each other. eg bearers supported on piles, joists supported on bearers and things like rafters onto walls"	2.4%	7.3%	19.5%	46.3%	24.4%
Q14. How much would you agree with this statement? "I liked the way the BIM viewer allowed me to see elements individually and then together with others shown transparent if I wanted "	2.4%%	2.4%	21.4%	54.8%	19%
Q15. How much would you agree with this statement? " Using the BIM model definitely helped me learn and understand more easily the way a timber frame system in a house works"	2.4%	0%	29.3%	39%	29.3%
Q16. How much would you agree with this statement? " Using the BIM model definitely helped me improve the quality of the assignment submissions I made to my courses"	4.8%	4.8%	38.1%	38.1%	14.3%

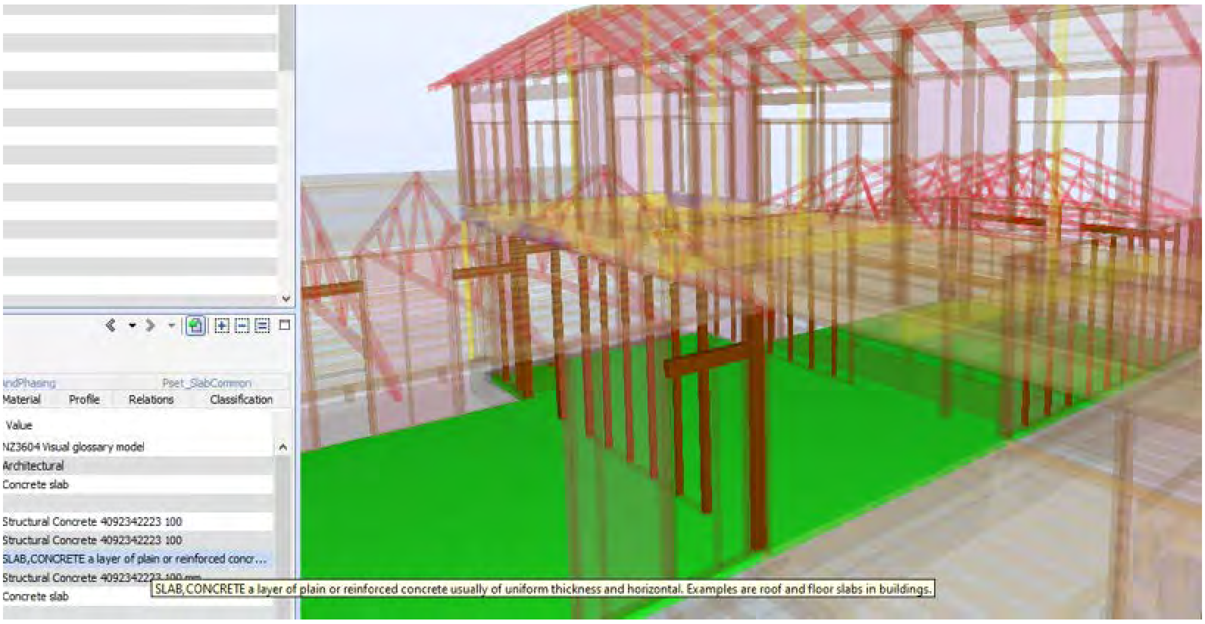

Fig. 5: Slab highlighted with overall frame context transparent.

A substantial majority (37 of the 42 respondents) stated that the model helped them see and understand how the separate elements of the timber framing system related to each other in support terms and 40 liked how they could view elements individually or in context with others shown transparently to clarify their understanding. Figure 5 shows an element selected by a student viewed with the other structural frame members shown transparent.

English was an additional language for 20 of the students surveyed and 88% of this group stated that the model helped overcome language difficulties. Overall 39 of 42 respondents stated that they enjoyed using the model and comments included some students claiming that the software was a very useful and helpful tool. One stated that he loved it as it helped him understand building and reminded him of a computer game. Another wished for more assignments to be linked to using Solibri and the model with an added benefit that students would become even more proficient in the software.

4.3 Comments from the course tutor across both cohorts.

The tutor who delivered the course provided feedback on the BIM model approach via a semi structured interview discussion. He had never really used Solibri prior to embedding it into his course delivery in 2018 and he learnt how to use the software himself as part of the project. The tutor found the software very simple in terms of acquiring the skills he needed to use the model for the purpose intended which was mainly model navigation and access to the embedded text information within specific timber elements. The researcher and tutor devised quizzes which required students to refer to the model in order to answer questions. The tutor observed students making use of the model during class and reported that many stated that they were using the model at home also. Students did not request tutor assistance with using the model as they found it relatively simple and referred to it to help them clarify questions put to the tutor relating to residential timber frame design. The tutor firmly believed that using the model was a much more useful method of explaining the element definitions of NZS3604:2011 than reading the standard alone and this he put down to the strong visual nature of the resource. He agreed with many students that the model was extremely beneficial in student identification of the individual system elements and their relationship to, and context within the overall timber frame design. He believed also that the model helped students appreciate better how elements support others within the overall timber frame and also to appreciate how the various elements transferred and sustained structural loads. The benefit of the model resource to students for whom English is an additional language was also noted by the course tutor and he found the model a valuable aid to their learning. In this respect he particularly liked how the NZS3604:2011 definitions could be made to pop out when individual elements were selected in the BIM model viewer. The tutor could not think of anything he disliked about using the BIM model approach. The tutor really bought in to the BIM model approach of teaching the course in 2018 compared to 2017 where it was not really considered a priority. As a result, he wants to investigate other ways to exploit this approach to address similar learning problems highlighted across other related courses he teaches. The tutor feels strongly that using the digital model was of great value to both him and his students and that it effectively addressed the problems students had in learning this subject matter in the past.

4.4 Discussion of findings and project relationship to literature.

In terms of BIM model experience the 2018 survey group had not been exposed to BIM as much as the respondents in 2017 but the majority across both groups found the support resources for getting started with the BIM viewer software useful. The 2018 group received more face to face assistance in class primarily as a result of the feedback received from the 2017 students requesting more support.

This aligns with literature where (Ibrahim 2007) remarked that students need to feel in control or empowered to encourage their further engagement with software applications. The improvement recorded in terms of satisfaction with resources and ability to access the model sufficiently is a positive as Unitec’s Construction Department is very keen to embed BIM across its courses to support student learning. This finding echoes Shelbourn et al.(2017) who stated that students should work with BIM models so that they can perform their future work roles more efficiently.

In terms of assessing the benefit of the digital model approach on improving student performance and grades, results from the cohorts involved in this study have been reviewed and are presented in Table3. The paper is studied by various disciplines in the Construction Department, but this research focused only on Architectural Technology students and commenced in 2017. Comparing the two cohorts who participated the overall pass rate for the course improved only marginally from 83% to 86%. However, the pass rate rose from 78% to almost 95% for the assessment which examined student knowledge of NZS3604:2011 specifically.

Table 5: Comparison of student success in Construction for Small Buildings

2016-2018.

Figures reviewed	2017-semester 2	2018 – semester 1
Course pass rate	83.3%	86%
NZS3604 test success	78%	95%
NZS3604 test average	62%	62.5%

In comparison with much of the literature on use of BIM applications in teaching, this study's requirements were aimed at a much more basic level. However the overarching purpose is shared in seeking to investigate ways to enhance student learning by encouraging greater engagement with the BIM model resource(Azhar et al., 2010).To this end both of the student sample groups in this study were in agreement that the BIM model was of great help to them in overcoming learning difficulties and this corresponded with their tutor's observations. This encompassed benefits such as seeing framing elements individually and in context with others, identification of elements and their form and shape, how elements related in structural support terms and the ability to access the element definitions within the BIM viewer. These findings align with those in literature where students had difficulties in reading drawings and therefore models were used to add visual annotation to augment the verbal annotation information provided to students(Kim, 2012):(Plass et al.,1998). The research has found that the BIM model was very helpful to English additional language students for similar reasons. Additional benefits across the student samples were that students felt that using the BIM model helped them improve the quality of their assignments. This finding mirrored some from the literature where the intention behind using the model was that students could use information found in the models to make more informed decisions equipping them to complete various other tasks with more success (Azhar et al., 2012).

Another important fact noted was that the students enjoyed engaging with the BIM model, again aligning with literature(Shelbourn et al., 2017). A prime challenge for teachers is often in achieving the balance between covering the course core content whilst concurrently trying to teach the various software applications necessary to enable BIM use as a learning tool(Shelbourn et al., 2017). The course tutor in this instance also faced such difficulties but really engaged with the digital model teaching strategy in 2018. He completely bought in to the whole ethos regarding the BIM model and how to exploit it as a learning tool. So much so that he has now declared himself a convert who wants to explore other ways that such models may be employed in the future in this course and elsewhere in his teaching.

5. CONCLUSIONS.

From this study it appears obvious that using BIM models can be a great help to students to improve their understanding of construction techniques and terminology. Both students and the tutor involved in this project agree on this. This teaching strategy has been found to assist in solving the issues identified with student understanding on the course around residential timber frame design. Students for whom English is an additional language found the model to be particularly helpful to their learning and the majority stated it helped them overcome their language difficulties. The embedded information BIM model approach can be used to address subject matter in other areas of construction such as reinforced concrete or steel framing and there is no obvious constraint to prevent this teaching method from being used in countries other than New Zealand. This project shows therefore that having a tutor support embedding BIM model use into delivery of a course substantially increases the prospects of the teaching strategy's success. In terms of supporting learning using similar digital models recommendations would include articulating the objectives of the model and how it is to be used very early in the process. Consider carefully the student end users and how they will navigate the model and access any embedded information. Ensure that such information aligns with the statutory terminology used in the course or any other relevant generic dictionaries, glossaries and reference material to ensure consistency and avoid student confusion. Most proprietary model authoring applications are suitable for model generation if they export to IFC file format permitting students to access the models produced using many of the BIM model viewers freely available online. Model authoring packages such as Revit and ARCHICAD allow various ways of linking their 3D objects to external reference sources such as dictionaries and websites. ARCHICAD was used in this study and it can through its' Custom Property Manager feature link via URL to a manufacturer's website to show details of proprietary products. It can also link to specific pages of a multi-page PDF document but this requires measures such as either an add on to the original base package or linking to the PDF document located in a cloud based file sharing service.

BIM is popular and students want more of it. Colleges should therefore seriously look at ways to exploit all the opportunities digital models can provide to enhance student understanding and bridge learning gaps in courses within their construction qualifications. These opportunities will encompass the ability to use the models in a virtual reality context in the near future as many model authoring applications can already export files in formats than can be modified fairly easily to make this possible. A student in our study remarked on how he enjoyed engaging with the BIM model as it reminded him of a computer game and therefore virtual reality functionality of future models and resources can perhaps develop around this observation. This can surely only add to student enjoyment of model engagement in the future and possibly build on those learning benefits observed to date.

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A LOCATION AWARE AUGMENTED REALITY COLLABORATIVE SYSTEM FRAMEWORK FOR FACILITY MAINTENANCE MANAGEMENT

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ABSTRACT: Facility management (FM), which is an integrated approach of managing and maintaining facilities in an organization, is essential to keep facilities functional. Among all FM activities, facility maintenance management (FMM) accounts for more than 65% of the total cost, illustrating the importance of improving FMM efficiency. An integral workflow of FMM can contain several consequent tasks, such as inspection, reporting, repair, etc., requiring multiple users at different places to collaborate with each other. To facilitate various collaborative FMM activities, a collaborative platform with a particular data source that can provide required facility information is needed for information sharing and decision-making. Another challenge of FMM is that many facilities are hidden, like ventilation ducts above ceilings and water pipes under floors, indicating the necessity of applying certain technology that can enable user to visualize and update the information of their surrounding facilities. Moreover, real-time location information is also needed so that users can be aware of their current location and the surrounding facility can be displayed accordingly. Therefore, this paper aims to develop a BIM-based location aware augmented reality (AR) collaborative framework for FMM, with building information modeling (BIM) as the data source, AR for interaction between users and facilities, and Wi-Fi fingerprinting for providing real-time location information. The developed system has the following features: (1) users can be aware of their locations in real-time and visualize their surrounding facilities and facility information; (2) users can interact with their surrounding facilities by modifying the virtual objects, looking up and updating information of facilities; (3) users in a remote location can visualize site situation and interact with site facilities in real-time.

KEYWORDS: *Augmented reality, Building information modeling, Wi-Fi fingerprinting, Facility maintenance management, Remote collaboration*

1. INTRODUCTION

Facility management (FM), which is an integrated approach of managing and maintaining facilities in an organization (Barrett and Baldry, 2009), is essential to keep facilities functional. Among all FM activities, facility maintenance management (FMM), which refers to activities taken to prevent functional failure of facilities, accounts for 65%~85% of the total cost (Lavy and Jawadekar, 2014). The larger amount of cost incurred from FMM illustrates the importance of optimizing FMM methods and improving FMM efficiency. However, managing facility maintenance tasks effectively is not easy. An integral workflow of FMM can contain several consequent tasks, such as inspection, reporting, repair, etc., requiring multiple users at different places to collaborate with each other. For example, when there is a water leakage in a particular room, people in the room will report this problem to the office in charge (e.g. facility management office). Then the people in charge will instruct mechanics to repair or replace the corresponding facility. However, as the mechanics may not know the site fully, they may have to go there to check the problem first, and it is quite likely that they need to go back to their workshop to bring any necessary tools. This kind of traditional FMM method is time-consuming, inefficient and expensive. Therefore, it is necessary to provide a platform for collaboration, information sharing, and real-time communication among different users. There are three prerequisites to developing such an effective collaboration platform: (1) a data source that can provide both geometric information and semantic information of facilities to help users understand the facilities and facilities' condition; (2) a user-friendly User Interface (UI) that lets FMM staff read and update facility information more easily; (3) a localization method that can provide location information to link site users with their surrounding facilities so that users can use the proposed UI to directly interact with the facilities.

Building information modeling (BIM) is an intelligent model-based approach that can be used to track, update, and maintain facility management information to support better decision-making in planning, operation and maintenance throughout a building lifecycle (Chen et al., 2016). Defined as an advanced approach to building design, construction and operation, BIM can facilitate the exchange and interoperability of information in digital format (Eastman et al., 2011). The information database of building assets contained in BIM can support various activities during a building's whole lifecycle, including FMM. However, it is difficult for current BIM software to enable FMM staff to have a direct interaction with site facilities in real-time. With current BIM software, facilities have to be manually located from the whole building models when FM staff need to check or update the facilities' information. A new technique with a more user friendly UI is needed to enable users to directly read and update facility information so that the rich information of BIM can be better utilized for FMM.

Augmented reality (AR) is an innovative technology that can enable digital information such as 3D models, images and animations to be overlaid on the real world to achieve a natural interaction between users and their surrounding environment (Cheng et al., 2017). By combining the virtual world with the real world, AR makes the information of users surrounding facilities readable and manipulable. AR applications can be classified into two categories – marker-based AR and markerless AR. Marker-based AR has to use a marker as a trigger, while markerless AR normally uses localization methods to link the virtual world with the real world. For FMM, it is difficult to attach markers to all facilities, as some facilities are normally hidden from users, like ventilation ducts above ceilings and water pipes under floors. As a result, an appropriate localization method can be used to match the required digital information with the real world to realize a markerless AR, as well as providing accurate location information for FMM.

To provide real-time location information for FMM, an appropriate localization technology is needed. 3 requirements have to be satisfied to guarantee the performance of localization and minimize the cost: (1) the technology can provide a high localization accuracy; (2) the technology need to be suitable for indoor environment as a large number of FMM activities are taken in indoor environment; (3) the technology can be applied to common mobile devices (e.g. mobile phones and tablets) so that FMM staff can easily access to the proposed technology. Currently, there are several localization technologies available, such as Global Positioning System (GPS), radio frequency identification (RFID), Bluetooth, ultra-wideband (UWB), etc. Although GPS has been widely used for markerless AR, the low accuracy of GPS has limited its application in FMM, especially in an indoor environment (Cheng et al., 2017). For some other technologies that can provide better accuracy in indoor environment, external devices are required to obtain real-time location information. For instance, RFID reader is needed for localization with RFID, Bluetooth beacons are needed for localization with Bluetooth, UWB beacons are needed for localization with UWB, etc. In comparison, Wi-Fi can be an ideal technology for localization for FMM as Wi-Fi can provide a high accuracy in indoor environment and can be applied to common mobile devices. Besides, nowadays it is very common that a building is entirely covered with Wi-Fi signals. According to a survey, the widespread use of Wi-Fi routers and mobile devices has made localization based on wireless signal detection possible (Vo and De, 2016). Propagation of different Wi-Fi signals from different Wi-Fi routers can form unique 'fingerprints' at different places (Wang et al., 2016). Based on this Wi-Fi fingerprinting theory, the real-time locations of users can be obtained. As a result, this paper proposes to use Wi-Fi fingerprinting to provide accurate location information for FMM.

In this paper, a BIM-based location aware AR collaborative system framework is developed for facility maintenance management. Section 2 presents the development of the framework. Section 3 provides an illustrative example to show the functionality of the developed framework. The conclusion part summarizes the features and highlights of the developed framework and discusses the limitations.

2. FRAMEWORK DEVELOPMENT

2.1 Framework Design

The developed framework is shown in Fig.1, which contains three parts: (1) localization, (2) database, (3) augmented reality. As mentioned in the introduction section, localization based on Wi-Fi fingerprinting can provide a high accuracy in indoor environment. At the same time, Wi-Fi fingerprinting can be applied to common mobile devices to be accessed by users easily as long as the working area is covered with Wi-Fi signals. Therefore, Wi-Fi fingerprinting is used to achieve the localization function. Mobile devices with Wi-Fi receiver are used to scan Wi-Fi information, including the media access control (MAC) addresses of surrounding routers and signal strength at the current location, to obtain Wi-Fi fingerprints. By comparing the fingerprint of a user's current location with the stored fingerprints for a certain area with K-nearest neighbor (KNN) and K-means clustering, the current location of the user can be obtained, and the system can then use this information along with a proposed room detection algorithm (to be discussed in the next section) to detect which room the user is in. An online database is constructed to enable multiple users to access required facility information at the same time. The database contains the following information: geometry and semantic information of facilities extracted from BIM models, maintenance and inspection records from FM systems, and location information obtained by the localization function. The information of facilities and rooms are extracted from BIM models by using application programming interfaces (APIs) of different BIM software. BIM models are also imported into the AR developing engine to generate augmented facilities. As users visualize virtual facilities in the real environment, multiple users can also simultaneously read and update facility information by interacting with the constructed database. Furthermore, users at remote locations can view the site in real-time via live video streaming function.

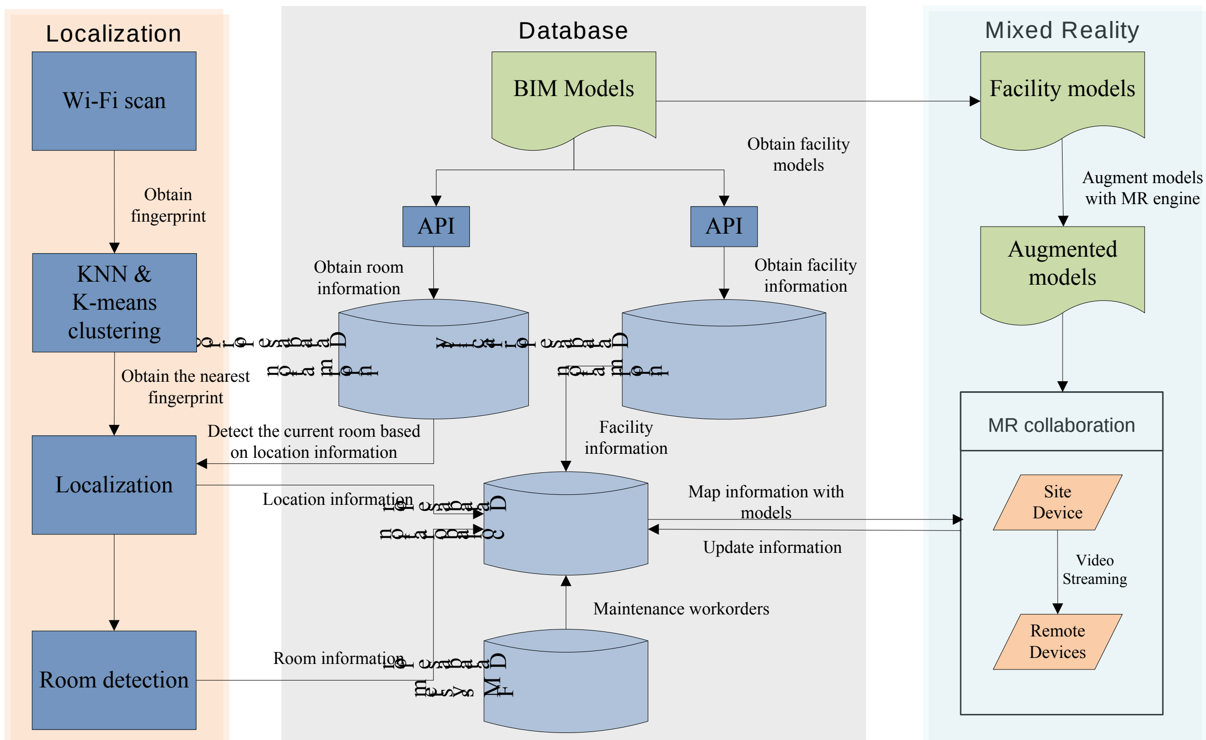

Fig. 1: The proposed framework

2.2 Indoor localization based on Wi-Fi fingerprinting

To use Wi-Fi fingerprinting for localization, Wi-Fi fingerprints need to be collected via Wi-Fi scanning and the current location of a user can be calculated by assigning the user' location to the nearest Wi-Fi fingerprint. Each Wi-Fi fingerprint consists of four attributes: 1) fingerprint ID, 2) the name of the indoor area, 3) the location of fingerprint in the indoor area, and 4) the measurements of Wi-Fi signal strengths obtained by Wi-Fi scanning. Attributes of a Wi-Fi fingerprint are shown in Table 1. Fingerprint ID can be assigned by users according to a particular principle (e.g. '00001' to '99999'). Name of the map is based on the area that the fingerprint is located at. The location of fingerprint is represented by the coordinate value in the corresponding relative coordinate system. The measurements of fingerprint refer to the MAC address and signal strength of each router in the fingerprint. After obtaining the information of each fingerprint, the system will upload the information onto the constructed database. As the user's location is represented by the nearest fingerprint, the density of fingerprint has a direct and significant effect on the accuracy and efficiency of the proposed method. Fig. 2(a) is an example of fingerprints created for localization and Fig. 2(b) shows the attributes of one of the fingerprints.

Table 1: Attributes of a Wi-Fi fingerprint.

Attributes	Remarks
Fingerprint ID	The ID of a Wi-Fi fingerprint
Map	Name of the map the fingerprint is located at
Location	(x, y) coordinates on the map
Measurements	BSSID and RSSI values

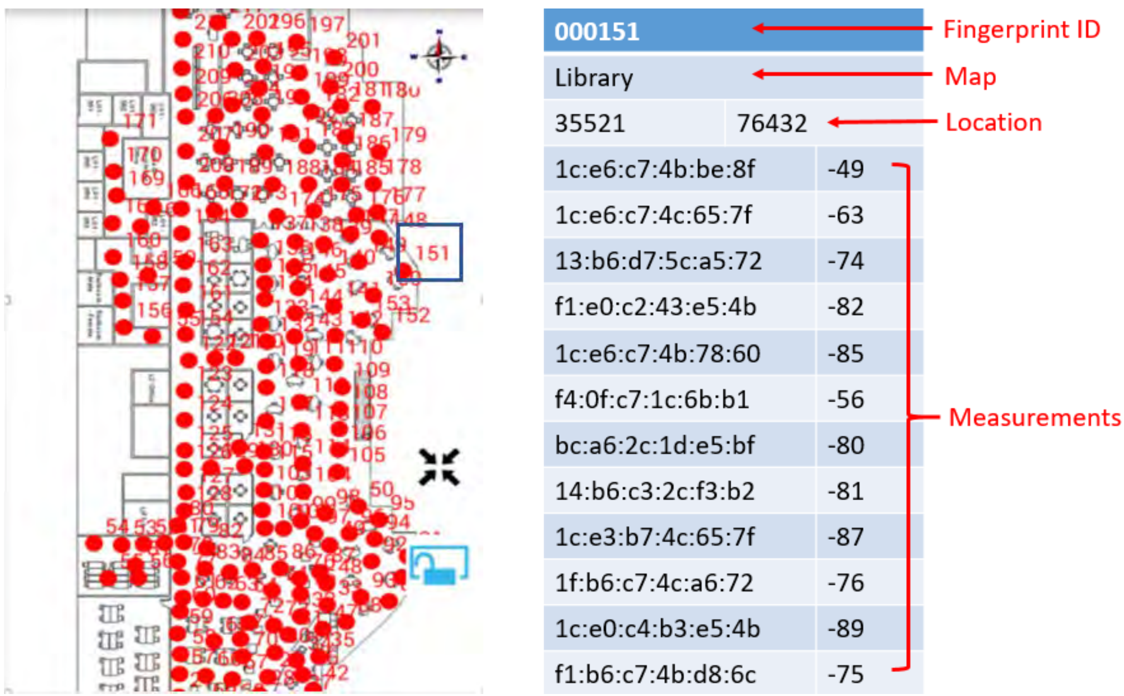

Fig. 2: (a). Fingerprints created in a building; (b) Attributes of a fingerprint

To improve the performance of the localization method, K-nearest neighbor (KNN) algorithm (Guo et al., 2004) and K-means clustering algorithm (Ruspini, 1969) are used. The purpose of the KNN algorithm is to obtain K nearest Wi-Fi fingerprints to the user location. It is important to emphasize that the K nearest Wi-Fi fingerprints are not based on calculating the geometric distance between the user position and the Wi-Fi fingerprints. Instead, the K nearest Wi-Fi fingerprints are based on the signal strength measurements of each Wi-Fi router in the environment. For example, if there are n routers in the surroundings, the nearest neighbor is found by the standard Euclidean distance of the difference of the Wi-Fi signal measurements which are obtained from the user position and the Wi-Fi signal measurements stored in the database:

$$D = \sum_{i=1}^{n} (X_i - Y_i)^2 \tag{1}$$

where D is the standard Euclidean distance; n is the total number of detected routers; X_i is the real-time RSSI value from the ith router; Y_i is the RSSI value from the ith router in the stored fingerprint. If a router is detected in real-time but is not present in the stored fingerprints, the RSSI of the stored fingerprint is set to -119, which is normally the minimum value of Wi-Fi RSSI. Similarly, if a router is present in the stored fingerprints but not detected in real-time, the value of the real-time RSSI is set to -119. Pseudo code for calculation of D is provided in Figure. 4. After calculating D for all fingerprints, the fingerprint with the minimum D is selected to represent the nearest fingerprint, thus representing the current location of the user.

However, implementing only the KNN algorithm will create a huge computation workload for the algorithm because the signal measurements of every single Wi-Fi fingerprint are compared with the received signal measurements from the user position. To tackle the problem of huge computation workload, a K-means clustering algorithm is implemented to complement the KNN algorithm. K-means clustering can divide fingerprint points to different representation groups by an iteration process. Firstly, the centroid of the cluster is randomly assigned to the area of Wi-Fi fingerprints. Secondly, fingerprints are assigned to the nearest clusters in terms of the distance between the cluster centroid and the fingerprint locations. Thirdly, the centroid of clusters is obtained from the coordinates of the assigned fingerprint locations. Then the second and third steps are repeated until convergence. Clusters are measured according to the weighted average of the measurements of the Wi-Fi fingerprint candidates in the cluster. After determining the nearest cluster, the algorithm will further compare individual Wi-Fi fingerprint measurements assigned to this specific cluster with the received measurements. The value of K is set according to a balance between the computation time and localization accuracy. Several K values will be tested until an appropriate K value that can provide less computation time and higher accuracy is obtained.

After obtaining the current location of a user, a room detection method based on the ray casting algorithm (Shimrat, 1962) is also proposed in this framework to detect which room the user is in. Coordinate information of the endpoints of walls extracted from BIM models can be used to generate polygons to represent the actual area of rooms (extracting room information from BIM models will be discussed in the next section). By comparing the current location of users and the coordinate information of rooms with the ray casting algorithm, the developed system can automatically identify which room the user is in, and help FMM staff get real-time corresponding information of the identified rooms.

2.3 Construction of Database

A database that can store all related information for FMM and can give simultaneous access to multiple users is required to achieve collaborative AR for FMM. The information stored in the database includes: 1) dimensions and coordinates of each facility, 2) some semantic information (e.g. material, model, manufacturer, etc.) of each facility, 3) room information, 4) inspection and maintenance record of each facility, 5) location information of each potential users, 6) fingerprints information (Fingerprint ID, BSSID, RSSI, etc.), and 7) collaborative information (e.g. whether an equipment is being inspected or not). This research uses the design concept of a relational database. Different modules of the database are designed based on the requirement and logic of the system framework, and are linked to each other by facility ID, as shown in Fig. 5 (a).

APIs of different BIM software are used to extract required information of facilities. The extracted information includes dimensions, family type, system type, material, manufacturer, etc., and is then stored in the constructed database. Facility ID is used to link each module in the database, and link each item in the database to its corresponding BIM models and augmented models. APIs of BIM software are also used to extract room information from BIM models. The extracted room information includes room information ID, room name, coordinates of corners of rooms, coordinates of center point of rooms, area of rooms, wall types, door types, incidents of rooms, and 2D drawings. The database of FMSs is also incorporated into the constructed collaborative database to provide information of inspection and maintenance record. Furthermore, one table in the database is reserved for storing the location information of potential users. Once the location of a user is detected by the system, it will be automatically uploaded onto the database so that the other users can also get to know the location of the site user. One table is used to store collected Wi-Fi fingerprints, especially the BSSID and RSSI values of each router. Another table is used to store collaborative information. For example, if the value of 'Inspecting' of a certain equipment is '1', it means that equipment is being inspected by the site user and the corresponding AR model will be highlighted.

ID	X	Y	Z	Scale
281716	-21	35	10	1

ID	Family Type	System Type	Connection Type	Material
281716	6 PVC	Hydraulic supply	Generic	PVC

ID	Inspection date	Condition	Instructions
281716	2017-11-05	Good	

ID	Inspecting	Updating
281716	1	0

ID	Name	Center Coordinate X	Center Coordinate Y	Altitude	Room area	Wall Type 1	Wall Type 2	Door Type
542953	LC Help Desk	0.450281	0.858296	387.139	0	n/a	n/a	n/a
550012	Lift A	0.290552	0.646877	387.139	18	Basic Wall Generic - 8"	n/a	n/a
550348	Lift B	0.304353	0.411966	387.139	10	Basic Wall Generic - 8"	n/a	n/a
550954	Media Resources	0.515343	0.08334	387.139	0	n/a	n/a	n/a
551442	Media Resources and Microforms Office	0.294981	0.339559	387.139	33	Basic Wall Generic - 8"	n/a	n/a
551911	Microforms	0.423858	0.262191	387.139	0	n/a	n/a	n/a
552933	Tutorial Spaces	0.245237	0.687039	387.139	65	Basic Wall Generic - 8"	n/a	Single-Flush - 36" x 84"
554040	Visually Impaired Workstation	0.432056	0.221177	387.139	0	n/a	n/a	n/a

Fig. 3: (a) An example of facility information in the database; (b) An example of room information extracted from BIM models

2.4 AR COLLABORATION

BIM models of facilities generated from BIM software are transferred to an AR engine. In the AR engine, all models are grouped according to the room they are in. Once the current location of the user is obtained and the room is detected, corresponding facility models will be displayed in the user's surrounding environment. A virtual view camera in the developing environment is used to decide the real view of users. Once the current location is obtained, the coordinate values of the location will be assigned to the view camera automatically so that users can get the correct view through the view camera. For example, if a user is standing under a fire sprinkler, the system can assign the coordinate values of the current location to the view camera so that the user can see the fire sprinkler above the user's head when the user looks up with a given device.

With the proposed localization method, the system can detect the current location of a user and display corresponding virtual facilities with appropriate relative position relationship. However, the alignment of facilities cannot be decided merely using the localization method. For instance, in the fire sprinkler example mentioned before, the user may find himself standing exactly under a virtual fire sprinkler while the whole virtual fire pipe system has a 90 degree error from the real fire pipe system. In the developed system, a gyroscope and a compass on a mobile device is used to deal with the alignment problem with the following steps: (1) a traditional compass or the compass on a smartphone is used to detect the direction of the facilities (e.g. south - north); (2) in the selected AR engine, a gyroscope is enabled to track the rotation of the mobile device and the compass is enabled to read magnetic information of the environment; (3) Quaternions (Unity, 2017) are used to set the relative angle relationship between the view camera and the developing environment; (4) in the selected AR engine, the directions of facility models are set according to the obtained magnetic information and the direction of the real facilities. For example, in the case of the developing environment of this research, the positive direction of the Z-axis of the coordinate system represent north.

In the user interface (UI) of the system, besides the virtual models of facilities, information panels are used to display different required information, including room information, facility product information, facility maintenance and inspection information. PHP files with SQL query commands are used to link the system to the constructed database, based on which multiple users can read and update information in the database. To enable users to interact with the system, different interaction methods have been applied: for mobile devices, users can directly use the touchscreen and virtual keyboard to interact with buttons on the UI or directly interact with facilities; for laptop computers and desktop computers, a mouse and keyboard are used to interact with the system; for AR HMDs (Microsoft HoloLens is used in this study), users can interact with facilities using voice commands and gesture commands.

A function of screen sharing among different users is needed to enable users from remote places to have a direct and clear understanding of site situation in real-time. MJPEG (or motion JPEG) format is used to achieve live video streaming. MJPEG is a video compression format with which each video frame is compressed as a JPEG image and each part of the sequence of JPEG frames can be sent over HTTP protocol (Chen et al., 2012) so that this format is suitable for live video streaming through network connection. TCP protocol is used to establish a network connection among different devices. A server device is connected to client devices using sockets, which are internal endpoints for sending or receiving data in a computer network. As shown in Fig. 4, live video streaming is achieved by the following steps: (1) the system captures each frame of the server screen; (2) each frame of the captured screen is compressed as a JPEG image; (3) the system sends the stream of JPEG images from the server device to the client devices through the network; (4) the remote device decompresses the received images; (5) the remote device displays the video.

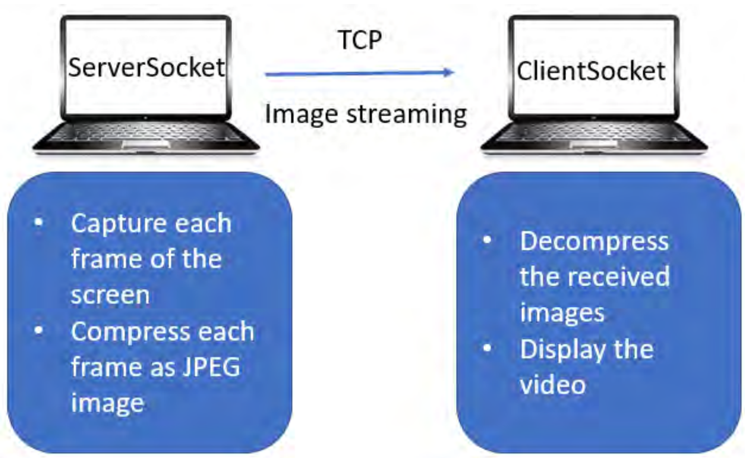

Fig. 4: Live video streaming

3. ILLUSTRATIVE EXAMPLE

An illustrative example is used to demonstrate how the developed system works. In this example, MySQL, which is an open source relational database management system (Oracle, 2012), was used to construct the collaborative database. MySQL supports the SQL language for data query to achieve reading and writing of information efficiently. Autodesk Revit was used to generate facility models. Two plug-ins of Autodesk Revit were developed using Revit API to extract facility information and room information. The required information was exported into a CSV file and imported into the MySQL database. In this paper, ARCHIBUS (ARCHIBUS, 2014) was used as the FMS, whose database was also incorporated into the constructed MySQL database. The selected AR engine in this paper is Unity 3D, which was used to develop the AR UI for smart phones, tablets, computers and AR HMDs. The supported devices of this example include smart phones with Android operation system (OS), tablets with Android OS, computers with Windows 7 or above OS, and Microsoft HoloLens.

The developed system in the example mainly used scripts with C# programming language in Unity 3D. There is one exception: to get the BSSID and RSSI of routers, a Wi-Fi scan function is needed. However, for Android devices, the Wi-Fi scan function cannot be enabled through Unity 3D directly. Therefore, an alternative approach was used in this research to complete the development of the Android version of this system. For the Android version, the Wi-Fi scan function was first developed in Android Studio with Java. Then the generated project and corresponding libraries in Android Studio were exported into a compressed file in arr format. In the end, the arr file was imported into the Unity 3D project as a plug-in.

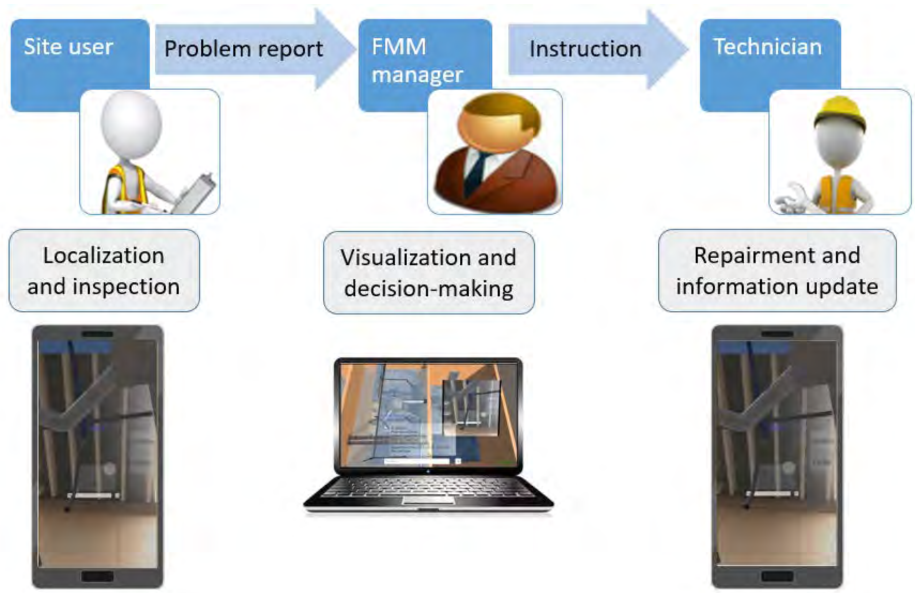

Fig. 5: Workflow of the illustrative example

Fig. 5 illustrates the work flow of the illustrative example. When a user on site opened the app installed on his smartphone, the app scanned the surrounding Wi-Fi information. Based on the proposed algorithm for localization, the nearest Wi-Fi fingerprint was obtained and the room number was detected. Then corresponding facilities and information were displayed on the device with the correct relative position relationship and relative angle relationship (the virtual facilities overlap with the real facilities). At the same time, corresponding facilities and information were also displayed on a remote computer. Both the user on site and the user in a remote office could interact with the facilities. The site user selected a fire pipe to check its information and the pipe was highlighted automatically so that all users knew which pipe was being inspected by site user. Then the site user updated the 'Condition' of the pipe from 'Good' to 'Leak' and the user in the remote office could see the updated information immediately. Once the facility was marked as failed, the color of the model would turn red. Furthermore, the user in the remote office visualized the site situation in real-time through the screen sharing function, which would facilitate his decision-making. Afterwards, the user in the remote office gave 'Instructions' to the site user. The site user would act according to the received 'Instructions' and update the condition information after repairing the pipe. All changes of facility information and the exact time of changes were recorded in the developed system database. Screenshots of the site device and the remote device are shown in Fig. 6.

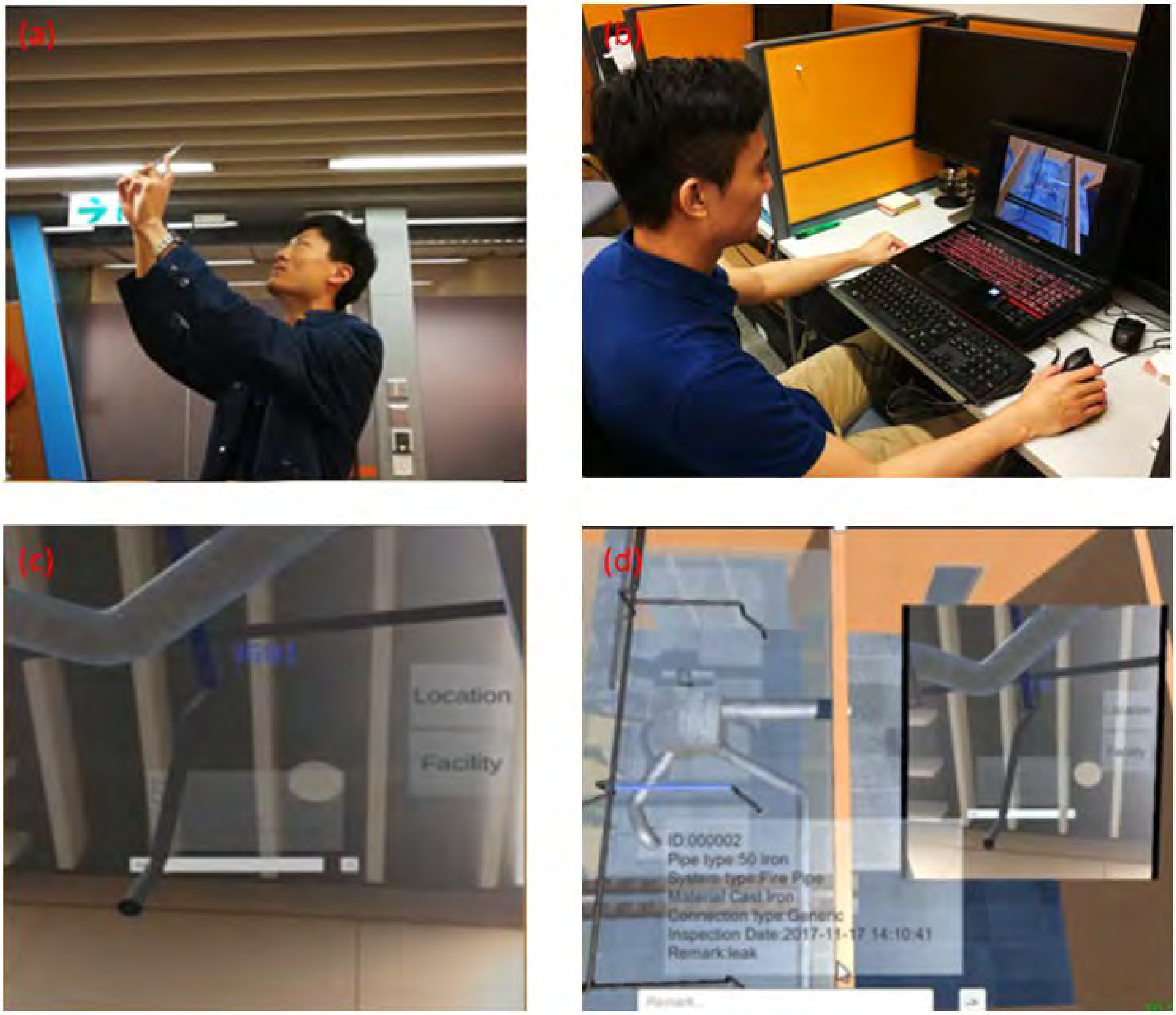

Fig. 6: (a) A site user with a mobile device; (b) A remote user with a laptop computer; (c) Screenshot of the site device, (d) Screenshot of the remote device

The capability of the AR system to find the failed facility depends on the accuracy of the proposed localization method, which can be affected by several factors, such as the distribution of routers, the stability of Wi-Fi signals, the density of stored Wi-Fi fingerprints, etc. With the experimental conditions mentioned in this section, the localization accuracy of the AR system was 30cm-50cm. As a result, the system cannot differentiate two pipes if the distance between them is less than 30cm. In the illustrative example, the distances among each facility were larger than 50cm. The correct ratio to locate the failed pipe would decrease if the pipes has a higher distribution density. On the other hand, with the developed AR system, users cannot differentiate facilities that are above the ceiling and horizontally overlapping with each other. Although the localization method based on Wi-Fi fingerprinting can achieve both horizontal and vertical localization, users cannot know which the failed facility is if facilities are overlapping above the users.

4. CONCLUSION

FMM, which refers to activities taken to prevent facility failure, incurs a large amount of cost of building facilities. To improve the efficiency of FMM, a BIM-based location aware AR collaborative framework is developed, with BIM as the data source, AR for interaction between users and facilities, and Wi-Fi fingerprinting for providing real-time location information. The developed system has the following features: (1) users can get to know their locations in real-time and visualize their surrounding facilities and facility information, (2) users can interact with their surrounding facilities by modifying the virtual objects, looking up and updating information of facilities; (3) users in a remote location can visualize site situation and interact with site facilities in real-time. An illustrative example is also used to demonstrate the functions, user interface and operation of the system.

The developed AR system in the illustrative example can provide a localization accuracy of 30cm-50cm so that the capability to find a certain facility is promising if the distances among each facility are larger than 50cm. However, the developed system cannot find a certain facility accurately if the facilities are arranged in a very high density. Another limitation of the developed AR framework is it has a high dependence on the environment. The whole area should be covered with Wi-Fi signals, so the system can hardly be used in outdoor environment or during a power failure period. On the other hand, the Wi-Fi fingerprints have to be collected again when there are any changes of the distribution of Wi-Fi routers or alignments of walls, which can influence the measurements of Wi-Fi fingerprints. Furthermore, varying Wi-Fi signals can influence getting the nearest Wi-Fi fingerprints, thus reduce the localization accuracy. Therefore, the future work of this study will focus on improving the localization accuracy and reduce the dependence on the environment.

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MIXED REALITY SIMULATOR FOR CONSTRUCTION WORKERS' MUSCULOSKELETAL DISORDERS PREVENTION

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ABSTRACT: *Health and security is a critical issue in the construction industry which ranks amongst the worst industries regarding injury and fatality statistics. In this field, if not performed correctly, some tasks lead to musculoskeletal pains. Currently, qualitative tools are available to prevent health risks as MusculoSkeletal Disorders (MSD). Yet, these tools fail to address evaluation process as it depends on the trainers' perspective. Recently, virtual reality (VR) has started to be used as a training tool for construction workers and showed its relevance in the improvement of the training process. However, it is not used for posture analysis in construction field. Therefore, UVSQ and Bouygues Construction have developed "Virtual Compagnon", a Mixed Reality (MR) platform, in order to evaluate the physical efforts involved, depending on the worker posture, during the lifting of formwork panels. This platform is composed of a head mounted display (HMD) for visual and auditory immersions on virtual construction sites extracted from a BIM model, a robotic platform dedicated to "realistic" haptic feedbacks.*
This paper presents the functional specifications of the MR simulator and the first results on the lifting task done by students.

KEYWORDS: *Force feedback, robotic platform, virtual reality, training, prevention, posture evaluation, BIM.*

1. INTRODUCTION

The construction sector is one of the sectors posing a significant risk on the health and security of its workers as they have to, amongst other things, manipulate heavy objects at height through the use of electrical tools. These different activities result in a risk of accidents on the construction sites.

According to the numbers of the British Health and Safety Executive (HSE) (Health and Safety Executive, 2017a), more than 30% of the accidents in 2017 involved the construction sector and more specifically the slides of workers during work at height on the sites. These accidents are easy to enumerate as they are visible, and a lot of solutions are now implemented by companies in order to avoid them. However, it is more difficult to highlight other health risks of the different construction activities for each profession, as they are generally invisible and might occur several years later. One of the most common occupational diseases is the Work-Related Musculoskeletal Disorders (WRMSDs). These WRMSDs emerge primarily during prolonged and repeated manipulation of heavy objects in unadvised postures. Another HSE report (Health and Safety Executive, 2017b) has ranked the construction sector as one of the highest rates of musculoskeletal disorders compared to the agricultural sector, the storage sector or other industrial sectors.

In this report, 45% of WRMSDs primarily affected the upper limbs and more than one third affected the back. The British organization mainly addresses the manual handlings and the repetitive actions as cause of these WRMSDs. It additionally presents an alarming finding that both the heavy lifting and the manipulation of materials account for more than half of the WRMSDs.

As a result, the construction sector is constantly innovating several of these processes in order to propose more ergonomically and efficient tools. In that way, the daily life of workers can be improved and WRMSDs avoided. For this, Bouygues Construction has set up a real awareness campaign that goes beyond training and is concerned in the day-to-day work of the workers. These include amongst other things; informative posters posted in construction sites, safety quarter-hour, morning warm-ups, robotization and industrialization and the desirable use of tower crane for the transport of heavy objects. One of these implemented innovations is the training of side workers in an immersive virtual reality (VR) environment. This technology has generated interest of the construction sector because of the appearance of effective Head Mounted Display (HMD).

Initially used by Bouygues Construction as a sales support tool following the democratization of the Building Information Modeling (BIM) (Azhar, 2011), VR is now used by the company to train its workers.

Workers are trained in safety measures and in detecting situations that might present a risk on a construction site (e.g. missing guardrails, wearing Personal Protective Equipment, risks of drug and alcohol consumption). They are also trained on a tool frequently used on site, namely the formwork panel as this tool represents one of the highest risks. Huang and Hinze observed that 5,83% of crashes happened while manipulating the formwork at height (Huang and Hinze, 2003) . Hallowel and Gambatese highlighted that 21,2% of collisions also induced the formwork (Hallowell and Gambatese, 2009). In addition, evidence of Welch and HAR underlined that repetition of gestures when lifting the panel represented a risk of discomfort and persistent pain (Welch, Hunting and Anderson, 2000; Har, 2002).

However, VR has its limitations. Regarding the formwork training, we noted that the lack of force feedback resulted in a useful exercise. Therefore, an accurate trainee posture during the training is not possible as this generally depends on the trainer's expertise.

As a result, we realized the *Virtual Compagnon platform*, a MR simulator in order to evaluate the physical efforts involved, depending on the constructions' worker posture during the lifting of a formwork panel.

This article presents the actual health and safety training process in the field of construction, the formwork manipulation process in particular and the role of VR application for training purposes (Rezazadeh *et al.*, 2011).

We will also describe the *Virtual Compagnon* robotic platform which we developed to be used in mixed reality (MR) in which the crowbar will be used to lift the formwork panel.

Then, we will explain the implemented test protocol that has been tested on 10 participants from the Versailles Engineering Systems Laboratory (LISV) and we will comment the obtained results.

Finally, we will conclude by discussing the limitations of our study and the future implications.

2. HEALTH AND SAFETY TRAINING IN THE CONSTRUCTION INDUSTRY

The construction sector is the sector that made the most progress in terms of health and safety (International Labour Organization, 2005). Moreover, construction workers face daily safety hazards such as working at height, using electrical machinery or risking their health by lifting heavy objects. This is followed by a high work-sites increasing their risk of injuries (Tak *et al.*, 2011). Therefore, it is crucial to educate workers on the risks of their business before commencing their actual work.

All these different construction situations such workings at height, handling heavy objects, working near machinery present a risk of injury and even death. This is followed by - the complexity of certain tasks and the interaction between co-workers – that are the main factors that lead to these risks. In order to reduce the accidents' rates, several methods are used to raise awareness of construction workers: Security awareness sessions, morning warm-ups, comics and posters, 3D videos depicting accident-prone situations etc... At the Bouygues Construction training centre, a training session is composed of two workshops:

One of these workshops is called a theoretical workshop. During this workshop, the basic rules are recalled in order for trainees to review the safety rules of every situation and every tool. While working in different situations such as at height, handling heavy objects or working near power generators of construction machinery, their behaviour is being conducted. Trainees also learn to detect risks, act in accordance with (for example: establish a perimeter of security, inform their supervisors...) and to remain alert towards themselves and their colleagues.

The practical workshop comes after the theoretical part. In this workshop, trainees are set in real situations where they discover different machinery such as tower and mobile cranes, front and back-end loader, but also power tools and their everyday tools are projected.

In order to improve training processes, numerous types of training exist such as presentations, group trainings, awareness videos, e-learning modules etc. (Ahlberg *et al.*, 2007; Diego-Mas and Alcaide-Marzal, 2014). But recently, VR technologies and more specific immersive headsets have proven to be successful as more efficient and more affordable devices were put on the market. As a result, the industry has been interested in these technologies using them in the context of sales support and project review because of their immersive power which allow the customer to better plan his future project (Burke *et al.*, 2006; Zhao, Lucas and Thabet, 2009; Dawood *et al.*, 2013). Instead of building show models, VR has proven to be less expensive, and useful in the projection of different projects (Miliano, 1999; Whyte, 2003). Many examples exist where the VR is used such as the Cave Automatic Virtual Environment (CAVE) training or the tablet application (Ahlberg *et al.*, 2007), yet these technologies fail to put the user in this immersive environment. Furthermore, the interaction is limited which lead to a lack of haptic return of objects.

Recently, the industrial sector has expressed its huge interest in immersive VR due to the increased VR-headset performance. The sector has also expressed its interest in virtual training as a way to train workers in the industrial sector. Therefore, we developed a MR simulator that captures the visual immersion as well as the haptic feedback, based on a frequently used construction site tool: The formwork panel.

3. FORMWORK PANEL

According to López-Arquillos, a formwork (Fig.1) is defined as a temporary casing-system used in the construction sector as mold in which concrete is poured to the desired shape and size (López-Arquillos *et al.*, 2014).

Figure 1: Formwork composed of two formwork panels

A formwork is composed of two panels. It is composed of several parts and accessories such as kickstands, screw jacks and so on. Therefore, it is important that construction workers can identify and recognize these elements in order to assure the progress of the setup, the adaption and the demolition. Moreover, the formwork is heavy: 250kg/m^2, equals 1Ton for a standard panel. Therefore, a good master ship of the operating mode is crucial in order to avoid injuries. Hence, an adequate training is necessary to better understand the tool and to use it effectively.

Currently, the training of the form worker is composed of two parts. In the first part, the trainer explains in a general way the procedure, the risks related to the formwork in terms of ergonomics and MSDs. In the second part, a practical session takes place in which the trainees handle the formwork and particularly the use of the crowbar. This session allows construction workers to handle the formwork and to adapt their body positions when using the crowbar. In this session, the alertness of the trainer is highly required. On the one hand, any wrong handling when using the formwork can cause the tipping of the form. On the other hand, any wrong body gesture when manipulating it (during the assembly for ex.) may lead to more or less serious injuries to the trainee.

The different stages in the set-up of the formwork are the following:

1. Assembly of the formwork on the ground
2. Lifting of the formwork with the crane
3. Stabilization of the fixed panel (External limit of the wall)
4. Closing the veil (bringing the second panel closer)

This last step is very important and very delicate because the second panel determines the desired depth of the wall. The worker construction must therefore move over short distances to reach the desired depth. There are two ways to close the veil:

1. Closure with the crane (Fig.2): The worker construction connects the mobile panel to the crane, and with the directions they give to the crane driver, pushes the panel to the intended location.
2. Closure with the crowbar (Fig.3): Usually done at short distances. The construction worker uses a metal bar that he puts under the box and presses on the bar to lift the panel slightly and move it in the desired direction (front or back, right or left)

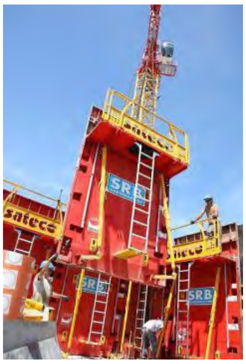

Figure 2: Formwork closure with the crane

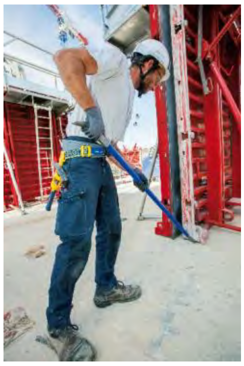

Figure 3: Formwork closure with the crowbar

We decided to focus on the second method: Closure with the crowbar (Fig.3).

This method represents a risk to the health of the worker construction, and in particular the work-related musculoskeletal disorders (Valero *et al.*, 2016). Repetitive actions during closing (rapid movement downwards), the weight of the panel, the state of the ground and the number of panels to close are factors that can lead to MSDs and can increase the risk of accidents that can affect the construction worker. It is therefore necessary to ensure good training in the use of the bar to minimize the risks and ensure the safety of construction workers on site.

These courses are necessary and cover both theory and practice. Yet, there is no mechanism that allows us to have data on the training session of each trainee. Indeed, there are no sensors on the crowbar or on the formwork that can inform the trainer about the efforts provided by the construction worker during the training session (for analysis the performance in time for example), and therefore cannot know quantitatively, the impact of prolonged use of the crowbar on the trainee. In addition, the trainee posture analysis depends on the trainer and is therefore completely subjective. The latter observes the construction worker during the session, and corrects orally, without any quantitative feedback or information on the posture or the gesture. It is possible that the user adopts a bad posture instead of the good posture or the good gesture.

4. VIRTUAL COMPAGNON

As explained in the previous part, the practical training takes place outdoors and requires the intervention of a crane for the formwork to be set up. Also, degraded weather conditions (high temperatures, cloudy periods etc.) can significantly alter the course of the training.

Virtual Compagnon is a MR simulator consisting of a robotic platform (Fig.4) and an immersive VR headset (HTC Vive). This platform is dedicated to the training of construction workers, and especially the form workers, to the proper use of the crowbar (Fig.7).

The robotic platform mechanically reproduces the facelift of the panel thanks to a crowbar. This platform is dedicated to the training of construction workers, and especially the form workers, to the proper use of the bar. It stimulates the tactile sense of the user by providing a force feedback for more immersion.

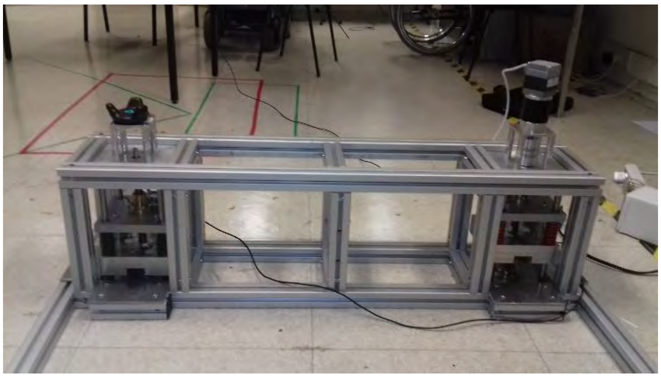

Figure 4: Virtual Compagnon robotic platform

It consists of two plates: a fixed plate above, and plate, which is raised with the crowbar, below. Between these two plates, we place 4 springs of known stiffness that will provide resistance and thus simulate the weight of a real formwork panel (Fig.5). This is the first mode: *the Passive mode (PM)*.

Figure 5: The two plates and the springs

We also added engines to have two other modes:

1. *Assistive mode (AM):* The assistance mode facilitates the manipulation of the system and can be used to train beginners. It is only functional dedicated.
2. *Resistive mode (RM):* The resistance mode simulates a heavy load. The handling is more difficult to manipulate. It could be used to simulate some situations, such as the movement of the formwork panel in real situation without the assistance of the crane.

These two modes, AM and RM, have been added for two reasons: The first reason is that the movement of the formwork by the crowbar can be handled by one or two construction workers. The second reason is that, in case of a shift by two construction workers, the notion of expertise comes into play. Indeed, on the construction site, the strength between an expert and a beginner form worker are not the same and can therefore impact the execution of the task. Hence, thanks to the different modes, we propose different scenarios to also form the collaboration between the form workers during the relocation of the formwork.

The platform also includes various sensors such as the Ultrasound sensor (Fig.6) that allows to return the movement (the compression of the springs) induced by the bar when lifting the unstressed plate (bottom plate). This information is useful in two ways:

1. Moving the virtual panel according to the displacement measured by the sensors
2. It gives us information on the force applied at the end of the crowbar by the trainee.

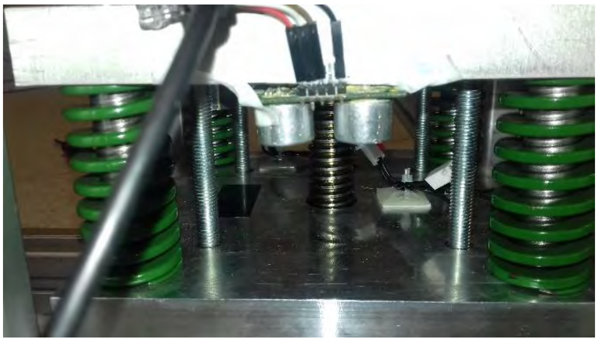

Figure 6: Ultrasound sensor between the two plates

The virtual headset can visualize a 3D site environment extracted from a BIM model and which communicates with the robotic platform. While projecting the virtual environment, the helmet, with its sound environment and the addition of objects specific to a building environment (crane, tools ...), provides a visual and auditory immersion.

5. MATERIAL AND METHOD

5.1 Protocol

In an attempt to compare an MR and VR approach, we have set up a test protocol with participants within the laboratory (LISV). These participants all had one thing in common: they were not from the construction industry and were not familiar with the use of the crowbar. We worked with 10 participants (Students/Novices) with an average age of 22 years (SD: 2.397) (Table.1). The test was done on Passive mode (PM).

Table 1: Participants

Participant	Age (Years)	Height (cm)	Education Level
1	24	170	Fourth-year university level
2	25	180	Fourth-year university level
3	21	173	Fourth-year university level
4	22	170	Fourth-year university level
5	21	183	Second-year university level
6	19	170	Second-year university level
7	26	186	Fifth-year university level
8	22	165	Fourth-year university level
9	23	166	Fourth-year university level
10	19	170	Fourth-year university level
Mean	22,2	173,3	/

We divided the test into 3 parts corresponding to 3 different workshops:

1. A "Real Situation" Workshop (Workshop 1)
2. A VR Workshop (Workshop 2)

3. A MR Workshop (Workshop 3)

Before starting the workshops, the participants get 5 minutes to get acquainted to the situation. After each workshop they get between 30 and 60 seconds of rest and between different sessions 10 to 30 seconds of rest.

In the “Real Situation” workshop (Fig.7), the bar is on the ground. The participant must grab the bar and insert it in the space provided on the *Virtual Compagnon* platform.

Figure 7: "Real Situation" Workshop

In the VR workshop (Fig.8), the participant finds himself in a virtual construction site environment in which a 3D model of the platform has been added. With the controller of HTC Vive, the participant must try to insert the virtual bar in the space provided just by using the controller.

Figure 8: VR Workshop

In the MR workshop (Fig.9), the participant is in the same worksite environment. The difference is that the actual bar and the real platform are tracked and represented in the VR environment thanks to the Vive Tracker (Fig.10). The goal is the same: place the crowbar in the platform.

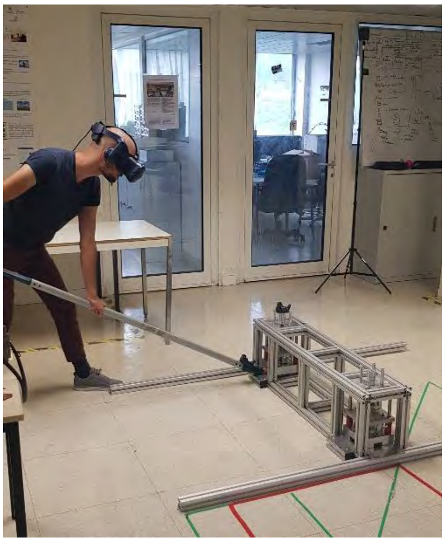

Figure 9: MR Workshop

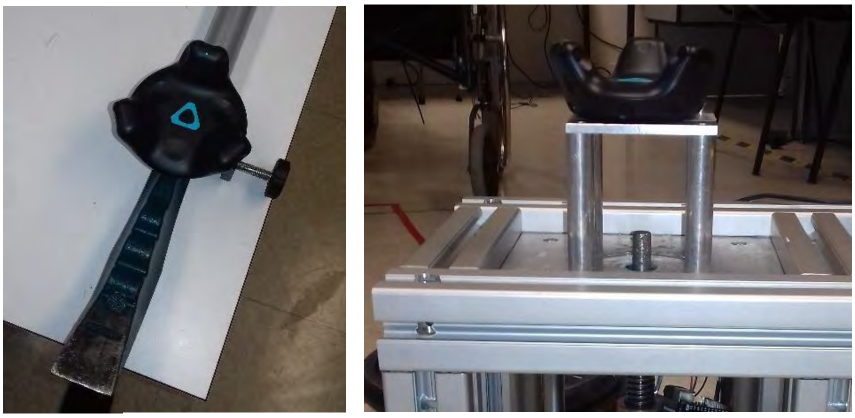

Figure 10: Vive trackers to track the crowbar and the platform

All participants perform each workshop 5 times. The order of the workshops were executed randomly by participants in order to ensure independent results (Hooton, 1991), for example participant 1 carried out workshop 2-3-1, participant 2 carried out workshop 1-3-2.. We have determined 3 different parameters (“Execution time”, “distance raised” and “number of errors”) of which we studied, the execution time of the task between the VR and the MR on the one hand (Test 1) and between the “Real Situation” workshop and the MR on the other hand (Test 2), the distance raised between the "Real Situation" workshop and the MR (Test 3) and the number of errors made between the VR and the MR (Test 4).

5.2 Results

The choice to compare these parameters comes from the assumptions made:

- We think that the execution time of the task in VR is weaker compared to that of the MR because the bar is absent, and the user does not have a feeling of extra weight, and he does not have constraint of the physical objects that surround it (see the simulator).
- The second hypothesis formulated is that the distance raised in a real situation is greater than that in MR because the bias brought by the virtual environment can hinder the perception of the user and inhibit his action.
- Thirdly, the number of errors committed by MR is greater compared to that of the VR because the weight of the bar comes into play as well as the presence of the simulator.
- The last hypothesis concerns the execution time of the task, which is lower in real-time situations compared to that of the MR. This is due to the bias of the virtual environment on the one hand and due to

the naturalness of the gesture of the participant on the other hand particularly when he sees the real simulator instead of a 3D representation.

For the statistical study, we used the Student test (paired t-test) after validation by the Bartlett test that the condition of homoscedasticity is verified.

When analysing the data, a participant's results were discarded. Indeed, following a tracking problem, the person could not perform the test in good conditions and the results were skewed. We conducted our analysis on 9 of the 10 participants.

While applying the student test on our various tests, we notice that the p-value is very low ($p < 10^{-6}$) on different statistical evaluations. This shows us that we do have a significant difference in the different studies. The VR environment present in the MR and the weight of the bar did not interfere with the participants in completing the task. This proves that MR is an interesting approach to VR when it comes to training on tools that require some expertise and low execution times as proved the author in (Grabowski, 2015) who showed that engaging the sense of touch can increase subjectively perceived realism of simulation by a factor of 2.

5.3 Limitations

Our study demonstrated that the MR approach for training was more relevant than a VR approach. Yet, our study shows some limitations in regard to the limited number of participants (10 participants, 9 included in the study), their absence of pose estimations and the fact that they are not experts in the assignment and the adaptation time is longer. Also, we worked with young participants who were more or less comfortable with the use of HMD while construction workers are more used to the use of the crowbar in real situations. Therefore, a study conducted with the latter could show interesting results and thus analyse, from a more expert point of view, the MR approach.

From a hardware point of view, we encountered some tracking and calibration problems with some sensors. This sometimes led to errors, and a time of adaptation for the participants.

5.4 Future works

The next step of the project is to improve the tracking system of the crowbar and the robotic platform in the virtual environment. We will also perform tests on a larger sample of people and integrate experts in handling the formwork. Finally, in future works a system of video acquisition following the movements and postures of the trainee will be added to the *Virtual Compagnon* platform in order to analyse his/her gesture and efforts during the manipulation of the formwork. For this, we will work in addition to the PM mode with the other modes (AM and RM) to evaluate the behaviour of trainee in different situations.

6. CONCLUSION

In this article, we introduced first functionalities of *Virtual Compagnon platform*, a MR solution that gathers a VR headset for visual and auditory immersion and a robotic platform for strength feedback. This solution is dedicated to the training of construction workers on a tool frequently used on construction sites; the formwork panel and more specifically the movement of the formwork thanks to the crowbar. The platform is configured to reproduce the effort felt when using the bar. The shift observed on the platform is retransmitted in the virtual environment in order to obtain a 3D representation of the formwork.

To show the interest of using a MR solution, we conducted a test with 10 novices from LISV. These tests showed the contribution of the MR to the VR, revealing a statistically significant result when comparing the time devoted to the execution of the task in the placement of the crowbar between the VR and the MR, and between “Real Situation” and MR, a statistically significant result when comparing the distance raised between “Real Situation” and MR and a statistically significant result when comparing the number of errors between VR and MR.

For the next version, we will improve the bar tracking system and the platform that has caused some desynchronizations.

Also, we will conduct tests with experts in the field, increasing the number of participants.

Finally, *Virtual Compagnon* allows to reproduce the gesture of the crowbar use. In future works, we will add a video capture system to study and evaluate the gesture and posture of the trainee during the execution of the task, in order to train him to position himself well.

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THE EFFECTS OF HAZARD LOCATION ON USER SAFETY BEHAVIORS IN A VR CONSTRUCTION SIMULATOR

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ABSTRACT:

Safety decisions made by construction workers on-site directly affect the rate of accidents and injuries. This study investigates whether the location of hazards influence people's noticing of the hazards. Studying the relationship between hazards and safety behaviors contributes to construction safety management in terms of site safety design. Virtual reality (VR) simulators have been created for training workers in site safety.

Eye-tracking technology is used to study how eye-catching different hazards are. To achieve high accuracy on tracking eye movements and create highly immersive experiences, the virtual environments are displayed using a VR headset with built-in eye-tracking. It is found that the hazards above eye level are less likely to be noticed. The results help to establish the fundamental design principles of VR construction simulators for training purposes. Future study will combine eye-tracking technology with brainwave measurements to study the brain's reaction to different stimuli.

KEYWORDS: Hints, Construction Safety, Virtual Reality

1. INTRODUCTION

The construction industry has high injury and fatality rates. Unsafe behaviors of construction workers may lead to accidents. Thus, it is important to train people to make safe decisions on construction sites. Virtual reality (VR) simulators have been created for training workers in site safety. Using VR for construction education avoids people being exposed to real dangers (Filigenzi et al., 2000), but there have not been any guidelines on what should be added to VR simulators for training purposes.

Previous research found that virtual construction simulators involving unsupervised interaction should be designed with sounds and their corresponding visual objects, without priming factors, and should contain "traps" that highlight unsafe behavior by ensuring that the trainees will always experience the negative consequences of unsafe decisions (Lu and Davis, 2018). To prevent unsafe behavior on construction sites, barriers should be set up, safety warnings should be displayed near hazards and safety management personnel should be present (Lingard and Rowlinson, 2005). However, sometimes people still ignore these protections and act unsafely. Therefore, to discourage these human errors, safety training in VR simulators is essential because trainees experience appropriate consequences after making mistakes in a virtual environment (VE) without being physically injured.

However, it is still unknown how people react to different cues in VR simulators. The most common accidents on construction sites are caused by falling from height or falling objects (Helander, 1991). Therefore, this study will investigate how the location of hazards influences whether or not particular hazards are noticed. Hazards that are not noticed should have extra effort applied to make them salient, or to protect workers from them. This would also help to establish the fundamental design principles of VR construction simulators for training purposes.

This requires eye tracking of VR users to determine what they see. To achieve high accuracy on tracking eye movements and create a highly immersive environment, the virtual environments will be displayed using a VR headset.

The hypotheses tested by this study are:

1. Hazards on the ground are more likely to be noticed than those above eye level in the virtual construction site.
2. Being "injured" in a VR construction simulator will subsequently make people act more safely.

2. BACKGROUND

Traditional methods that have been used in education and training involve lecture/discussions, demonstrations, conferences, simulation, videotapes, programmed instruction, and interactive video (Xie et al., 2006). Traditional construction training is usually delivered in the classroom, on-the-job, by interactive videos or by hands-on instruction (Stromme, 2011). However, with the fact that people get tired of the traditional training methods, more realistic and interesting methods are desired (Filigenzi et al., 2000). Following the existence of the World Wide Web, and with the advancement of computer technology, e-learning has become a widely used method for construction training. Ho and Kuo (2010) defined e-learning as computer-aided or internet-based learning and includes remote learning and on-line learning modes. It not only reduces the cost of construction training, but also provides a flexible learning environment (Ho and Dzeng, 2010).

Zhao and Lucas (2015) suggested a pyramid of learning effectiveness for construction safety training, from where it could be seen that ideally, by simulating a real practice or going through the real-life task/experience, trainees can remember more than 75% of the learning content (Fig. 1).

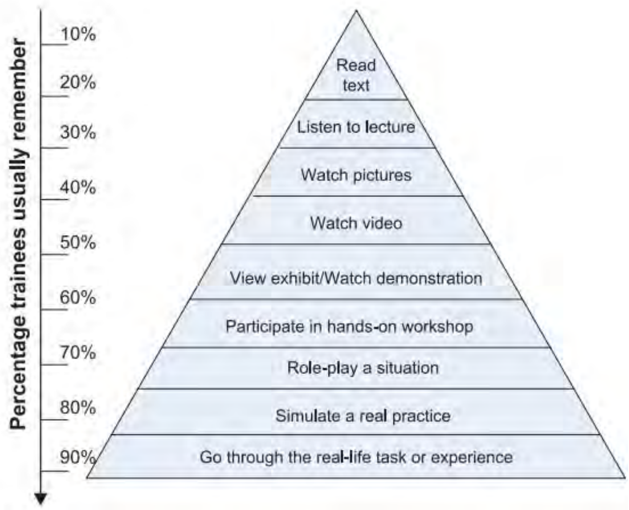


Fig. 1: Pyramid of learning effectiveness (Zhao and Lucas, 2015)

However, on the job training is often time and resource consuming, and the opportunity of being involved in real-life tasks is also limited for trainees. Therefore, computer software has started to play an important role in modelling and simulating real world processes (Kellner et al., 1999). Although software simulation modelling can help people to predict the result of an activity, people do not feel like they are performing a real task, for the reason that 2D displays lack immersion (Sharples et al., 2008).

In the last few decades, a new technology, virtual reality (VR) simulation, has been used as a training tool. Kinateder et al. (2014), and Rüppel and Schatz (2011) have studied fire safety behaviors in VR. Using VR for construction education avoids people being exposed to real dangers (Filigenzi et al., 2000), but there is also the challenge of ensuring that the trainees take the consequences seriously in a virtual world, and that they learn from the VE.

Several researchers have compared the efficiency of training with VR and conventional training methods. Ausburn and Ausburn (2004) pointed out that VR should not aim to replace conventional training methods but to play a supplementary role. It appears that students are motivated by VR but they also prefer live instruction where they can ask questions and receive feedback. Tate et al. (1997) studied the supplementary effect on learning by adding VR training to traditional firefighting training. The trainees made fewer mistakes and finished faster after training in the VR simulator than those who only went through traditional training.

3. STUDY METHODS

This study investigates whether the location of hazards affect whether people notice them. The virtual environment used in the study contains different hazards:

1. Falling objects from a scissors lift
2. Falling objects from a crane
3. Falling soil from an excavator into an excavation
4. Moving trench box lifted by a truck crane
5. A reversing truck
6. Electric shock from electric cables lying in water

The first three hazards are above eye level. However, the equipment related to each of these three hazards is placed on the ground. The trench box is lifted at/above eye level. A reversing truck is at/below eye level, and the electrical cables are on the ground. This choice of hazards aims to investigate whether people look up when they are immersed in a virtual environment.

A FOVE eye tracking headset was used in the study to show the point where people are looking at any particular time. This can then be linked with what the participant subsequently does in the simulation. The virtual environment was run on a Dell Alienware personal computer and an Xbox controller was used for user input.

3.1 Test procedure

5 PhD students from the School of Civil and Environmental Engineering (3 males and 2 females) were invited to test the headset and environment.

They were asked to sign a consent form before the experiment introducing the aim, requirements, potential risks and benefits of the experiment. Since it is common that users feel sick in VR environment, they were told that once they feel any sickness, they are free to quit the experiment or, if they prefer, to continue participating using a 2D monitor.

The investigator introduced the user interface to the participants and briefed them that this experiment was to teach people how to build a scaffold and their tasks were searching for the materials needed. They were told that the eye tracking device was used to study how people look for things. The aim of this briefing that it was not about safety was to distract participants from looking for hazards so that they would act normally as construction workers.

The participants started the test after the briefing. The screen was recorded during the test.

They started the test standing outside the construction site, and were told to find a blackboard (as shown in Fig. 2) to activate the task. As the eye tracking loses accuracy during physical movement such as head turning, a relatively small "Hint" button was added to the blackboard. Participants need to gaze at the button and press a key on the controller to activate the hints, which then activated NPCs who can tell them where the materials are. Pressing the key when the gaze point was outside the button, hints wouldn't be activated. Therefore, the participants would need to periodically correct the gaze point with another key. Gaze point correction can be used any time but adding the "Hint" button was to make sure that gaze point was accurate enough at the beginning of each task (about every 2 minutes).

Fig. 2: Quest blackboard

After the test, participants were asked to complete a questionnaire and were debriefed that the experiment was actually about safety and testing whether people can notice the hazards, rather than about searching for objects.

4. RESULTS

There were 10 tasks in the complete experiment. Among the 5 participants, only one of them finished the whole experiment with the VR headset on for the whole time. One participant quit the experiment after the first task because of dizziness. One student took off the headset after the first task because of dizziness, and then finished the next 6 tasks using a 2D display. The other two students switched to the 2D display after the 5th task and finished the experiment.

4.1 Case study

The data collected from the participant who completed the experiment in VR headset will be discussed below as a case study.

The participant is a male PhD student with a Bachelor in Civil Engineering. He has two month's construction industry work experience and 2 years of first person computer game experience. However, he has not played first person computer games for 2 years.

4.1.1 Answers from questionnaire

1. What do you think of the level of difficulty of the environments?
   Easy (Boring)

The tasks were activating quests, find the objects on the map and collect the object. The tasks themselves are not difficult. However, if a participant is not familiar with the user interface or feeling uncomfortable from wearing the VR headset, they may perceive more difficulties.

2. How similar did the virtual world feel to the real world?
   Moderate
3. How much do you think human activities in the virtual world are similar to that of the real world?
   Very much

In this test environment, the activities that the avatar can do include: walking, turning around, jumping, interacting with the quests, interacting with NPC (find the NPC and renew the hints on the map), interacting with the environment (being injured and collecting items). The human activities may also include colliding with objects.

According to all the feedback, the participants who thought that the human activities in the VE are very similar to that of the real world also thought that the tasks were easy. Future studies can investigate if the user interface and mechanics influence users' evaluation of the difficulties of the tasks.

4. Do you agree that virtual reality is a helpful tool for safety training?
   Strongly agree
   What improvement could be done with the virtual environment?
   Improvement on head tracking sensitivity.

The eye tracking lost accuracy if the headset slides on user's face, which can be caused by head movements. Therefore, a correction function must be added to the test environment. However, doing a correction every minute would also annoy users.

5. Please choose the risks that you perceived when you were doing the tasks.
   a. Falling objects from a scissors lift
   b. Falling objects from a crane x
   c. Falling soil from an excavator to an excavation
   d. Moving trench box lifted by a truck crane
   e. A reversing truck x
   f. Electric shock from water and electric cables x
6. Please choose the hazard that you think other students may be injured from.
   a. Falling objects from a scissors lift
   b. Falling objects from a crane x
   c. Falling soil from an excavator to an excavation
   d. Moving trench box lifted by a truck crane x
   e. A reversing truck x

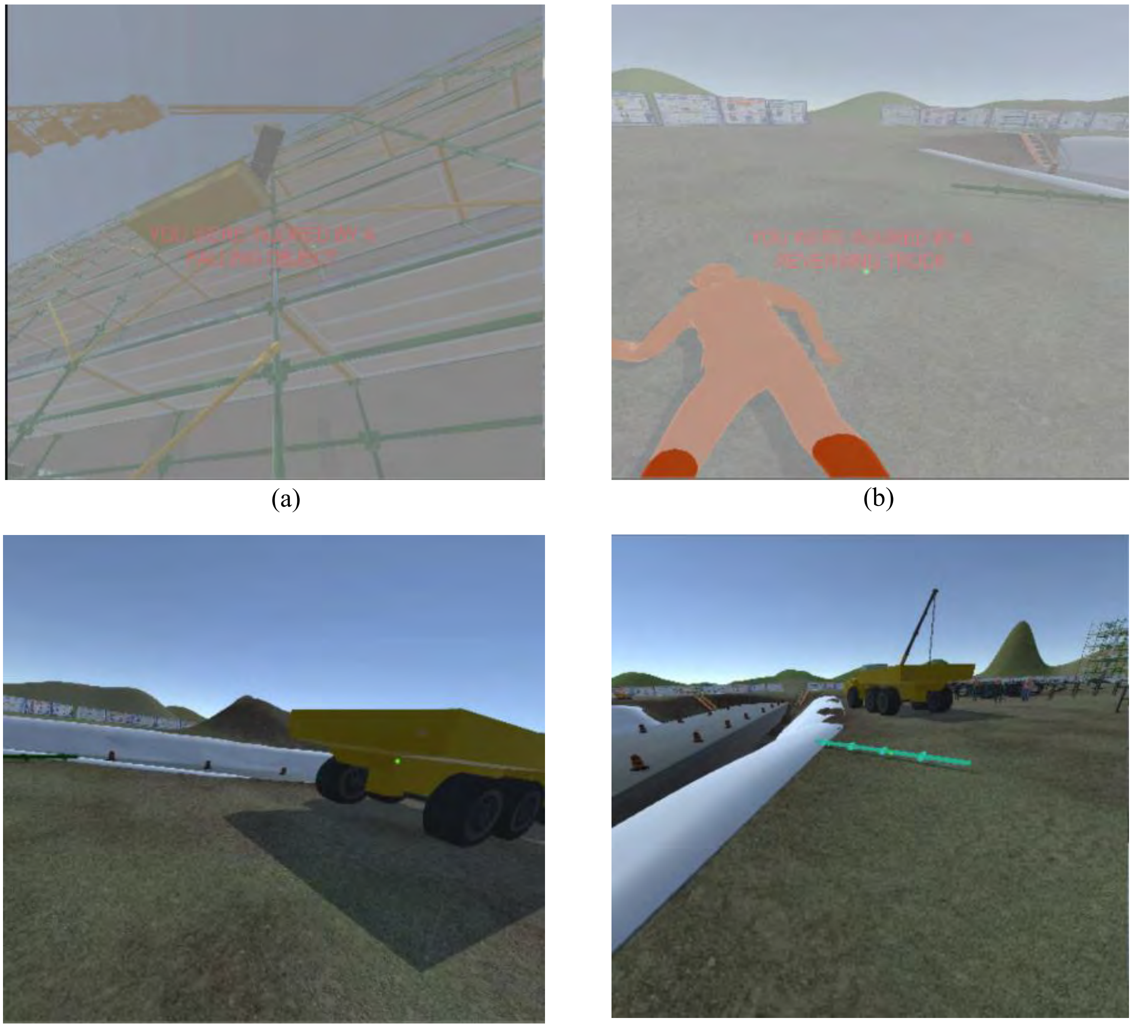
f. Electric shock from water and electric cables x

The purpose of asking the participants to predict other students' performance instead of asking what hazards they will be able to avoid next time is to avoid the Hawthorne Effect. Predicting what hazards other students may be injured from reflects what hazards gave the participants themselves deep impression.

7. What do you think of learning with VR compared to traditional learning methods? (video/fieldtrip)
   It's a form of visual learning which helps students to better visualize the theoretical knowledge, as it feels more relatable to real world experience, putting theoretical work into practice.

4.1.2 Observations from the test

1. The participant was injured from:
   a. Falling objects from a scissors lift x
   b. Falling objects from a crane x
   c. Falling soil from an excavator to an excavation x
   d. Moving trench box lifted by a truck crane
   e. A reversing truck x
   f. Electric shock from water and electric cables x
2. Each time the participant was injured, he started to look for the hazards, and avoided them next time he walked past (Fig. 3).

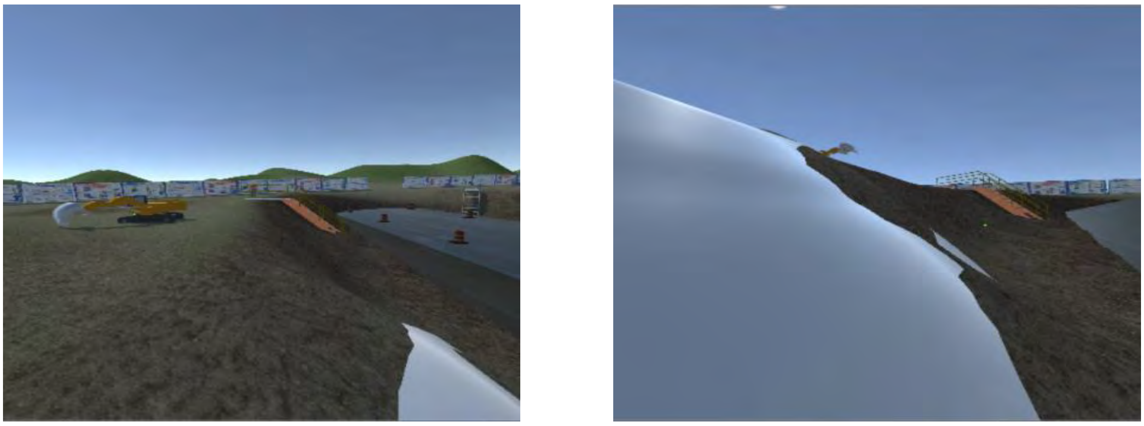


(a) (b) (c) (d)

Fig. 3: (a) looking at the crane after being injured (b) injured by the reversing truck (c) looking at the truck after

being injured (d) walking around the area behind the truck to collect the standard

3. The participant gazed at the excavator for one second when first walking past, but then did not remember that the excavator was above him after he walked into the excavation, leading to "injury". Future work will involve measuring brainwaves to determine the level of concentration when looking at such objects.



(a) (b)

Fig. 4: (a) looking at the excavator (b) walking in the excavation

4.2 Quantitative analysis

The following section aggregates the results from all 5 participants.

4.2.1 Injuries

Among all the tasks that have been finished with VR headset display, the number of injuries were:

Table 1: Injuries

Hazard	Number of Accidents	Participant Sample Size	Injury Rate	Rank
Falling objects from a scissors lift	3	4	75%	3
Falling objects from a crane	10	5	200%	1
Falling soil from an excavator into an excavation	2	4	50%	5
Moving trench box lifted by a truck crane	4	5	80%	2
A reversing truck	2	4	50%	5
Electric shock from water and electric cables	3	4	75%	3

It can be seen from Table 1 that objects falling from a crane has a much higher injury rate than the others. There are three main reasons:

1. This hazard was placed near one of the entrances of the building. The NPC was outside the building near this entrance and the object to be found was inside the building near this entrance. The falling objects were quite high. When the participants were focusing on their task searching for the materials on the floor, they did not devote much attention to the hazards around.
2. Even though they have been injured from the falling objects, most of them still used this entrance hoping that the accident before would not happen again. Only one participant started to look for other entrances after being injured.

3. The other entrance of the building is far away from the blackboard, and an injury only freezes the player for 10 seconds. Therefore, to save time, two participants decided to let their VR avatar be hit by the falling objects instead of spending more time using the safer route. This indicates that they were not seeing the avatar as themselves. However, this only happened after they switched to the 2D display.

4.2.2 Perceived hazards

The participants were asked to select the risks that they perceive while doing the tasks. (Table 2)

Table 2: Perceived hazards

Hazard	Number of Risks	Participant Sample Size	Perceived rate	Rank
Falling objects from a scissors lift	2	4	50%	4
Falling objects from a crane	3	5	60%	3
Falling soil from an excavator to an excavation	1	4	25%	6
Moving trench box lifted by a truck crane	2	5	40%	5
A reversing truck	4	4	100%	1
Electric shock from water and electric cables	4	4	100%	1

It is obvious that hazards on the ground were easier for the participants to identify. An average of 43.75% of the first four hazards (above eye level) in Table 2 were identified, while the last two hazards (on the ground) were both 100% identified.

4.2.3 Prediction from participants

The purpose of asking the participants to predict others' injuries is to study whether the hazards that people think to be most unnoticeable match the reality.

Table 3: The hazards that the participants think other people may be injured from

Hazard	Number of Hazards	Rate	Rank
Falling objects from a scissors lift	5	100%	1
Falling objects from a crane	3	60%	3
Falling soil from an excavator to an excavation	2	40%	6
Moving trench box lifted by a truck crane	3	60%	3
A reversing truck	4	80%	2
Electric shock from water and electric cables	3	60%	3

Interestingly, the hazard that was predicted to have the highest injury rate (Falling objects from a scissors lift) in Table 3 has 75% injury rate (rank No. 3) and 50% perceiving rate (rank No. 5 together with excavator).

It was predicted that the first four hazards that were above eye level would have an average of 65% chance of causing injuries, and the hazards would have an average of 70%. However, in reality, the first four hazards caused more injuries and were less likely to be identified.

4.3 Other comments

The participants also gave some feedback on training with VR vs. traditional training methods. They think that learning with VR has lower risk and is more convenient, also it saves time and has higher efficiency compared with traditional training methods. However, one participant also mentioned that it was not comfortable wearing the headset because of the weight and dizziness.

Participants without first person shooter (FPS) game experience felt different levels of dizziness.

5. DISCUSSION AND LIMITATIONS

From the results above, it can be seen that hazards on the ground are easier to be noticed than hazards at/above eye level. Even though the equipment/vehicles that are related to the hazards are on the ground, the participants still did not relate them to possible safety issues. Therefore, visual hints should be placed at ground level to attract their eyes, and salient sound should be added to where the hazards are located to help people identify their locations.

Moreover, looking at a direction does not necessarily mean that people have seen the object in that direction. Therefore, brainwaves should be measured to study whether people have seen a hint and thought about the hint.

Learning from "injuries" in the VR simulator helps people to act more safely in the virtual construction site when they are immersed using a headset. However, if the users are not immersed, they do not take the injuries seriously and use the shortcuts.

VR sickness is a hindrance to experiments. Usually first-time users start to feel sick after one or two minutes and take off their headset after 10 minutes, especially if they turn around a lot. Using hand held controllers to turn causes more dizziness than turning controlled by head tracking. Most VR simulators use "teleport" as the solution to avoid turning, however it is not suitable in this simulator, because teleport to the destination may jump over the hazards. Therefore, in the future experiment, the rotation input method will change from rotating while pushing the thumb stick to turning 30 degrees every time the thumb stick is pushed.

Limitations of this study include:

1. It is based on a small sample size.
2. Dizziness caused a large proportion of participants quit using the VR headset.
3. The immersion of the participants reduced after switching to the 2D display, which may have caused an increase in unsafe behaviors.
4. People may behave differently on real construction sites compared with inside virtual simulators.

6. CONCLUSIONS

The conclusions that can be drawn from this study are:

1. Hazards on the ground are more likely to be noticed than those above eye level.
2. The effect on safety behavior after being "injured" in a VR construction simulator depends upon the level of immersion.

This study provides fundamental knowledge of how people identify hazards. Future study will measure brainwaves together with eye tracking technology to further explore users' mental activities during the tasks and test what type of hints are most eye-catching.

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POSTURE ESTIMATION OF CONSTRUCTION EQUIPMENT FOR CONSTRUCTION SITE SAFETY USING COMPUTER VISION TECHNIQUES

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ABSTRACT: *For safety on construction sites, it is important to track the location, posture and movement of construction equipment (e.g. excavators, trucks, cranes, and bulldozers). Currently with the aid of surveillance cameras on construction sites, computer vision techniques can be applied to process the captured videos and images, which can be used to identify the site conditions and potential hazards. Previous research studies have attempted to identify and locate different kinds of construction equipment on construction sites based on surveillance camera videos using computer vision techniques. However, there is a lack of research studies that automatically identify the posture and movement of on-site construction equipment, which would also affect the safety condition of construction sites and the utilization of the equipment itself. This paper presents a methodology framework based on computer vision techniques that can automatically identify the posture of construction equipment from videos captured on construction sites. First, surveillance camera videos are used to build an image library of different construction equipment. Meanwhile, the posture of construction equipment is defined by its skeleton in this built image library. Based on the proposed image library, a computer vision technique namely Convolutional Neural Network is leveraged and modified to get the posture of a construction equipment. A demonstration example is presented to illustrate and evaluate the developed framework.*

KEYWORDS: *Convolutional Neural Network (CNN), Construction equipment, Posture estimation, Computer vision, Safety monitoring.*

1. INTRODUCTION

The construction industry is one of the most hazardous industries, according to the report of National Census of Fatal Occupational Injuries (2016) in the United States. Due to the high on-site accident rate, construction safety has attracted increasing attention in recent years (Zhou, Goh and Li, 2015). As a key component on construction sites, construction equipment (e.g. excavators, trucks, cranes and bulldozers), have great influence on construction safety. The safety issues related to construction equipment include transportation incidents and interaction with other objects on construction site. Those issues are mainly resulted from the dynamic location, posture and movement of construction equipment during construction work. Therefore, it is necessary to track the location, posture and movement of construction equipment so as to monitor their working state and avoid the occurrence of dangerous conditions in advance. Based on the extensive installation of surveillance cameras on construction sites, videos and images could be easily captured with the information of site environment and construction working state. Currently, most of the site managers still watch the videos to track motion of construction equipment and evaluate risks manually, which is time-consuming and not accurate.

With the large number of videos captured from surveillance cameras, computer vision techniques provide good means to process video frames and achieve automatic monitoring. Previous studies have attempted to identify and locate various kinds of construction equipment using computer vision techniques (Kim *et al.*, 2018). However, both position and posture of construction equipment would change during on-site activities, which would have influences on the safety condition. There are only few researches estimating the postures of the arm and boom of excavators using conventional computer vision techniques (Rezazadeh Azar and McCabe, 2012a; Soltani, Zhu and Hammad, 2017). The overall posture estimation of construction equipment still needs to be studied.

Currently, deep learning techniques such as convolutional neural network (CNN) models have achieved good performance for estimating human posture after trained with human posture dataset annotated by keypoints (Charles *et al.*, 2015). CNNs have also been utilized for identifying and locating construction equipment and achieved high accuracy. However, the posture estimation of construction equipment is still lacking. Therefore, this research proposed a CNN-based approach for automatically estimating the overall posture of construction equipment from videos captured on construction sites. In this study, an image library with 1,090 images of different construction equipment is built by extracting frame images every 10 seconds from surveillance camera videos. The videos are taken under different situations, such as from different points of view to the construction equipment, in different weather condition, and at different working time (daytime and night). Meanwhile, the location of construction equipment is known, and the posture of construction equipment is defined by its skeleton using keypoints annotation. With the proposed image library and posture annotations, the keypoints of equipment skeleton can be identified using the constructed CNN model.

The rest of this paper is outlined as follows. Related works on the applications of CNN on construction and posture estimation of construction equipment are introduced in Section 2. Section 3 includes details of the proposed methodology. The posture estimation of excavator is used to illustrate and evaluate the proposed methodology in Section 4. Section 5 concludes the paper.

2. RELATED WORK

2.1 Motion Tracking of Construction Equipment

There are many methods developed for motion tracking of construction equipment. Various sensors are usually applied to monitor positions and motions of construction equipment on site. For example, Radio Frequency Identification (RFID) (Chae and Yoshida, 2010) and Ultra Wideband System (UWB) (Cheng *et al.*, 2011) have been utilized for real-time tracking the location of construction equipment. In addition, some researchers used angular and linear displacement sensors to estimate the posture of construction equipment (e.g. crane) with low degree of freedom (Li and Liu, 2012). Although sensors could achieve high precision in tracking equipment and estimating their motion, numerous and complicated installations on construction equipment make this technique difficult to be applied widely. Another common practice is monitoring equipment's motion by watching videos and images from surveillance cameras, which are essential facilities on construction sites. Due to the low efficiency of manual observation and evaluation, conventional computer vision techniques such as background subtraction, support vector machines (SVMs), and k-means clustering were studied to track the motion of construction equipment (Rezazadeh Azar and McCabe, 2012b). However, in those studies, researchers need to carefully select handcrafted features for interpreting videos and tracking equipment, which affect the accuracy of the tracking results. Compared to conventional techniques, CNN model has achieved promising performance in various computer vision tasks such as image classification and object detection. In one CNN model, filters on a stack of convolutional layers, pooling layers and fully connected layers are applied to extract different features and the filter weights are optimized automatically during the training, which is more accurate and efficient. Although CNNs are employed in some studies to track motion of construction equipment and got high accuracy (Soltani, Zhu and Hammad, 2017), they could only classify the type and get the location of construction equipment. The application of CNNs for tracking movement and posture of construction equipment is still in its infancy stage.

2.2 The Applications of Computer Vision Techniques on Construction Sites

Before utilizing deep learning methods such as CNNs, there have been applications of conventional computer vision techniques for attacking issues on construction sites. For example, researchers have detected workers and equipment through combining histogram of gradient (HOG) and SVMs to process RGB images captured from construction sites (Golparvar-Fard, Heydarian and Niebles, 2013). Recently, Soltani et al. (2017) evaluated the performance of a CNN model for on-site equipment detection with a dataset containing both real and synthetic images of construction equipment. Fang et al. (2018) employed CNN to detect safe harness to prevent falling-from-heights issues. Kim et al. (2018) combined region-based convolutional neural network (RCNN) and transfer learning to build a model for detecting construction equipment with good performance. Based on detection results, locations of construction-related entities on construction sites could be obtained by object matching (Lee, Park and Brilakis, 2016). In addition to location information, the posture of workers and construction equipment also influence safety on construction sites. Thus, some researchers have estimated overall posture of workers (Yan *et al.*, 2017) and partial posture of the excavator boom and arm (Soltani, Zhu and Hammad, 2017) with location information. However, there is a lack of research on detecting the overall posture of construction equipment, which is important for identifying the working status as well as the interactions between equipment and the environment.

3. METHODOLOGY

In this study, an approach is proposed to track the posture of construction equipment, through estimating keypoints of the equipment skeleton using a CNN model. Based on known location of construction equipment, a CNN model is leveraged and modified for estimating posture of construction equipment through detecting keypoints. The overall workflow of the proposed framework is shown in Fig. 1. Firstly, image library of construction equipment is generated and keypoints of equipment skeleton are defined. Second, the ground-truth labels of keypoints are created for model training using Human Annotation Tool (Lubomir and Jitendra, 2011). The location of construction equipment is determined in each training or testing image. With known location, the created image library and ground-truth labels are used for training the proposed model. Using the weights acquired from model training, keypoints of construction equipment in an image are predicted. In the end, the postures of the equipment are estimated by connecting keypoints to generate the skeleton.

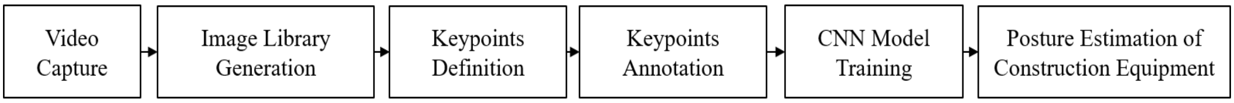

Fig. 1: Overall workflow of the proposed approach.

3.1 The Developed Posture Estimation Model

The overall architecture of the developed CNN model(Bouvrie, 2006) is shown in Fig. 2. The developed model contains 8 layers with weights, among which the first five layers are convolutional, and the remaining layers are two dense (fully-connected) layers and output dense layer. Each convolutional layer consists of several convolutional filters, and the parameters of each convolutional filter are optimized by a back-propagation algorithm. The purpose of the convolution operation is to extract different features of the input image. One convolutional layer may only extract some low-level such as edges, lines and angles. More layers of convolution can extract more complex features from low-level features. In the proposed model, five convolutional layers are used for extracting different levels of features from the input image through different sizes of kernels and filters. Pooling layer is to abstract the original features extracted from the input image, thereby greatly reducing parameters needed by the training model. In the proposed model, max pooling is used for pooling layer, which divides the input image or feature map into several rectangular areas and outputs the maximum value for each sub area. Using max pooling, the model only focuses on the most important features of the input image or feature map, which increases the efficiency of image processing and decreases the total number of required parameters. Dense (also named fully connected) layer maps the learned features to the given labels. Before the last dense layer, there is a dropout layer for avoiding overfitting. The output of the last fully-connected layer is fed to 12-way linear function, which predicts the coordinates of 6 keypoints of an excavator. The first two convolutional layers filter the 224x224 input image with 32 kernels of size 3x3. The following two convolutional layers use 64 kernels of size 3x3. And 128 kernels of size 3x3 are used for the final convolutional layer. The kernel stride in each convolutional layer is 1. Each fully-connected layer has 1024 neurons.

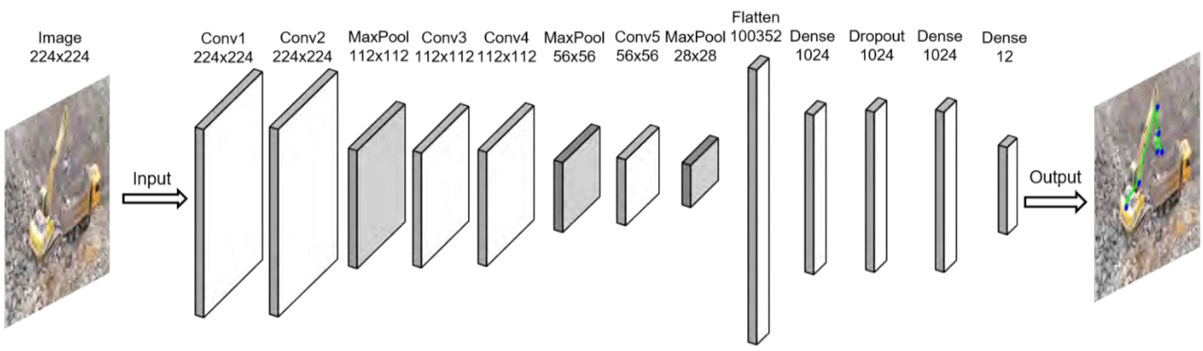

Fig. 2: Architecture of the improved CNN model for excavator keypoints estimation.

During the training of a CNN model, the overfitting problem should be considered. Dropout layer (Srivastava *et al.*, 2014) abandons the output of each hidden neuron with a probability of 50%. A certain set of neurons is not considered during a particular forward pass and do not participate in the corresponding backward propagation during the whole training process of the proposed architecture. Hence, dropout layer prevents co-adaptations among neurons and using dropout layer forces the developed model to learn more robust features from fed images. Therefore, a dropout layer is implemented between two fully connected layers in the model architecture proposed in this research.

3.2 The Model Training Process

3.2.1 Image library generation

In the proposed approach, images required for model training are captured from available videos by every 10 seconds. Considering the similarity between extracted frames from the same video, histogram matching algorithm (Russakovsky *et al.*, 2015) is used to eliminate relatively duplicated images. After calculating gray histograms of all extracted frames from one video, the probability distribution of gray values in each extracted frame could be obtained. After that, the similarities among extracted frames are calculated and compared by histogram matching algorithm through matching the probability distribution of gray values. If the matching result indicates two frames are similar to each other, the previous extracted frame would be saved, and the latest extracted frame would be deleted. Some example images of image library are shown in Fig. 3.

Fig. 3: Example images in the generated image library.

3.2.2 Keypoint definition and annotation

To track posture of equipment such as excavators by tracking their skeleton from images using deep learning, it is necessary to define the keypoints to get the skeleton of an excavator. Therefore, 6 keypoints of excavator were selected and defined as shown by the dark dots in Fig. 4: (1) Body_end: it is the point of boundary of equipment and the surroundings; (2) Body_boom: it is the interaction point of boom and excavator body; (3) Boom_arm: it is the joint of boom and arm; (4) Arm_bucket: it is the joint of bucket and arm; (5) Left_bucket_end: it is the upper left corner of excavator bucket at the viewpoint from body to bucket ; (6) Right_bucket_end: it is the upper right corner of excavator bucket at the viewpoint from body to bucket. Through connecting the defined 6 keypoints in sequence, the skeleton of an excavator is determined as the orange lines show. The overall posture of an excavator could be estimated, and the facing direction of bucket could be known.

After keypoints definition, the coordinates of those keypoints are required to create the ground-truth labels for deep learning model training. The ground-truth labels containing the information of keypoints coordinates are created by a keypoints annotation tool named The Human Annotation Tool (Lubomir and Jitendra, 2011), which is commonly used for human keypoints annotation and could be used for equipment key point annotation. For each keypoint, the annotation is (x, y, v). x and y are lateral and vertical coordinates of the keypoint while v represents visibility of the keypoint. v=1 if the keypoint is visible; v=0, otherwise. The created ground-truths are saved in XML format.

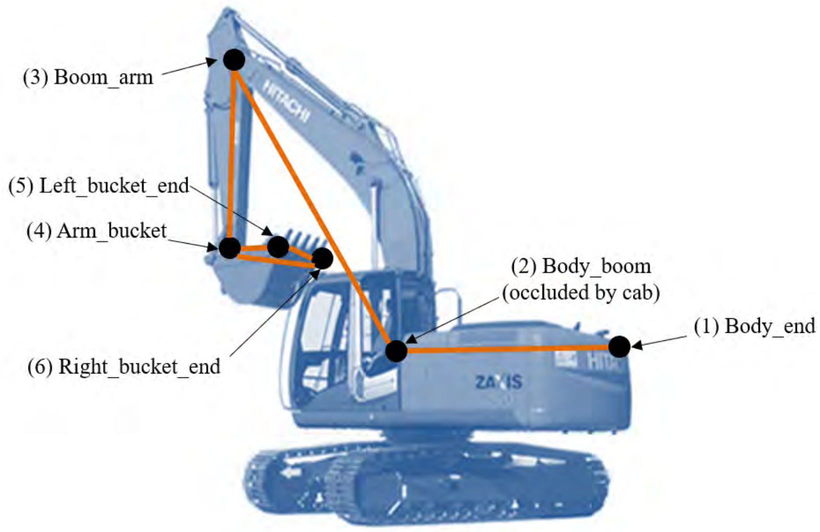

Fig. 4: Keypoints definition of an excavator.

3.2.3 Model training

The model is trained with a batch size of 64 images and a momentum of 0.9. During each training iteration, 64 image are randomly selected and fed into the proposed network which can improve the training efficiency as well as reduce the computation cost. All the weights in the proposed model architecture are initialized by glorot uniform initialization (Glorot and Bengio, 2010), which draws samples in a uniform distribution. The neuron biases in the convolutional layers and dense are initialized with 0. The activation function for each neuron is a rectified linear unit (ReLU) method. Euclidean distance is adopted to calculate loss function during training because this research mainly concerns about the position difference between prediction and ground-truth of keypoint. During training, stochastic gradient descent (SGD) is used as gradient descent optimizer with decreasing learning rate changing with the number of network epochs. The network is trained for 200 epochs on the images of the training set. After 200 epochs training, the model weights with the best overall accuracy on the validation set will be saved and utilized for testing.

3.2.4 Model evaluation

The accuracy of the pose estimation model is evaluated based on the probability of a correct pose (PCP), which measures the percentage of correctly predicted keypoint (Charles *et al.*, 2015). An estimated keypoint is deemed correctly located if the distance between this point and the ground-truth point is less than the defined threshold. The overall accuracy is calculated as the percentage of correctly estimated keypoints over the total amount of points, as shown in equations (1) and (2),

$$Result(r) = \begin{cases} 1, & d < threshold \\ 0, & d \geq threshold \end{cases} \tag{1}$$

$$Accuracy = \frac{1}{n} \sum_{r \in \{0,1,2,\ldots,n\}} Result(r) \tag{2}$$

where r indicates the r^{th} estimated keypoint of all the test images; d represents the distance between predicted position and ground truth of r^{th} keypoint; and n is the total number of estimated keypoints of all the test images.

4. EXPERIMENT

The proposed approach aims to automatically identify the posture of excavators on construction sites through detecting 6 keypoints of excavators as defined in Section 3.2.2 based on the images captured from on-site surveillance videos. Experiments are conducted to validate the applicability of the proposed approach.

4.1 Experiment Setup

Available image library used in this research has a total of 1,090 images of excavator captured from the videos available in Youku (Koo, 2006). With the availability of on-site surveillance videos, images required for training the model in this study are captured from those videos by every 10 seconds. At first, 4,800 images of excavators are obtained. After deleting duplicates by histogram matching algorithm, there are 1,090 images in total remained and annotated in the image library for the experiment, 80% (872 images) of which are used as the training set, 5% (54 images) are used as the validation set, and 15% (164 images) are used as the test set. Experiments are conducted by the proposed model based on Keras (*Keras Documentation*, no date) and TensorFlow (Abadi *et al.*, 2016), which provide packages to build deep learning models. The experimental environment is Ubuntu 16.04 operating system and Intel Core i7-4790 CPU.

4.2 Experiment Result and Discussion

The developed CNN-based posture estimation model is firstly trained with the training dataset, after which the model with the highest overall accuracy on validation set is saved and applied for detecting the posture of construction equipment. In the end, the performance of the proposed approach is evaluated on the testing set (164 images in total). The examples of experiment results are shown in Fig.5. Obviously, 6 keypoints are well estimated by the proposed model and they are annotated by black dots in each test image from different view. Connecting 6 keypoints with white lines, the skeleton and the overall posture of an excavator in the given test image could be obtained. Through the angles of the excavator skeleton, more information about the excavator such as the working state, working area and influential area of the excavator can be obtained, which are important for understanding the on-site safety condition.

Fig. 5: Examples of construction equipment posture estimation results.

Based on the testing results, the overall accuracy and the accuracy of each keypoint in test set are calculated according to equations (1) and (2). As illustrated in Fig. 6, the overall accuracy of excavator posture estimation increases with larger threshold. It gets 71.82% at threshold of 20 pixels. Accuracies varied in different keypoints, as shown in Fig. 7. For example, when threshold is 20 pixels, the accuracy of body_boom keypoint, boom_arm keypoint, and body_end keypoint are 83.64%, 80.61% and 81.21%, respectively. The experiment result indicates that most of keypoints on excavator are correctly detected and the overall posture could be determined. Therefore, this framework has the potential to estimate overall posture of construction equipment.

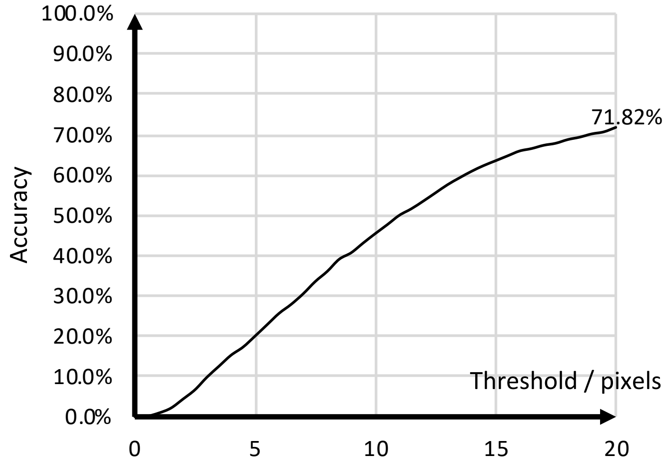

Fig. 6: Overall accuracy of keypoints on excavator.

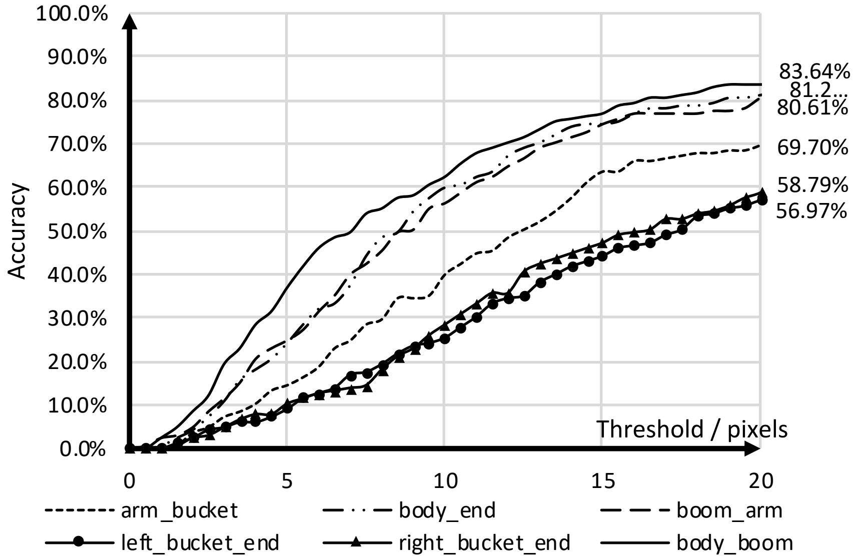

Fig. 7: Accuracy of each keypoint on excavator.

Although the framework can estimate overall posture of construction equipment, there are still keypoints not detected correctly as shown in Fig. 8. There are some potential causes of errors. Firstly, occlusion is a main cause for errors, as shown in Fig. 8 (a) and (b). Some keypoints (e.g. arm_bucket keypoint, left_bucket_end and right_bucket_end) are often occluded by soil or rocks during working period of excavators, which makes it hard to estimate these keypoints. When the equipment is observed from front view or back view, it is also difficult to estimate the posture of occluded part without enough image features. In addition, color and illumination of images influence the accuracy, as shown in Fig. 8 (c) and (d). The color of excavator body is often similar to the working environment and some images are captured at night, which increases the difficulties in distinguishing keypoints from working environment. Moreover, similarity between keypoints would lead to errors. For example, the proposed model sometimes makes mistakes when estimating left_bucket_end and right_bucket_end of excavators, which are similar with each other. To improve the accuracy of the proposed model and to address some of the limitations mentioned above, the whole construction site should be monitored by placing enough cameras at appropriate positions. In this way, a richer image library could be obtained and the construction equipment could be observed from different viewpoints.

(a) (b) (c) (d)

Fig. 8: Examples of inaccurate estimation results. (a) shows the inaccurate estimation result when excavator is observed from front view and most of its keypoints are occluded by the excavator body; (b) shows the inaccurate estimation of left_bucket_end and right_bucket_end when the bucket is occluded by soil; (c) presents the case that the excavator body and its working environment have similar color; (d) presents the inaccurate estimation case when videos captured at night and the illumination condition is poor.

5. CONCLUSION

Construction equipment (e.g. excavators, trucks, cranes and bulldozers) is a key component on construction site. Transportation incidents and attack incidents are often caused by the motion of construction equipment. It indicates that the location, posture and movement of construction equipment would have great influence on construction safety issues. Therefore, it is important to monitor the location, posture and movement of construction equipment during their working process so as to avoid potential dangers. With the widely installation of on-site surveillance cameras, it is convenient to monitor construction equipment through processing video frames without installing sensors on construction equipment. Compared with manual processing on the on-site videos, computer vision-based approaches can be applied for more efficient video interpretation. Additionally, the performance of CNNs in other tasks indicates their potentials for automatic processing videos captured from surveillance cameras on construction sites, such as to track location, posture and movement of construction equipment.

In this research, a CNN-based approach is proposed for automatically identifying the overall posture of a construction equipment from images captured from surveillance cameras on different construction sites. Based on the 2-dimensional RGB images, the proposed approach estimates the overall posture of a given construction equipment from different viewpoints. The overall accuracy of the proposed approach reaches 71.82% at a threshold of 20 pixels when identifying postures of construction equipment. Compared with conventional methods, the proposed approach can get rid of sensor installation on construction equipment, as well as reduce costs of time and workforce for monitoring site conditions. In addition, the proposed method estimates overall posture of construction equipment instead of merely focusing on certain special parts, which offers more information for construction safety analysis. In the future, the causes for the bad estimation will be explored and the proposed model will be improved.

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DEVELOPMENT OF HUMAN POSE USING HYBRID MOTION TRACKING SYSTEM

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ABSTRACT: *In modular construction, especially in a factory, awkward and repetitive motions of the workers are frequently occurred. These motions may cause the injuries and accidents which lead to safety and productivity reduction. To identify and reduce these motions for safety and productivity improvement, factory managers utilize ergonomic risk assessment which requires body joint angles, limb length etc. as inputs. Human motion capture systems (HMPS) have been approved to support this risk assessment. However, the existing HMPS have not been effectively applied due to the challenges like occlusion, lack of accuracy and complex environment. To address these limitations, this paper proposes a methodology which consists of (1) the detection of 2D body joint locations; (2) the detection of 2D body parts; (3) the refinement of 2D body joint locations by using results of 2D body parts detection; and (4) the estimation of 3D body pose and shape using a parameterized 3D body shape model SMPL and the refined 2D joint locations. The preliminary experimental results indicate the detection of 2D body parts can effectively serve as a reference information to improve both the accuracy of 2D joint detection, and of 3D body pose and shape.*

KEYWORDS: *2D body joints; 3D Human Pose; Optimization; Safety Management.*

1. INTRODUCTION

Unsafe or non-productive motions of workers occur frequently in the construction field and these motions are harmful to human health, because they are the cause of physical fatigue and musculoskeletal disorders, and even might lead to the accidents in the workplace. Taking the province of Alberta in Canada as an example (WCB, 2016), Table 1 effectively illustrates the seriousness of the unsafe motions. In 2016, unsafe motions were the most common cause for both lost-time and disabling injury claims in Alberta. They accounted for 42.1 per cent of the lost-time claims and 46.3 per cent of the disabling injury claims.

Table 1: Types of injuries and diseases, 2016 (data were adapted from (WCB, 2016))

Types of injuries and diseases	*Lost-Time Claims*	*%*	*Disabling injury Claims*	*%*
Unsafe Motions	9,953	*42.10%*	20,635	*46.30%*
Overexertion	5,112	21.60%	10,568	23.70%
Bodily Reaction	3,005	12.70%	5,903	13.30%
Repetitive Motion	771	3.30%	1,980	4.40%
Other Bodily Reaction/Exertion	1,065	4.50%	2,184	4.90%
Contact with Objects or Equipment	5,021	21.20%	10,972	24.60%
Falls	4,517	19.10%	7,323	16.40%
Others	4,518	17.5%	5613	12.6%
Total	23,649	100%	44,543	100%

Ergonomic assessment is helpful to reduce the occurrence of unsafe motions and it is often conducted when an individual is experiencing pain or discomfort with his or her job demands (Mattison, 2016). The assessment can analyze current working conditions to identify unsafe motions. Also, it could recommend the proposed technical design of workplaces and working methods. Therefore, it becomes critical to create a system offering accurate and effective data of the anthropometry to meet the requirements on ergonomic assessment.

Most human motion capture system *(HMPS)* can generate the motion capture data such as the angles of the joints, their degrees of freedom and limb length that are commonly used in the ergonomic assessment (Kale et al, 2016). Existing HMPS can be divided into four categories: magnetic, inertial, mechanical and optical system (Han et al, 2013). Magnetic systems calculate the position and orientation of joints by the relative magnetic flux of three orthogonal coils on both the transmitter and receivers. Inertial systems mainly rely on the miniature inertial sensors to capture the motion data. Mechanical systems are often referred to as exoskeleton motion capture systems which directly track body joint angles through the sensors attached to the body. All the three systems require the sensors/markers attached on the workers physically to obtain motion data. Also, most of the auxiliary equipment used in these systems for motion data transmission, analysis and/or visualization is expensive and not portable. As a result, they may provide more accurate motion data but significantly interrupt workers' motions during task operation. Due to this reason, most workers are not willing to be tagged by wearing the sensors or markers, which limits the practical use of these systems in construction workplace. Compared with the magnetic, inertial, and mechanical systems, optical HMPS do not need to attach any markers or sensors on the workers' human bodies. They are more efficient and economic which have been rapidly developed in recent years (Chen et al, 2013). However, the accuracy of the motion data must be improved, due to the challenges of the variation of body poses, complicated background, occlusion and depth ambiguities.

The aim of this research is to improve the accuracy of both 2D and 3D human pose generation given the videos captured by one single camera. The effectiveness of 3D human modelling for ergonomic analysis has been proved by previous works (Golabchi et al 2015; Li et al 2017). Considering the accuracy of 3D model generation is highly dependent upon the accuracy of 2D pose generation, this paper proposes a hybrid method to improve the 2D pose estimation at first and then generate the corresponding 3D pose. The proposed methodology consists of three stages: (1) tracking the worker in the videos. The tracking results are extracted to detect his or her body parts and initial 2D pose; (2) refining the 2D initial pose based on the detection result of the body parts. A parameterized 3D body model is further fitted to the joints in the refined 2D pose; (3) the final 3D human pose and shape of the worker could be obtained. The proposed method has been implemented in the Python 2.7 environments. The tests were conducted on a 20 second video clip collected in a workshop in Alberta. The preliminary results showed that the proposed method could improve the accuracy of locating worker head and shoulders by 2% and 10% and help to generate more realistic 3D human poses.

2. BACKGROUND

Optical HMPS currently focused on the generation of 2D and 3D human poses from images and videos. Below are detailed descriptions of existing 2D and 3D human pose generation methods, which this research study was built upon.

2.1 2D human pose generation

Pose estimation from a single-color camera has been widely researched. Historically, early work focused on using pictorial structural model such as deformable parts model *DPM* (Felzenszwalb et al, 2010), to break down the whole body into local body parts and infer their final poses based on spatial relationships and constraints (Pishchulin et al, 2013). The early work did not show promising results. The 2D pose estimation has been significantly developed after the introduction of *DeepPose* (Toshev A et al, 2014). It is the first deep network used to directly provide the x, y coordinates of the joints through regression. However, the regression methods have two primary limitations. First, their accuracy is low especially when the human body has a large deformation (Newell et al, 2016). Also, it is difficult to extend the methods to get the poses of multiple persons presented in the videos. In 2015, Pfister et al. (2015) presented a novel method, *Flow ConvNets,* which can regress heatmaps indicating a per-pixel likelihood for each key joint location on the human skeleton. The method significantly improved the performance of 2D human pose generation, compared with the results from the regression methods. However, the method was limited to estimating the pose of the upper body only.

After that, two major research studies, the convolutional pose machines (*CPM* method) and stacked hourglass method (Newell et al, 2016) were introduced to address the limitation of *Flow ConvNets*. The *CPM* (Wei et al, 2016) proves that sequential CNN is capable of learning a spatial model for pose by communicating increasingly refined uncertainty-preserving beliefs between stages in the network. But it requires a huge amount of training data to achieve good estimation results. In the hourglass method, the network structure is like an hourglass, repeatedly using top-down to bottom-up to infer the location of the human body. Every top-down to bottom-up structure is an hourglass module.

However, the methods above could be applied only to single-person pose estimation. For multi-person pose estimation, *DeepCut* (Pishchulin et al, 2016) achieved state-of-the-art results for both single person and multi person pose estimation. It adopted the top-down approach, first finding out and clustering all candidate joint points of an image and then determining which joint point belongs to which person by an optimization formula. The computation cost is huge in *DeepCut* since it uses the adaptive fast R-CNN for human detection and Integer Linear Program (*ILP*) at the same time. So, its accelerated version, *DeeperCut* (Insafutdinov et al, 2016) was introduced to adapt the newly proposed residual net for body part extraction, and achieved higher accuracy.

In addition to the top-down approach, the bottom-up approach is another way to detect multi-person's pose. Typical work is Part Affinity Fields (*PAF*) (Cao et al, 2017). The *PAF* method can achieve high accuracy and real time performance (approximately 5ms per image); but it might fail when the image only contains one person, as shown in Fig.1. The reason is that the *PAF* used a greedy search algorithm to detect candidate body joints. As a result, non-joint points are considered as joints by mistake.

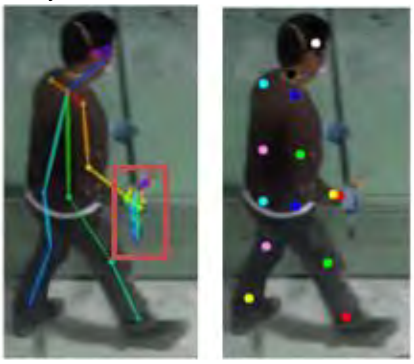

Figure 1 Comparison between *PAF* (left) and *DeeperCut* (right)

2.2 3D human pose generation

In the field of 3D human pose generation, there are mainly two categories (1) depth-based approach using RGB-D cameras; and (2) RGB-based approach using multiple or single color cameras. The RGB-D cameras can generate depth images which infer point cloud to estimate 3D pose. The value of each pixel in a depth image indicates the calibrated distance between the camera and the scene. Although depth images can significantly simplify 3D pose estimation process and lead to robust solutions (Xia et al 2012; Buys et al 2014), they have the limited scope of applications. RGB-D cameras often fail in situations such as the human are obscured in the scene or the shooting distance is far. For example, the most popular depth camera Kinect will produce holes in the depth images when the shooting area cannot be seen by both the projector and RGB camera.

So far, the RGB-based approach is still one of the promising and popular research directions. The approach could be divided into multi-view methods and monocular methods depending on the number of color cameras adopted. Multi-view methods were inspired by human vision which infers 3D human pose from two (or more) different views of RGB cameras (Trucco and Verri, 1998). The main mechanism behind is always to obtain the 2D pose in each view of the cameras at first, and then reconstruct the 3D skeletal pose from the 2D poses in different views (Han and Lee 2013; Hofmann and Gavrila 2009). Recently, research efforts (e.g. some papers (Stoll et al, 2011) (Rhodin et al, 2015) were even made to optimize the online 3D pose reconstruction process by shifting its computational pressure into the off-line stage. This way, the high computational cost in the methods could be saved. However, the accuracy of the multi-view methods is still not high and affected by the factors, such as environmental illumination changes, camera installation positions and cameral calibration precision.

3D human pose generation using monocular RGB camera is a much harder challenge but has developed rapidly in recent years. Researchers tried to obtain the 3D pose by creating the relationship of selected features (like 2D silhouette) and 3D skeletal pose (Atrevi et al, 2017). More advanced methods were built on deep learning, such as *Vnect* (Mehta et al, 2017) and Hourglass (Newell et al, 2016). The former regressed 2D and 3D poses jointly by a new CNN-based pose prior with Kinematic skeleton fitting. The latter generated the 3D pose using its special "stacked hourglass" network based on the successive steps of pooling and up-sampling (Newell et al, 2016). Both methods resulted in remarkable achievements, but they can only get the skeletal 3D pose of human. Instead, Federica et al. (2016) described the first way to automatically estimate the 3D pose of the human body as well as its 3D shape from a single unconstrained image.

3. OBJECTIVE AND METHODOLOGY

The main objective of this paper is to improve the accuracy of both 2D and 3D human pose generation given the videos captured by monocular camera. A hybrid method has been introduced to achieve this objective which combines the 2D pose detection method with the 2D body part detection method. To be more precise, the results of 2D body part detection are utilized to improve the 2D initial detected pose and then the 3D human pose can be improved since the accuracy of the 3D pose is highly relied on the accuracy of the 2D pose. The results of the experiment in the paper can verify the feasibility of the hybrid method.

The methodology proposed in this paper can be divided into three stages: preprocessing, refinement and fitting. The preprocessing stage is only responsible for tracking the human in the video. After the human has been tracked in the video, there are five steps to obtain the final 3D human pose and shape (see Fig. 2). The first four steps belong to the refinement stage. In the first step, the initial body pose is predicted by *Deepercut* (Insafutdinov et al, 2016); and the body parts are detected by *Deeplab v2* (Chen et al, 2016) in the second step. The third step utilizes the heatmap produced in *Deepercut* to identify the reliable part detection results. Then the reliable parts in turn are used to refine the initial pose (notice the change in position of head and shoulder joint in Fig. 2). The refined 2D pose with its joint information is further used to infer the corresponding 3D pose and shape in the last step which belongs to the fitting stage. Below is the detailed description of each stage.

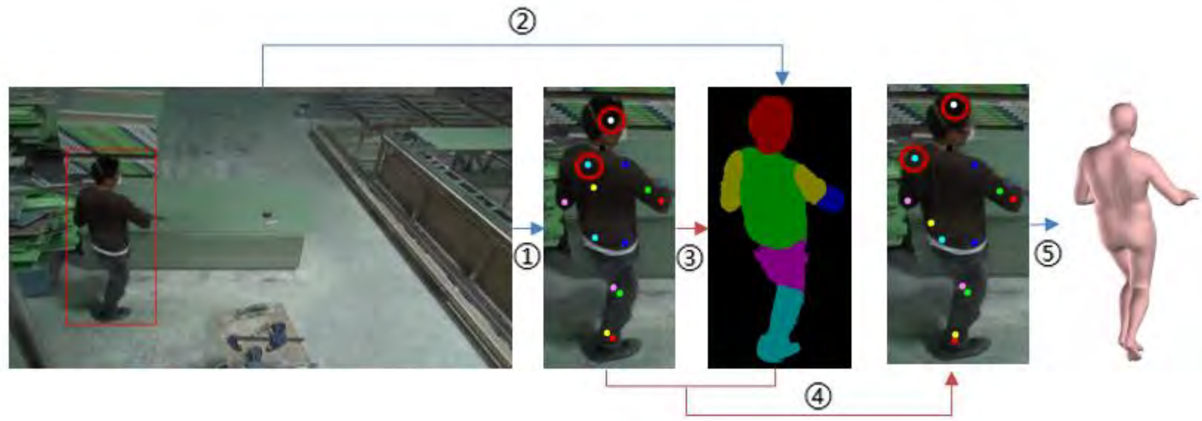

Figure 2 System overview

The task of preprocessing stage, human tracking, is popular in the field of human pose estimation with videos. This step is indispensable due to the following reasons:(1) most of the CNN networks for 2D pose estimation require that the size of the input image is not too large; (2) original image always contains plenty irrelevant background information which can distract the pose detection result; (3) processing larger images demands higher computer memory and computational power. This paper adopts the CNN-based network *MDNet* (Nam and Han , 2016) because of its high-performance on human-tracking task (Kristan et al, 2013).

The original video frames are cropped according to the bounding boxes which are the outputs of *MDNet* that can denote human location on each video frame. It is essential to resize the cropped images to a suitable and unified size before implementing the 2D pose estimation. This is because the accuracy of the pose estimation can be affected by the size of the input images. The previous work (Chen et al, 2017) denoted that the 2D pose estimation result will be the best when the ratio of the image height over width is around 4 over 3. Furthermore, Pishchulin et al. (2016) found that scaling images to a standing height of 340 pixel performs best. In this paper, the human tracking results are resized at 340 (height) by 255 (width) based on these two criteria.

In the refinement stage, the first step is to obtain the initial body pose that composed of 14 body joints. The initial pose is achieved by *Deepercut* (Insafutdinov et al, 2016) which is a CNN-based network and can perform well in both single-person and multi-person pose estimation. *Deepercut* is capable of producing the heatmap for each joint to indicate the target joint based on the reliable probability of each pixel in an image (see Fig. 3). In the Fig. 3, left is an example image with the detected joints denoted by assorted colors; on the right are heatmaps for 14 joints. First row includes the heatmap for right ankle/knee/hip, left hip/knee/ankle and right wrist and second row has the heatmap for right elbow/shoulder, left shoulder/elbow/wrist, neck and head respectively. The heatmaps will be used to evaluate whether the part detection results (generated in next step) are reliable and which detected part can be used to refine the initial pose.

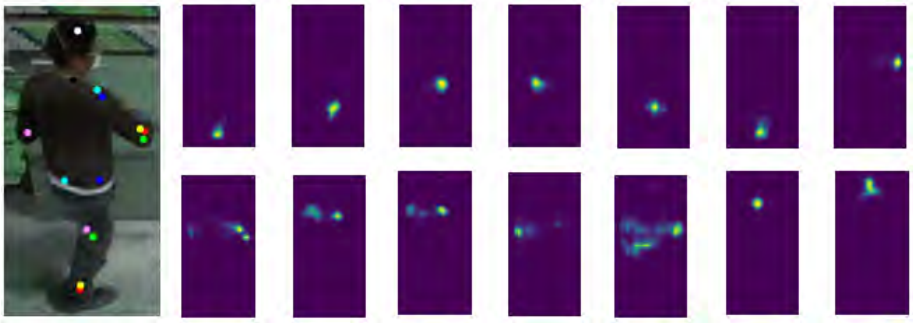

Figure 3 An example image for initial pose and the heatmaps for its 14 joints

In order to get human body parts in the second step, the method mainly relies on *Deeplab v2* (Chen et al, 2016) for semantic segmentation performed on the human tracking results. It achieved 87.4% accuracy on person segmentation in PASCAL VOC Challenge (Everingham et al, 2015). One modification made here is to merge the 24 detailed human part annotations in the Pascal-Person-Part dataset (Chen et al, 2014) into 6-part classes which are head, torso, upper/lower arm and upper/lower leg in *Deeplab v2.*

Next step is to evaluate the result of part detection by the heatmaps produced in the *Deepercut* network. The value of each pixel on the heatmap varies from zero to one. The higher the value of the pixel, the more likely the pixel is the joint point. Here, the detected part can be regarded reliable when its region contains the pixel with a high value (larger than 0.2 in this study) on the corresponding joint heatmap. For instance, if one head part detected contains a pixel with the value higher than 0.2 in the head heatmap, that head part is reliable to refine the head joint later. The evaluation of other parts detection can be implemented in the same way. The value 0.2 is selected, since it is the maximum probability in the heatmap of most occluded joints and the near-minimum value in the bright area of the well-detected joints' heatmap (see Fig.3).

The last step in the refinement stage is to refine the initial pose based on the reliable part detection result. In the *DeeperCut* (Insafutdinov et al, 2016), the pixel with the highest confidence value in the heatmap is selected as final joint point. In fact, this criterion may not always be correct. For example, the detection of the left shoulder joint is wrong in the Fig.3, due to the reason that the pixel with the highest confidence value in the left shoulder's heatmap locates in the right shoulder part. Although the pixel in the real position of the left shoulder has a high value in heatmap as well, the pixel is not be selected. This mistake results in a bad 2D pose. Therefore, the refinement is necessary to address this issue.

The refinement for joints is built on a case-by-case basis. Take the head joint as an example. If the initial detected head joint is not in the reliable head part region, then the pixel with the highest confidence value in the head part region should be selected as the head joint. If the detected head joint locates on the head part region, the height and the width of the head part region should be compared in next step. It is because that the refinement will be processed in the condition that the direction of the head is vertical which means the height of the head part should be larger than the width of the head part. If the height of the head part is larger than the width of the head part, the pixel with the highest confidence value in the top ¼ of the head part region is selected as the head joint. The corresponding refinement process for the header is illustrated in Fig. 4.

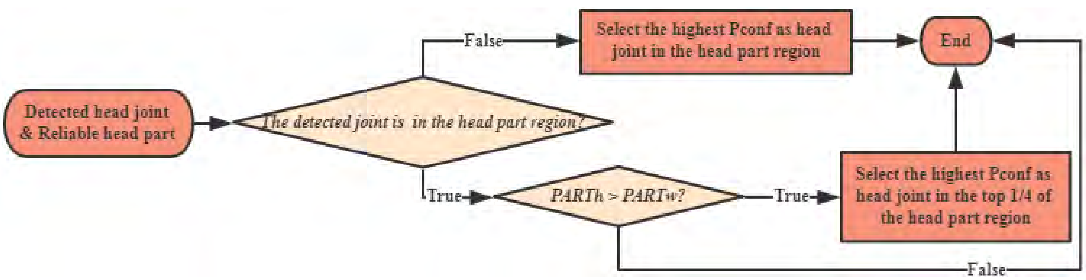

Figure 4 Workflow of head location improvement

As for the joints of the shoulder, the number of the reliable upper arm part should be firstly checked. If there is only one reliable upper arm part, then the part should be checked whether belongs to the left arm or the right arm.

If the part only has the pixel with the highest value in the left shoulder's heatmap, the part is identified as the left upper arm. Then the pixel with the highest confidence value in the part region will be selected as the left shoulder joint. The right shoulder joint can be refined in the same way when the part is identified as the right upper arm. If there are two reliable upper arm parts and one shoulder joint is in one part while another shoulder joint is not in both parts, the pixel with the highest confidence value in the no-joint part region is selected as the second shoulder joint. If there are two reliable upper arm parts and two shoulder joints are in the same part, the shoulder joint with lower confidence value in its heatmap is modified and the pixel with the highest confidence value in the no-joint region is selected as this shoulder joint. The corresponding process for the shoulder refinement is illustrated in Fig. 5.

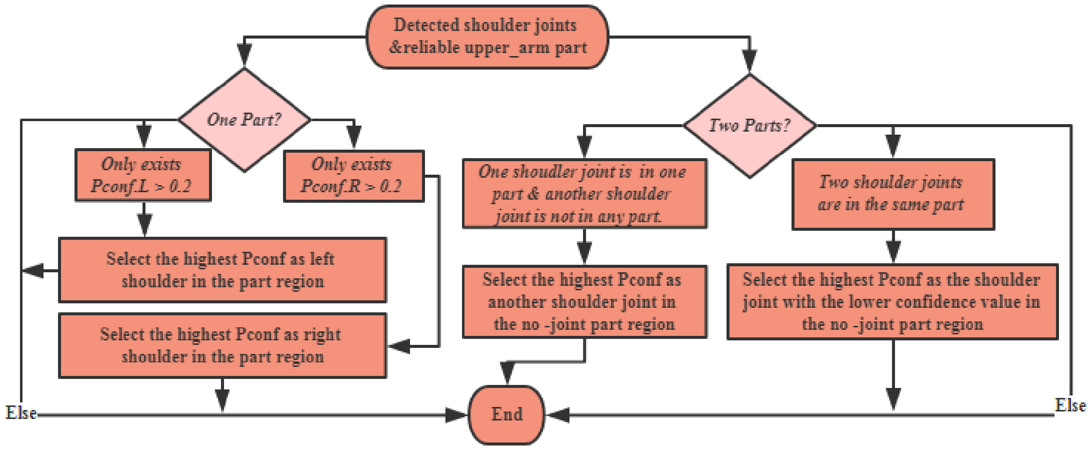

Figure 5 Workflow of shoulder location improvement

The refined 2D joints are further used to obtain the 3D human body pose and shape in the final fitting stage. The fitting relies on the 3D generative Skinned Multi-Person Linear *(SMPL)* model created by Loper (2015). The 3D *SMPL* model is a skinned vertex-based model that accurately represents a wide variety of body joints and shapes in natural human poses (Loper, 2015). Following the workflow of Bogo et al. (2016), the purpose of the fitting is to reduce the error between the projected 3D *SMPL* joints and the 2D joints refined in the previous step. This way, the 3D pose and shape that optimally match the refined 2D joints are obtained.

4. IMPLEMENTATION AND RESULTS

The proposed method has been implemented in the Python 2.7 environments. It was tested on a 20-second video clip (300 frames). The test video was recorded in the Fortis LGS Structures Inc. which has adopted a modular construction method for constructing using light gauge steel material. The production line in the Fortis consists of four stations: (1) assembly table in which all the raw light gauge steel materials are classified and assembled; (2) framing table in which the light gauge steel materials are collected as wall components; (3) sheathing table in which the drywall is sheathed to the wall frames and (4) panel racks is responsible for hanging the sheathed walls on the racks to facilitate subsequent processing. The test video is mainly recorded around the sheathing table due to the third station is the bottleneck which may delay the whole production line according to the diagnose (Youyi et al, 2016). Moreover, the 20-second video clip should be considered as typical and representative since it contains the most common motions of worker in the modular factory. The Fig. 6 shows the preliminary test results based on the video clip, including 2D refined body pose and 3D generated model.

Figure 6 The final pose of 32nd, 105th, 120th and 282nd frame respectively with their corresponding 3D model

According to the test results, it was found that the refinement step played an important role on the correctness of the final 3D pose/shape generation. Fig. 7 shows some examples for the initial 2D pose generation results as well as the refined 2D pose results. The corresponding 3D models generated by the initial 2D pose results and the refined 2D pose results are also shown in the figure to do the comparison. The method generating the initial pose can give the accuracy rate 90% for the head detection and give the accuracy rate 96.4% for the shoulder detection. After introducing the hybrid method, the accuracy rate for the head detection improves to 100% while the accuracy for the shoulder detection improves to 98.2%. Almost all the refined 2D pose can obtain a better 3D pose afterwards. Also, based on the criterion to verify the reliability of parts presented in this paper, the part detection result of *deeplab v2* has 14.8% failure rate which may influence the refinement results.

Figure 6 The comparison of initial and refined 2D & 3D detection results

5. CONCLUSION

This paper aims to improve the 2D and 3D human pose generation to offer more accurate data (e.g. joint angles) for ergonomic analysis. By doing this the unsafe motions of the worker can be reduced. A hybrid method has been proposed to improve the 2D pose detection and further improve the 3D pose generation. The human has bee n tracked in the video at first. The tracking results are extracted to detect human body parts and the initial 2D pose. Then, the 2D initial pose is refined based on the detection of the body parts. A parameterized 3D body model is further fitted to the refined pose to obtain the 3D body pose and shape. The method has achieved good results. For instance, the accuracy of the head detection has been improved from 90% to 100% while the accuracy of the shoulder joints detection has been improved from 96.4% to 98.2%. Almost all the refined 2D pose can obtain a better 3D pose afterwards. However, there are two main limitations to this method: (1) the accuracy of the body part detection is a premise to do the refinement on the initial pose, but the body part detection still have a 14.8% failure rate; (2) the body part detection cannot distinguish the left and right body part of the human which makes the refinement difficult to perform when the left and right body part is connected. Also, the future work should consider to directly optimize the 3D body pose. The extra features like silhouette can be used to search the best 3D pose in addition to the joints information.

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WHICH IS IT – AUGMENTED-, MIXED-, OR VIRTUAL REALITY? A META-ANALYSIS OF TERMINOLOGY IN RECENT RESEARCH

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ABSTRACT: *Mixed, augmented, and virtual reality technologies have been steadily gaining attention in the construction industry. These have been used in applications such as: assembly; site monitoring and documentation; hazard avoidance; training platforms; and improving collaboration. When the terms 'mixed reality', 'augmented reality', and 'virtual reality' were initially defined by researchers, they were effective at describing these unique visualization experiences. Now, with the plethora of technologies and use-cases studied that support very different experiences for users, the traditional definitions may not be sufficient for defining a user experience in order to be adequately understood by readers of the research. Therefore, this paper conducts a meta-analysis on construction research published in the last 10 years that is related to mixed-, augmented-, and virtual-reality. In order to illustrate the general trends in terminology usage, the authors identify the specific definitions cited among the publications as well as the specific visualization experiences reported in the works. Once all data is collected, results are organized to show trends, commonly cited definitions for different interpretations of the various visualization technologies, and aspects where there is not consensus among the research community. The contribution of this work is in demonstrating, through a structured meta-analysis, opportunities for clarification of critical research terms that are not currently agreed upon among the research community. These findings may help future researchers to more clearly articulate their research in order to present their findings with less chance for misinterpretation by readers.*

KEYWORDS: *Augmented Reality, Virtual Reality, Mixed Reality, Meta-Analysis.*

1. INTRODUCTION

Mixed, Augmented, and Virtual Reality (MR, AR and VR) have gained attention from various industries due to the development of new platforms and steady decrease in hardware prices (Cakmakci and Rolland, 2006; Ricci *et al.*, 2015). Although the entertainment, healthcare, marketing and education industries have embraced the technologies at faster rates (Wang *et al.*, 2014; Kade *et al.*, 2015), the Architecture, Engineering and Construction (AEC) industries are increasingly interested in advanced visualization technologies, creating a trend in visualization research (Rankohi and Waugh, 2013).

Recent research has illustrated various high-potential AR/MR/VR use-cases to support different construction processes. Kunz enabled designers to walk through a virtual factory using VR to check for mistakes before construction starts (Kunz *et al.*, 2016). El Ammari utilized MR to enable users to access maintenance information during maintenance operations (Ammari and Hammad, 2014). Schall developed an AR system to aid field workers in the visualization of underground infrastructure during excavation tasks (Schall *et al.*, 2009). These use-cases illustrate both the potential for these visualization technologies to benefit the AEC realm, and also the interest among researchers to explore these different visualization tools.

When the terms AR, VR and MR were originally defined, the definitions aimed to explain these technologies based on the levels of "virtuality" or "reality" incorporated into the experiences (Milgram and Kishino, 1994). With the increasing availability of new technologies that enable different types of virtual and physical interactions with virtual content, it becomes difficult to understand the experience the term is referring to. While the recognition of this lack of agreement in terminology may seem apparent based on a cursory review of AR/MR/VR literature, there is not a current understanding of the trends in usage of these terms as it relates to specific applications. As a result, there is not a consensus of what these terms mean among scholars. This poses a major potential challenge when future researchers read findings reported in publications and interpret the claims differently, and use these different interpretations to guide future research.

To understand the current terminology usage trends, this work conducts an analysis of AR/MR/VR literature in the construction domain within the last 10 years. This paper aims to identify the most cited work referenced to define AR/MR/VR and also to understand the different interpretations of the terminology being used. The findings will illustrate general trends in terminology usage among the building construction research community and highlight the necessity to adopt a more specific nomenclature that may reduce the possibility for misinterpretation by subsequent researchers.

2. BACKGROUND

The term Virtual Reality (VR) was first published in the late 1980s by Jaron Laneir, the CEO of VPL research, a VR equipment manufacturing company (Steuer, 1992). The term Augmented Reality (AR) was coined in the 1990's by Caudell and Mizell (Caudell and Mizell, 1992). Both terms have been used extensively in taxonomies after they were coined.

Milgram and Kishino developed a taxonomy of AR/MR/VR technologies by using a virtual spectrum (Milgram and Kishino, 1994). The spectrum extends from the real environment on one end to an entirely synthetic environment on the other (Milgram and Kishino, 1994). In between, neither complete reality nor complete synthetic immersion exist, but a combination of both where Mixed Reality is defined (Milgram and Kishino, 1994). Augmented Reality is a subset of Mixed Reality which represents any case of a virtual environment being overlaid on a real environment (Milgram and Kishino, 1994). Azuma defines AR as a supplement to reality that allows the user to see the real world, with virtual objects superimposed upon or composited with the real world (Azuma, 1997).

In the AEC industry, numerous taxonomies of classifying AR/MR/VR systems according functionality and tasks have been created. Duston developed a hierarchical methodology to relate MR systems to AEC tasks (Dunston and Wang, 2011). Li built a taxonomy organized by technology characteristics, application domains, safety enhancement mechanisms, and safety assessment and evaluation (Li *et al.*, 2018). The taxonomy was developed to identify trends and implementation potential in construction safety (Li *et al.*, 2018). Rankohi classified journals about augmented reality research according to research methodology, industry sector, target audience, project phase application area, technology used, state of technology maturity, and target audience to evaluate the state of augmented reality research and identify emerging trends (Rankohi and Waugh, 2013). Although taxonomies regarding functionality, output and input, and industry phases have been proposed in the AEC, taxonomies of the terminology itself do not exist.

3. METHODOLOGY

The aim of this research is to highlight the current trends in AR/MR/VR terminology usage among researchers in the AEC domain. This aim is accomplished by both: identifying trends among research literature that cite specific papers to define the targeted terms; and also identifying examples of papers that interpret these terms differently to illustrate potential variations in current understandings of the terms. To provide these targeted insights, this paper presents a detailed meta-analysis of research publications from the AEC realm in the past 10 years.

3.1 Journal Selection

Databases and search engines were used to identify relevant publications for this analysis. These include: Google Scholar, Science Direct, IEEE Xplore and American Society of Civil Engineers (ASCE). Table 1 shows the keyword combinations used to extract journals that fit the research scope.

Table 1: Keyword Entries

	Keywords
Combination1:	("Mixed Reality" OR "Augmented Reality" OR "Virtual Reality") AND "AEC"
Combination 2:	("Mixed Reality" OR "Augmented Reality" OR "Virtual Reality") AND "Construction"

Only papers that contained advancements using one of the targeted visualization technologies were considered for this analysis. In total, 100 journals were initially identified in this process. Journals related to AR/VR/MR technologies increased at a greater rate after 2008 (Li *et al.*, 2018). Therefore, a ten-year time frame was selected to explore the recent surge in publications. The selected ten-year time frame resulted in the inclusion of 80 publications for analysis.

3.2 Data Extractions

A literature review of the selected articles was conducted. From each article, five data points were extracted: Technology Terminology, AEC Use, Definition Used, Display Device and Publishing Year. Technology Terminology refers to the terms chosen by the author to specify the function of the system he or she used: AR, VR, MR or other. The AEC Use column specifies to which of the AEC industry categories it provides a contribution. Definition Used refers to the type of definition the authors used to introduce the technology: (1) No definition, meaning the author considered the technology used self-descriptive, (2) Own definition, which refers to a definition coined by the author, or (3) Others definition, which refers to some citation of other work. Display Device refers to the hardware or setup being used in the article. Finally, Publishing Year refers to the year the article was published.

3.3 Data Analysis

The data was stored in a database to enable statistical and graphical analysis. Descriptive statistics were provided, and advanced filtering was used to extract trends and meaningful relationships between the enlisted variables. Specifically, the researchers were interested in capturing trends of defining the technology used. Many papers cited other work to define the technology, so a secondary analysis on the referred work was subsequently done. The traced number of citations in our sample was also compared to the total number of citations of these articles. To highlight the difference between current nomenclature used and modern technology and devices, the researchers also identified a number of papers that use the same terminology for different applications, and similar applications being referred to by different terminology.

4. RESULTS

4.1.1 Defining AR/MR/VR

The “Citied Definitions” category represents 30% of the sample. The publications that did not include a definition of AR/MR/VR consisted of 53% of the sample, whereas 17% used their own definition. Figure 1 illustrates the percentage of publications in each category.

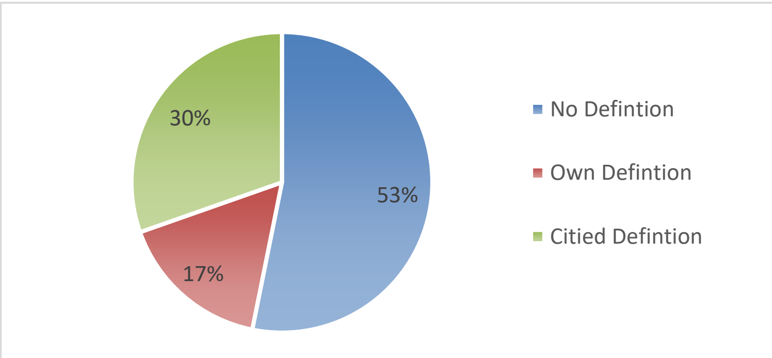

Fig. 1: Distribution of Types of Definition Used in Publications

Four journal papers were cited most frequently: Azuma (Azuma, 1997), Milgram (Milgram and Kishino, 1994), Krevelen (D.W.F. van Krevelen and R. Poelman, 2010), and Benford (Benford *et al.*, 1998). Figure 2 summarizes the number of citations of each definition in this AEC sample and in total.

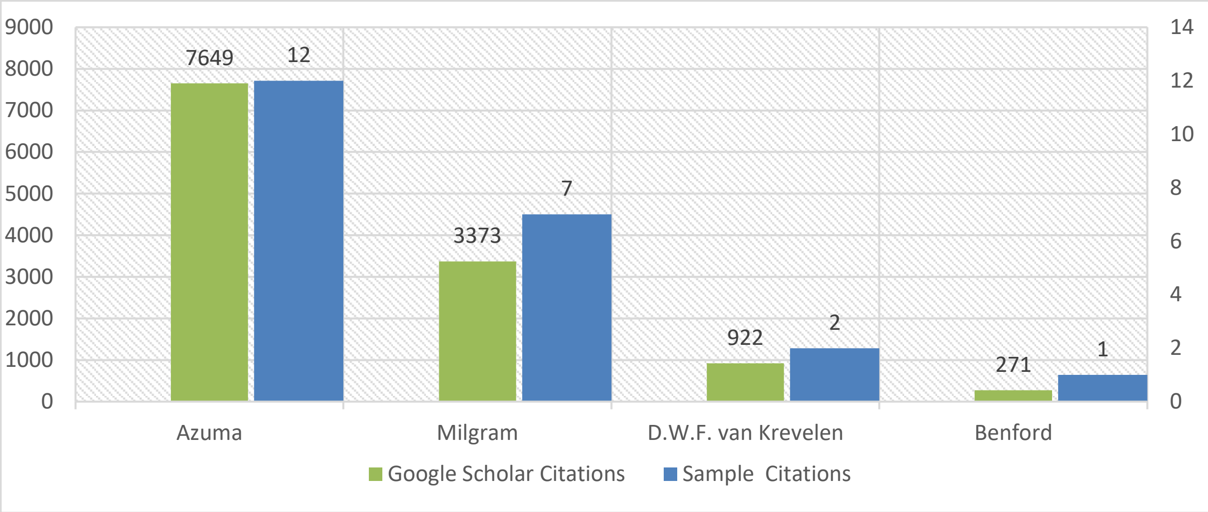

Fig. 2: Total Citations vs Sample Citations

The most citied publications in our sample belonged to Milgram and Kishino an Azuma (Milgram and Kishino, 1994; Azuma, 1997). The number of citations present in our sample was found to be proportional to the total number of citations these publications have. While there appears to be several sources that are frequently cited when defining AR/MR/VR, only two account for the vast majority of citations (90% of the total). This potentially indicates that, while there may be some differences in definitions of AR/MR/VR, the research community generally has reached a consensus in terms of the papers cited. Perhaps a challenge related to true consensus relates to the fact that 70% of papers do not provide a definition or they use their own definition. This poses a further challenge to reaching consistent definitions of these terms.

4.1.2 Most common AR/MR/VR terminology with different implementation

The term Augmented Reality was used frequently in many of the publications in the sample. The same terminology was used to describe different implementations. Generally, there was consensus that AR referred to somehow overlaying virtual objects onto a user's view of the real world, but the ways in which this was achieved were very different. For example, some studies leveraged smartphones or tablet computers to overlay virtual objects using a marker-less approach (Schall *et al.*, 2009; Park and Kim, 2013; Zollmann, Hoppe and Kluckner, 2014; Meža, Turk and Dolenc, 2015; Yokoi *et al.*, 2015; Hedley, 2017). This type of AR environment can enable users to freely move in a space while holding the mobile computing device to see relevant virtual content without the need to constantly view a fiducial marker for content tracking. Conversely, these approaches can potentially have challenges with registering content exactly on top of the physical space when users are in environments that are challenging for marker-less registration.

Other studies that explored "AR" used mobile computing devices through a marker-based approach (Diaconu, Petruse and Brindasu, 2016). This strategy leverages printed fiducial markers that track placement of virtual content in the physical environment. While these approaches can be good for registering content indoors, they often require a user to keep the marker within the field of view of their mobile device's camera, which can limit mobility while exploring the AR environment.

Finally, additional studies explore "AR" through the use of head-mounted displays (HMD) (Lee and Akin, 2011; Cirulis and Brigmanis, 2013; Dong, Feng and Kamat, 2013; Kuo, Jeng and Yang, 2013; Kim, Kim and Kim, 2017). HMD's can work with or without markers with the same benefits and limitations mentioned above, but they do not require users to hold a computing device to experience AR. This can be especially necessary for applications that require users to be able to use their hands in the AR environment.

The different interpretations of AR are mentioned in this analysis not to suggest that any of the prior researchers have misunderstood the definition of AR, but rather to illustrate the differences in understanding among the research community. In all cases, the prior works do explore the use of these technologies to superimpose virtual content onto a user's physical view of a space. The challenge that arises when reading these papers is that they achieve AR through very different means that impact the experiences and abilities of a user. To further illustrate these different experiences, Figure 3 indicates three different use-cases commonly presented in the literature. All use-cases use the same terminology to define the user experience, but it is evident that the abilities and functionality afforded to the user through the different experiences vary substantially.

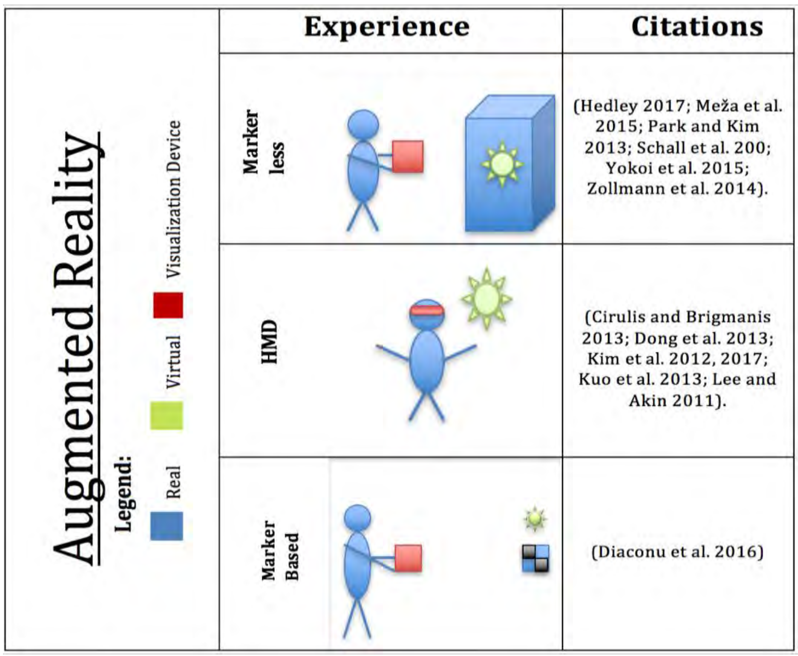

Fig. 3: Same Terminology and Different Implementation

4.1.3 Most common types of AR/MR/VR implementations with different terminology

While there are instances of using similar terminology for seemingly different AR environments, the opposite is also true. There are instances where various different terms were used to describe a seemingly similar visualization environment. For example, Figure 4 illustrates several different publications and terms that were used to describe instances when a user holds a mobile computing device to visualize virtual objects superimposed onto the real environment. These different publications have used various terms to define them, as shown in Figure 4.

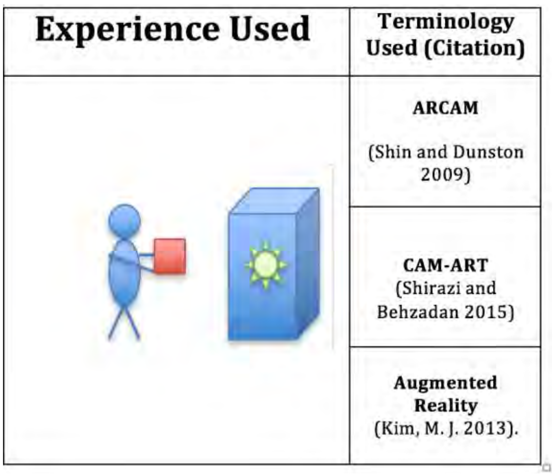

Fig. 4: Same Experience Using Different Terminology

The use of different terminology should not be interpreted as an error on the part of the researchers identified. It is likely that each use has some unique attributes that differentiate their targeted visualization experience from others'. However, the challenge that arises from the difference in terminology is that readers of the published works may not find the results of the works because of the different terms used when searching for publications. Conversely, readers may assume that the environments are fundamentally different because of the terms used, when the visualization experience described remains largely consistent among the different works. This creates a potential challenge for readers when attempting to learn from prior works to guide the direction of future studies.

4.2 Trends

The researchers also examined the trends in the technology nomenclatures in the body of knowledge not limited to construction. Specifically, the researchers identified four main publications that are typically cited to define the technologies: Milgram and Kishino is typically used to define MR, while Azuma and Krevelan are used to define AR. Figure 5 shows the progression of citations per year for each of the four publications.

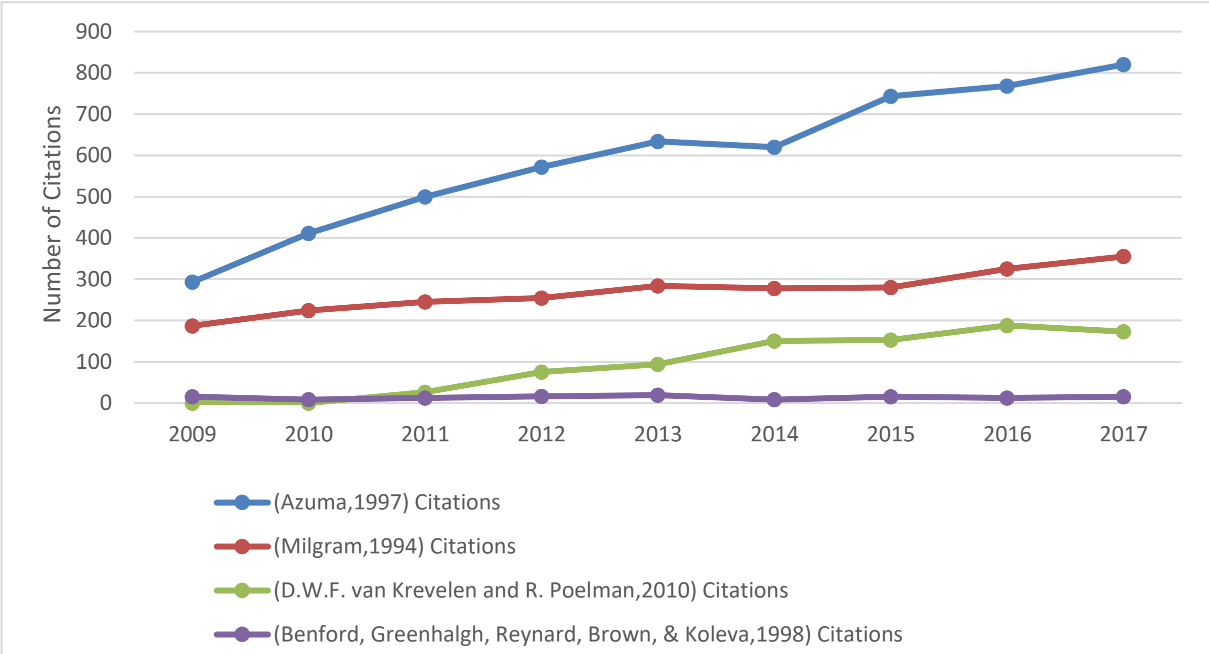

Fig. 5: Citations per Year

In general, the citations per year for the articles by Azuma and Kervelen increase at a faster rate compared to those by Milgram and Kishino, which have stayed mostly constant. This trend does illustrate that, in general, AR terminology is being adopted at a faster rate compared to MR terminology. However, it is also significant that most cited papers refer to works that were done more than 20 years ago, and were written to define a primitive form of the technology. On the other hand, when an article does not provide a definition at all, the understanding of the experience will be up to the interpretation of the reader. A standardized, adaptive nomenclature may better describe the different nuances of AR experiences better so the reader would better conceptualize the outcomes.

5. CONCLUSION

This paper presents the findings from a meta-analysis of peer-reviewed publications in the AEC realm that explored AR/VR/MR over the last 10 years. The results indicate that there is a range of interpretations of definitions for AR/VR/MR. For the works that elected to reference prior papers for defining AR/VR/MR, there is a general consensus among the papers that are commonly selected for reference, with most papers citing Milgram and Kishino (Milgram and Kishino, 1994) or Azuma (Azuma, 1997). For the majority of papers that did not specifically reference prior papers to define AR/VR/MR, there is no direct evidence to indicate consensus in their interpretations of the terms, but there are some commonalities in the definitions reported.

Regarding the reported uses and definitions of AR/VR/MR, there appear to be variations in understanding among the construction research community. This was evident by the different applications that appear to describe different user experiences using the same terminology. Conversely, there were also many studies that reported similar user experiences, but used different terminology to describe those experiences. The combination of these findings suggests that the construction research community has not reached a consensus in the definitions and applications of these terms.

The authors of this paper do not aim to suggest that any of the prior researchers have incorrectly described or interpreted the definitions that they state. Instead the aim of this work is to demonstrate that these prior researchers simply interpreted terms, or defined them, differently. While this is understandable, it poses a major challenge to future researchers. Readers of these publications, who aim to conduct future research, will likely want to form an understanding of the current literature to guide subsequent studies. If similar terms are used to describe different use-cases, it is possible for these future researchers to extrapolate incorrectly on the prior findings. Conversely, if readers see different terms used to describe similar use-cases, they may not interpret findings in conjunction with one another, which may also hinder their understanding. The problem that can arise with both of these scenarios is that future researchers may generate understandings based on their reading that will guide their work in directions that have little or no theoretical basis. This can lead to ineffective research that fails to advance the field of AEC visualization research.

The development and adoption of a new nomenclature by the AEC realm could potentially enable more granularity, while identifying different visualization technologies. This research may act as a basis for future research to develop this nomenclature to form a consistent method of defining visualization experiences. The authors suggest that an ideal naming nomenclature would not replace the existing literature and understanding that exists related to AR/VR/MR, but instead would complement it. Having an additional code or description that would help researchers to understand the specific type of experience targeted could help authors to communicate their work in a method that is less conducive to misinterpretation by readers. Furthermore, a consistent naming approach like this would also enable researchers to use the specific code of interest when searching publication databases to target specific implementation strategies in order to generate consistent understandings of the current body of knowledge related to a given strategy.

6. ACKNOWLEDGEMENTS

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VISUALIZATION OF PHYSICAL BARRIER FOR WHEELCHAIR USERS USING DEPTH IMAGING

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ABSTRACT: *Recent years, Japan is facing the issue of rapid aging society. Apparently, the number of potential wheelchair users is growing rapidly, as more and more seniors need long-term cares. The government has been working on prevailing the barrier-free environment by establishing a law regarding promotion of smooth transfer for elderly and physically disabled people. Barrier-free maps, for example, are prepared in many municipalities, but they cover only existences of facilities, e.g., lifts, slopes, and handrails, in major public institutions. On the other hand, they miss the details of physical barriers, such as bumps and width clearances on the path, needed for the independent mobility of the wheelchair users. This paper addresses a method to find out physical barriers by using a depth camera to visualize them efficiently through augmented reality, so the facility managers can easily check and improve the environment by themselves. A depth camera acquires three-dimensional point cloud data in the target space and checks the existence of interference between the environment and the volume of an actual wheelchair would occupy to pass through. The proposed system robustly estimates the floor surface from the point cloud by using RANSAC method. The verification of the achieved accuracy of the barrier check by the proposed system, as well as the implementation scheme, are reported in the paper.*

KEYWORDS: *Wheelchair, Barrier-free, Depth Camera, Point Cloud, Augmented Reality, RANSAC*

1. INTRODUCTION

In recent years, the declining birthrate and the aging of the society are accelerating rapidly in Japanese society, and the proportion of elderly people in the national population continues to rise. As of October 2018, among the population of 126.93 million people, the elderly population aged 65 years and over has a population of 34.59 million people and the elderly population in the total population is 27.3% (Cabinet Office, Government of Japan, 2017). In addition, the number of care recipients of elderly people is also on the rise, and it is reported as 569.1 million at the end of FY2013.

Wheelchairs are used not only for physically handicapped persons but also for care recipients as a means of daily transportation. However, the users of the wheelchair easily feel physical barriers such as small steps, gaps and small bumps on the street. With such obstacles, wheelchair users, especially elderly users, not only cannot move around freely, but they may even face physical danger. Based on the background as stated above, the barrier-free new law was enacted in 2006 in Japan. Additional improvements such as barrier-free toilets of railway stations and public buildings, slopes, barrier-free maps, etc. have been advanced. Also, for many newly constructed buildings, barrier-free designs are given in advance. Also, by providing information on the locations of restrooms equipped to service the physically challenged as well as the location of uneven surfaces on pathways, barrier-free maps are gradually becoming familiar as informative tools for elderly people and wheelchair users. In recent years, such maps have been provided on the Web as well as in published form, such as incorporation into booklets. However, the concept of barrier-free mapping is still in the development stage and oftentimes such maps are designed from an administrator's preconceptions rather than from a user's viewpoint. Additionally, while the barrier-free information on such maps is often expressed with specific pictograms designed by industrial standard bureaus or ministries, there are also numerous unique pictograms created and used by local governments, and there has been little effort to date to achieve uniformity. Furthermore, information regarding barrier information details and the investigative methods used to confirm the validity of barrier-free maps differ from place to place. As a result, the barrier-free maps themselves are not always trusted by their intended users.

Eventually, wheelchair users cannot really obtain detailed barrier information in everyday life environment. For existing buildings and facilities, it is difficult to advance to barrier-free. One of the reasons is that there are many physical barriers which are difficult to notice for non-handicapped persons. Also, it takes time and cost to implement on-site verification to barrier-free. Therefore, in this research, we propose a system that visualizes physical barriers for wheelchair users and enables barrier verification in real time. By facilitating the awareness of the barrier to make it easier for facility managers to grasp and improve the actual condition current situation, for wheelchair users and healthy volunteers who will increase in the future.

2. RELATED WORK

2.1 Barrier-free Verification Technique

In the United States, for instance, the Americans with Disabilities Act (ADA) was established in 1990. This law prohibits discrimination and ensures equal opportunity for persons with disabilities in employment, State and local government services, public accommodations, commercial facilities, and transportation (ADA website). And for ensuring the accessibility for disabled people, Accessibility Guideline (ADAAG) was implemented under ADA (ADAAG website). Han et al. (Han et al. 2002) proposed to the performance-based approach for the wheelchair accessible route analysis. The "performance-based" approach means that the model of a wheelchair moves gradually in a 2D map virtually with considering the specification of a wheelchair. The authors use it as an antonym of the "cord-based" approach, that is, enumerating accessible patterns like ADAAG (ADA Accessibility Guideline). The accessibility for wheelchair users is one of the main themes of ADAAG. This performance-based approach is very flexible and applicable to any environment. Moreover, Yasumuro et al. have proposed a method for judging whether the given route is barrier-free or not (Yasumuro et al, 2013). Yasumuro et al. created a three-dimensional (3D) model of the target space by acquiring the 3D coordinates of the real space, the distance image, the trust image, and the freshness image by the 3D measurement camera and derived from the depth map and the minimum trajectory of the wheelchair. The barrier verification is carried out by combining the smallest trajectory model of the wheelchair and changing the color of the part where the model interference occurs.

Although a 3D model is constructed from a plurality of data obtained by taking a target area from multiple angles with a three-dimensional measurement camera, it takes time and cost for creating such a 3D model of the target environment. Therefore, it is necessary to have a system capable of immediately grasping the current barrier information by performing real-time. In addition, it may be necessary to develop easy system tools so that barriers can be validated not only by facility managers, carriers, but also by wheelchair users.

2.2 Objective

This paper focuses on the investigative methods used to detect barriers to wheelchair users. We begin by acknowledging that administrators face difficulty in fully comprehending potential barriers in their facilities, especially since many spaces are filled with a variety of objects with complicated 3D geometries, unless they bring in an actual wheelchair and user into the space to physically verify accessibility (see Fig. 1). As a result, one of the major difficulties involved with existing barriers is the labor cost related to identifying such barriers and determining the degrees of difficulty they impose. Manual inspections are supposed to be conducted by the care-managers or environmental welfare coordinators responsible for evaluating such barriers, and efforts are expected towards the redesign and renovation of existing buildings and facilities into barrier-free environments.

Fig. 1: Example of on-site check for accessibility by a wheelchair user (Kumagaya City Homepage, Japan)

This paper proposes an effective method for investigating the existing physical barriers for wheelchair users that utilize an TOF (time-of-flight) type of depth camera, which is capable of compiling depth image information on physical locations. The contact-free and speedy measurement capabilities of depth cameras make it easy to collect onsite information on geometric conditions, and then to virtually overlaying a wheelchair of real dimension on the spot. So, the 3D environmental conflictions can then be examined in various ways to detect obstacles, and thus eliminate the need to actually bring a wheelchair and user to the target site, as Fig.2 shows an ideal use case in the future.

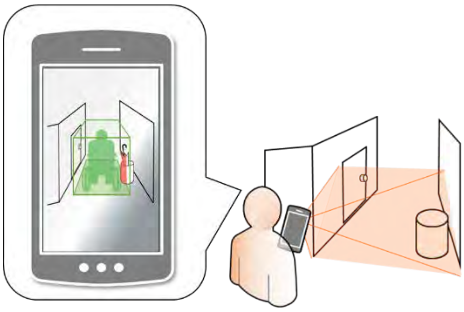

Fig. 2: Schematic image easy-to-use barrier inspection tool

3. METHOD

3.1 Overview

In this research, we aim to visualize the possible physical barriers in AR (Augmented Reality) representation, considering distance relationship between camera position and the physical space, together with actual size of a wheelchair volume. In order to provide highly accurate barrier information visually and in real time, we use live stream signal from depth camera. We also propose a barrier verification tool that can be used for mobile terminals equipped with 3D sensing camera technology in order to make it easier for various users.

3.2 Process Chain

We set the floor surface from three-dimensional distance data by depth measurement by the depth camera and realize interference judgment with wheelchair model range created from wheelchair dimensions. 3D point cloud data is acquired as a distance from the camera in the object space using the depth camera, and a wheelchair model is created on the estimated floor plane. The processing procedure of the system is as shown in Fig. 3. First of all, as a wheelchair model based on the specification of the wheelchair, it is created as a wheelchair model,

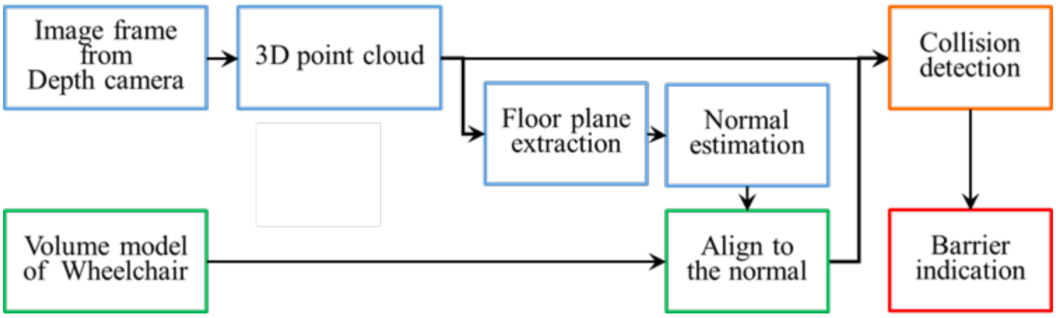

Fig. 3: Use of figures and graphics is encouraged. So is the use of color but make sure that they print well on black .

To allow wheelchair users free and unencumbered access, a certain amount of space is required for the user's body, hands, and arms when maneuvering the wheelchair. This requirement is in addition to the width of the wheelchair base itself. Referring to the Japanese Industrial Standards (JIS) and ergonomic dimensions (Ministry of NITI, Japan), for example, regulations call for pathway widths of more than 90 cm and doorway widths of more than 80 cm in order to ensure wheelchair accessibility, and 130 cm in averaged height. In practice, turning a wheelchair also requires a specific minimum space, and it is also important to consider normal two-way pedestrian traffic in public spaces to ensure that sufficient space is available for passing when necessary. Furthermore, it is necessary to ensure that pathway surfaces are sufficiently smooth, and that any slopes are gradual, with specific design elements incorporated if there are differences in floor heights (Osaka Association of

Architects & Building Engineers). In this paper, as the minimum clearance of a single wheelchair size, we settle a cylindrical volume sizes as shown in Fig. 4.

As the way to handle the depth camera, we assume that the user looks at the wheelchair from the viewpoint of the person who pushes the wheelchair from the behind. So, the depth camera is supposed to point the center position on the floor area where a wheelchair would occupy. And as the user moves through the target area, camera's view volume sweeps the floor, acquiring 3D point cloud continuously.

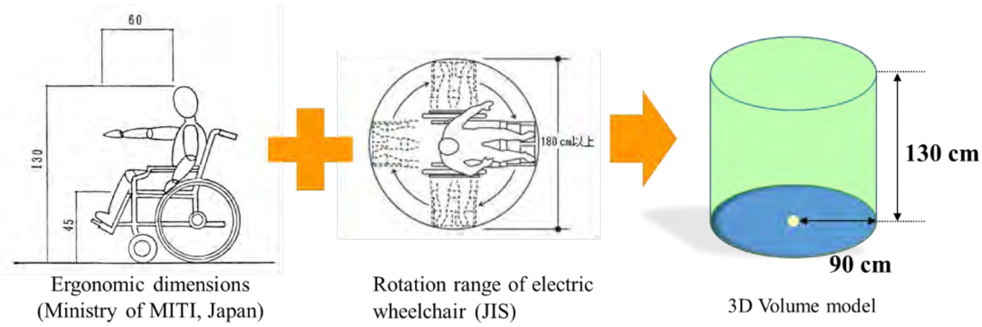

Fig. 4: 3D wheelchair volume model, considering an ergonomic dimensions and industrial standards

3.3 Floor Plane Estimation

One of the key processes is to find the floor plane stably. In our method, since the user is supposed to maneuver depth camera to trace the wheelchair's path to examine, we set the sampling area of the depth data for approximating the floor plane to the area surrounding the center of the depth image. The sampled points could be the one within a certain radius (number of points) from the center of the depth image. When an outlier is included in the sampled points, accurate plane approximation cannot be performed by the least-squares method. So, we use RANSAC algorithm to select inlier points for estimating the floor plane robustly. The procedure is shown in Fig. 5. First, we divide the sampled points into two group of *n* inlier points and *m* outlier points. And plane approximation is performed on the inlier points by using the least squares method and calculate the normal vector of the plane. Next, a randomly select single point from each of the inlier and outlier points is exchanged, and plane approximation is performed on the inlier points using the least squares method. At this time, the squared error is improved from the previous one, the groups of inliers and outliers are adopted, if not, the exchange is canceled. By repeating this process, we can acquire the inlier points that support the identical floor plane with the least error.

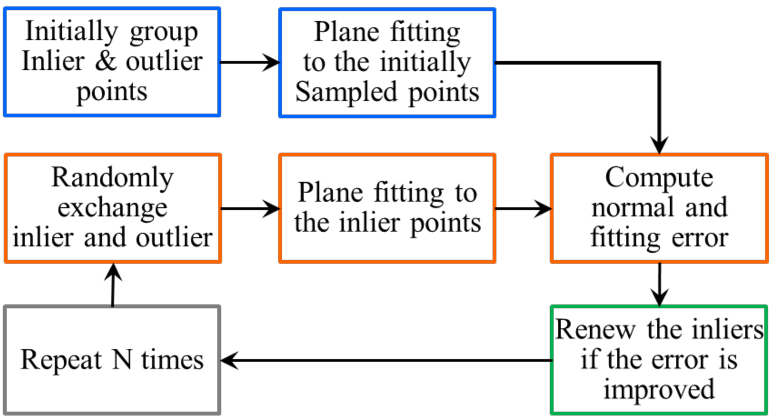

Fig. 5: Floor plane estimation with RANSAC

Since the field of view of the camera does not change, as shown in Fig. 6 (left), if the camera position is far, the sampling area for floor plane is also widely taken naturally. Then the outliers are likely to be included in the sampled points and the error possibility increases. Therefore, we choose suitable physical sizes of the sampling area relative to the distance between the camera and the floor. The physical distance between the camera and the floor surface can be monitored by the range information that each pixel possesses in the depth images. We prepared 5 different fixed sizes of sampling area according to the distance.

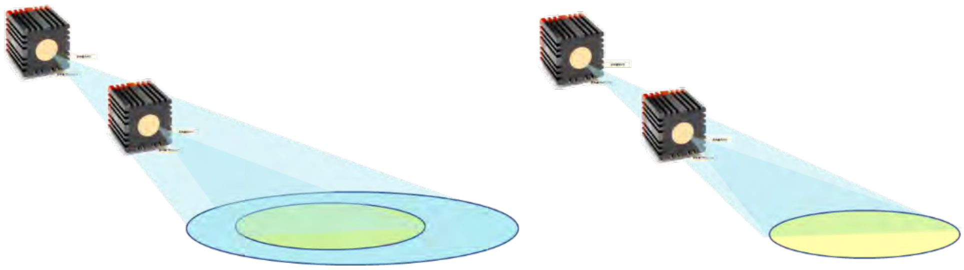

Fig. 6: Fixed sampling area size (right) for the floor plane estimation and range dependent area size (left).

4. IMPLEMENTATION

4.1 Setup and Functionality

In this research, assuming the barrier verification in the daily-life circumstances of wheelchair users, we conducted experiments by using SwissRanger SR 4000 (176 × 144 pixels, Mesa Imaging) (R. Lange ,2001), a near-infrared TOF type of depth camera. Depth information in pixel units was acquired in 60 Hz of frame rate. Visual Studio 2010 (Microsoft Corporation) is used for developing software to implement the proposed method. We also used the libraries, OpenCV for image processing and OpenGL for AR display. Using the depth camera connected to a laptop PC as shown in Fig. 7 (left). Holding the camera and walk through the target space with the camera facing the floor (Fig. 7 (right)).

As shown in Fig. 8, plane approximation excluding outliers by RANSAC realized stable floor estimation. The left-hand side column shows the target scene within the field of view. The green cylinder depicts the volume model of the wheelchair overlaid of the live information of the depth camera. The cylinder is supposed to be placed on the floor plane aligning to the estimated normal vector. The yellow dots are the sampled 3D points as inliers from the depth image of the captured scene. The 3D points within the inside of the cylinder are highlighted in red color. As shown in the middle column in Fig. 8, sampled points on the legs of furniture and electrical cables on the floor directly affect the normal estimation, and as a result, the cylinder is arranged with a large inclination. In contrast, the sampled points in the right column are identified as outliers on the cables and the legs of furniture, and the inliers are chosen to avoid them. As a result, a green cylinder is placed perpendicular to the floor surface, and the points position higher than the floor are highlighted in red. Consequently, 1-2 cm precision for the barrier detection is available.

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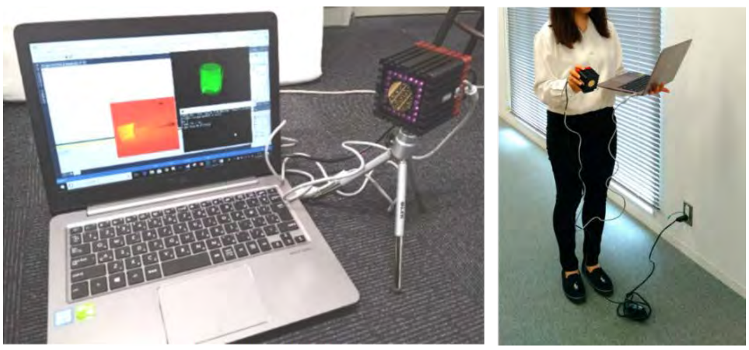

Fig. 7: Device used for implementation

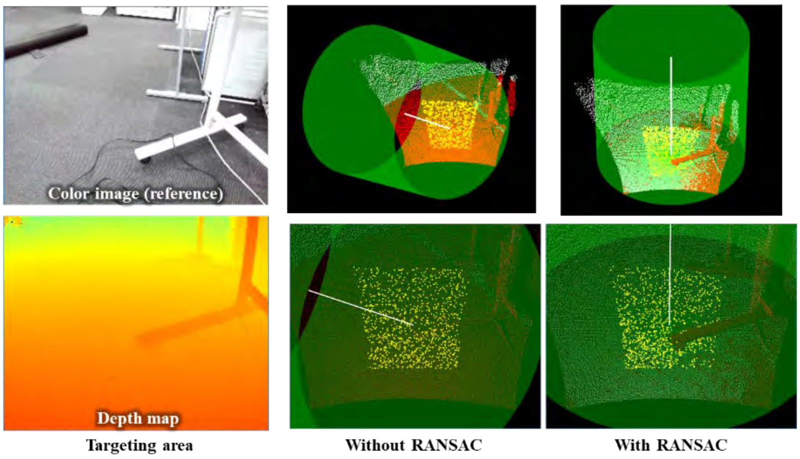

Fig. 8: Effect of RANSAC

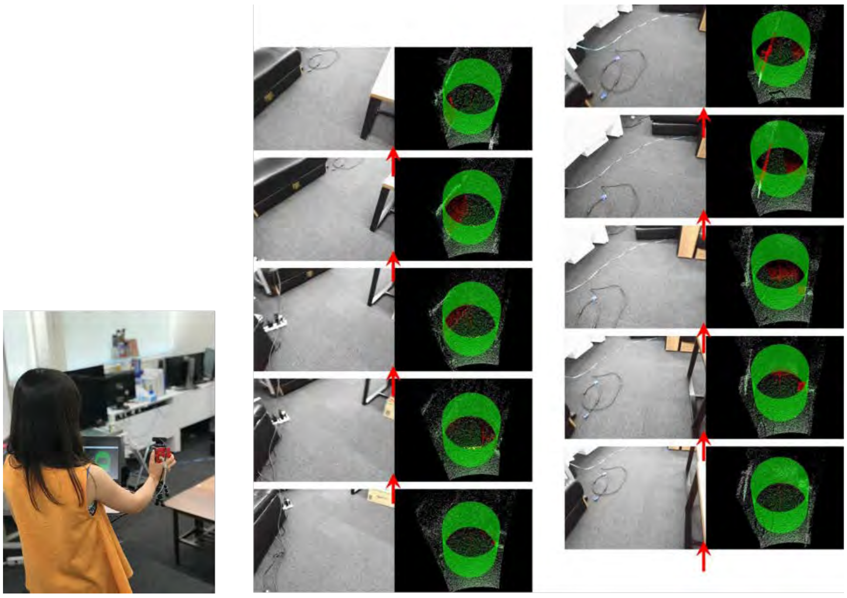

Fig. 9: Examples of physical barrier extraction

In an office room shown in Fig. 9, barrier check was performed continuously as the user walk along the narrow path. In the right-hand side part of middle and right column in Fig. 9, the legs and corners of the furniture are stably detected and highlighted, while the thin cables on the floors are neglected since their heights are less than 2 cm from the floor surface.

4.2 Case Study

We also conducted verification in an actual public space in a class room in our university, where several wheelchair users of the students are using. As shown in the top row in Fig. 10, The authors checked the narrow passage between the desk and the desk in the lecture room by our system. In this case, even if a wheelchair user can pass, it was apparent that the passage was so narrow that the wheelchair can only advance in one direction, so we reduced the diameter of the cylinder to the actual width (60cm) of the wheelchair. Although there was no space margin at all, we found it was possible to pass through by a standard size of wheelchair eventually. We confirmed that the accrual width of the passage was 58 cm.

Another target area in the same room is around the movable desks prepared for the wheelchair users as shown in the bottom row in Fig. 10. This desk is placed near the entrance door of the classroom and can be moved easily while all the other desks are fixed on the floor. However, as depicted in the bottom right figure, as long as this desk is not far apart from the entrance door, it turned out to be easy to become their obstacle. Moreover, since the desk supports and legs are designed diagonally, depending on the orientation of the desk, it is complicated to know which part between the desks and the wall will be an obstacle for the wheelchair. Our method is capable of easily operating the wheelchair volume model on the spot, and interactive handling is useful to know the spatial barriers in real-time.

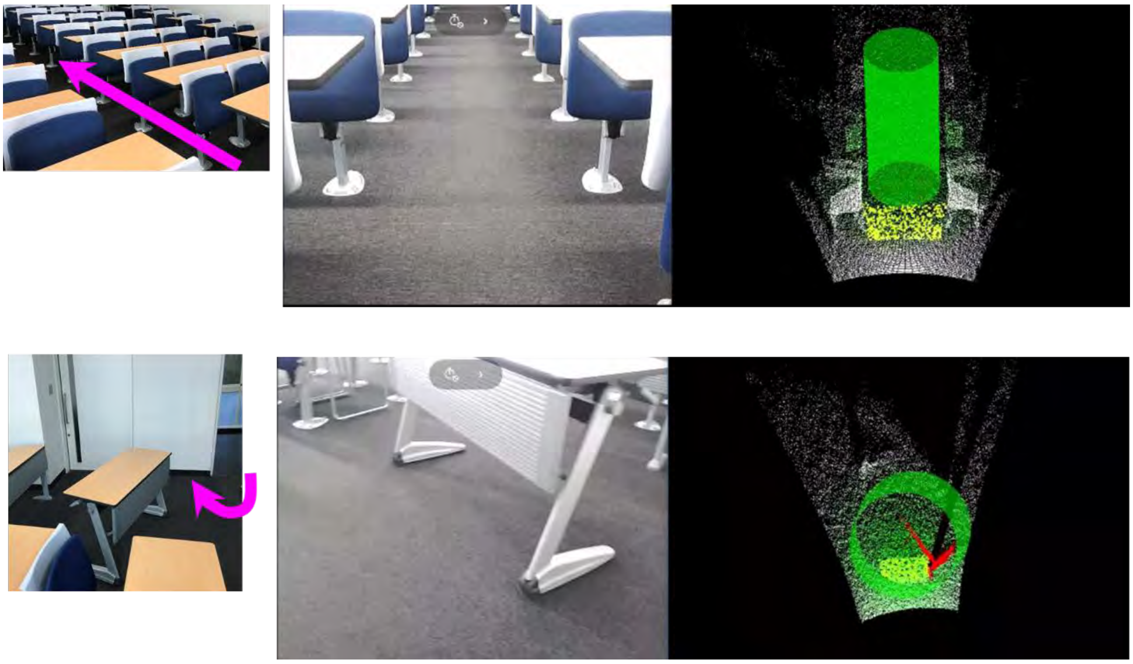

Fig. 10: Examples of the results in physical barrier extraction in a class room

5. DISCUSSION

In this research, we could verify and visualize the presence or absence of the barrier in real time from arbitrary viewpoint and direction through the proposed approach. Also, the rotation width and height of the wheelchair can be changed during the verification, and the barrier can be visualized according to required clearances. Although there is no color information in the spatial information that cannot be acquired with SR 4000, it was possible to grasp the degree of barrier existence from multiple angles, and it can be confirmed while comparing with the real space on the spot. Some more detailed information such as the extent of the margin between the obstacle and the wheelchair model and the size of the depth width height of the detected barrier would be useful to the user. Moreover, if it becomes possible to store and read the barrier information once obtained, it will be possible to create a 3D barrier map by accumulating and aggregating the barrier information. Now we are trying to implement our method on integrated small-sized devices, such as Google Tango platforms. (D. Keralia, 2014)

6. CONCLUSION

This paper addressed an AR system that can perform physical barrier verification in real time based on robust floor detection with RANSAC for a live stream of 3D point clouds obtainable by a depth camera. The result shows that it is possible to confirm the barrier without actually bringing a wheelchair to the target space. We consider that it can contribute to the need to facilitate the confirmation of the barrier by shortening the time required for the barrier verification for the wheelchair user and simplifying the work.

As a future work, we will acquire more detailed barrier information of detected barrier and the clearances from the point cloud. We are also considering a system reflecting the detailed map of barrier information and further simplification of barrier verification by utilizing a smartphone device equipped with a depth camera, and making application at a terminal which is familiar and close to the ordinary user.

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MARKERLESS AR APPROACH WITH LASER SCAN DATA FOR VISUALISING INUNDATION PREDICTION IN UNDERGROUND SPACES

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ABSTRACT: *Recently, short-time heavy rainfalls have frequently occurred in Japan due to the global warming, and the damages by the flood in the urban areas tend to increase. If rainfall per unit time exceeds the rainwater drainage capacity of the sewage, inundation occurs readily even in urban areas, where large underground spaces are used for parking lots, subway, shopping malls, etc. Therefore, people in underground spaces may have higher risks of inundation, since they hardly notice the rapid change of the weather on the ground. There are many types of research for analysis and simulation of the underground inundation risks. However, their results on two-dimensional water-depth distribution are not sufficient to notify the people of the possible dangers for individual locations. In this research, we propose a visualization system to interactively display the predicted flooded damage through a mobile terminal of individual users on the spot. The predicted flood depth at an arbitrary place can be visualized by positioning the user's terminal based on a viewpoint estimation technique with the pre-scanned point cloud data by a laser scanner. The paper shows the applicability and practicality of our proposed method based on experiments at an actual train station in an underground.*

KEYWORDS: *Inundation risk, Markerless Augmented reality, Point cloud, PnP problem*

1. INTRODUCTION

Recently, risk of inundation in underground structures and malls have been increasing due to more and more frequent localized heavy rainfalls around the city in Japan as shown in Fig. 1, due to the global warming and heat island effects. Such heavy rainfalls often exceed drainage capacity of sewerage systems of the local area and lead to damage of inundation above and/or under the floor flooding. On August 25, 2013, due to the local short-term torrential rain in the vicinity of Osaka City, inland flooding occurred and damages by inundation above and under the floor and roads were also covered with water. The same damage occurred near Nagoya City on September 4, 2013 of the following week. This means that modern pioneering cities in Japan have exposed vulnerability to water disasters.

As a countermeasure against the current flood damage, the Ministry of Land, Infrastructure and Transport (MITI) announces the water disaster prediction area when flooding happens. And flood hazard maps are promoted in each municipality. However, this hazard map is only color-coded according to the predicted flooding depth distribution on the plan view and is often difficult to understand the conditions of water depth. Eventually, the flood situation that may occur in each place is hardly imagined by the citizens. Also, the information descriptions including many kinds of legends tend to be complicated as well.

Therefore, measures against flooding under the ground due to inflows from the ground are still not sufficient. In

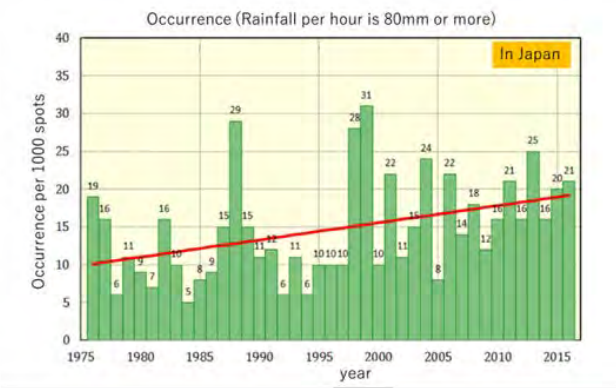


Fig. 1: Trends in the number of annual occurrences with an hourly precipitation of 80 mm or more

fact, the Ministry of MITI conducted a survey on the use of hazard maps for ordinary people across the country in 2017. Those who answered that they had confirmed the disaster prevention situation with the hazard map were 31.2%, which is even less than half in total. The result shows that the hazard map is not familiar medium for notifying water disaster information to the public.

This paper addresses to develop a system that functions as a display interface of hazard map by making interactive visualization of predicted risk information of groundwater damage at mobile terminals for general users. In cooperation with the existing flood simulation, we aim to visualize flood risk according to the standing position and viewpoint of the user in a mobile terminal such as a smartphone and realize a technique useful for flood control and evacuation preparation at the time of disaster.

2. RELATED WORK

2.1 Visualization of the Inundation Risk in the Underground Space

In order to estimate the underground flooding level caused by rainfalls relative to time and place, simulation of inflow discharges by different profiles of short-time high intensity rainfall can be conducted, by using 1D-2D urban flood model (Ishigaki et.al. 2011, 2013). Ishigaki et al. conducted highly accurate inundation analysis by using roughness coefficients that are taken into consideration by examining the ground height, subsurface structure, and usage form of space at various underground malls. It clarifies the inflow characteristics of inundation flood water into the underground shopping area for each heavy rainfall scale. This result contributes to the planning of flood control measures in the underground space as a particular dangerous area against urban flooding. However, as shown in Fig. 2, the analysis result is displayed by coloring the flood depth on the map on a time-by-hour basis, so it is difficult to understand the flood damage situation intuitively. Therefore, means for displaying predicted inundation conditions in an easy-to-understand manner is necessary, so that each user in the underground space including the facility managers and workers and visitors can take an appropriate initial action at the time of a disaster.

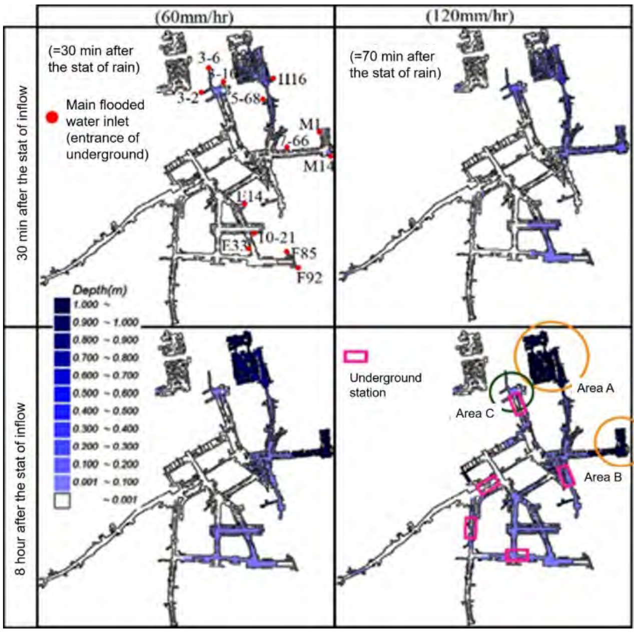


Fig. 2: Examples of predicted inundation of underground shopping districts by heavy rain patterns

2.2 Visualization of Inundation Risk

AR (Augmented Reality) is one of the interactive visualization techniques, to add, reduce, or update information related to the physical view of the users. In this technique, by superimposing characters, images, and CGs related to what the user see through the camera view of the mobile terminal, the user can receive location-oriented information dynamically. As an advantage of AR display, it is possible to provide spatiotemporal information in a reasonable and selective manner, according to the user's location and the spontaneous searching behavior, instead of stuffing and layout every information on a map.

Cad Center Co., Ltd. has been developing an application that can synthesize the contents of a hazard map into a live-action image captured with a smartphone. Hazard information matching to the position of the user can also be displayed by positioning with GPS. The user can be visually informed of the height of the assumed tsunami in the hazard map, and it is also possible to help disaster prevention education and preparation for daily disaster measures. However, the synthesized inundation information overlaid on the live-action photograph is an abstract expression, and missing the intuitive water depth sensation. Besides, since the hazard information of the current position is displayed by the GPS, which is not available in the underground space.

Fig. 3: Example of existing AR hazard map application for mobile terminals

Therefore, the authors have been studying suitable AR method for conveying the visual information of estimated flooding risk in the underground space. We have been developed a framework that allows us to consider the visual occlusion relationship between the water surface and the physical objects in order to represent the flooding information naturally. Also, in order to acquire the user's position information independent of GPS, position estimation is performed using natural feature points extracted from the image captured by the camera-equipped mobile terminal. Utilizing dense point cloud data as information of real space, the position of the user terminal can be estimated by associating data with feature points in the user input image, and AR display is achieved as shown in Fig.4. (Hirose et al. 2017) However, the resultant AR representation contains unnatural gaps between physical objects and the CG water surface. This is mainly caused by the errors in shapes of 3D

Fig. 4: An example results of AR representation by (Hirose 2017)

models created from SfM data. Also, the overhead for loading 3D data was problematic for prompt use of the system. Therefore, the authors are motivated to design a framework that the server side shares a heavy load and performs AR image generation directly, so that terminal client is supposed to only browses it with low overhead.

3. METHOD

3.1 Overview

In this paper, we focus on not only offering visually perceptible risk of flooding but also reducing overhead in AR display on mobile terminals. Based on the previous research, we draw a water surface on the 3D model of the target space based on the actual measurement and carry out the visualization expression which makes the predicted inundation situation easier to imagine. In this paper, the server-side performs this process instead of the mobile terminal, and furthermore, 360-degree panoramic imaging processing is performed and distributed to the user's terminal through the low overhead of HTML-based browsing. By adopting such process configuration, the mobile terminal can browse the appropriate flooding AR condition from the panoramic image by merely designating the direction the user wants to see based on the built-in sensor of the gyroscope and the compass.

3.2 Process Chain

We render the virtual flooded water surface with CG reflecting the depth of flooding according to the estimated user's position and predicted inundation information in our foregoing research (Hirose 2017) and create a 360-degree panoramic image of the target space. We prepare a photo-realistic 3D model of the target space as preparations based on on-site measurement in advance. Image of target space is captured comprehensively, and 3-dimensional restoration of the target space is performed by SfM, and a 3D model of the scene is generated. This 3D model plays a role of expressing how the surface of the water wrapped around the feature in the targeted local space. In other words, by showing the concealment relationship between the water surface and the local object, it can be expected that the depth of flooding is expressed intuitively.

To create a panoramic image, the following process is performed. First of all, we specify the viewpoint with the 3D model in which the flooded surface is drawn with CG and generate an omnidirectional rendering image. By performing rendering in the CG space, it is possible to prepare a flooded image actually occurring in the target space.

A 360-degree panoramic image at an arbitrary user position can be generated by stitching multiple CG images rendered by perspective projection with a proper field of view where optical distortion is inconspicuous. The generated panorama image can be converted to HTML format by authoring software. By uploading HTML file and linked panoramic image to the server, the user can also browse it on the mobile terminal as visualized risk of estimated flooding condition.

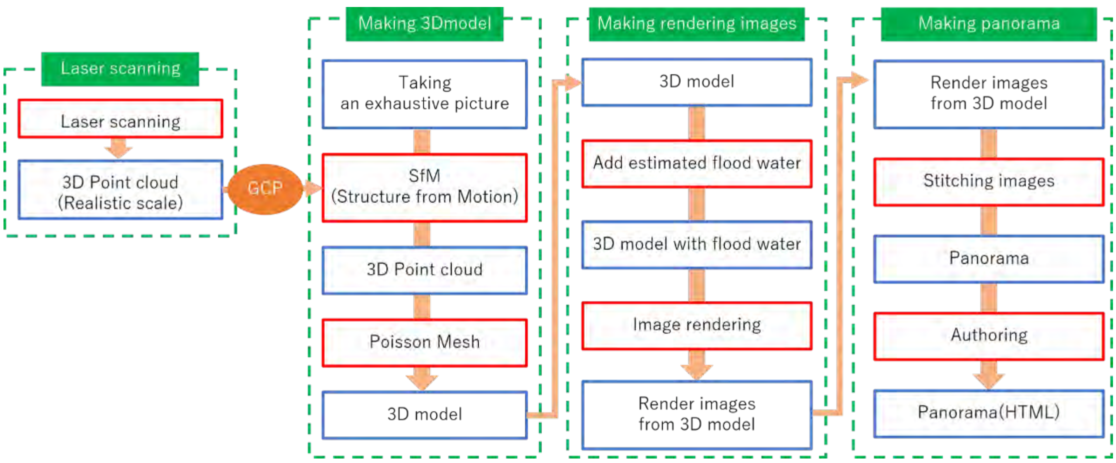


Fig. 5: Process chain of the proposed method

3.3 Panoramic Imaging

Image stitching technology has dramatically prevailed since technological features with excellent performance have been proposed. (D. Gledhill 2003, M. Brown 2006) Even for photographs taken with a limited angle of view, it is possible to generate images with a wide angle, even 360 degrees, by ensuring overlap and stitching and merging the images together as shown in Fig.6. Meanwhile, specific cameras, such as Ricoh THETA, that can shoot a 360-degree photo with one shot also appear in the market, environments where an interactive display of images and viewpoints from arbitrary viewpoints are also made by sharing pictures and videos with SNS and others. In this research, to augment the scenic view with flooding risk, we combine rendering a 360-degree image from photo-realistic CG with overlaid flooding information and distributing it to the user via a network-sharing mechanism so that the user can observe it on the terminal according to the viewing direction.

Various views in different directions viewed from an arbitrary viewpoint are generated by CG to create a panoramic image centered on the viewpoint. By distributing the line of sight direction evenly using the polar coordinate system, it is possible to set the view angle and overlap of each view image. As shown in the Fig. 7, the line of sight direction is uniquely determined by specifying the inclination from the x axis direction as θ and the inclination from the x-y plane as ϕ. An arbitrary rendered image can be created by specifying this visual line direction as the center of the rendering image. The overlap of images can be changed according to the angular interval between the rendering images in the line of sight direction and the set angle of view of the camera.

Fig. 6: Image stitching for making 360-degree panoramic image (selected from M. Brown 2006)

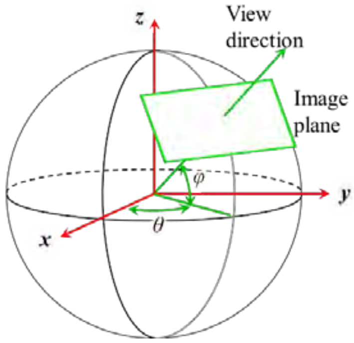
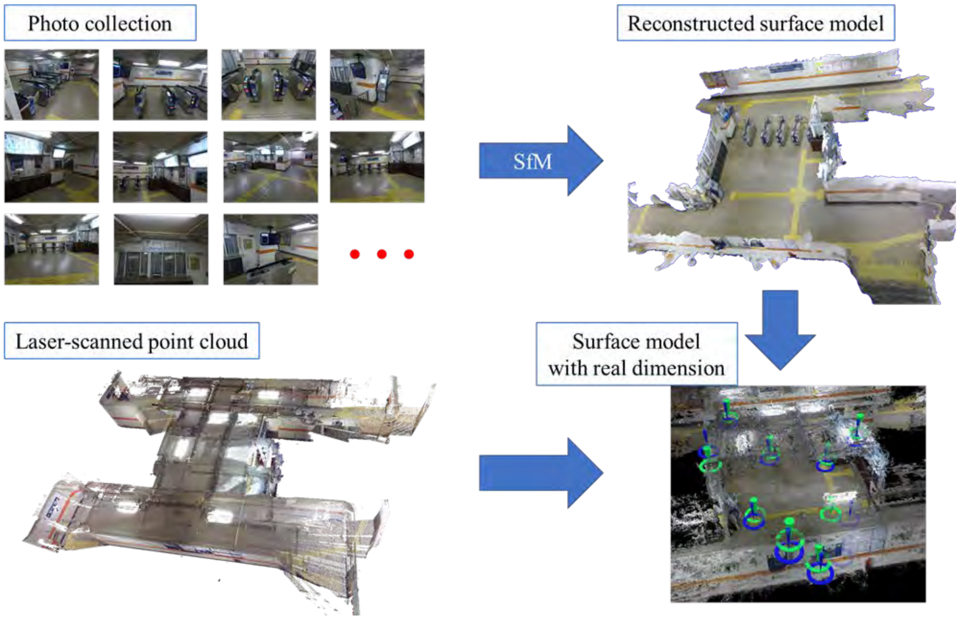


Fig. 7: View direction arrangement for making 360-degree panoramic image

4. IMPLEMENTATION

We chose a part of an actual railway station (Kandai-mae Station on the Hankyu Railway in Suita City, Japan) as the underground target area and acquired 394 images by using a digital camera (GoPro Hero6). The image was reconstructed three-dimensionally with SfM software Pix4D mapper (Pix4D Inc.). Also, in order to give the actual dimension to the reconstructed 3D shape of the inside of the station, this time we also use a terrestrial laser scanner, Focus3D X330 (FARO Inc.) and scanned 3 shots to capture the scaling marker points (GCPs). 3D data in the target space with actual size was acquired by integrating SfM data and the scanned data (Fig. 8). The created 3D model is saved as a combination of obj file, mtl file and texture images. We used OpenGL to render the scenery with specified view directions and field of view. In this paper, the horizontal field angle of the camera is set to 80 deg, and the aspect ratio of the image is set to 4: 3. The viewing direction is made to be 30 deg at both the horizontal direction and the vertical direction so that about half of the image overlaps. We rendered 35 CG images in total. The obtained rendering image group is joined by stitching software PTGui Pro (product of New House Internet Services BV) as shown in Fig. 9. The panoramic image created by stitching is represented by a forward-angle cylindrical projection method as shown in Fig. 10, and this image is converted to



HTML format by Panotour Pro 2.5 (Kolor Inc.) . By uploading the obtained HTML file to the server, the panorama image can be viewed at each terminal. (Fig. 11, 12)

Fig. 8: image arrangement for making 360-degree panoramic image

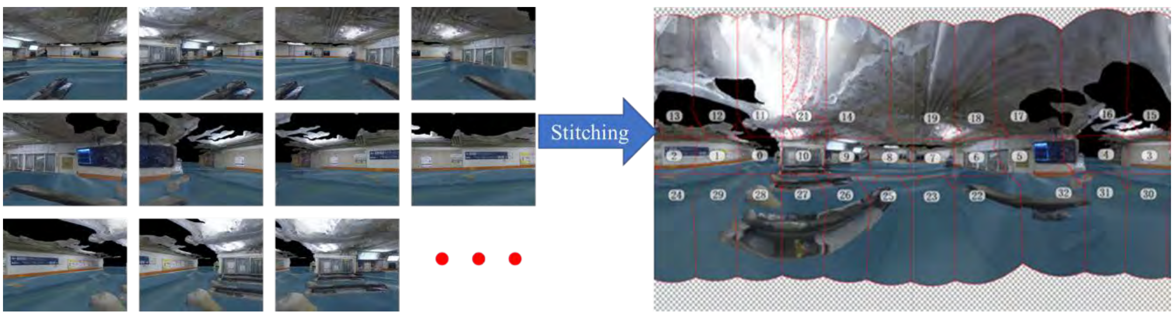


Fig. 9: Stitching the Rendered Images

5. DISCUSSION

In this research, panoramic images with AR representation of flood risk can be created and referenced for arbitrary viewpoints. It is necessary to prepare the laser scanned data of the site beforehand, but it is possible to correctly express the situation in which flooded water wraps around the features such as walls and ticket gates. The depth of flooding can also be changed quantitatively when rendering, and it can be expressed according to the predicted flooding depth which varies with rainfall and location. By storing 3D data of the site in the main memory on the server side in advance, it is possible to reduce data communication to the terminal with the most overhead; such as 2-3 minutes for millions of point cloud. On the client side, data access can be done only by light HTML communication, and by holding the terminal in the direction the user wants to see, it is possible to interactively view the inundation situation AR at a fast frame rate. The implementation is limited to only a small area in the station so far. We are planning to try to apply our method to a larger scale of the 3D point cloud data sets that should be handled for generic use in many underground constructions. As a future work for the context of the system, spatial representations such as which water will flow from either side based on direction information in the underground space, the creation of a virtual evacuation guidance indication, etc. can be considered.

6. CONCLUSION

In this research, we propose a technique to visualize predicted inundation situation by panoramic image based on 3D data of 3D shape restoration of the target space. As a result, the general user can browse the panoramic image at that point on the terminal by selecting an arbitrary viewpoint. This system performance will contribute to the disclosure of the flood information analyzed in the past research. In the future, by harmonizing with the AR system conducted in the previous study, based on the method of displaying a panoramic image matching the arbitrary photographing viewpoint/direction from the photographed image of the user terminal and the information of the flow rate obtained by the inundation analysis. We are planning to consider representation methods closer to disaster information assumed in reality.

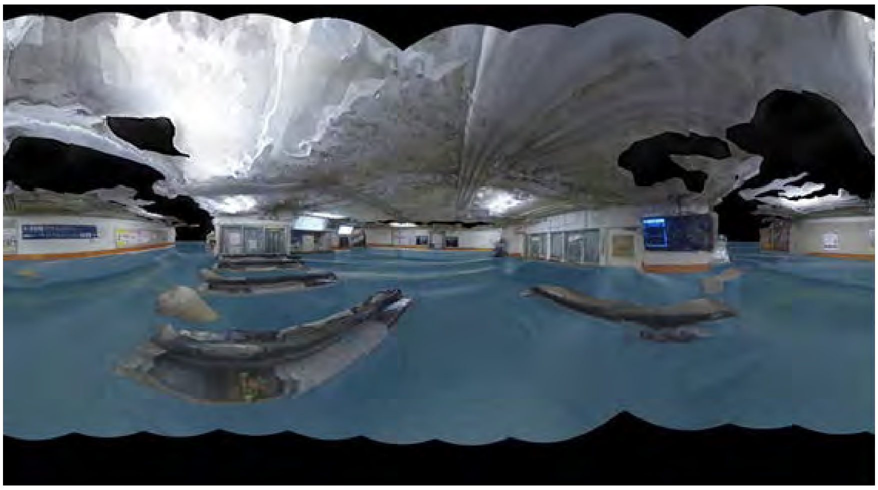


Fig. 10: Result of the stitching and developing for the 360-degree panoramic image

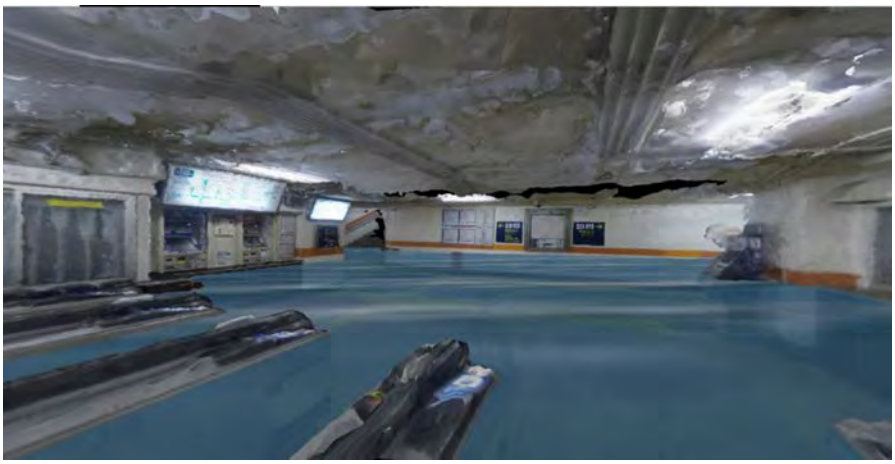


Fig. 11: Display results of the inundation image in 350-degree panorama,

Fig. 12: Example of the display results on a smartphone

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PERFORMANCE EFFECTS OF USING MIXED REALITY FOR ELECTRICAL POINT LAYOUT TASKS

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ABSTRACT: *Although Building Information Modeling (BIM) is increasing in the industry, most office-to-site design communication still happens using 2D paper plans. Mixed Reality (MR) may be able to deliver design information to end users, but the degree to which it affects different construction applications is yet to be fully investigated. Some theoretical classifications of construction activities suggest that composite tasks might benefit from MR communication, but these theoretical claims have not been empirically validated. Point Layout is a composite task that consists of finding and marking points of interest on the construction site. Point layout is essential to multiple practices in construction, including electrical construction. This paper compares the effect of using MR on the performance of a point layout task compared to using typical paper plans. Thirty-two current electrical construction practitioners participated in the point layout task eight different times each, half of which using MR and the second half using paper. The paper answers the following question: how is the precision and performance of point layout process be affected by using MR instead of paper plans? The researchers observed significantly faster point layout, but accuracy may be reduced using current technologies. The findings will empirically validate the use of MR for some composite tasks, and enable researchers and practitioners to make informed decisions when considering MR for a point layout tasks. Future work will further study the effect of different complexity factors on the performance of MR for point layout tasks.*

KEYWORDS: *Mixed Reality, Augmented Reality, HoloLens, BIM*

1. INTRODUCTION

Mixed Reality (MR) enables the viewing of both virtual and real content in the same view (Milgram and Kishino 1994). In the Architecture, Engineering and Construction (AEC) industry, MR can be used in conjunction with Building Information Modeling (BIM) to visualize full scale models directly on construction sites. In recent years, researchers identified many potential use cases for MR during the construction phase (Wang et al. 2014), planning phase (Jiao et al. 2013) and in construction training (Wang and Dunston 2007).

Some other research classified all construction tasks based on their potential to use MR (Dunston and Wang 2011). Point layout is a construction task currently dependent on the cognitive capabilities of practitioners to map plans to their surroundings (Kwon et al. 2014), and is theorized to benefit from MR implementation. Moreover, a recent study has shown that MR can enable significantly faster placement of assemblies on their final location on a construction site (Chalhoub and Ayer 2018), reinforcing the potential of MR for positioning tasks. This paper empirically validates the viability of using MR for electrical layout tasks and compares its performance to the performance when using traditional paper plans. Specifically, this paper answers the following questions: how is the precision and performance of the points layout process affected by the using MR compared to when using paper? The findings contribute to the body of knowledge by providing guidelines on the use of this technology for point layout tasks in construction and to guide developers towards other high-potential use cases of the technology.

2. BACKGROUND

After the economic crisis of 2008, many researchers have understood and anticipated a labor shortage in the construction industry (Albattah et al. 2015a). Some US cities are already reporting shortage in workers in key crafts (Albattah et al. 2015b). In turn, labor shortage leads to cost and schedule overruns (Toor and Ogunlana 2008). As a response to these problems, researchers have proposed exploring new, innovative solutions to complete the required work using less qualified or untrained labor (Karimi et al. 2016).

Building Information Modeling enables the creation of 3D information-rich models, allowing designers to iteratively experiment with design concepts virtually before actual construction starts. Due to its many benefits, BIM adoption in the industry continues to increase (McGraw-Hill Construction 2014). Research has focused on extending the use of the intelligent models to the construction site. Currently, the majority of office-to-site communication happens through paper plans, and onsite workers may have access to the 3D model through dedicated BIM stations or handheld devices (Murvold et al. 2016). However, both methods still rely on the user's capabilities of reinterpreting the design to the construction site. Due to recent technological advancements, MR has become a stable and viable method of viewing virtual content at full scale, superimposed on real surfaces in the user's field of view.

Recently, efforts have been made by researchers to identify potential use cases for MR in the different construction phases and applications. MR has been used to improve access to 3D details by using 2D plans as paper markers (Sabzevar et al. 2018) and to aid in the digital construction of complex modular surfaces (Fazel and Izadi 2018). MR has been shown to enhance performance and reduce mistakes during experimental construction tasks (Chu et al. 2018). MR has also been used for timely construction monitoring and documentation (Zaher et al. 2018) and to support discovery based learning in civil engineering (Behzadan et al. 2018). However, most efforts used hardware and software prototypes in controlled lab settings.

Dunston and Wang classified construction related tasks based on feasibility of implementing MR (Dunston and Wang 2011). A five-level hierarchical system was proposed. Composite tasks, the fourth type on the hierarchical level, were theorized to benefit from MR. One such task is point layout, which includes the finding and marking of points relative to other points in space. Point layout is performed in many construction disciplines, such as electrical construction. In this task, a practitioner identifies where electrical devices, such as receptacles and switches, are to be installed in a room, and then creates a mark of their locations. After this point layout task is completed, an installation crew follows to actually install the devices at the points identified. This paper compares the performance of practitioners laying out the points when using paper plans to when using MR.

3. METHODOLOGY

This research aims to determine the performance impacts of using MR for electrical device layout tasks compared to using traditional paper plans. This section describes the experiment designed by the researchers to address the research questions.

The researchers partnered with a large electrical specialty contractor in the US. The partner company has an extensive national and international footprint and has an internal research and development group. During the proposed experiment, practitioners from the company would layout the same space multiple times using MR and traditional paper plans, and the performances would be compared to understand the viability of the technology for the proposed task.

A conference room in the partner company's offices in Phoenix was identified for this experiment, creating a safe yet realistic space for laying out the devices. The researchers also collaborated with designers and modelers from the partner company to design eight different designs of electrical devices laid out in the same room. For each design, modelers from the partner company created the designs using standard BIM processes and software, and provided the researchers with a set of paper plans and a 3D model. Figure 1 below shows the sample plan sheet for one design.

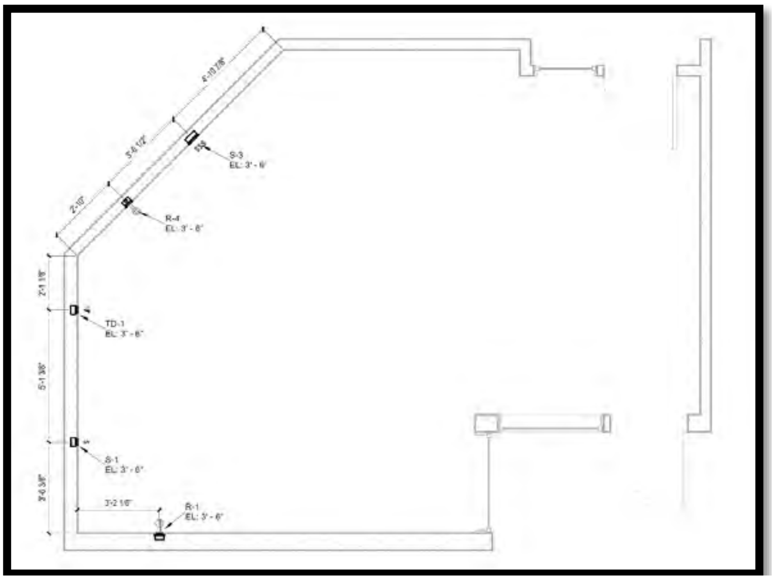


Figure 1: Sample plan sheet for one of the designs

The researchers chose to use the Microsoft HoloLens as the MR device for this experiment. The HoloLens is an untethered, hands-free, Head Mounted Display (HMD). Using it would allow the participants to see the real world with virtual content overlaid on top of it, while also being able to move freely around the room and use both hands freely to complete the task as they normally would. The researchers received the model in a Revit file and then modified it to only include the electrical devices to be laid out. All other items, such as walls, windows, ceiling and others were removed to eliminate element redundancy when viewed through the headset, since the walls and windows were physically installed. The methodology detailed in (Chalhoub et al. 2018) was then used to deploy the 3D content to the headset. The application utilizes a marker to place the content accurately onsite. Figure 2 shows an image of a sample marker.

Figure 2: Sample marker image

Traditionally, when practitioners are laying out devices onsite, spray paint or marker pens are used to mark the location of devices and names. The installation crew that follows would then install the appropriate device at the location of the mark. For this experiment, a set of reusable sticky notes was created to mark the location of each device. Each sticky note contained a cross, centered in the middle of it, and the name of the corresponding device in the top right corner. The participants were instructed to tape the sticky note to the wall, in such a way that the center of the cross on the sticky note falls on the center of the BIM-based device in MR. Figure 3 shows a sample sticky note used in the experiment taped to a wall.

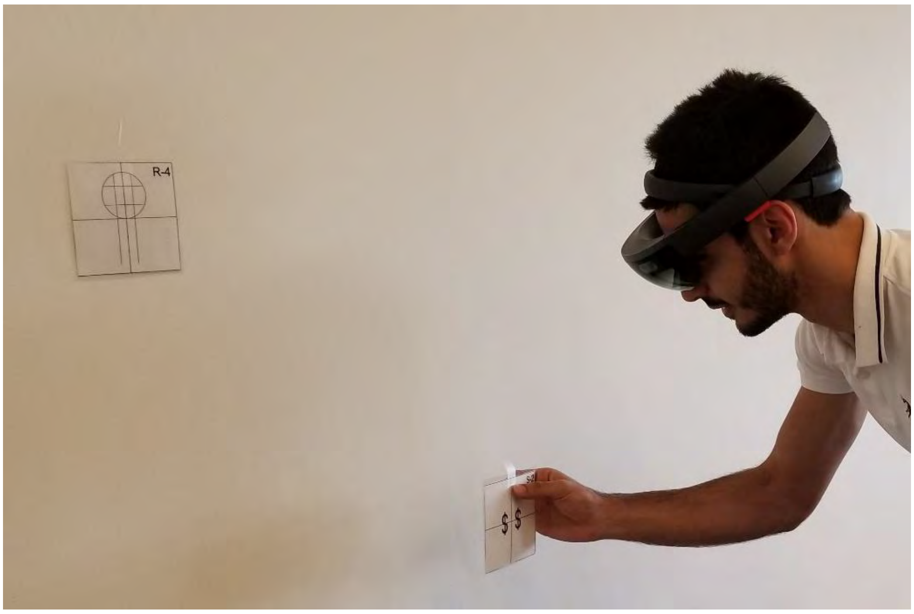


Figure 3: Sticky note placed on the wall, with the name of the device in the upper right corner

The experiment was carried out over the span of two weeks. Each participant signed an informed consent form and filled out a pre-session questionnaire before the experiment started. During the experiment, each participant was assigned a randomized list of eight electrical point layout designs. Four designs were laid out using MR, and the other four were laid out using traditional 2D paper plans. For each design, the participant would be handed either the paper plans corresponding to the design or the HMD with the MR model loaded, and an envelope with the corresponding sticky notes. The designs were created in pairs: each two designs had the same type and number of devices and placement, but the exact location of the devices was changed. One of the two designs was laid out with paper plans, and the other with the MR headset. These samples were compared pairwise to ensure that similar levels of difficulty were compared to one another. Furthermore, if one design was laid out with paper by the first participant, it was laid out using the headset by the other, balancing out any slight differences in difficulty that may be present between the designs.

Once a participant completed the layout of one design, the researchers measured the distances from the center of the sticky notes to the walls and the floor using a high accuracy laser tape measure. The sticky notes were then removed from the walls and the participant was handed the next design and the corresponding envelope with a new set of sticky notes. This process was repeated until all eight designs were laid out by the participant. The experiment was video-taped from multiple angles for analysis. On average, each participant required an hour and a half to finish all eight designs.

The collected data was digitized and stored in a spreadsheet. The authors also watched and coded the videos, and the duration of each task was computed. The accuracies along the X- and Y-axis were computed by comparing the onsite measurement with the coordinates from the BIM using relative and absolute measurements, and were then stored in the same spreadsheet. The data was then analyzed using various statistical software, such as R and SPSS.

4. RESULTS

In total, thirty-two practitioners participated in this experiment. The participants included electricians, BIM modelers, construction managers, coordinators and interns. Of the participants, only four has less than 1 year of experience, and their ages ranged from 21 to 59 years old. Seventeen of the participants (53%) had laid out electrical devices in rooms as part of their jobs in the past year.

4.1 Accuracy

Accuracy is an important factor in point layout tasks, especially for electrical devices. Depending on the type of project, tolerances can be as low as 1/8th of an inch (0.3175 mm). The distances measured for each point on site were compared to the designed distances, and the absolute accuracies along the X-axis and Y-axis were subsequently calculated. During the experiment, the researchers noted that some practitioners misread the values on the paper; in other cases, the participant expressed that the model suddenly jumped from its location, but he or she continued working regardless. These cases created severe outliers and were subsequently removed from dataset.

Since each participant laid out four designs using paper plans and four using MR, a paired statistical test was used to compare the accuracies. In order to chose the correct statistical test, the Shapiro-Wilk test of normality was run on the datasets. Table 1 summarizes the findings.

Table 1: Results of the Shapiro-Wilk tests of normality

	Raw Data		All Outliers Removed	
	W-Value	P-Value	W-Value	P-Value
X-Paper	0.57468	<2.2e-16	X-Paper	0.57468
X-MR	0.6505	<2.2e-16	X-MR	0.6505
Y-Paper	0.21754	<2.2e-16	Y-Paper	0.21754
Y-MR	0.7827	<2.2e-16	Y-MR	0.7827

All significances are smaller than 0.05, suggesting that the datasets are not normally distributed. Thus, the Mann-Whitney non-parametric set was used. The results are summarized in the Table 2.

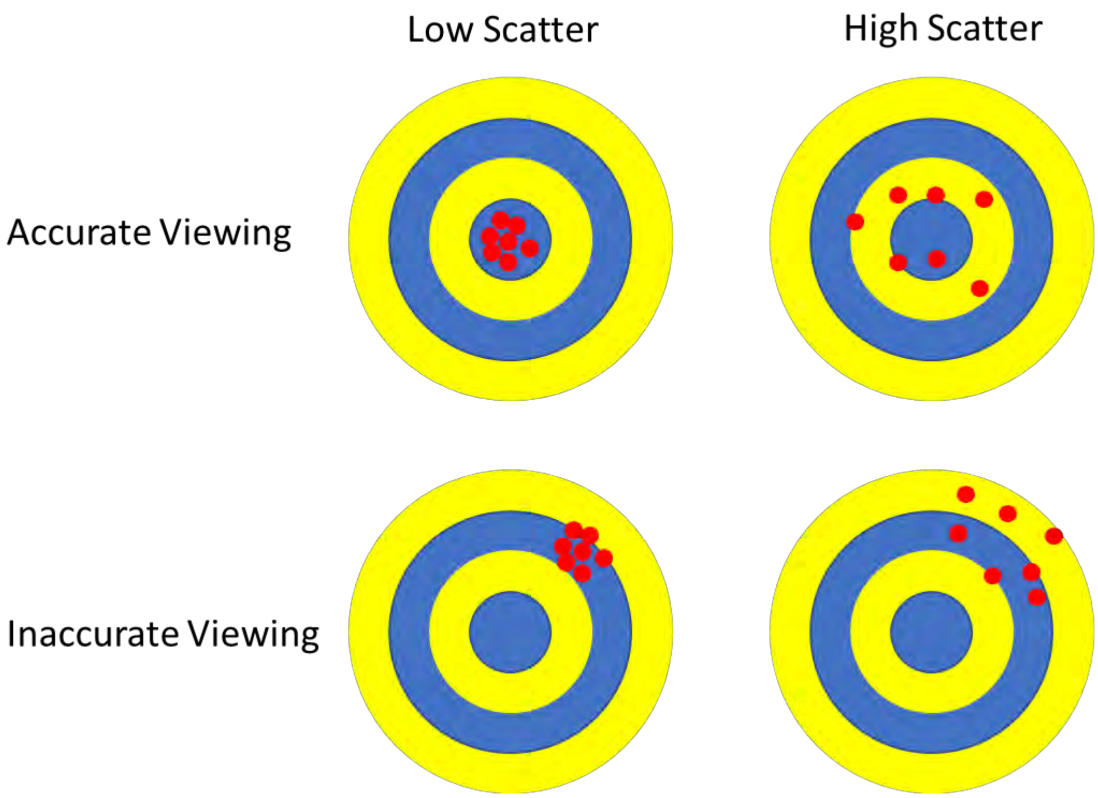
Table 2: Results of the paired Mann-Whitney tests along the X- and Y-Axis

Testing	Number of Pairs	MR Mean (Inch)	Paper Mean (Inch)	Mean Difference	V-value	P-Value
X-Axis	624	1.20	1.00	0.19	110,760	0.002528
Y-Axis	598	1.11	0.18	0.93	162,320	<2.2e-16

The results suggest that using paper plans is, on average, 0.19 inches more accurate than using MR on the X-axis, and the difference is significant (p-value <0.05). Similarly, using paper plans is, on average, 0.93 inches more accurate than using MR on the Y-axis, and the difference is significant. The results suggest that MR is not useful in cases where high accuracy is required, which aligns with the expectations of the researchers: current generation MR devices are not built for high accuracy. However, in some cases, electrical devices are attached to the nearest stud in a room, and MR level accuracy might be enough to get the placement close enough to the final intended location.

4.2 Grouping effect

While the absolute accuracy of the placement of the points is important, another important factor is the grouping of the placed points. Grouping refers to the distance between the placed points regardless of their initial intended location. When using MR, if all the points are placed near one another, it indicates that the user was seeing the virtual content off-target, but the placing the points correctly considering what he or she was seeing. On the other hand, if the user placed the points placed far from one another, it indicates that either the device was not displaying the points consistently where they should be, or that the user was not able to place the points accurately to overlap with the virtual content. Figure 4 shows the four possible combinations of accuracy and grouping.



The variances of the points placed were computed along the X- and Y-axis for laying out using paper plans and using the MR device to quantify the grouping of the points. The results are presented in Table 3.

Table 3: Variances of the locations of the points for paper and MR along the X- and Y-Axis

	Paper	Mixed Reality	Ratio
X-axis	0.0449	0.0256	1.75
Y-axis	0.1082	0.0147	7.36

The point layout accuracy variance when using MR is smaller than when using traditional plans along both axes. This indicates that the participants were probably viewing the virtual content skewed from its intended place but were correctly placing the points relative to the content. Future work may be able to accurately quantify the amount and reasons behind the shift. If this were performed correctly, an artificial offset could potentially be introduced to correct the viewing location of the virtual content. Then, the accuracy of placing points using the device would likely increase.

Additionally, current tasks that require placement of the points near one another but not necessarily accurate in space may benefit from using MR viewing devices. Additional work may be required to quantify the interpoint accuracy of current generation MR devices.

4.3 Time

Another important metric in point layout tasks is time to complete layout. The different room designs had different numbers of electrical devices to be laid out, and in order to have a fair comparison, the layout time per device was

Figure 4: possible relationships between variance and accuracy

used. The same paired analysis process was used, and the Shapiro-Wilk test was employed to check the normality of the datasets. Table 4 below summaries the results.

Table 4: Results of the Shapiro-Wilk tests of normality

	W-Value	P-Value
MR Time	0.64132	<2.2e-16*
Paper Time	0.96673	7.231e-12*

Since the two datasets are not normally distributed, the paired Mann-Whitney test was used. Table 5 below summarizes the findings.

Table 5: Results of the paired Mann-Whitney test

Testing	Number of Pairs	MR Mean	Paper Mean	Mean Difference	V-value	P-Value
Time Per Device	675	27.7	92.	65	18850	<2.2e-16*

On average, a device laid out using MR requires 27.7 seconds, compared to 92.7 seconds using traditional paper plans, and the difference is significant at the 95% confidence level (p-value < 0.05). When laying out using MR, the practitioner only has to find the virtual device on the wall and tape the marker to the correct spot. Conversely, when using paper plans, the practitioner has to find the device, pull measurements from the walls and the ground, and tape the sticky note without losing the location. The significant time saving is attributed to these additional steps.

4.4 Limitations

While this work employed industry standard models and current practitioners, the space used for the experiment is not an active job site. Noise, congestion, climate and other factors may severely hinder the usability and expected performance of current generation MR devices. In several instances during the experiment, the device lost tracking or exited the application, and had to be reset by the researcher. While the results presented do include all the down time experienced, it does not include the development time of the MR applications and solutions are not accounted for in the comparisons. Currently, it takes a significant amount of time to modify the model and export it to the MR device, but an automated deployment process should be implemented if the approach is to be widely deployed.

Also, the extended use of the HMD is yet to be tested. Fatigue, head-heaviness, and other discomforts have been reported, which could hinder the widespread deployment of the technology in its current form. However, the technology is expected to keep improving and miniaturizing, so the deployment of future generation devices may be more feasible.

5. CONCLUSION

The work presented tests the feasibility of using MR to enable onsite electrical device layout tasks, and compares the performance of current industry practitioners when using MR compared to their performance using traditional paper plans. The experiment compares the speed and accuracy of the layout task for each of the information delivery methods. Furthermore, the experiment uses industry standard modeling and shop-drawing creation processes. A paired analysis of performance showed that practitioners can layout devices 60% faster when using MR compared to when using paper, but the accuracy when using paper is marginally better. While other, more accurate point layout tools exist, they often require significant expertise and setup time to use, making MR particularly important for jobs that require less accuracy and faster layout process. s

This paper contributes to the body of knowledge by highlighting the benefits and challenges with using MR for one specialty construction pre-construction task. Future work will include studying the effect of experience, age and task complexity factors on the performance of the technology.

6. ACKNOWLEDGMENTS

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VIRTUAL REALITY-BASED STUDIES OF HUMAN EMERGENCY BEHAVIOR IN BUILT ENVIRONMENTS: A SYSTEMATIC REVIEW

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ABSTRACT: *Human behavior is one of the most influencing factors of safety during emergencies. Having a robust understanding of human behavior can improve both emergency management practices and design strategies for built environments. Traditional methods to study human behavior include emergency drills, post-event surveys, controlled laboratory experiments, and emergency video analyses. However, these methods suffer from intrinsic limitations, such as scarcity of available data and lack of flexibility to quantify the impact of various factors (e.g., corridor width, number of exits) that might influence human behavior. With the recent advancements in virtual reality (VR) technologies, an increasing number of VR-based human behavior studies are seen in the literature. This study presents a systematic review of existing VR-based research on human behavior during emergencies in built environments. The review results demonstrate that fire emergencies and wayfinding behavior are widely studied while other emergency or behavior types are not well explored yet. The review results also suggest that many VR-based studies did not specify a target population or explore the impact of a particular type of built environment. In the light of the review findings, recommendations for future VR-based research on human emergency behavior in built environments are discussed.*

KEYWORDS: *virtual reality; human behavior; emergency; built environment; review.*

1. INTRODUCTION

Various natural and man-made disasters could occur in built environments, putting human safety in peril. For example, in 2016 only, 475,500 structure fires occurred in the United States, resulting in 2,950 civilian deaths and 12,775 civilian injuries (Haynes, 2017). Human behavior is one of the most decisive factor for human safety during emergencies. It was reported that in many emergency situations, most victims were killed or injured by the non-adaptive behavior of the crowd (e.g., pushing and trampling on each other), instead of by the actual cause of emergencies (Pan et al., 2006). One way to mitigate the risk of emergencies in built environments is to use a "behavioral design" approach by taking human factors into consideration for developing effective risk-reduction strategies, which requires comprehensive knowledge of human behavior during emergencies (Bernardini, D'Orazio, et al., 2016).

It is not a trivial task to understand human behavior during emergencies. Unlike in normal situations, people tend to behave differently in emergencies under high physiological and psychological stress (Ozel, 2001). Human emergency behavior is based on the perception of the situation, intention to act, and considerations involved before actions (Kobes, Helsloot, de Vries and Post, 2010). For example, people may not evacuate a building when they hear a fire alarm. Instead, they may first attempt to understand the situation, wait for more cues (e.g., smell of smoke, others leaving the building), and seek more situational information (Latane and Darley, 1968). Social behavior is also common during emergencies. When emergencies occur, people with strong social relationships (e.g., families and close friends) usually act as a group and may even take detours to search for missing members (Kobes, Helsloot, de Vries and Post, 2010). Moreover, it has been illustrated that many building attributes, such as visual access, architectural differentiation (i.e., unique building characteristics which people could use for orientation purposes), signage, and plan configuration, could impact people's evacuation performance in emergencies (Raubal and Egenhofer, 1998), which makes human behavior during emergencies more complex.

Due to legal and moral reasons, it is virtually impossible to expose people to life-threatening conditions to study their behavior during emergencies (Hancock and Weaver, 2005). In response, a variety of alternative approaches have been proposed. Emergency drills have been widely performed in emergency behavior studies (Kobes, Helsloot, de Vries, Post, et al., 2010). However, a major limitation of emergency drills is the lack of sense of presence, which may cause different evacuation behavior from real emergencies (Muir, 1996). Although unannounced drills could partially mitigate this limitation, it is still costly to conduct drills and difficult to control environmental variables (Haghani and Sarvi, 2017a). Additionally, post-event surveys and interviews have been widely used. However, bias may exist in participants' memory and responses, even if they have real emergency experiences (Kuligowski, 2016). Hence, the collected data may not accurately reflect their actual behavior during emergencies. Controlled laboratory experiments provide an alternative way to study human behavior during emergencies. Unlike emergency drills, controlled laboratory experiments normally take place in temporary physical setups in laboratories, which offers better environmental manipulation and field observation (Haghani and Sarvi, 2017a). However, controlled laboratory experiments may suffer from insufficient sense of presence experienced by participants, and whether the experiment results amount to reliable reflection of real-world scenarios remains uncertain in many cases. A variant way of conducting controlled laboratory experiments is using non-human subjects (e.g., mice and ants) and exposing them to real hazards. While this approach could avoid exposing human participants to hazardous situations, the behavioral similarities between humans and other animals are still debatable (Parisi et al., 2015). Alternatively, video records could be used to obtain behavioral data from past emergencies. The major advantage of this approach is that it is based on real behavior. However, it is limited by the scarcity and incompleteness of available data (Haghani and Sarvi, 2017a). Also, various simulation tools have been developed to model human responses during emergencies by setting predefined rules for human behavior. Nevertheless, human psychological responses and physical behavior are usually highly complex in emergencies and difficult to predict, while comprehensive behavioral theories to guide simulations are lacking (Kuligowski and Gwynne, 2010). As a result, it is very challenging for simulations to represent fine-grained human behavior in emergencies.

Apart from the above approaches, virtual reality (VR) has become a promising tool. VR generally refers to the technology used to generate computer-simulated environments that give a viewer a convincing illusion and a sense of being inside an artificial world in the computer (Castronovo et al., 2013). Compared with other approaches, VR-based behavioral experiments can provide safe and non-invasive environments, the flexibility to cover a wide range of topics, and the capability of retaining various control variables (Haghani and Sarvi, 2017a; Kinateder, Ronchi, Nilsson, et al., 2014). In recent years, VR applications in this research area have been exploited, whereas an understanding of the current status of this area is lacking. Moreover, with the rapid growth of VR technology, VR has increasing potential of being used to study human behavior during emergencies. Thus, it is necessary to shed light on future research directions by synthesizing prior studies. To address this gap, this study presents an in-depth review of VR-based research on human behavior during emergencies in built environments, identifies the latest accomplishments and limitations of current studies, and provides recommendations for future research.

The remainder of the paper is organized as follows: Section 2 describes the objectives and methodology of this review. Section 3 provides a comprehensive review of VR-based research on human behavior during emergencies in built environments. Discussions and recommendations for future research are presented in Section 4. Section 5 concludes the paper.

2. RESEARCH OBJECTIVES AND METHODOLOGY

The first objective of this study is to advance our understanding of the current achievements and limitations of VR-based research on human emergency behavior in built environments. The second objective of the study is to put forward recommendations, based on the synthesis of prior studies, for future research to promote the use of VR in studying human emergency behavior in built environments. To systematically present this research area, the literature was analyzed from 6 perspectives: (1) Since the main aim is to develop our understanding of human emergency behavior, what human behavior has been investigated in prior studies was described; (2) Different populations may have distinct behavioral patterns, due to their different lifestyles, abilities, and roles (Gerges et al., 2017). Thus, the target population of prior studies was analyzed; (3) It has been pointed out in prior research that human behavior may vary in different emergency scenarios (e.g., fires, earthquakes, flood, etc.) (Bernardini, Quagliarini, et al., 2016), thus the types of emergencies examined in prior studies were presented; (4) Built environments can have critical impacts on human behavior during emergencies (Kobes, Helsloot, de Vries and Post, 2010). Therefore, built environments and their attributes studied in prior studies were reported; (5) The attributes (e.g., display size, stereoscopy, head-tracking) of VR devices can impact the sense of presence experienced by participants (Castronovo et al., 2013). VR environments, including built environments and hazards mentioned in the last two points, and non-playable characters (NPCs) are also essential for implementing VR tools and experiments (Rüppel and Schatz, 2011). Thus, the VR systems (i.e., VR devices and NPCs) used in prior studies were reviewed and discussed; and (6) An essential concern of using VR to study human emergency behavior is the ecological validity – whether the experiment results can be repeated in real-world scenarios (Zou et al., 2017). In response, the validation methods used in prior studies were presented.

Driven by the above objectives, major electronic databases of scientific publications, including the "Web of Knowledge," "Scopus," and "Google Scholar," were used to search for the relevant articles. A combination of keywords, including "human behavio*", "emergency/disaster/extreme event/extreme environment", and "virtual reality/virtual environment/virtual experiment/immersive virtual environment/immersive virtual reality" were used in the search process. Since virtual environments refers to computer-simulated environments in this paper, the search was limited to 2000 and beyond. To gain a comprehensive view of the research area, (1) theoretical studies (e.g., studies that analyzed the feasibility of VR applications), (2) studies that developed VR tools that aimed at investigating human emergency behavior without conducting VR-based experiments, and (3) studies that involved VR experiments were all included in the review. Articles beyond this scope were excluded. Examples of excluded studies, which were manually filtered from the search results, included those that did not focus on human emergency behavior in built environments (e.g., aircraft emergencies), those that developed VR tools for emergency training purpose only, and those that did not use computer-simulated environments for the claimed virtual experiments (e.g., hypothetical-choice experiments). In addition, to complement the search results, the forward and backward snowballing method was applied (Wee and Banister, 2016), by examining the references of articles in the search results, to find more relevant papers that met the above inclusion criteria. Duplicate recordings of the same work were removed (some journal papers are based on earlier conference papers, where the contents are similar, thus only the journal versions were included in this review). After this search procedure, a total of 48 articles were included in the review.

Fig 1. illustrates all of the reviewed articles sorted by the publication year and article type (one article was released on arXiv.org in 2018, thus not included in Fig. 1). The set of articles sparsely distributed in a wide range of sources, including journals and conference proceedings, which demonstrated the highly interdisciplinary nature of the research area. The titles, in which most of the articles were published are: *Applied Ergonomics* (6), *Fire Safety Journal* (5), *Pedestrian and Evacuation Dynamics* (3), *Ergonomics* (3), *Computers in Human Behavior* (2), and *Journal of the Royal Society Interface* (2). Additionally, the publication year of the articles demonstrated that this research area has attracted an increasing attention in recent years.

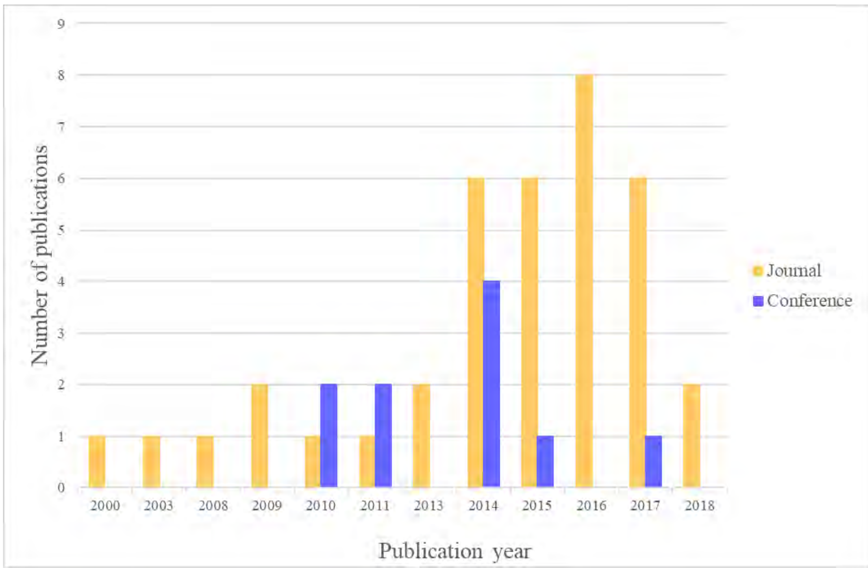

Fig. 1: Publication years and source types of the reviewed articles

3. REVIEW FINDINGS

3.1 Human behavior

Wayfinding and egress route choice are the most widely studied human behaviors in VR-based studies. The impact of building attributes on wayfinding during emergencies has been a popular topic. For instance, a hotel fire evacuation, conducted in both virtual and real-world experiments, demonstrated that the presence of exit signs could facilitate wayfinding during emergencies (Kobes, Helsloot, De Vries, et al., 2010). When smoke was perceptible, exit signs at the floor level was found to be more effective compared with signs at the ceiling level. In terms of corridor configurations, evacuees in a VR-based experiments tended to choose the corridor with more lighting at corridor intersections (Vilar et al., 2014). When both signage and different corridor configurations were present, evacuees' egress route choice was less likely to be influenced by the signage. Additionally, one VR-based experiment about the evacuation in a high-rise hotel showed that flashing green lights at the evacuation elevators could persuade evacuees to choose elevators (Andrée et al., 2016).

Furthermore, social interactions are crucial to the formation of human behavior during emergencies. Thus, social influence on wayfinding and egress route choice during emergencies has been examined in VR-based studies. Evacuees' egress route choice in tunnel fires under non-conflict (i.e., an NPC moving to the exit) and conflict (i.e., an NPC staying passive or moving to the opposite direction of the exit) social conditions were studied in VR-based experiments. The results demonstrated that evacuees were less likely to move to the exit in the conflict conditions compared with the non-conflict condition (Kinateder, Müller, et al., 2014). The combined effects of environmental and social factors on wayfinding and egress route choice during emergencies were also explored. The VR-based experiment in one study revealed that the presence of smoke, long distance of the exit, and high number of other evacuees near the exit reduced the probability of an exit to be chosen, while emergency lighting near the exit and flow of other evacuees through the exit had a positive effect (Lovreglio et al., 2016). Moreover, exit choice during emergencies was impacted by both the evacuees' familiarity of the built environment and other evacuees' choices. A VR-based experiment demonstrated that participants were more likely to exit through their familiar door, and this tendency was increased when the familiar door was chosen by other evacuees and decreased when the unfamiliar door was chosen (Kinateder et al., 2018). Compared with the social influence on wayfinding and egress route choice, social behavior amongst evacuees have been less studied in prior VR-based research. Drury et al. (2009) studied cooperative and competing behavior during emergency evacuations in an underground railway station. The VR-based experiment results illustrated that collective bonds might be strengthened and even created through the mutual experience of an emergency, and the amount of help that one would offer was affected by the level of danger. Gamberini et al. (2015) conducted a VR-based experiment in an office building in a fire emergency. The experiment demonstrated that light-skinned participants offered less amount of help to a dark-skinned NPC than to a light-skinned NPC, which indicated racial discrimination could occur during emergencies.

3.2 Target population

Target population refers to the population to which the findings of the studies are meant to generalize. In reviewed prior studies, only three specified their target population, while majority of the studies did not. One study targeted at light-skinned people to study racial discrimination in terms of the amount of help offered during emergencies (Gamberini et al., 2015). Another study investigated the influence of professional backgrounds on wayfinding performance in emergencies. Participants of the VR-based experiments from professional backgrounds (e.g., employees of construction companies, firefighters) did not show significant difference in their wayfinding performance (Tang et al., 2009). Moreover, a study focusing on helping and competing behavior during emergencies targeted at people with high or low sense of identification (i.e., whether they psychologically consider themselves as part of the crowd or not). The results demonstrated that those with high sense of identification were more concerned about others and offered more help (Drury et al., 2009). Apart from specific groups of population, demographic information (e.g., age and gender) was also collected in prior VR-based experiments. However, the information was used as control variables in most cases (i.e., balancing participants in different experiment groups) (Kinateder, Ronchi, Gromer, et al., 2014; Vilar et al., 2014). Only a few studies identified the impact of participants' demographics on their evacuation behavior. For example, male participants were found to have better wayfinding skills than female participants in building evacuations (Tang et al., 2009), and female and older participants appeared to have longer reaction times during virtual evacuations (Bode and Codling, 2013).

3.3 Emergency situations

With respect to the types of emergencies, the majority of prior studies (32 out of 48) were focused on fire emergencies. The prevalence of fire in the literature could be explained by three possible reasons. First, fire is one of the most frequent and disastrous types of emergencies in built environments (Haynes, 2017). Second, the study of human behavior in fires dates back to the 1950s, which provides theoretical support for the VR-based research (Fritz and Marks, 1954). Third, fire attributes, such as flames and smoke, can be modeled and visualized by particle systems embedded in many game engines (Rüppel and Schatz, 2011). 13 out of 48 studies did not specify their target emergencies. In these studies, hazards were not included in the virtual environment, and participants were only informed that there was an emergency, or an emergency alarm was played to them (Kinateder et al., 2018; Tang et al., 2009). The studies in this category mainly focused on the impact of emergency evacuation installations (e.g., signage systems) on human behavior (Tang et al., 2009), and evacuees' egress route choice during general building emergency egress (Bode and Codling, 2013). However, since hazards present in higher level of realism can provide more sense of presence experienced by participants (Zou et al., 2017), virtual environments without specified hazards may not elicit participants' sufficiently realistic emergency behavior. Terrorism related emergencies were only explored by one study. Chittaro & Sioni (2015) developed VR-based experiments that presented a terrorist attack in a train station. The virtual environment included smoke, metal debris and fire as the attack attributes. The experiment results showed that the interactive virtual environment could better enhance participants' risk perception and emotional response to the presented threat than the non-interactive version. Earthquake emergencies were only explored by two studies, in which VR-based experiments of a hospital experiencing an earthquake were prototyped (Lovreglio et al., 2018). The damaged environment was included in the virtual environment, and the shaking effect was simulated by setting up a vibrating platform on which the participants were seated.

3.4 Built environments

Built environments are critical in the formation of human behavior during emergencies (Bernardini, D'Orazio, et al., 2016). Fig. 2 illustrates the types of built environments and attributes of built environments considered by prior VR-based studies.

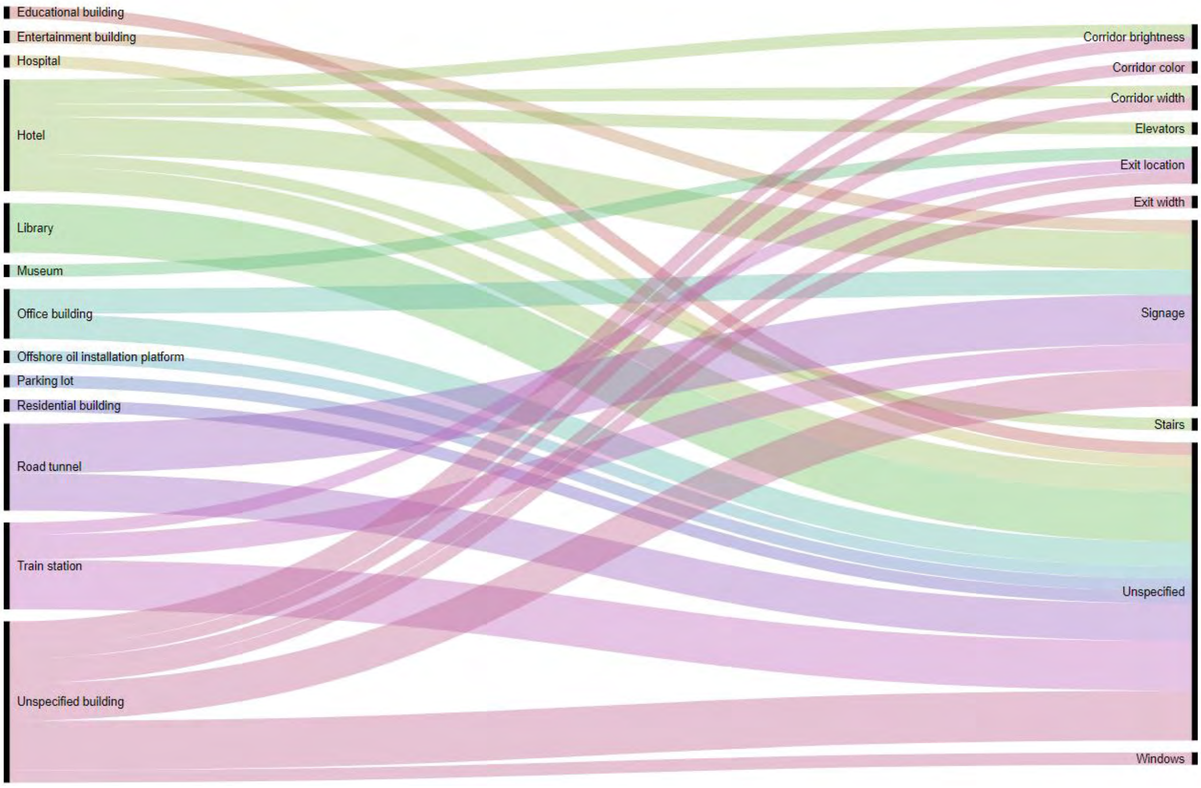

Fig. 2: Types and attributes of built environments considered in the reviewed articles

As shown in Fig. 2, Unspecified buildings are the most frequently studied type of built environments in prior VR-based research. In these studies, virtual environments were mainly based on buildings with no specified usage, or part of a building such as a room or a corridor (Bode and Codling, 2013; Vilar et al., 2014). Although a variety of built environments, including train stations (Drury et al., 2009), office buildings (Gamberini et al., 2015), hotels (Andrée et al., 2016), and so on, have been included in prior studies, the focus of these studies was mainly on human behavior exhibited during emergencies, while how these built environments impact human emergency behavior was not well explored. Among various attributes of built environments, signage, corridor and exit configurations have been most frequently studied. Other than these, one VR-based study investigated the impact of windows and corridor color on evacuees' route choice. The study reported that people tended to choose corridors with open windows and light color during evacuations (Abu-safieh, 2011). In another VR-based study, participants were asked to evacuate a high-rise hotel via stairs or elevators. It was found that participants generally waited either a limited time (less than 5 minutes) or a long time (more than 20 minutes) for elevators (Andrée et al., 2016). The possible reason for participants waited for a long time is that there was an announcement in the virtual environment, saying that the elevator could be used as an emergency exit.

3.5 VR systems

3D interactive desktop VR was the most widely used in the reviewed articles. When this technology is used, participants view 3D virtual environments through a monitor in front of them, and use controllers or keyboards and mice to navigate in the virtual environment (Drury et al., 2009; Tang et al., 2009). The main advantage of this method is that it is not demanding in terms of VR equipment, however, the level of immersion it can offer is limited (Nilsson and Kinateder, 2015). Head Mounted Display (HMD) was also commonly used. Participants' head orientation and movement can be tracked, and the virtual environment in participants' view can be updated accordingly in real time. HMDs can offer a feeling of immersion to participants, which makes it a promising tool for human emergency behavior studies (Nilsson and Kinateder, 2015). However, the usability of HMDs is still limited by technological challenges. For example, participants could not see their own body in many of the HMD systems (Nilsson and Kinateder, 2015). Cave Automatic Virtual Environment (CAVE) was another type of mainstream VR system used in prior studies. For the CAVE system, participants are placed in a room-sized cube and the virtual environment is projected on three to six (including the ceiling and floor) walls around the participant. In the environment, participants can use controllers or other interactive devices to navigate and interact with virtual objects, and their actions are tracked in real time (Nilsson and Kinateder, 2015). The main advantage of a CAVE system is the high immersion provided to participants, since participants can see their own body and are truly inside the virtual environment (Nilsson and Kinateder, 2015). However, compared with HMDs, CAVE systems are more cost-intensive and have higher requirements for space and computational power. Another VR technology is the powerwall. Virtual environments are presented stereoscopically on a powerwall screen, and participants can wear polarized glasses for 3D effects (Kinateder, Müller, et al., 2014). Apart from these methods, 2D interactive desktop VR was used only in two studies, in which participants could only see the virtual environment from a top-down view (e.g., (Bode and Codling, 2013)). Additionally, two studies used 3D non-interactive desktop VR, in which participants could only view pictures or videos of virtual emergency scenarios, without interacting with the virtual environment (e.g., (Lovreglio et al., 2016)). Furthermore, one studies conducted VR experiments with multi-participant enabled virtual environments, in which participants could virtually see and interact with each other (Moussaïd et al., 2016). However, the application of this system is highly subject to the available devices, such as the number of available HMDs and the graphics card performance (Lovreglio et al., 2017).

Including NPCs in the VR environment can provide the possibility to investigate the impact of other evacuees on evacuation behavior (Lovreglio et al., 2017). It also increases the sense of presence as in most cases, people evacuate with others. As shown in Fig. 3, many prior studies did not have NPCs in the VR environment. These studies mainly asked participants to perform tasks individually (e.g., wayfinding and exit choice) during the VR-based experiments and identified the impact of built environments on human behavior (e.g., the influence of signage systems on wayfinding) (Abu-safieh, 2011; Andrée et al., 2016). Crowds of NPCs were included in several studies. These studies mainly looked into how crowd movements induce stress and impact participants' egress route choice during emergencies (Bode and Codling, 2013; Lovreglio et al., 2016). Meanwhile, one NPC was used in VR-based experiments to examine the social influence on participants' egress route choice (Kinateder and Warren, 2016). Apart from evacuation behavior, other behaviors presented by NPCs, such as requesting help from participants, were incorporated in VR-based experiments as well (Gamberini et al., 2015). However, direct interactions between participants and NPCs are still lacking, which may limit the sense of presence experienced by participants (Nilsson and Kinateder, 2015).

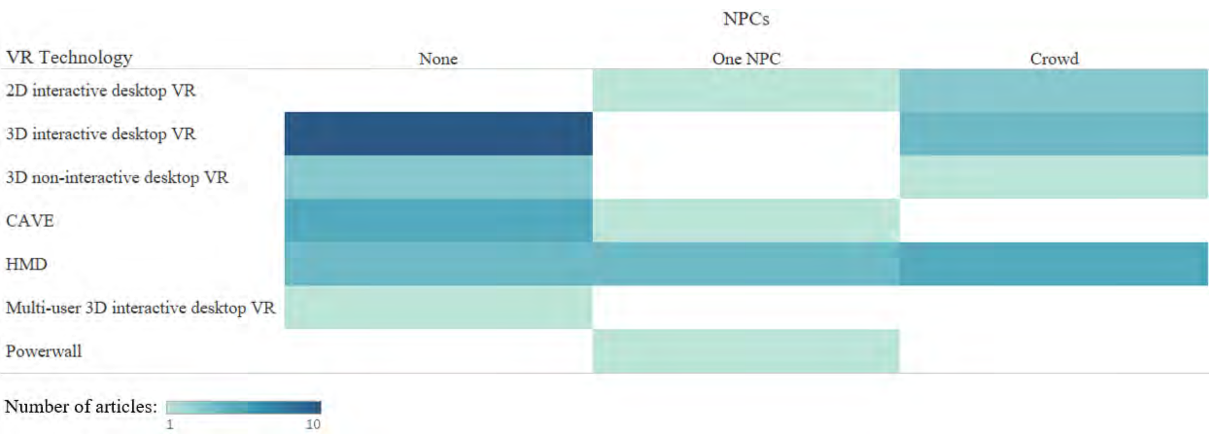

Fig. 3: VR systems and NPCs involved in the reviewed articles

3.6 Validation methods

Regarding the validation methods for VR-based experiments, 44% of prior studies used post-experiment surveys to measure ecological validity of the experiments. In these surveys, participants were often asked to evaluate their experience in virtual environments. Participants' anxiety, sense of presence, and simulator sickness during the experiments were often collected as an indicator of their feelings during the experiments (Kinateder, Ronchi, Gromer, et al., 2014; Zou et al., 2017). The possible reason for the wide use of surveys is that they are convenient to implement. However, survey data are based on participants' subjective responses, which may not always be a reliable indicator for ecological validity. Surprisingly, 31% of prior studies did not validate the virtual experiments, thus whether the experiment results could be transformed to real-world emergency scenarios was questionable. Physiological measurements were employed by 13% of prior studies. Skin conductance, heart rate, breath rate were commonly used in physiological measurements (Zou et al., 2017). The difference or ratio of physiological indicators before, during and after the experiment were analyzed to reflect the change of participants' feelings during the experiment. The physiological measurements generally showed that VR was capable of inducing emotional arousals, which was analogous to real-world emergency scenarios (Tucker et al., 2018). Comparison with real-world data is another validation method that can provide high credibility, which was used by 10% of prior studies. For example, one study compared moving trajectories in corridors in real and virtual environments and found the real-world data could be reproduced in the virtual environment reasonably well (Moussaïd et al., 2016). One difficulty in applying this method, however, is the lack of available real-world data. Additionally, one study considered participants' behavior in the virtual environment to measure the effectiveness of VR-based experiments. The study hypothesized that collisions between participants' virtual bodies and objects in the virtual environment, as well as participants' backward movement in the virtual environment would be more frequent during emergencies (Gamberini et al., 2015). To further validate the results of VR-based experiments, some of the above methods have been used in combination (e.g., questionnaires and physiological measurements) (Tucker et al., 2018; Zou et al., 2017). These psychological and physiological assessments showed that emergencies in the virtual environment could induce the emotional arousals experienced by participants.

4. DISCUSSIONS

Understanding human emergency behavior is the primary objective of this line of research. This review found that prior VR-based studies mainly explored participants' individual behaviors (e.g., wayfinding and egress route choice) and identified the impact of certain building attributes (e.g., signage systems and corridors) on human behavior (Tang et al., 2009; Vilar et al., 2014). Social influence has also been examined by prior studies, where the main focus has been the impact of crowd movements on people's egress route choice during emergencies (Bode and Codling, 2013). Although these investigations could provide valuable insights into human emergency behavior, the value of VR applications could be further advanced by more in-depth investigations of social interactions (e.g., helping and group-seeking) during emergencies. Moreover, people with different backgrounds may have distinct behavioral patterns, due to their different lifestyles, abilities, and roles (Gerges et al., 2017). For example, elderly people and people with disabilities were found to cause obstructions during evacuations because of their impaired mobility, thus special evacuation strategies need to be proposed for them (Gerges et al., 2017). By involving participants with different backgrounds in VR-based experiments, how human emergency behavior relates to their background (e.g., people's cultural background, daily roles, etc.) could be examined.

In addition, this review revealed that the types of emergencies studied in the literature are highly unbalanced. Human behavior during fires has been extensively studied, whereas other emergency situations (e.g., earthquakes and terrorist attacks) were much less investigated. Human behavior is subject to the impact of emergency situations, and some of the assumptions of human behavior (e.g., following crowd movement blindly during evacuation) may not always apply in all types of emergencies scenarios (Haghani and Sarvi, 2017b). Moreover, human behavior is also likely to vary significantly in different types of emergencies, such as earthquakes vs. fires (Bernardini, Quagliarini, et al., 2016). Thus, future VR-based research in this area could conduct experiments in different emergencies and examine how human behavior varies accordingly.

More importantly, human behavior and built environments are two interwoven elements in emergencies. Human emergency behavior is greatly influenced by built environments. Building layout, installations, size, etc. can all contribute to the formation of human behavior (Kobes, Helsloot, de Vries and Post, 2010). People's knowledge of built environments could also influence their egress route choice. It was observed that the familiar paths evacuees chose to go through might not be the shortest or safest ones (Kobes, Helsloot, de Vries and Post, 2010). In prior VR-based studies, only limited attributes (e.g., signage and corridors) of built environments were widely studied, while the impact of other attributes was less examined. Given that various attributes of built environments can be manipulated in virtual environments, future research could further study how built environments impact human behavior during emergencies. For example, the impact of attributes that belong to specific built environments (e.g., train platforms and ticket booths in train stations) could be explored.

Lastly, in terms of the ecological validity of VR experiments, it was repeatedly found that VR can be a valid tool to study human emergency behavior (Tucker et al., 2018; Zou et al., 2017). However, it is still difficult to achieve complete ecological validity. There remains technological challenges to promote VR applications in this area, such as limited multisensory (e.g., olfactory, haptic, and thermal) simulation, simulator sickness, and limited interactivity with the virtual environment (Nilsson and Kinateder, 2015). To address these issues, more advanced VR technologies (e.g., feedback gloves, omnidirectional treadmills) could be used in future research, and more appropriate validation studies would be valuable (Nilsson and Kinateder, 2015).

5. CONCLUSIONS

Human behavior is one of the most crucial determinants of human safety during emergencies in built environments. VR technologies, with the rapid developments in recent years, have been increasingly used to study human emergency behavior. Thus, the objective of this paper was to present a systematic review of VR-based studies on human emergency behavior in built environments and provide recommendations for future research. Six aspects of prior studies in this area, including human behavior, target population, emergency types, built environments, VR systems and validation methods, were analyzed to yield a holistic review of the state of the art. Wayfinding and egress route choice are the most widely studied types of human behavior during emergencies, while social behaviors (e.g., helping and group-seeking) among evacuees and how people's background (e.g., nationality, educational levels) influence their behavior have been less investigated. In terms of the types of emergencies, fires have been extensively explored, whereas other types of emergencies that can occur in built environments, such as earthquakes and terrorist attacks, received less focus. In addition, the impact of built environments on human emergency behavior was insufficiently examined in the literature, with only several individual attributes of built environments, such as corridors, signage ad exits having been investigated. Moreover, the interactions between participants and virtual environments including the NPCs included in these studies were limited in prior VR-based experiments. Future research could be done to further study human emergency behavior considering the interactions among humans, built environments and emergencies, and to increase the interactivity of VR-based experiments so as to further improve the validity of VR-based research in this area.

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AUTOMATING PRESCRIPTIVE COMPLIANCE PROCESS FOR BUILDING ENERGY EFFICIENCY THROUGH BIM

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ABSTRACT: *Energy efficiency requirements in building codes serve as the primary measure for ensuring the energy efficiency of the buildings. In the United States, different states adopt various models to better tailor building energy codes to energy efficiency goals. California is among the few states which have adopted the most recent commercial and residential building energy codes (i.e. ASHRAE 90.1-2010). California's Title 24 requires new residential construction to be zero net energy by 2020 and new commercial buildings to reach this goal by 2030. The 2016 California's nonresidential Building Energy Efficiency Standards can be met through two different methods to demonstrate compliance: Prescriptive or Performance. The usual practice to adopt Prescriptive method is to perform manual analysis for the prescribed set of requirements. This can be done by hand or through simple spreadsheets. On the other hand, the Performance compliance method requires energy analysis through an approved computer modeling software that allows for energy trade-offs between different building components. Although the Performance method offers flexibility with the energy analysis and provides more accurate results for the energy consumption in a building. This method, however, requires using additional software on top of the one used by architects and designers to create their working designs and construction documents. The purpose of this project is to investigate the adoption of the simplest method of the two, namely the Prescriptive approach through a widely used building information modeling (BIM) software. In this integrated approach for design, energy analysis, and documentation, the need for using multiple software platforms is eliminated. The goal is to leverage the simplicity of the Prescriptive method together with flexibility of BIM to automate the Title 24 compliance process. Results are presented through a case study to comply with indoor lighting Prescriptive requirements of nonresidential buildings.*

KEYWORDS: *BIM, Building Energy Efficiency, California, Prescriptive method, Autodesk Revit.*

1. INTRODUCTION

The building energy efficiency standards, also known as Title 24 was adopted by California in 1978 to reduce buildings' energy consumption. As a result of these standards, the State's energy consumption per capita was nearly flat for the last four decades, despite the growth of the economy and increased demand for energy (California Energy Commission Fact Sheets, 2016). These standards have reduced the needs for new power plants, energy costs, and greenhouse gas emission and improved building comfort and energy efficiency (California Energy Commission Fact Sheets, 2016). As such, California Building Energy Efficiency Standards require all residential and nonresidential buildings under certain categories to comply with a list of measures and energy efficiency requirements. The local jurisdiction examines the plans and specification for a proposed building and verifies the compliance with the applicable standards before issuing the building permit and certificate of compliance (Nonresidential Compliance Manual, 2016)

California's Title 24 requires new residential construction to be zero net energy by 2020 and new commercial buildings to reach this goal by 2030 (California Energy Commision releases, 2016). There are two basic compliance approaches; "Prescriptive" and "Performance", to achieve the energy efficiency requirements. The Prescriptive approach is the most direct approach of the two and the simplest path to use but offers little design flexibility. It requires each energy component of a building to meet a prescribed minimum efficiency requirements. However, it does not consider the interaction between different building systems that could provide more cost-effective solution for compliance. On the other hand, the Performance approach provides more flexibility than the Prescriptive method and allows energy efficiency trade-offs. In other words, if the builder decides to choose a more energy efficient measure than the minimum in one building system, then he/she can choose a less energy-efficient measure in another system to make up the difference. However, the Performance approach requires an approved software program that creates an energy simulation model for the proposed building, calculates its energy use, and evaluates the 'whole" building energy Performance (Nonresidential Compliance Manual, 2016).

Selecting the appropriate compliance needs careful consideration as there are major differences between the two that call for appropriate adoption. Although the Prescriptive approach is the simplest to use, it needs additional time and resources to manually conduct the required calculations and fill up the compliance forms. Alternatively, the Performance approach provides more design flexibility and uses the aid of a computer software to perform the data analysis and generate the compliance forms. Yet, it also needs additional time and resources to create an energy analytical model through an approved computer software program different from the one used to create the construction documents like AutoCAD or Revit. Adoption record data are not readily available to assist in choosing the right compliance path to follow on a given construction project. In most cases, it depends on the complexity and type of the project in addition to many other factors such as availability of qualified resources and energy budget. The energy commission recommends the use of the best energy efficiency techniques to comply with the energy standards.

This project investigates the improvements that can be achieved on Title 24 compliance process with the involvement of the widely used building information modeling (BIM) software, Autodesk Revit. Although Revit has not been approved yet by California Energy Commission as an authorized computer program to demonstrate the Performance compliance of Title 24. However, it has many powerful features that help improve the Prescriptive compliance process. The adoption of such features will be demonstrated in this project through a case study. Towards this goal, an add-on has been developed in Revit to automate the Prescriptive compliance process for indoor lighting in nonresidential buildings. The research hypothesis is that the tool can reduce the time and money needed to validate the design, the required calculations, and generate the required forms and documentations. The integrative process has been developed and validated through multiple workshops and interviews with industry experts. Results indicate considerable time and cost savings achieved through the use of the developed framework. Depending on the size and complexity of the building, the conventional method usually takes a few days to ensure compliance compared to a few hours that it takes using the developed automatic system. This, on average, translates into 60 to 80 percent cost saving mainly through reduced man-hour.

2. BACKGROUND

Prior studies have investigated the methods to enhance the compliance process of building energy codes through BIM software and energy analysis platforms. Also, a few studies focused on how to enhance both compliance methods to achieve a high-energy efficiency design.

Tripp (2016) discussed the lack in the industry for having a single platform that can perform the required energy analysis, and generate the entire set of construction documents. The focus of Tripp's (2016) study was on the Performance compliance method and how it can be conducted through the three certified software programs, namely CBECC-Res, Energypro, and Right-Energy Title 24. It also investigated the possibility of using BIM platform as a means to conduct the Performance approach and complete Title 24 documentation. The study concluded that BIM software has the capability but it has to be adjusted to fit title 24 compliance requirements and generate the certificates of compliance. Moreover, it has to be authorized by the state of California to be used under the Performance approach method of compliance (Tripp, 2016).

According to Arent et al. (2016) the complexity of California's Building energy efficiency code has increased dramatically in the last two decades. They discussed the need to improve both the energy code and compliance tools to achieve high-performance design. The study addressed that despite the increasing trend toward the Performance compliance approach, Prescriptive standards still have a practical role in the industry and still provide some flexibility (Arent, Contoyannis, & Hedrick, 2016).

In another research study, the Performance-based approach in building design control and energy efficiency in China and Hong Kong was investigated (HUI, 2002). By evaluating the current situation and future development of building energy codes, the researchers indicated that the performance-based codes require detailed building energy analysis. Therefore, higher levels of technology integration than current manual methods will be required to demonstrate the code compliance. It was also concluded that more integrated and holistic methodologies are required to ensure energy efficiency and to realize true benefits of sustainable building design in long-term (HUI, 2002).

An ad-hoc assembly of energy code and policy experts from the four Pacific Northwest states and California organized by the New Buildings Institute (NBI) and the Northwest Energy Efficiency Alliance (NEEA) was convened in 2009. The meeting was focused on the changes that needed to be made in code structure and language, implementation, and enforcement strategies towards the 2030 zero-net-energy buildings challenge (Cohan , Hewitt, & Frankel, 2010). Among the guiding principles for code development outlined by this assembly is that "The code enforcement process must be modified to extend beyond initial building completion so that actual building performance comes under regulatory purview". The use of BIM for compliance process enforcement assists in covering the "that actual building performance" during beyond design and construction.

U.S. Department of Energy Roadmap for the Future of Commercial Energy Codes outlines a vision to serve as a roadmap for future building energy code development. Although this study concentrated on the commercial sector, the outcomes based on building-specific prescriptive packages is of tremendous value to other sectors. The review of different code formats indicates that highly automated approaches with the potential to be applied to most buildings are needed to provide convenience in compliance enforcement and high accuracy (Rosenberg, Hart, Zhang, & Athalye, 2015).

3. COMPLIANCE PROCESS

At the early stage of a construction project, effective communication and coordination between the project owner, designers, and builders are recommended to identify the energy saving strategies (Nonresidential Compliance Manual, 2016). Ultimately, it is the responsibility of all involved parties to understand and comply with the requirements of building energy standards during the lifecycle of the facility. Recently, a growing number of design and construction firms are adopting the use of BIM as a powerful tool that helps efficiently to plan, design, construct, and manage a construction project. A research by McGraw Hill Construction shows that 77% of contractors in the U.S. have implemented BIM in institutional projects (such as universities) while 66% of them used this technology for commercial projects. (SmartMarket Report, 2014). BIM is an intelligent 3D model-based process that includes a collection of computable database of building components (BIM, 2017). BIM software offers integrated tools that enable architects and engineers to conduct energy analysis on the building design and help them optimize the building's energy consumption.

For example, with the energy analysis feature provided by Autodesk Revit software, a user can perform a building energy simulation that measures expected energy use based on the building's geometry, climate, building type, envelope, and active systems. This feature also generates an energy analysis report that includes charts and tables describe the energy performance of a building. Autodesk Revit provides powerful features to create a complete model with all project information and geometries, perform an energy analysis, and generate construction documents. However, it does not include all the tools and logics required to become an authorized program to be used under the Performance method of compliance for the 2016 California Building Energy Standards. As such, the remainder of this project will investigate a methodological procedure to employ Revit to comply with Title 24, part 6 requirements through the Prescriptive approach. Due to its high level of implementation (Quirk, 2012), the study chose Revit to utilize its features to achieve the desired approach. With this in mind, an Add-on was developed to demonstrate an automated procedure for the compliance process for indoor lighting in nonresidential buildings. The presented study lays the foundation for further studies that can be built upon this one to cover the rest of building systems' requirements.

The primary goal of the energy standards for indoor lighting is to limit the allowed lighting power installed in a building and design an effective lighting system which combines the right type of light fixture and the appropriate lighting controls for the desired function (Nonresidential Compliance Manual, 2016). The compliance process begins with the completion of certificates of compliance, which shows the information of the proposed project complying with the energy standards. The certificates must be submitted for review and approval by the code enforcement agency. An indoor lighting system for nonresidential buildings has six compliance certificates. Some of them are mandatory for every project, while others are required only if the system design includes specific component or strategies (Nonresidential Lighting and Electrical Power Distribution Guide, 2017). Figure 1 shows the process for complying with indoor lighting requirements in nonresidential buildings. The Mandatory Measures are required regardless of the compliance method selected.

In addition to the Performance approach, the energy standards allow for three different lighting compliance methods under the Prescriptive approach: Complete Building method, Area Category method, and Tailored method. All the three methods involve multiplying the area of a space by the allowed lighting power density (LPD) for that area adding the display and decorative lighting. This process will result in the allowed lighting power for a building. On a parallel process, the designer needs to calculate the actual lighting power installed in the proposed building considering the credits that can be received from the lighting control. In summary, the lighting design complies with the energy standards if the installed lighting power is less than or equal to the allowed lighting power.

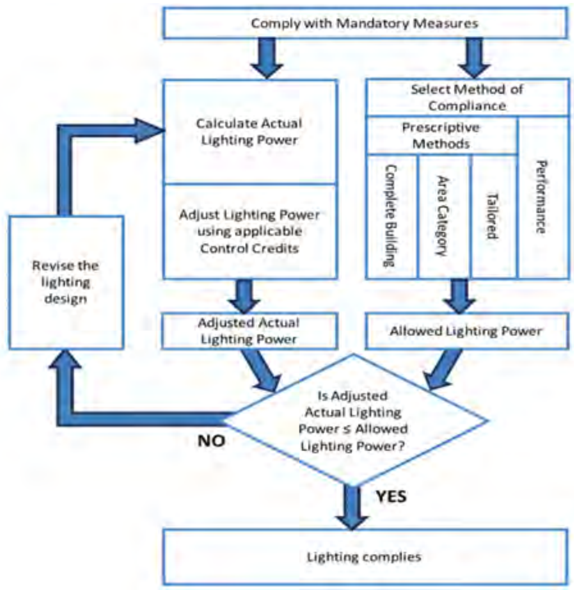

Fig. 1: Lighting Compliance Flowchart (Nonresidential Compliance Manual, 2016)

The process depicted in Figure 1 can be described as follows:

1. Comply with all the mandatory measures which mainly require the lighting controls and equipment to comply with the applicable requirements and installed by the manufacturer's instructions. In addition, they must include provisions for the use of area controls, multilevel lighting, automatic shut-off controls, automatic daylighting controls, and demand response control systems.
2. Choose the appropriate Prescriptive approach method based on the building type and use to calculate the allowed indoor lighting for each room or area of the building in question. Calculation of the allowed lighting power density for the spaces must be completed by the tables prescribed by the energy standards. Appendix A, shows the values for Lighting Power Density (LPD) used for the complete building method, Area Category method, and Tailored Method in accordance with 2016 Title 24 Energy standards.
3. Calculate the installed lighting power of all building areas considering all permanent and portable lighting systems in all areas.
4. Calculate the total Power Adjustment Factors (PAFs). The PAF is an option provided by the Energy Standards for lighting power reduction credits when specific lighting controls are installed. It reflects control strategies that exceed the requirements of the Energy Standards.
5. Verify whether the total installed lighting power is less than or equal to the allowed lighting power to meet the compliance.

Indoor lighting system complies only if:

$LP_I \leq LP_A$

where LP_A is the allowed lighting power and LP_I is the adjusted installed lighting power including installed permanent lighting plus the installed portable lighting and excluding the lighting control credits.

The described procedure assumes that the initial lighting design with all fixtures and controls are included in the Revit model for a proposed building. The initial design could be prepared through Revit itself or with the help of external lighting design software such as DIAlux or ReLux. After evaluating the spaces' characteristics such as size and function and identifying the suitable light fixtures and controls for a given space type, the engineer reviews the energy standards requirements that could impact the placement of light fixtures and controls.

4. CASE STUDY

In this section, first, the conventional method to comply with the standards by the use of the Prescriptive approach is presented using an example. Then the features of the developed add-on are described to demonstrate the feasibility and advantages of the conventional manual method.

4.1 Conventional Method

The following example demonstrates the conventional method of the Prescriptive method used to determine whether the indoor lighting system will comply with the energy standards using the Area Category Method based on Figure 2. The Figure shows a 1910 ft^2 office plan area which includes ambient and task lighting fixtures that have been selected and distributed by the design team to meet the desired function and effect.

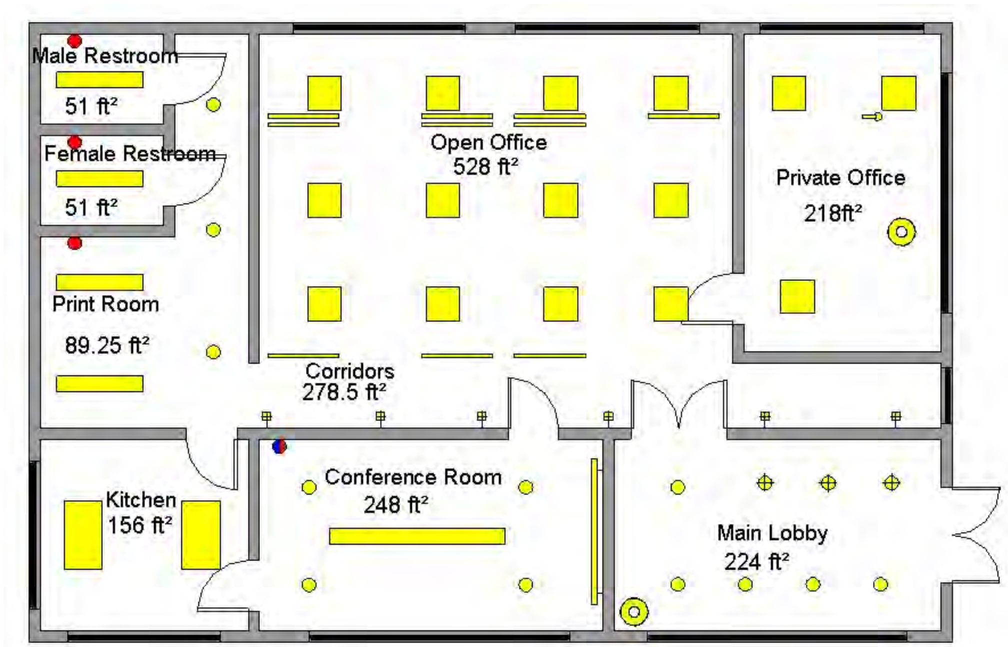

Fig. 2: Case Study Office Lighting Plan

Using the conventional, the following steps must be followed:

4.1.1 Calculation of the LP_A:

The office building plan shows six primary function areas. The allowed lighting power density (ALPD) for each area is determined according to table 140.6-C Area Category Building Method Lighting Power Density Values of the Title 24 (Nonresidential Compliance Manual, 2016).

$LP_A = ALPD\ (W/ft^2) \times Area\ (ft^2)$

For Office Area > 250 ft²: $LP_A = 0.75\ W/ft^2 \times 528\ ft^2 = 396\ W$

For Office Area ≤ 250 ft²: $LP_A = 1\ W/ft^2 \times 218\ ft^2 = 218\ W$

For Classroom, Lecture, Training, Vocational Area: $LP_A = 1.2\ W/ft^2 \times 248\ ft^2 = 297.6\ W$

For Lobby: $LP_A = 0.95\ W/ft^2 \times 224\ ft^2 = 212.8\ W$

For Kitchen, Food Prep Area: $LP_A = 1.2\ W/ft^2 \times 156\ ft^2 = 187.2\ W$

For Corridor, Restroom, Stair and Support Area: $LP_A = 0.6\ W/ft^2 \times 470.02\ ft^2 = 282\ W$

Total $LP_A = 396\ W + 218\ W + 297.6\ W + 212.8\ W + 187.2\ W + 282\ W = 1593.6\ W$

The plan shows suspended luminaire in the lobby and whiteboard lighting in the conference room which are eligible for additional lighting power allowance according to the footnotes of Table 140.6-C. The additional lighting power is determined as 67.7 W using the table and similar simple calculations as before. Therefore, the total LP_A including the power allowance is:

LP_A = 1593.6 W + 67.7 W=1661.3 W

4.1.2 Calculation of the total Installed Lighting Power:

Permanent and portable lighting power is calculated based on the actual wattage specified in the lighting schedule and shown in Tables 1 and 2.

Table 1: Total permanent installed lighting power.

Symbol	Luminaire	Qty.	System Wattage	Total Watts	Efficacy
	2X2 LED RECESSED TROFFER	15	35	525	90-100
	1 x 4 1-LAMP FLUORESCENT RECESSED TROFFER	4	28	112	89
	2 x 4 2-LAMP FLUORESCENT RECESSED TROFFER	2	54	108	89
	8' LED SUSPENDED LUMINAIRE	1	85	85	84
	8' LED LINEAR WALL MOUNT LUMINAIRE	1	45.2	45	57.3
	6" LED RECESSED DOWNLIGHT	12	12	144	90
	LED WALL SCONCE	6	8	48	50
	LED PENDANT	3	10	30	76
	LED SUSPENDED LUMINAIRE	2	22.5	45	100

Based on Table 1, the total permanent lighting watts is equal to 1142.2 W. Also, Table 2 shows the total portable installed lighting power.

Table 2: Total portable installed lighting power.

Portable Lighting					
	45" LED UNDERCABINET TASK LIGHTING	10	12.2	122	62.2
	LED TASK LIGHT	1	6.5	6.5	-

According to Table 2, the total portable installed lighting power is 128.5 W. Therefore:

LP_I = 1142.2 W + 128.5 W = 1270.7 W

4.1.3 Determining the Lighting Control Credits:

Only Lighting Adjustment Factors listed in Title 24 Table 140.6-A (Nonresidential Compliance Manual, 2016) are qualified for a control credit. According to Table 140.6-A, this lighting design is not eligible for any credits.

Lighting Control Credits = 0 W

4.1.4 Calculating Adjusted Actual Lighting Power:

Adjusted LP_I = 1270.7 W - 0 W = 1270.7 W

4.1.5 Determine Compliance:

In this step the LP_I is compared to the LP_A to determine if the indoor lighting system is compliant. Based on the calculated results:

$LP_I = 1270.7$ W < $LP_A = 1661.3$ W

which means that the system is compliant.

Once all the aforementioned steps are takes, there is still an effort needed to manually fill out all required compliance documents that will be submitted for review and approval by the code enforcement agency.

4.2 Automated Compliance Process Tool

Autodesk Revit has the features to create schedules, quantities, and material takeoffs to quantify and analyze the components and materials used in a project. It also helps to place spaces in all areas of the building model to store information used for performing the required analysis on the building model. Also, Revit provides an application programming Interface (API) that allows to extend the functionality of the software, so customized commands can be added to the Add-on tab (Autodesk Knowledge Network, 2017).

The developed add-on tool uses a database to store (1) California climate zones with the list of all zip codes associated with each zone, (2) luminaire library for the proposed project which includes a list of lighting fixtures with lamp, ballast types and total wattage for each fixture, (3) list of lighting power density values for all types of areas (the value is determined based on the building type, each primary function area, and the Prescriptive compliance approach used), (4) list of lighting controls and associated power adjustment factors (PAFs). To demonstrate the implementation of the tool, the Add-on was loaded to Revit and applied to the same office building model example explained in the Conventional Method subsection. Figure 3 shows the commands used in the Add-on tab.

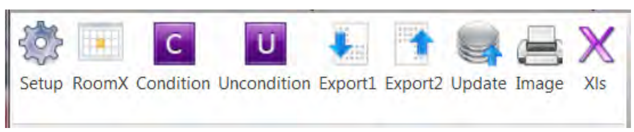

Fig. 3: Developed Title 24 Add-on Tab

The options available in this tab are listed and described here:

Setup: Opens a dialog with multiple tabs, specify the following:

- Project Information includes: Project Name, Number, Address, Status, Climate Zone, and information about Client, designer, and Title 24 Documentation Author.
- List of Lighting Compliance Documents that will be included.
- Declaration of required Installation Certificates will be submitted.
- Declaration of required Acceptance Certificates will be submitted.
- List of Mandatory Lighting Control Declaration Statements that apply.

RoomX: Identifies any unoccupied/untagged spaces in the floor plan.
Condition: Identifies the Conditioned spaces in the floor plan.
Uncondition: Identify the Unconditioned spaces in the floor plan.
Export1: Calculates the Allowed Wattage for each room based on the room type, area, Allowed Lighting Power Density (ALPD) as specified in the standards. Exports the results to Microsoft Excel Sheet.
Export2: Calculates the Actual Wattage per Room based on number of Luminaires, Wattage per Luminaire type. Also calculates the Power difference between Allowed Wattage and Actual Wattage per room and color code on the floor plan areas don't comply. Exports the results to Microsoft Excel Sheet.
Update: updates Revit file with any corrections might apply on the Excel Sheets.
Image: Prints a color-coded floor plan and indicates rooms that don't comply with the Energy standards.
XLS: Exports all selected Lighting Compliance Documents to Microsoft Excel Sheet in the same Template Format of the Energy Commission Forms.

The compliance process through the add-on tool can be implemented through the following steps:

4.2.1 Setup the File:

By clicking on "Setup" command, the tool will extract the project information from Revit and allow the user to determine the Lighting Compliance, Installation, and Acceptance Certificates will be submitted. Also, it allows to indicate all mandatory measures that apply as shown in Figure 4.

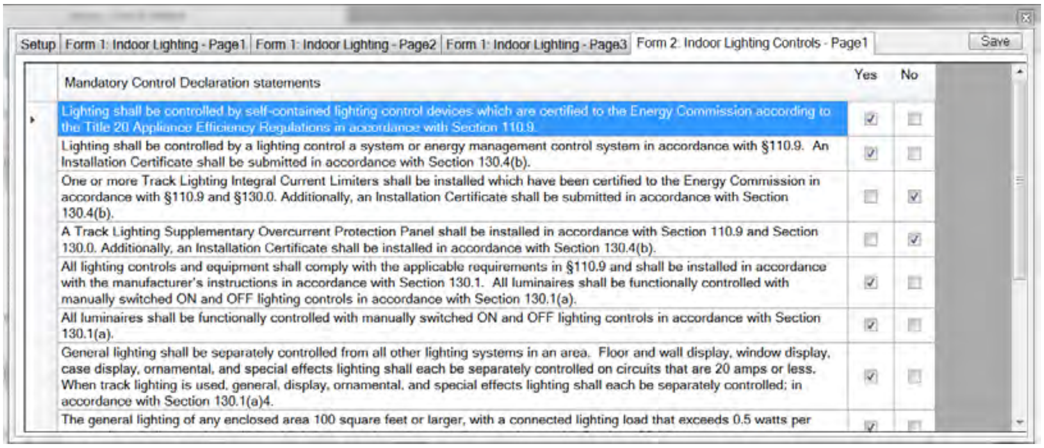

Fig. 4: Setup Dialog - Title 24 Add-on

4.2.2 Identifying Unoccupied/Untagged Spaces

Identify any unoccupied/untagged spaces in the floor plan by clicking on "RoomX" command so the user will be able in a further step to specify the primary function of the untagged space. This action is necessary for the tool to recognize all functional areas in the floor plan and determine the allowed lighting power for each area in a further step.

4.2.3 Identify Conditioned and Unconditioned Spaces

Identify all conditioned and unconditioned spaces in the floor plan by clicking on the "Condition" and "Uncondition" commands. This step is necessary in order for the tool in a further step to fill out a separate page of the compliance form for conditioned and unconditioned spaces as required by the Energy Commission.

4.2.4 Calculating the LP_A

By clicking on "Export1" command, the tool will automatically calculate the Allowed Lighting Power Density (ALPD) value for the primary function areas or for the whole building based on the method selected for lighting compliance. Also, it will export the results to Microsoft excel Sheet as shown in Figure 5.

A	B	C	D	F	G	H
S No	Location	Room Name	Room Number	Area (SQ. Ft)	ALPD	Allowed Wattage
1	Level 1	Private Office	1	218.00	1	218.00
2	Level 1	Open Office	2	528.00	0.75	369.00
3	Level 1	Main Lobby	3	224.00	0.95	212.80
4	Level 1	Conference Room	4	248.00	1.2	297.60
5	Level 1	Kitchen	5	156.00	1.2	187.20
6	Level 1	Print Room	6	89.25	0.6	53.55
7	Level 1	Female Restroom	7	51.00	0.6	30.60
8	Level 1	Male Restroom	8	51.00	0.6	30.60
9	Level 1	Corridors	9	278.50	0.6	167.10

Fig. 5: Results generated by clicking on "Export1" button in the Add-on

In this step, the user will be able to correct any untagged area and add any additional lighting power allowance for special type of fixtures in the Excel file and update the file by clicking on the "Update" Command.

4.2.5 Calculating the LP_I and Determining Compliance

By clicking on "Export2" Command, the tool will automatically calculate the total installed watts for all luminaires (permanent and portable), determine the applicable lighting control credits, and calculate the Adjusted Actual Lighting Power. These calculations are performed based on the information extracted from the lighting schedule in Revit and evaluating the values listed in the compliance tables which were inserted in the tool database. This step will determine the compliance by comparing the LP_I with the LP_A.

4.2.6 Generate the Lighting Compliance Documents

By clicking on "XLS" command, the tool will generate the required compliance documents filled out with all provided information and calculated results. The compliance documents will be generated through Microsoft Excel sheet which allow the user to add any missing information before printing the documents in a PDF format.

5. DISCUSSION AND CONCLUSIONS

With the strive to make the implementation of the Energy standards as practical as possible, there is always a need for more effective ways to improve the compliance process. BIM is a powerful platform that can help to achieve this goal. In this project, an Add-on tool was developed in Autodesk Revit to optimize the workflow for the Prescriptive approach of Title 24-part 6. This tool provides many advantages to the conventional procedure through the (1) optimizing the workflow through automatic information process so the user does not need to manually reference data provided in the Energy Standards manual; (2) Automatically conducting the required calculations which eliminates errors and mistakes could happen with the manual method; (3) Addressing code compliance issues and identify any missing information which minimize any manual intervention; (4) Automatically generating the required compliance certificates which save time and effort to fill them out manually; (5) Cost and time saving on the overall process to produce the compliance documentation.

That latter is more noticeable on bigger size projects. For example, producing the indoor lighting compliance documentation for a 150,000 ft^2 nonresidential building through the conventional prescriptive method requires 3 to 5 days on an average cost of $2200. This Estimate is based on the data provided by different local service providers (Title 24 Report estimator, 2017). However, using the developed automatic system takes only a few hours to ensure compliance on the same of building which translates up to 80 percent cost saving mainly through the reduced man-hour.

The results indicate significant improvements on the conventional Prescriptive compliance process for indoor lighting system in nonresidential building. This is considered an initial step for further development should be applied on the tool in order to cover the remaining building measures as required by Title 24 standards.

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ENHANCING BLIND LIFT SAFETY ON OFFSHORE PLATFORMS THROUGH REAL-TIME SENSING AND VISUALIZATION

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ABSTRACT: *Crane lift operations are human-centric tasks where lift safety heavily relies on the operator's awareness of potential spatial constraints and associated safety risks. Blind lifts on congested offshore platform (OP) environments, therefore, are inherently dangerous because of substantial presence of spatial conflicts in the crane workspace and the operator's limited visibility to the load. This research aims to improve operators' spatial awareness in blind lifts in the OP environment through real-time crane states sensing and visualization. We propose a technical framework that consists of two sensing modules (i.e., crane motion monitoring and load sway monitoring) and a visualization module. An inertial measurement unit (IMU)-based approach and a computer vision (CV) based approach are introduced to track load position for load sway monitoring. A prototype system was built and tested in an offshore platform to validate the crane motion monitoring and visualization modules. A lab experiment was conducted to evaluate the CV-based load sway monitoring method. Results from the field and lab tests indicate the proposed framework and methods were able to continuously monitor and visualize the crane states in real-time and thus provide the operator adequate assistance to identify and mitigate unsafe conditions during blind lifts.*

KEYWORDS: *Offshore platform, Crane operation, Blind lift, Real-time, Sensing, Visualization*

1.. Introduction

An offshore platform (OP) is a large structure comprising facilities for well drilling to extract, store and process petroleum and natural gas, as well as the facilities to house the onboard crew (Fig. 1). In the daily operation of an OP, cranes are heavily used in a series of essential activities such as the installation of new assets and equipment, maintenance of existing facilities, and transportation of equipment and supply containers from vessels. Therefore, it is imperative to ensure the safe and efficient operation of offshore cranes. However, the offshore environment is inherently a high-risk place for a crane to operate. The scarcity of space on an OP yields a very congested layout design, leaving extremely limited workspace for the crane to maneuver. More importantly, the congested platform layout severely hampers the visibility of the crane operator and the lift crew. In cases where the crane operator does not have direct visual contact with all or part of the object being lifted, a blind lift is inevitable. Blind lifts pose significant issues for crane operators as they limit the operator's field-of-view that potentially slows down execution of lifting tasks, and most importantly induces potential risks of colliding load with surrounding objects. The current practice to reduce the risks associated with blind lifts is to position a designated signal person in a location where he or she can directly see the load. The signal person is responsible to monitor the lifting process, instruct crane maneuver, and warn the operator of potential hazards, in particular proximity to surrounding objects. Furthermore, the signal person and the crane operator need to maintain an effective and efficient communication. Nevertheless, this practice is highly human-centric and subject to the signal person's competency to recognize hazards correctly and timely. In addition, such practice also suffers from the inefficient radio and hand signal communication between the signal person and the operator.

Fig. 1: Crane lift operations in offshore platform environment; Left image: two pedestal-mounted lattice boom cranes on an offshore platform (Chevron 2018); Right image: cab view from one of the cranes (image by Yihai Fang).

This study aims to improve blind lift safety in the OP environment by leveraging sensing and visualization technologies for real-time lift assistance. This paper first summarizes the safety risks in crane lift operations in the offshore platform environment and reviews the state-of-the-art sensing methods for real-time equipment monitoring. Then, a technical framework that addresses the challenges in real-time sensing and visualization is presented and two methods for monitoring load sway are explained in detail. Two tests in the field and the lab follow to demonstrate the proposed methods in real-world and controlled settings. This paper is concluded by a summary of the contributions and discussions about future research in the final section.

2. Related work in equipment motion monitoring

Within the large workspace of cranes, the presence of built structure, storage of materials, and power lines introduces massive potential spatial conflicts in crane lift operations. Suruda et al. (1997) reported that 40% of the deaths in crane-related accidents were related to spatial conflicts. Comparing to building construction site environments, due to the limited space and crowded layout, the offshore platform environment presents more significant safety challenges to crane lift operations. Therefore, the first and most important task for a crane operator is to understand the states of the crane and the payload. Traditional crane computer systems such as load moment indicators (LMI) mainly monitor crane's lift capacity in optimal conditions. Capturing crane motions in real-time is essential for analyzing the crane capability and stability as well as its interaction with the surrounding environment. Basic requirements for technologies used to capture crane motions comprise high accuracy, low latency, durability, scalable system setup, and non-intrusive to the crane and other tasks related to the lift operation. A number of technologies that have been investigated for the crane motion sensing purpose are summarized as follows.

Real-time location systems (RTLS) are technologies that track the location of tagged objects in real-time. To estimate mobile crane poses, Zhang et al. (2012) employed a high-precision RTLS technology named Ultra-wide band (UWB) with UWB antennas deployed around the lift site and UWB tags mounted on different spots of crane boom and payload. Using a similar technology, Hwang (2012) studied the characteristics of different collision types and developed a computer program for monitoring crane motions and sending warnings if a potential collision hazard was detected. Li et al. (2013) took advantage of Global Positioning System (GPS) and Radio Frequency Identification (RFID) for a real-time crane motion monitoring system. Tracking crane parts and construction workers, this system aims to assist the safety operation in blind lifts by detecting the presence of unauthorized workers within a risk zone. Although these efforts demonstrated the feasibility of using RTLS to monitor crane and load states, the RTLS technology suffers from several limitations including sophisticated sensor system setup, signal interference in harsh construction environments, and high cost for RTLS with higher accuracy (e.g., UWB).

Computer vision techniques extract high-dimensional data from digital images or videos. Recently, the construction research community began to embrace the benefits of computer vision techniques in equipment operation applications. Feng et al. (2015) introduced a marker-based computer vision approach that uses a set of cameras and markers to identify the pose of articulated equipment. With at least two cameras and multiple planer markers on each of the articulated part and on a pre-survey fixed location near the equipment, this method was able to yield centimeter-level tracking accuracy with a flexible and cost-effective system. Although this method performed well in tracking the pose of an excavator in a small workspace, limitations such as sensitivity to occlusions and increased complexity in system setup can be expected when applying this method to track crane states on a much larger scale and more dynamic workspace. Yang et al. (2013) proposed an algorithm to track the jib pose of a tower crane by processing and analyzing the images captured by a single site surveillance camera. With the known locations of the surveillance camera and the configuration of the tower crane, a set of synthetic images were generated using a virtual 3D model of the crane. The crane poses in actual images can be identified by comparing them to the synthetic images. This method requires pre-surveying the location of the camera and crane, which is possible for tower crane settings but is challenging for mobile crane setting as the system needs to re-setup every time the mobile crane relocates. The increasing availability of UAVs (Unmanned Aerial Vehicles) with high-definition cameras offers a new way to monitor crane states. Roberts et al. (2017) used a convolutional neural networks (CNNs) algorithm to automatically detect cranes and their parts from UAV-captured site images. Using this method, crane poses can be estimated accurately in real time, which makes it possible for end-to-end machine vision applications such as payload tracking or 3D crane pose estimation. Despite promising progress in equipment pose sensing, computer-vision based methods suffer from several limitations including prevailing visual noise and occlusion, limited coverage, poor performance at low lighting and visibility conditions, and rather low reliability (Azar and Kamat 2017).

Laser scanning is a non-intrusive sensing technology that rapidly and accurately captures the 3D shape of physical objects in the format of a point cloud. To help equipment operators rapidly perceive the crane pose and surrounding environment, Cho and Gai (2014) introduced a dynamic object recognition and registration method using laser scanning technology. The 3D point cloud is projected to a 2D space where the geometric features represented by a local SURF descriptor are compared to a prepared template database for recognition. This method is effective and efficient for recognizing target objects that are known to be present on the construction site. Wang and Cho (2015) proposed a smart scanning technique for tracking the location and pose of mobile cranes. By updating the crane's point cloud data while keeping the previously scanned static workspace data, this method greatly improves the modeling and updating rate, which makes it suitable for real-time visualization and decision-making support. Another benefit of laser scanning-based approaches is that it is non-invasive, meaning that there is no need to deploy any sensors or devices on the equipment. Instead, it requires a data acquisition system to operate in proximity to the equipment, and sophisticated infrastructure setup for real-time data processing and transmission.

Rotary encoders are electromechanical devices that are used in various electronic and mechanical devices for measuring angular position or motion of a shaft or axle in the device. From a kinematics perspective, a crane can be understood as an entity comprised of multiple rigid bodies connected by different types of joints, depending on the crane type and configuration. For example, a typical pedestal-mounted lattice boom crane can be decomposed into two independent modules: the manipulation module and the suspension module. The manipulation module is comprised of two rigid bodies: crane cab and boom. The suspension module consists of a normal rigid body, the lifted load, and an extensible rigid body for the hoist line. The connections between the rigid bodies can be modeled by two types of joints: prismatic joint and spherical joint. This simplification makes it possible to represent any possible crane pose by measuring the critical angle of a particular joint that connects every two rigid bodies. Lee et al. (2009) proposed a crane motion monitoring system using multiple encoders and laser sensors, which successfully captured and visualized the motion of a tower crane in real-time. However, this system configuration of a laser sensor and reflection board cannot reliably measure the load elevation during excessive load sway.

Compared to the RTLS, computer vision, and laser scanning technologies, direct measurement using rotary encoders or inclinometers hold several advantages. Firstly, hardware employed in the systems is usually more cost-effective and durable in long-term use. Once securely installed on the crane, these sensors require little maintenance and with proper enclosure they can work properly in harsh environmental conditions. Secondly, direct measurement methods do not require external hardware deployment on the site, and thus it introduces minimal interruption to other construction activities. Nevertheless, computer vision techniques have shown great potential as a supplement mean for monitoring crane states.

3. Methods

3.1 Framework for real-time crane motion and load monitoring

As shown in Fig. 2, the proposed real-time sensing and visualization framework consists of three main parts: 1) crane motion monitoring, 2) load sway monitoring, and 3) visualization and user interface. Crane motion monitoring aims to reconstruct the crane motion by measuring multiple critical kinematics values of crane parts (i.e., slew angle, boom angle, hoist length). Accurate measurement and low latency are essential for this task. Therefore, this framework proposes to use rotary encoders and digital inclinometers that connect to the processing unit via a wired connection to minimize delay. In the second part of this framework, two methods using inertial measurement unit (IMU) and computer vision (CV) respectively are explored for the purpose of monitoring the load sway. Load sway monitoring stands along as a separate part in the framework because the sensors (IMU or camera) have to be deployed wirelessly due to the long distance between the load and the processing unit locating in the crane cab. Details of these two methods will be presented in the following sections. The third part of the framework addresses the visualization and interaction with the user, namely the crane operator. Sensing data from the first two parts are fused to reconstruct the crane motion and load sway in a game engine for analysis and visualization. A graphical user interface (GUI) provides interactive visualization of the crane states and safety warning messages to the operator in real-time.

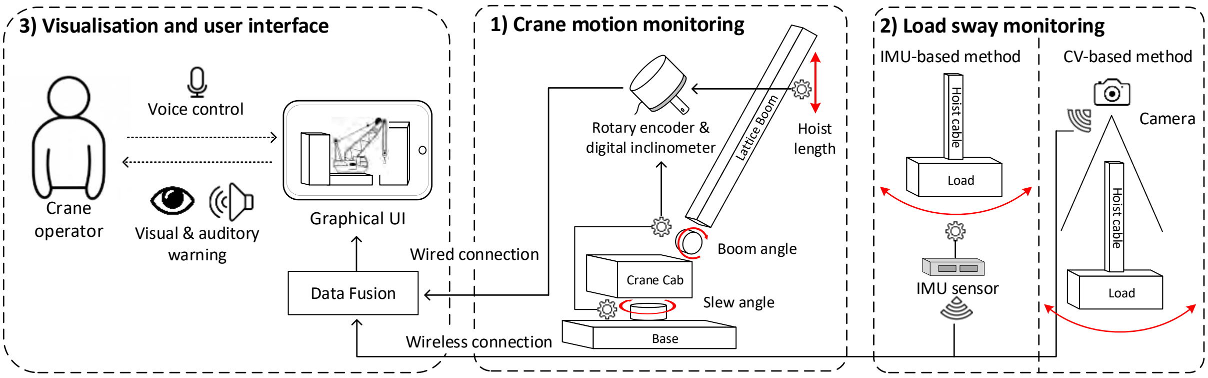

Fig. 2: A technical framework for real-time sensing and visualization in OP crane operations

3.2 Load sway monitoring

Load sway is a common phenomenon in lift operations usually due to excessive crane maneuver or strong wind. Timely recognition and control of load sway are critical to maintaining the crane and load stability. Sway should be mitigated under all circumstances to avoid undesired lateral loading. Two sensing approaches were investigated for monitoring the sway of the lifted payload by tracking its position in real-time: 1) inertial measurement unit (IMU)-based and 2) computer vision (CV)-based approach.

3.2.1 Inertial Measurement Unit (IMU)-based load position tracking

Inertial Measurement Unit (IMU) is an electronic device that measures velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes, sometimes also magnetometers. In the particular case of load sway, it is assumed that the cable length is known and the cable is rigid. Therefore, the load sway motions can be simplified to a typical 3-dimensional (3D) pendulum motion. Given the measured angular orientation on each axis and the cable length, the estimated position of the load relative to the fixed point can be calculated by converting the Euler angle measurements to Cartesian coordinates in the local coordinate system (Fang and Cho 2015). To be specific, the IMU sensor can be mounted on the crane hook to measure the load 3D orientation. The orientation is then converted to a 3D position relative to the boom tip by a multiplying a transformation matrix with the unit vector (0, 0, 1) and the length of the hoist line L using Eq1. Using this approach, the load sway can be captured and visualized in real-time. Fig. 3 shows the monitoring and visualization results of both a 2D and 3D sway motions of a load in lab tests.

$$P\ \ (x,y,z) = R\ \ (\alpha,\beta,\gamma)\cdot\begin{bmatrix}0\\0\\1\end{bmatrix}\cdot L = \begin{bmatrix}cos\alpha\cdot sin\beta\cdot cos\gamma + sin\alpha\cdot sin\gamma\\ sin\alpha\cdot sin\beta\cdot cos\gamma - cos\alpha\cdot sin\gamma\\ cos\beta\cdot cos\gamma\end{bmatrix}\cdot L \quad \text{(Eq1)}$$

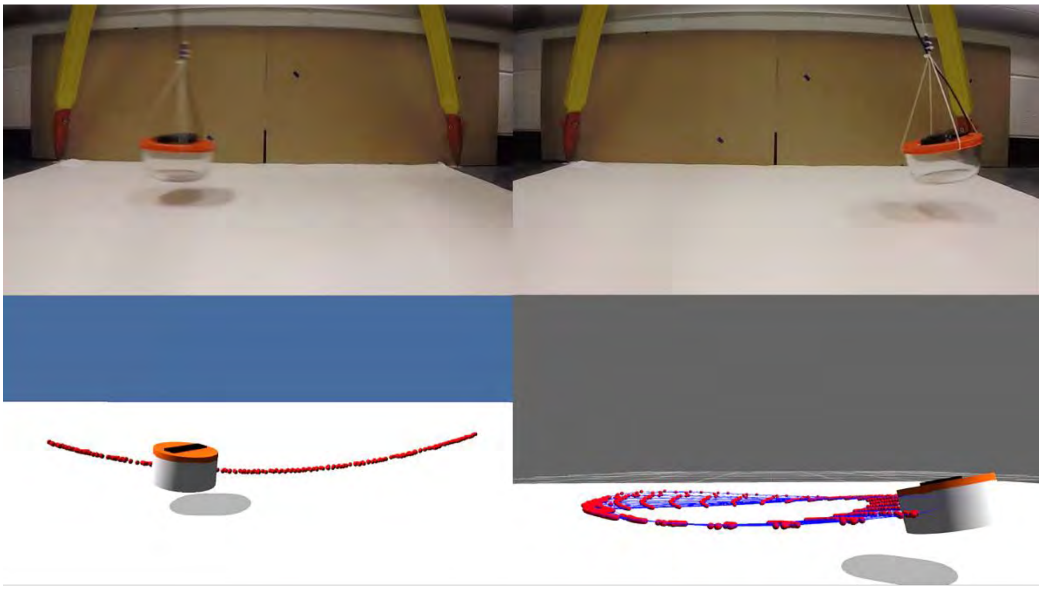

Fig. 3: Real-time load sway monitoring and visualization using a wireless Inertial Measurement Unit

3.2.2 Computer Vision-based load position tracking

To overcome the problem of load tracking error due to IMU interference, this study also proposes a vision-based method to track the displacement of the crane load from the center position. A weatherproof, wide-angle camera is mounted on top of the crane boom and provides a live video feed of the load swing from an overhead view. A prominent visual marker, such as a brightly colored tag, is attached to the top of the hook to aid the vision tracking process. The algorithm uses a kernel-based method (Chen et al. 2017), which identifies the area occupied by the colored visual marker through each frame of the video. The RGB color images are first converted to LAB color space and reduced to a set of K standard color clusters using K-means clustering. The color cluster corresponding to the color of the visual marker is then identified at the start of the video sequence. Next, a flood-fill algorithm is applied to label pixels that match the color of the visual marker. The convex hull algorithm is used to form a bounding box around the labeled pixels and the 2D load position is determined by the centroid of the bounding box.

The following equations (Eq2 to 5) are used to calculate the 3D position (x,y,z) of the load center in world coordinates given the detected 2D position (u,v) in the image frame. L indicates the cable length, f indicates the camera focal length, while (u',v') indicates the center position of the load in the image frame, obtained by averaging the 2D load positions over time.

$$x^2 + y^2 + z^2 = L^2 \text{ (Eq2)}; \quad x = \frac{u-u'}{f} z \text{ (Eq3)}; \quad y = \frac{v-v'}{f} z \text{ (Eq4)}$$

$$z = \sqrt{\frac{L^2}{\left(\frac{u-u'}{f}\right)^2 + \left(\frac{v-v'}{f}\right)^2 + 1}} \text{ (Eq5)}$$

4. Field and lab tests and results

4.1 Field tests of crane motion monitoring and visualization modules

Based on the proposed framework, a prototype system for real-time lift assistance was developed for a lattice boom pedestal-mounted crane on an offshore platform. In total four sensors were deployed capture the crane motion and load sway. Two rotary encoder sensors were used to measure the slew angle and the hoist line length respectively. A digital inclinometer sensor was employed to monitor the boom lift angle. Finally, an IMU sensor was attached to the hook block to monitor the load sway using the method introduced in Section 3.2.1. Fig. 4 illustrates the sensor deployment on the test crane.

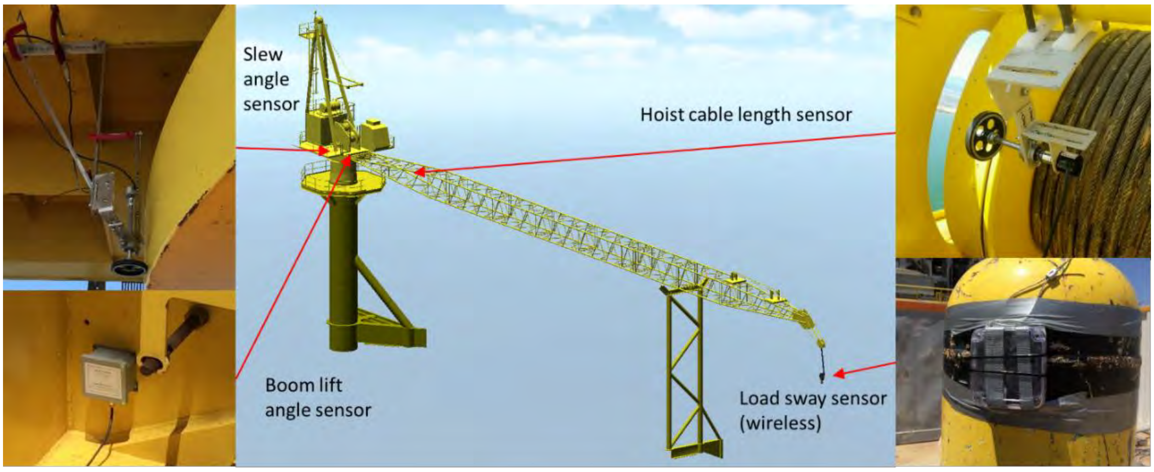

Fig. 4: Sensor deployment on a lattice boom pedestal-mounted crane

Four lift tasks A to D were designed to test the accuracy of the crane motion monitoring and reconstruction in a game engine (Fig. 5). The drop locations of all these four lift tasks were in the operator's blind spot. The drop locations of lift task A and C were in a very congested space whereas task B and D were in a comparatively more open space. The monitoring error in each lift task was quantified by the location difference between the actual load in reality and the virtual load in the game engine. In each task, once the actual load was placed exactly at a target position marked on the floor, the error was recorded in the program by measuring the location of the virtual load and the target drop location. Fig. 5 also shows in each task the horizontal and vertical discrepancies in the program when the actual load was placed at the target location. The results indicate an average vertical positioning error of 0.5 m and horizontal positioning error of 0.3 m. Based on the sensor system design, it can be concluded that the error in horizontal positioning was contributed by the error of the slew angle measurement from the rotary encoder sensor. The error in vertical positioning was a result of combining errors from the hoist length measurement (rotary encoder sensor) and the boom angle measurement (inclinometer).

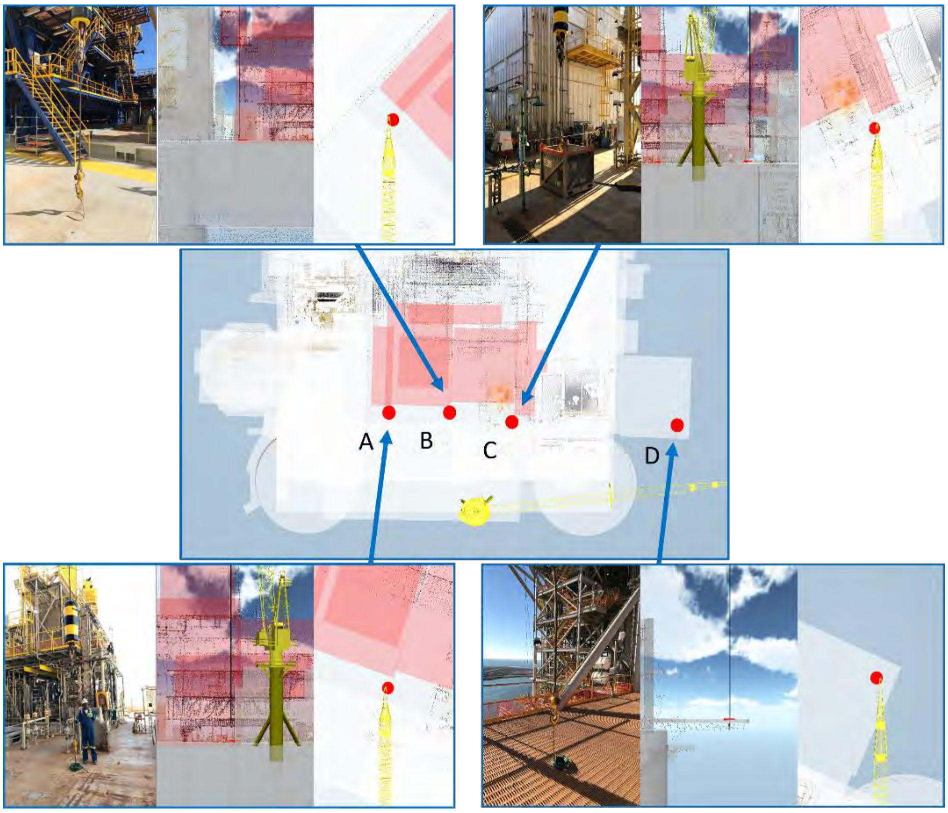

Fig. 5: Horizontal and vertical placement discrepancies in four placement locations

In addition to the sensing system, a graphical user interface (GUI) was developed to visualize the crane states to the crane operator. As shown in Fig. 6, a tablet computer with a 10.8-inch (27 cm) screen was installed in the crane cab. The GUI comprises three views (i.e., free camera view, top view, and elevation view) to provide the operator with a comprehensive visualization of the entire crane workspace. The interactive GUI allows the user to manipulate the view angle and zoom-in level of the free camera view for closer examination of the situation when necessary. In addition, the GUI is designed to be a hands-free interface to minimize the disruption to the operator’s typical operation behaviors. Therefore, all functions in the interaction with the GUI can be realized by voice command. Feedback from the users after a training session shows the information on GUI is easy to comprehend and the interaction with the system via voice control is intuitive.

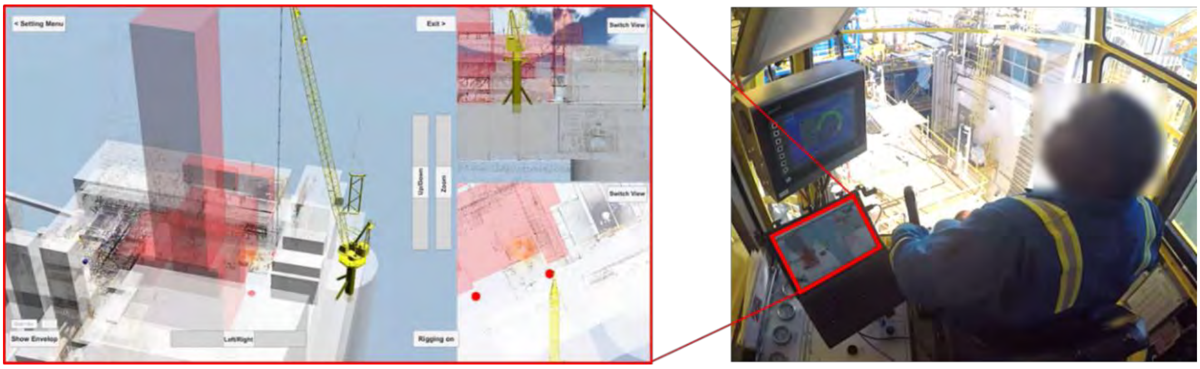

Fig. 6: Monitor cabin setup and user interface for real-time visualization

Another important observation was made in the field test. Because of the substantial presence of metallic objects in the OP environment, the IMU sensor was constantly experiencing significant signal interference, making the load positioning data too inaccurate and unreliable to be used for load sway monitoring. To increase the accuracy and robustness of the load sway monitoring module in an OP environment, a CV-based load position method was further investigated. Next section presents the lab test results for the CV-based method.

4.2 Lab tests for crane load monitoring module

Lab experiments were conducted where a steel load is hung from a test rig and manually set in motion. The lab test examined different configurations of experimental parameters such as cable length, marker color and background scenery. Two cases of successful tracking of the steel load motion with different cable lengths (2.1 m and 5.2 m) are shown in Figs 7 and 8.

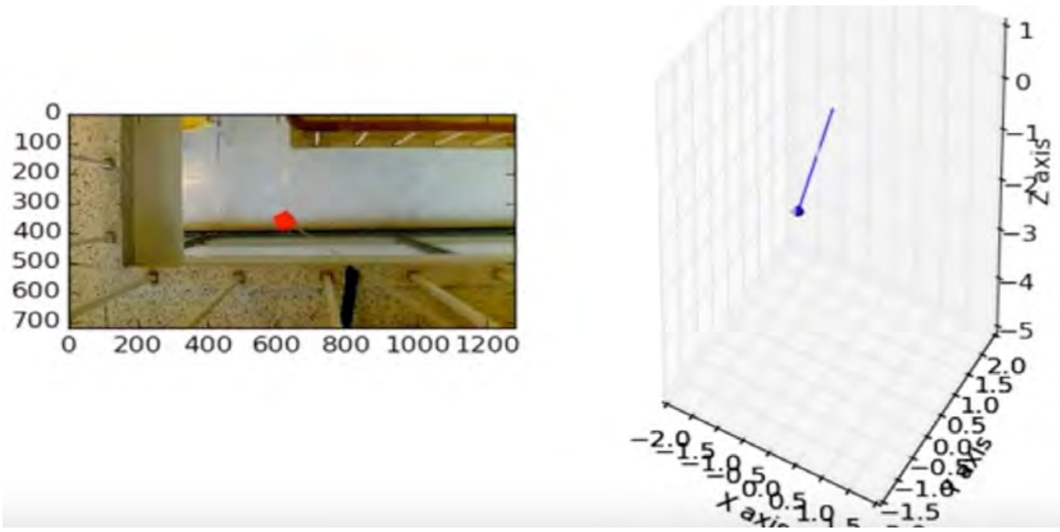

Fig. 7: Indoor load swing simulation with a cable length of 2.1m. Left image represents the camera output with the estimated load position marked in red whereas right image represents the 3D model of the load.

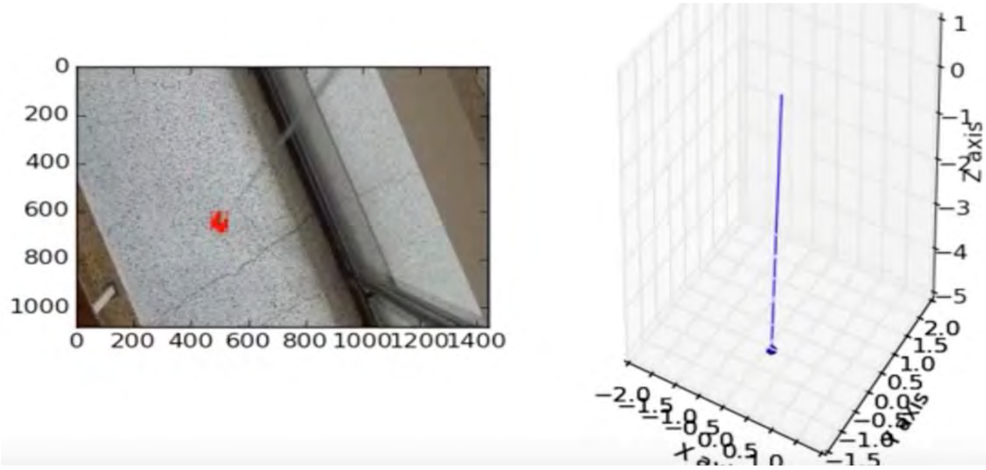

Fig. 8: Indoor load swing simulation with a cable length of 5.2m. Left image represents the camera output with the estimated load position marked in red whereas right image represents the 3D model of the load.

These experimental results show that the proposed vision-based tracking of load position is feasible across different cable lengths and background scenery, as long as the marker color is sufficiently distinct from the background (e.g. a bright color against a dull background). If the cable length is too large, is it expected that the size of the marker in the camera view will be too small to be clearly observed. However, it is possible to use a camera with optical zoom to expand an area of interest in the visual field. In terms of accuracy, prior work has shown that the visual tracking method is able to achieve normalized accuracy values of 82 – 94%, measured by the overlap area between predicted and actual object bounding box (Chen et al. 2017). This vision-based load tracking method has not yet been implemented on the offshore platform, but lab tests showed that is it a promising alternative to the IMU-based load tracking.

5. Conclusions

Offshore platforms present a challenging working environment for cranes lift operations. Massive spatial conflicts and blind spaces require effective tools to provide the crane operator real-time assistance during the lift job. This paper presents a sensing and visualization framework to provide such a service. Through real-time monitoring of crane pose and load sway, the crane state is analyzed and visualized in a game engine and presented to the operator through an interactive graphical user interface. A prototype system was developed and deployed on an actual offshore crane. Results from the field tests indicate the system was able to accurately track the crane motion and the interactive GUI can effectively improve the operator's spatial and safety awareness during blind lifts. During the field tests, it was observed that the metallic environment significantly compromised the accuracy and reliability of the IMU sensor used for load positioning. Therefore, a computer vision based method for load sway monitoring is proposed and evaluated in lab tests. The results show this method can continuously track the position of the load through the image captured by a bird view camera. Future work is directed to the development of an algorithm that fuses the data from both the IMU and computer vision methods to increase the accuracy and robustness of the sensing results in harsh OP environments. Another field test will be carried out to evaluate the new sensing approach.

6. Acknowledgement

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VR BASED ASSESSMENT OF EFFECTS OF GENDER AND STRESS ON INDOOR WAYFINDING DURING BUILDING EMERGENCIES

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ABSTRACT:

Prior studies have found significant gender effect on people's wayfinding strategies in indoor environments. It is unclear, however, whether the gender effect is significant on people's actual wayfinding performance, especially when the wayfinding task is performed under stress, such as in a building fire evacuation situation. To address this gap, wayfinding behavioral experiments were carried out in this study in immersive virtual environments, which involved two independent variables, including gender (male or female) and environmental condition (normal or fire emergency). The participants were asked to complete a treasure hunting task which allowed the participants to freely explore a virtual museum. and then an egress task to exit the museum. The wayfinding performance of the participants during these two tasks was measured, and their physiological and emotional responses were also collected. Analysis of the experiment results revealed significant or marginal significant gender effect on the wayfinding performance during the two tasks, as male participants spent less time and traveled shorter distance. The results also revealed that the virtual fire emergency made participants feel stressful and hence adversely impacted their wayfinding performance during the egress task. No significant interaction effect between gender and environmental condition was found during the egress task.

KEYWORDS: *Wayfinding; Virtual Reality; Gender; Fire Emergency; Spatial Ability.*

1. INTRODUCTION

Cognitive research has found that gender can affect people's wayfinding abilities (De Goede and Postma, 2015) and wayfinding behavior (Lawton, 1996). For instance, it was reported in prior research that males generally outperformed females in forming and manipulating spatial knowledge in cognitive map when they were exposed to unfamiliar space (De Goede and Postma, 2015). Males and females may also differ with respect to their preferred wayfinding strategies (Lawton, 1996). Females usually choose landmark-based strategy (route strategy) whereas males usually choose global reference directions (orientational strategy). However, such gender effect has not been thoroughly examined under building fire emergency scenario, where wayfinding is complicated by the stress to quickly egress from hazardous environment. Whether the gender effect on wayfinding abilities and wayfinding strategies can be translated to effect on actual wayfinding performance, which is usually measured by travel time and travel distance, also largely remains unclear. Understanding whether and how the gender would affect people's wayfinding performance under building fire emergency could not only lead to more accurate crowd evacuation simulation (Meng et al., 2013) but also enable better building fire emergency responses (Kinateder, et al., 2014a).

Laboratory experiments are usually used to analyze the causal relationships with the power of controlling variables. To study building fire evacuation behavior by conducting fire evacuation experiment, however, is challenging as creating real building fire emergency environment is prohibited due to legal and moral reasons. Immersive Virtual Environments (IVEs), which are built on Virtual Reality (VR) technologies, provide a promising alternative approach (Zou et al., 2017). IVEs can present virtual building fire scenes and make users feel stressful, and hence have been introduced in evacuation wayfinding experiments (Gamberini et al., 2015). This paper aims to study the gender effect on wayfinding performance under both normal condition and building fire emergency conditions, by conducting an VR-based experiment. The remainder of this paper is organized as follows: section 2 presents a brief overview of related research, followed by section 3 that introduces the methodology of this study. Section 4 discusses the findings of the experiment, and section 5 concludes the paper.

2. RELATED RESEARCH

2.1 Wayfinding behavior and gender

Cognition research has found significant gender difference in spatial abilities, such as mental rotation (De Goede and Postma, 2015). Thus, several studies tried to analyze gender effect in wayfinding behavior under normal condition. Prior findings indicated that females relied more on route strategy, whereas males relied more on orientational strategy (Lawton, 1996). Meanwhile, Schmitz (1997) reported that females were better at learning and using landmark knowledge while males were better at learning and using directional knowledge. She explained the gender effects on wayfinding strategies by two mediators, including wayfinding strategies formed and practiced during childhood, and affective-mediators such as wayfinding anxiety. Livingstone-Lee et al. (2014) claimed that the gender effect on wayfinding strategies might be small and could be eliminated by other impact factors, such as prior choices of wayfinding strategies. De Goede and Postma (2015) found the spatial ability of forming and retrieving cognitive map was affected by gender. They found males usually actively manipulated and transformed mental images in their cognitive map, whereas females were good at using static images of spatial knowledge. Despite the above studies about gender effects on wayfinding strategies, however, gender effect on people’s actual wayfinding performance, as measured by travel time and travel distance, has been barely studied in indoor environments, neither under normal conditions nor under emergency conditions.

2.2 VR and wayfinding in evacuation

VR technologies have been used in a range of research domains, such as cognitive science (Matheis et al., 2007) and wayfinding behavior (Kinateder, et al., 2014a). VR technologies provide a promising alternative for conducting indoor wayfinding behavior studies, because spatial cognitive process and behavior in IVEs are similar to those implicated in the navigation of a real environment (Wallet et al., 2011). Due to moral and legal constraints, evacuation wayfinding experiments cannot be conducted in a real building emergency environment, such as a real building fire. Therefore, IVEs have been introduced in these experiments. The virtual stressful environments can be used to elicit similar mental and behavioral responses that people have in real stressful environments (Gamberini et al., 2015). A comparison of advantages and disadvantages of VR technologies with other methods used in fire evacuation research can be found in (Kinateder, et al., 2014b). A number of studies have used IVEs to examine different evacuation wayfinding behaviors in fires, such as route choice (Kinateder, et al., 2014a) and evacuation time and distance (Duarte et al., 2014). Kinateder, et al. (2014a) used IVEs to analyze the impact of social influence on tunnel fire evacuation behavior. Duarte et al. (2014) studied behavioral compliance for signage system in IVE. The ecological validity of VR-based experiment is critical for justifying the use of VR technology to support emergency evacuation studies. Zou et al. (2017) developed an emotional response–based approach for assessing the sense of presence in virtual building evacuation studies as an indirect way to assess the ecological validity.

3. METHODOLOGY

3.1 Experiment design and participants

The experiment used a 2 × 2 design and lasted approximately seven weeks. The two independent variables were gender (male and female) and environmental condition (normal condition and fire emergency condition). Thirty-six Chinese undergraduate and graduate students from a major university in Beijing, China, were recruited in this study. Having normal or corrected-to-normal vision, and having no color blindness were used as exclusion criteria during the participant recruitment. Each of the participants received fifty CNY as monetary incentive for taking part in the experiment, which took around thirty minutes to complete. This study was approved by the Ethics Committee of the Psychology Department of Tsinghua University. Of all thirty-six recruited participants, four participants were not able to complete the experiment as scheduled. A total of thirty-two participants completed the experiment, and their experiment data were collected and analyzed in this study. The thirty-two participants were randomly divided into four groups of the same size, with the constraint of having uniform gender in each group, as summarized in Table 1.

Table 1: Assignment of participants into four study groups.

	Gender	Number of participants	Environmental condition
Study group A (SG A)	Male	8	Fire emergency
Study group B (SG B)	Female	8	Fire emergency
Study group C (SG C)	Male	8	Normal
Study group D (SG D)	Female	8	Normal

3.2 Apparatus and VR environment

An HTC VIVE head-mounted-display (HMD) virtual reality system was used. Unity3D game engine was used to create IVEs and run the experiment. The virtual building used in this experiment was a 38 m (length) × 15 m (width) × 3 m (height) monetary museum (see Fig. 1 for the layout). All participants were kept at least 50 cm away from the display cabinets and showcases with crowd control queue stanchion posts and barriers. The spreading of fire and smoke under the condition of fire emergency was computed using the Fire Dynamics Simulator (FDS) software and visualized and displayed using the particle system in Unity3D (see Fig. 2 for an illustration). Standard fire alarm with medium volume would be heard by the participants from headphone (default headphone in HTC VIVE set) at the same time. During the experiment, the participants physically sat still on a chair, and manipulated the Xbox joystick to move forward or make turns in the IVE at a constant speed of 1.5 m/s. The system automatically monitored and recorded their travel distance, travel time and travel routes.

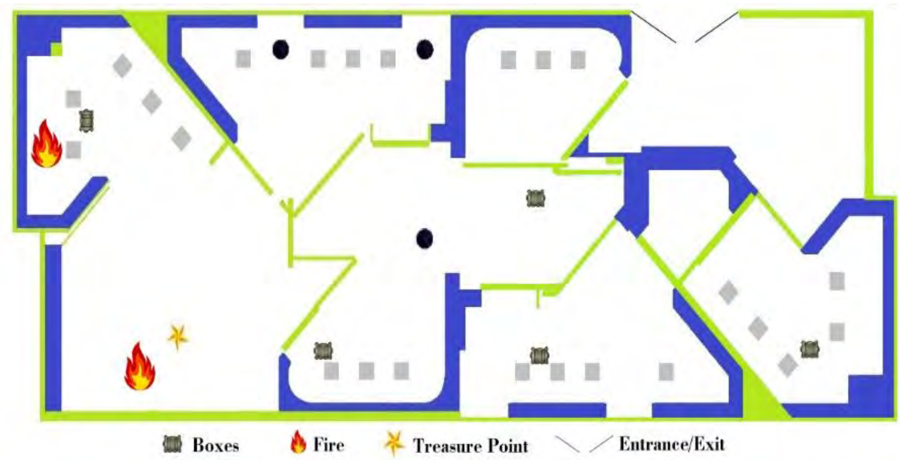

Fig. 1: Layout of the virtual monetary museum.

Fig. 2: Fire and smoke in the virtual monetary museum.

3.3 Experiment procedure

Participants answered a recruitment questionnaire hosted on an online survey service (Wenjuanxing, 2017) when they first signed up for this study. The recruitment questionnaire included questions on basic demographic information about the participants, such as age, gender, and the Chinese version of Santa Barbara Sense of Direction Scale (SBSOD; Hegarty et al., 2002).

When the participants arrived at the laboratory, they were asked to sign a consent form for signing in to the experiment, and informed that they could choose to quit the experiment at any time if they felt sick or uncomfortable. Then, the participants were instructed to put on a skin conductivity sensor for collecting electrodermal activity (EDA) data throughout the entire experiment. The experiment included a pre-experiment questionnaire, a training phase, an experimental phase and a post-experiment questionnaire. The pre-experiment questionnaire was composed of the Chinese revision of Positive Affect and Negative Affect Scale (PANAS; Qiu, Zheng, & Wang, 2008) and the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993). During the training phase, participants played with a simply demo IVE to get familiar with basic VR operations such as navigation and interaction with virtual objects, and the sense of immersion in the virtual environment. In the experimental phase, participants were instructed to complete two tasks. The first task was a treasure hunting task, in which they needed to find five boxes in the monetary museum and retrieve five treasure keys (see Fig. 1 for locations of the boxes), which could then be used to retrieve a hidden treasure in a treasure point (see Fig. 1 for its location). The second task was an egress task requiring the participants to egress from the museum as fast as possible through the only exit. The default position of the participants in the IVE when the experimental phase started was the entrance of the museum. Immediately after they finished the treasure hunting task, a visual sign with the following instructions would pop up to instruct the participants to exit the museum: “Treasure found, please exit the museum immediately”. For participants in SGs A and B, who were assigned to egress under fire emergency, they would witness the breakout of fire and smoke and start hearing fire alarm at the same time. The experimental phase ended when the participants reached the exit. It was followed by the post-experiment questionnaire, which included PANAS, SSQ, and a self-report questionnaire about their wayfinding spatial anxiety (Lawton, 1994).

3.4 Data collection and analysis

To evaluate wayfinding performance, participants’ travel time and travel distance in the two tasks were recorded and analyzed, including travel distance (d1) and travel time (t1) in the treasure hunting task, and the travel distance (d2) and travel time (t2) in the egress task. Possible confounding factors, including simulator sickness, spatial anxiety, and sense of direction, were also recorded and assessed by standard scales, SSQ, wayfinding spatial anxiety questionnaire, and SBSOD, respectively. The presence of stress was measured by emotional responses reported by PANAS and physiological responses recorded by EDA sensor. The change in EDA sensor data, which is associated with the sympathetic activation of the autonomic nervous system, is reflective of the change in emotions (Zou et al., 2017). Prior VR-based studies also validate the emotional arousing and sense of presence of participants in virtual environments by EDA (Zou et al., 2017). Skin Conductivity Mean (SC Mean) was the indicator of EDA used in this study. ErgoLAB platform (Kingfar International Inc., 2017) was used to record and process raw segment EDA data and report the value of SC Mean.

4. RESULTS AND DISCUSSIONS

4.1 Demographics of participants

To avoid the impact of inherent confounding factors, the following variables were measured and compared among four study groups: age, wayfinding anxiety, sense of direction, and prior VR experience. Results of one-way analysis of variance (ANOVA) (Mchugh, 2011) are shown in Table 2. Significance level of 5% and marginal significance level of 10% were used. The results showed that participants in all four study groups had comparable age, scores of wayfinding anxiety and scores of simulator sickness (p-value>0.10). Participants had marginally different scores of sense of direction ($F(3, 28)=2.793$, p-value=0.059). There was significant difference in their prior VR experience among the four groups (p-value=0.042). Such difference of sense of direction and prior VR experience could affect the participants’ wayfinding performance in IVE, which were therefore taken into further consideration in the following analysis.

Table 2: One-way ANOVA results of participants' demographics among four study groups.

Demographics	Study group	Mean	SD	F (3, 28)	P-value
Age	SG A	20.75	1.753	1.021	0.398
	SG B	21.75	2.053		
	SG C	20.88	1.356		
	SG D	20.25	1.753		
Wayfinding anxiety	SG A	17.50	3.423	0.269	0.847
	SG B	16.75	8.481		
	SG C	18.13	6.958		
	SG D	19.88	8.887		
Sense of direction*	SG A	68.38	4.534	2.793	0.059
	SG B	61.63	6.886		
	SG C	66.88	4.704		
	SG D	62.25	6.205		
Simulator sickness	SG A	0.03	0.149	0.892	0.458
	SG B	0.11	0.150		
	SG C	0.09	0.214		
	SG D	0.18	0.215		
Prior VR experience**	SG A	1.88	0.641	3.111	0.042
	SG B	1.38	0.518		
	SG C	1.13	0.354		
	SG D	1.63	0.518		

Note: ** indicates p-value < 0.05 between groups. * indicates p-value < 0.10 between groups.

4.2 Wayfinding performance in treasure hunting task

Multivariate General Linear Model (MGLM) based on Pillai's Trace (Olson, 1974) was applied to analyze the gender effect on the participants' wayfinding performance in treasure hunting task. MGLM was firstly conducted with one between-subjects factor (gender) and two covariates (sense of direction and prior VR experience) on two dependent variables (t1 and d1). Backward stepwise in MGLM based on the significance was applied to find all the significant factors. The stepwise process ended with adjusted R^2 value of 0.906 for t1 and 0.921 for d1 when only one between-subjects factor (gender) was considered, as shown in Table 3. The results indicated that the effect of gender was significant ($F(4, 60)=16.297$, p-value=0.000) and had strong power of explaining the difference in participants' wayfinding performance in the treasure hunting task.

According to the experiment results, male participants traveled shorter distance and spent less time on completing the treasure hunting task than female participants, which was consistent with prior studies that examined the gender difference in outdoor wayfinding (De Goede and Postma, 2015). One possible reason for such difference could be related to the theory that males, unlike females, usually actively manipulate and transform mental images in their cognitive map (De Goede and Postma, 2015). Specifically in this study, it could be that male participants were able to complete the task with less time than female participants (t1) because male participants actively processed and retrieved spatial knowledge from newly formed cognitive map. Another possible reason could be the gender difference in spatial ability. Prior studies (De Goede and Postma, 2015) found that males could learn and memorize relative positions of different places more accurately than females. This might help male participants to find the short paths and avoid searching spaces that they had already been to, leading to savings of time (t1) and distance (d1) to complete the treasure hunting task.

Table 3: MGLM results of wayfinding performance in treasure hunting task.

Performance indicator	Gender	Study groups	Mean	SD	N	F (2, 30)	P-value
t1	Male	SGs A and C	116.75	45.112	16	155.230	0.000
	Female	SGs B and D	145.75	39.489	16		
d1	Male	SGs A and C	944.81	295.031	16	186.651	0.000
	Female	SGs B and D	1012.44	278.110	16		

Note: p-value < 0.05 indicates significant effect of gender.

4.3 Wayfinding performance in egress task

Then, MGLM based on Pillai's Trace was applied to analyze the effect of gender and environmental condition and their interaction effect on participant's wayfinding performance (t2 and d2) in egress task. MGLM was conducted with two between-subjects factors (gender and environmental condition) and two covariates (sense of direction and prior VR experience) on two dependent variables (t2 and d2). Backward stepwise in MGLM was used to find all significant factors. The backward stepwise resulted in adjusted R^2 value of 0.798 for t2 and 0.827 for d2 when two between-subjects factors (gender and environmental condition) and one covariate (prior VR experience) were considered. The results are shown in Tables 4 and 5.

Table 4: Wayfinding performance in egress task.

Performance indicator	Study group	Mean	SD	N	Performance indicator	Study group	Mean	SD	N
t2	SG A	50.50	27.959	8	d2	SG A	512.88	260.665	8
	SG B	63.75	37.522	8		SG B	562.38	325.835	8
	SG C	27.00	4.175	8		SG C	306.63	39.511	8
	SG D	45.00	20.050	8		SG D	390.63	116.175	8

Table 5: MGLM results of wayfinding performance in egress task.

Performance indicator	Factor	F (1, 27)	P-value	Performance indicator	Factor	F (1, 27)	P-value
t2	Gender*	3.325	0.079	d2	Gender	0.830	0.370
	Environmental condition*	3.539	0.071		Environmental condition*	4.033	0.055
	Gender× Environmental condition	0.465	0.501		Gender× Environmental condition	0.475	0.497
	Prior VR experience*	4.091	0.053		Prior VR experience*	3.832	0.061

Note: * indicates p-value < 0.10.

As the results showed, gender was a marginally significant factor for t2 ($F(1, 27)=3.325$, p-value=0.079) but was insignificant for d2 (p-value>0.10). Compared with treasure hunting task, the significance of gender effect on wayfinding performance decreased in the egress task. The difference in the objective and setting of the two tasks was possibly responsible for such difference in observed gender effect. The treasure hunting task required more complete spatial knowledge in cognitive map to quickly find all six positions, whereas the egress task only required spatial knowledge related to the exit. Prior research found that gender difference in spatial abilities helped males outperform females in difficult wayfinding tasks in unfamiliar outdoor space (De Goede and Postma, 2015). The results in this paper again validated this hypothesis, but in a virtual indoor setting.

Environmental condition was a marginally significant factor for both t2 ($F(1, 27)=3.539$, p-value=0.071) and d2 ($F(1, 27)= 4.033$, p-value=0.055). Participants under fire emergency traveled longer distance and spent more time than participants under normal condition. The results were consistent with findings in prior studies (Meng and Zhang, 2014). Fire emergency environment reduced the visibility of the environment by fire and smoke, which negatively affected the search and recognition of landmarks and hence decreased wayfinding performance (Darken and Peterson, 2001). Besides, fire emergency made participants stressful. Stress accelerated information processing, such as environmental perception and retrieving of cognitive map, which could result in random route choice of participants (Meng and Zhang, 2014). The results showed no interaction effect of gender and environmental condition on t2 or d2 (p-value>0.10). Prior VR experience, a marginal significant factor for both t2 ($F(1, 27)=4.091$, p-value=0.053) and d2 ($F(1, 27)=3.832$, p-value=0.061), might have affected the wayfinding performance through it effect on the level of stress participants experienced in the VR environment (Grandin, 1997).

4.4 Validity

The validity of this study was evaluated by internal validity, statistical validity, construct validity and external validity. For internal validity, confounding factors of this study, including simulator sickness, sense of direction and wayfinding anxiety (Kennedy et al., 1993; Lawton, 1994; Hegarty et al., 2002), were assessed and no significant effect on wayfinding performance was found. Sample size, level of significance and statistical method were carefully selected to meet the requirement of statistical validity (Mchugh, 2011; Olson, 1974).

Furthermore, to assess whether the virtual fire emergency environment aroused psychological and physiological reactions of participants, such as mental stress, the change of the positive emotions, negative emotions and skin conductivity of the participants before and after the experiment were analyzed. SC Mean were used to analyze the change of skin conductivity. The MGLM based on Pillai's Trace was conducted with one between-subjects factor (presence of fire emergency) on three dependent variables (positive emotions, negative emotions, SC Mean). The results are shown in Table 6. The results indicated that the virtual fire emergency environment significantly affected negative emotions and SC Mean, but did not affect positive emotions. The results suggested that the virtual fire emergency environment was generally effective in arousing psychological and physiological reactions of participants under fire emergency.

Table 6: MGLM results of psychological and physiological reactions of participants.

Reaction	Environmental condition	Study groups	Mean	SD	N	F(2, 30)	P-value	Adjusted R^2
Positive emotions changes	Normal	SGs C and D	-0.44	4.844	16	2.368	0.111	0.079
	Virtual fire	SGs A and B	-2.63	4.938	16			
Negative emotions changes**	Normal	SGs C and D	0.19	2.167	16	7.231	0.003	0.280
	Virtual fire	SGs A and B	3.56	4.844	16			
SC Mean changes**	Normal	SGs C and D	3.25	4.123	16	6.049	0.006	0.240
	Virtual fire	SGs A and B	-5.06	8.873	16			

Note: ** indicates p-value < 0.05.

Different aspects of external validity were also considered. Various prior studies reported that findings about spatial knowledge and wayfinding behavior from virtual environment might also be applied in real environment (Wallet et al., 2011), suggesting reasonable external validity of the results reported in this paper. Yet, two limitations related to external validity of this study should be noted. First, the sample of participants was composed of university students. The external validity of the results on elders or children would require further investigation. Second, Lawton & Kallai (2002) found no statistically significant cultural effect on wayfinding strategies, although, they noticed that significant gender effects on wayfinding strategies were observed in some but not all countries. Considering that all participants in this study were Chinese, generalizing the findings of this study to populations with different cultural backgrounds would require caution.

5. CONCLUSIONS

This study assesses the gender effect on indoor wayfinding performance in both normal condition and fire emergency conditions. An experiment utilizing IVE was conducted. The travel distance and travel time of participants when conducting two wayfinding tasks in the IVE were collected to analyze the gender effect on indoor wayfinding performance in both normal condition and fire emergency conditions. Physiological and emotional responses, sense of direction, wayfinding anxiety and simulator sickness were collected to ensure the validity of the study. The results revealed significant or marginal significant gender effect on wayfinding both in treasure hunting task and in egress task. Male participants spent less time and traveled shorter distance for hunting all treasures than female participants due to difference in spatial abilities. Fire emergency marginally significantly decreased wayfinding performance of the participants in egress task. No interaction effect between gender and environmental condition was observed. Future research could be done to further investigate the gender effect under various other wayfinding scenarios, and explore possible gender-specific strategies for wayfinding training and emergency evacuation preparation.

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ADOPTION OF BUILDING INFORMATION MODELLING INNOVATIONS TO REDUCE OCCUPATIONAL ACCIDENTS IN THE AUSTRALIAN CONSTRUCTION INDUSTRY

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ABSTRACT: *Safety performance records of the construction industry are unenviable, as the number of injuries and fatalities around the globe continue to plague the industry. The adoption of Building Information Modelling (BIM) in the construction projects has opened up gateways for the safer execution of the projects. While several studies in the recent years concentrated on developing BIM applications as promising solutions to improve safety performance, there is a need for understanding the nature of the accidents and critical success factors (CSF) to leverage these applications. This study first analyses 109 fatal accident cases across Australia to understand the nature of the construction accidents through a rigorous accident model. Then six interview sessions were held by highly-experienced industry experts to identify the BIM applications in preventing causes of the accident and the CSFs for the adoption of these applications in the industry. This study contributes to the body of knowledge through developing a road map for the construction industry to improve the safety performance of the industry using BIM.*

Keywords: *Innovation adoption theory; Critical success factors; Building Information Modelling; Accident causations; Australian construction industry.*

1. INTRODUCTION

Safety performance of the construction industry has always been a concern across the globe. Lingard (2013) reported that every year occupational accidents on the construction sites cause the death of over 60,000 workers around the world. In the United States (US), the construction industry accounted for 19% of all occupational fatalities in 2012 while the industry only employs 4% of the US workforce in the same period (Bureau of Labor Statistics (BLS) 2017). Similarly, in the United Kingdom (UK), the construction industry accounted for 31% of all the UK occupational fatalities in 2014 despite it accounted for only 5% of the UK labour force (Naomi Billington 2017).

The potential uses of Building Information Modelling (BIM) can drastically alter the occupational health and safety (OHS) practices in the construction industry. BIM facilitates project information exchange and management, supports better collaboration and project planning by virtual visualisation of the construction process (Zhou, Whyte and Sacks 2012; Zou, Kiviniemi and Jones 2017). All these attributes have resulted in an exponential growth of interest towards the digitalised management of construction safety in the past five years (Guo, Yu and Skitmore 2017).

BIM-enabled approaches toward OHS management are extensive and at the same time relatively new for the construction industry of Australia. Therefore, diffusion of such innovative interventions with the current practice of the industry in a practical manner requires a proper identification of effective areas and evaluation of their impact on key criteria's of the projects and organisations. In the construction industry context, Slaughter (1998) described an innovation as the actual use of a nontrivial alteration in terms of an enhancement of a system or working procedure that is new to the corresponding organisation. As suggested by Slaughter (1998, the first step for implementation of an innovation in a project or organization is to identify areas requires intervention. Therefore, in the case of diffusion of BIM-enabled approaches to improve OHS performance of construction organizations, unearthing how construction accidents happen is a key to prioritise areas that require intervention (Swuste 2008). Secondly, adoption of the new innovations in the construction organisations and projects requires an understanding of the critical success factors (CSF). These factors are fundamental to tackle the major obstacles on leveraging BIM applications towards improving construction projects' OHS performance.

This study aims to develop an innovation adoption model for the construction industry to adopt BIM for improving the construction OHS. To achieve this aim, the following objectives are devised:

- to investigate causes of construction accident based on a rigorous model from the existing literature;
- to evaluate BIM approaches applicable to prevent the identified causes of the construction accident; and
- to identify CSFs for adoption of BIM for improving construction OHS.

The contribution of this study to the body of knowledge lies in revealing causes of construction accidents, BIM application on controlling causes of accidents and developing a roadmap for the construction industry to improve the safety performance of the industry using digital tools.

2. RESEARCH BACKGROUND

2.1. Innovation Adoption Theory

Mahajan and Peterson (1985) define innovation as "… any idea, object, or practice that is perceived as new by members of the social system …". For the construction context, Slaughter (1998) described an innovation as the actual use of a nontrivial alteration in terms of an enhancement in a system or working procedure that is new to the corresponding organisation. BIM-enabled approaches to improve OHS is not a widely-experienced practice within the context of the construction industry, thus seems to be new to a large number of organisations (Enshassi, Ayyash and Choudhry 2016; Ganah and John 2015; Malekitabar et al. 2016; Zhang et al. 2016).That is, embracing BIM to improve OHS follows the process for the spread of a new phenomenon within the traditional structure of construction firms. For the construction context, the stages associated with the implementation of an innovation could be divided into 5 main successive stages drawing from the innovation diffusion theory on construction projects (Banihashemi et al. 2017; Slaughter 2000). The stages are identification, evaluation, commitments, preparation, and implementation. Identification stage refers to identifying objectives of an organization or project to be achieved by integration of an innovation. The objectives followed in this study is to employ BIM to control causations of construction accidents in Australia. Evaluation stage refers to the level of influence that an innovation would bring into the organisations or projects. At this stage, evaluation of the innovative approaches needs an accurate understanding of the values. Next, commitments, preparation, and implementation factors needs to be identifies for a successful adoption of an innovation.

2.2. Construction Accident Causations

A review of accident models by Katsakiori, Sakellaropoulos and Manatakis (2009) shows a gradual paradigm shift over time from looking for a singular cause of accidents to a number of systematic failures. Systemic accident causation models describe the existence of dynamic interaction of environmental, cultural, organizational, etc. factors in creating a hazardous situation.

The Loughborough ConAC model is one of the systemic accident causation models that is developed for investigating construction accidents. Gibb et al. (2006) analysed 100 mostly minor construction accidents (e.g. accidents result in few days lost time and no significant injury) within a 3-year research program at Loughborough University. A hierarchical ConAC was developed to facilitate identifying a set of events leading to unfortunate incidents. As defined by Behm and Schneller (2013), the ConAC is not a checklist but rather a comprehensive model developed based on Reason's 'Swiss cheese' model (Reason 1998) to identify and break down accidents to organisational and individual level flaws. The Loughborough ConAC framework became a prominent method because of comprehensive nature of the primary research and collecting possible details from the interview and focus groups with the victim(s) and witnesses, site observations, photographs, etc. The Loughborough ConAC model is presented in three levels of contributing factors, namely immediate accident circumstances, shaping factors, and originating influences as depicted in Figure 1. Also, Figure 1 shows causal relationships between the factors of each level starting from originating influences and ending with four immediate accident circumstances of the work team, workplace, materials, and equipment. Behm and Schneller (2013) utilised the ConAC framework to investigate 27 non-fatal construction accidents that took place within State Department of Transportation of the US. In addition, Cooke and Lingard (2011) used the same model to analyse causalities in 258 fatal accident in Australia. Both research teams reported credibility of the ConAC framework for construction safety research domain and organizational learning. Behm (2009) in the technical report to the US Department of Transportation elaborated terminologies of the ConAC model in more details.

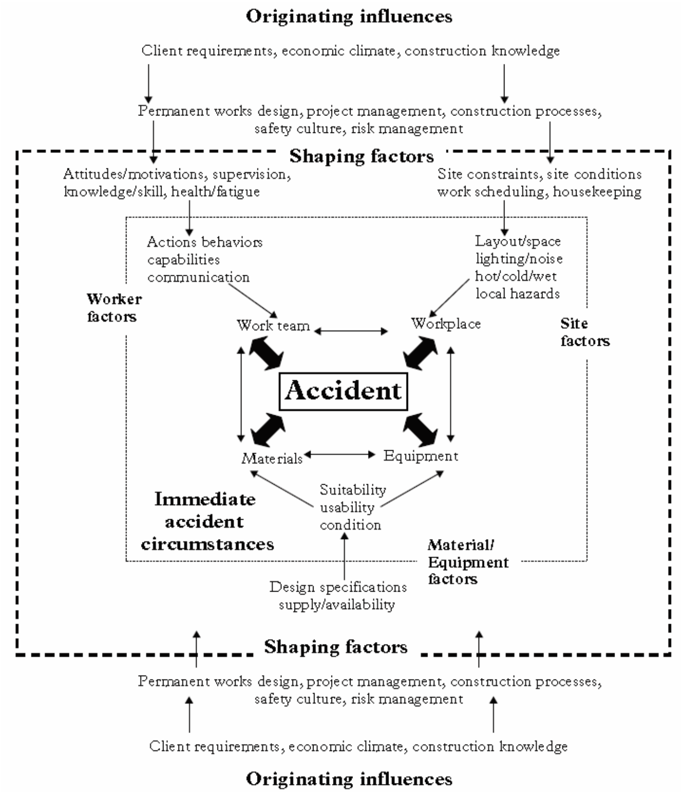

Figure 1: The Loughborough ConAC model (Gibb et al. 2006)

2.3. BIM application to prevent the accident causations

A review of the available research regarding BIM applications on OHS identified six general trends; 1) virtual training and education; 2) prevention through permanent and temporary work design; 3) 4D risk assessment at planning stage; 4) Project monitoring and management at construction stage using visualised sensing technologies; 5) Digital Knowledge Management (KM) of the project lifecycle safety information; and 6) Digital material and equipment supply management. The potentials of the identified trends on accident causations are tabulated in Table 1. This shows that BIM potentially can reduce the construction accidents through different tactics.

Table 1: Summary of existing BIM research on construction safety

	BIM research	Factors of accident causations
1	Virtual training and education (Albert et al. 2014; Bosché, Abdel-Wahab and Carozza 2015; Chen et al. 2016; Guo, Li and Li 2013; Sacks, Perlman and Barak 2013)	• Workers capabilities • Safety culture
2	Prevention through permanent and temporary work design (Malekitabar et al. 2016; Qi et al. 2013; Sacks et al. 2015; Solihin and Eastman 2015; Zhang et al. 2013)	• Equipment suitability • Permanent (and temporary) work design
3	4D risk assessment at the planning stage (Benjaoran and Bhokha 2010; Choi et al. 2014; Golparvar-Fard et al. 2009; Hu and Zhang 2011; Kim and Ahn 2011; Kim, Cho and Zhang 2016; Moon, Dawood and Kang 2014; Zhang et al. 2016; Bansal 2011; Bansal and Pal 2011)	• Site constraints, site layout/space • Risk management
4	Project monitoring and management at construction stage using visualised sensing technologies (Akula et al. 2013; Altaf, Hashisho and Al-Hussein 2014; Arslan et al. 2014; Cheng and Teizer 2013; Costin, Teizer and Schoner 2015; Fang et al. 2016; Han and Golparvar-Fard 2017; Hu and Zhang 2011; Lee et al. 2012; Li, Chan, et al. 2015; Lin et al. 2014; Riaz et al. 2014; Teizer, Cheng and Fang 2013; Wang et al. 2016)	• Workers actions and behaviour • Communication • Immediate supervision • Working environment • Work scheduling • Project management • Risk management
5	Digital knowledge management of the project lifecycle safety information (Fahlbruch and Schöbel 2011; Li, Lu, et al. 2015; Martinez-Rojas, Marin and Vila 2016; Motawa and Almarshad 2013; Wetzel and Thabet 2015; Zhang, Boukamp and Teizer 2015; Zou, Kiviniemi and Jones 2016)	• Site condition • Local hazards • Material condition • Equipment condition • Construction process
6	Digital material and equipment supply management (Goulding et al. 2012; Zhong et al. 2017)	• Material suitability • Equipment suitability

3. RESEARCH METHODS

3.1. Accident Investigation

BIM applications in construction safety are not 'magic bullets' that will always hit the target of zero accident and their influences substantially depend on the context and the implementation. Therefore, this paper first identifies the causations behind construction accidents. Descriptions of 105 fatal accidents that occurred from 2008 to 2018 were collected from National Coronial Information System (NCIS) of Australia as case studies for this research. The NCIS is an internet-based data storage and retrieval system that enables coroners, government agencies, and researchers to monitor deaths reported to coroners in Australia and New Zealand and to identify cases for further investigation and analysis (Lingard, Cooke and Gharaie 2013). In each jurisdiction, coroners investigate deaths in accordance with the relevant Coroners Act. While the requirements of reportable deaths vary between jurisdictions, a death is generally reported where it was unexpected, unnatural or violent, or where the cause of death at the time was unknown. The collected cases are set to conduct content analysis using the ConAC model. The model that each accident could have multiple causations.

3.2. Interview

In the second step, this study conducted 6 interview sessions with highly experienced industry experts (Table 2). The sample was deemed representative of a rich variety of expertise. Interviews were conducted in March 2018 with all the interview sessions recorded. Interviewees were given a list of BIM applications that could potentially improve the construction OHS performance. They were asked to point out applicable approaches to prevent the identified accident causations. Then, through open ending questions, they were asked to describe the CSFs for the adoption of these applications in the construction projects.

Table 2: Profile of interview participants.

ID	Experience (years)	Role	Organisation
Interviewee 1	12 years	BIM manager	Construction contractor
Interviewee 2	8 years	BIM coordinator	Construction contractor
Interviewee 3	23 years	BIM manager	Consultant
Interviewee 4	10 years	HSE & Systems Manager	Construction contractor
Interviewee 5	20 years	Project Manager	Construction contractor
Interviewee 6	15 years	Designer	Consultant

4. FINDINGS AND DISCUSSIONS

4.1. Accident Causations

From analysing the descriptions of 105 accident cases that were collected from the NCIS database, 487 causations were found (Table 3). The average number of the factors found to contribute to every accidents was 4.64 which was 3.5 in the previous study (Gibb et al. 2014). Among the factors, immediate supervision, workers' actions and behaviours and risk management had the highest number. In addition, factors like housekeeping, Scheduling, and suitability and usability of materials were found to have the least influence on the accidents. Since the accident reports were written based on the coroner's discovery of the sites and each had a different method of developing their reports, some of the factors might be unrecognised.

Table 3: Causations found in the construction accident cases analysis

	Fall from height	Contact with electricity	Being hit by moving objects	Being hit by falling objects	Trapped between or in equipment	Vehicle collision	Other	Total
Worker actions and behaviours	19	11	8	4	9	3	4	58
Worker capabilities	8	7	2	2	7	0	3	29
Communication	2	2	1	0	4	0	4	13
Immediate supervision	24	7	6	7	10	1	5	60
Worker health/fatigue	5	0	0	0	1	1	6	13
Site conditions	2	0	3	1	3	1	2	12
Site constraints, site layout/space	0	4	0	1	2	0	0	7
Local hazards	0	3	0	0	0	0	2	5

Working environment	1	2	1	1	0	0	4	9
Work scheduling	0	2	0	0	0	1	1	4
Housekeeping	0	1	0	0	0	0	0	1
Suitability of materials	1	1	0	1	0	0	1	4
Usability of materials	1	3	0	0	0	0	0	4
Condition of materials	2	6	0	2	0	0	2	12
Suitability of equipment	11	2	0	2	3	0	1	19
Usability of equipment	2	1	1	0	2	0	1	7
Condition of equipment	8	0	3	3	4	2	3	23
Permanent (and temporary) work design	20	7	3	1	4	2	8	45
Project management	9	4	4	2	3	0	3	25
Construction processes	15	11	4	3	8	2	5	48
Safety culture	14	6	3	4	3	1	4	35
Risk management	14	12	7	4	7	1	9	54
Total number of the cases	**34**	**18**	**10**	**8**	**15**	**4**	**16**	**487**

4.2. Interview Results

The interviewees were first provided with two documents; BIM OHS applications found from the literature review describing each application in details and accident causations found from the accident analysis. Accident analysis was presented in a cumulative and unanimous form to the interviewees. These documents were utilised in assisting the interviewees to acquire an accurate understanding of the concepts investigated in this study. This was to make sure all the respondents have a common comprehensive understanding of the topic of the study and their appreciations of the meanings of terms, concepts and requirements are analogous. They were asked to express their views about applicability of each BIM application's regarding the accident causations and suggest modifications to BIM applications, if any required. After collecting all interviewee's point of view and refining them through a content analysis, the findings are summarised in the following parts.

Although the one of the top contributor to the accidents is the workers' unsafe actions and behaviours, the use of technology can support improving workers' perception of the risks and outcomes of their actions. Virtual training and education using VR, AR, or simply BIM models can enhance workers ability in identifying real risks in the construction sites. This approach is effective in the training of workers, safety culture of the workers, developing safer work method statement, and communicating safety issues to those of workers with language barriers.

Prevention at the design stage using automated or semi-automated model checkers can identify unsafe designs based on predefined safety rules. Also, BIM models provide a clearer platform for the safety in design meetings involving the client, consultant, and contractors. BIM facilitates identifying and clash detecting of the suitable static equipment like scaffoldings or guardrails in the sites.

4D modelling and risk assessment at the planning stage is identified as an effective approach to provide a simulation of the site activities and modifying the work method statements. While 4D BIM is capable of visualising the activities, it is also capable of providing some analysis that at the current stage large companies have produced their own version of risk analysis of the dynamic equipment like machineries and assess their suitability for the tasks. 4D BIM in nature is a tool to develop the construction schedule and in this manner, it facilitates recognising the required equipment at the right time. It is also repeatedly mentioned that 4D BIM can provide a platform for assessing sub-contractors' level of understanding in safely performing their contracts.

Monitoring functions of the BIM applications are mentioned as the most effective approach among the others. Although this approach covers a range of approaches, it mainly deals with digital monitoring of the sites. It is stated that although using sensors to pinpoint the location of the workers and alerting them if they are entering to an unsafe proximity of a hazard will not %100 prevent them from putting themselves at risks, it can prevent a large proportion of the accidents. BIM 360 Field is also mentioned as a practical application for systematic monitoring of the site by the site supervisors. Similar applications provide a collaborative platform for the project team to communicate the existing hazards related to site condition, condition of the equipment, reporting sub-contractors safety performance, and it improves safety culture among the members of the organisation.

Sensors attached to the body of the workers that are connected to a BIM model can measure health condition of the workers and report it to the management team as well as alerting the workers. In addition, environmental sensors can measure the severity levels of the weather and provide immediate alerts in indoor and outdoor areas. Connecting these sensors to a model can pinpoint the location of hazards and consequently help the management team to come up with a proper action.

Laser scanners are also another type of the sensing tools that capture the real situations on site and importing these captures to a BIM model can help to identify the variations, unsafe conditions on site, and recognising suitability of the operating equipment.

BIM to be used as a digital repository of project lifecycle safety information can store all necessary OHS information of the project and handed to different trade workers and sub-contractor during maintenance of an asset. This approach is effective in transferring the special requirements related to site condition that may not be recognised by the maintenance workers. This approach is very effective in transferring the knowledge learned to the projects to the next projects. It can identify the workers with a poor OHS performance record, equipment operating condition, modified work method statements, and workers health conditions.

BIM applications among the material and equipment suppliers are very limited in the industry, while the use of the BIM models can assist the suppliers in assessing the suitability of their supplies. 4D BIM is also can leverage the on-time provision of equipment and material that can prevent accidents taken place because of unavailability of them.

Last but not least, as the ConAC network presents, there are several factors contributing to the accidents and controlling these factors all in all can result in preventing the accidents. Therefore, BIM is not an ultimate solution to achieve zero accident, but it can be a major component of the plan.

4.3. CSFs to Leverage BIM's OHS Applications

The second part of the interviews dealt with identifying the CSFs of BIM's OHS application. Interviewees were asked to express the critical actions needed to be taken by the client, contractor, designer, software vendors, and the government. The CSFs identified from the interviews were categorised into commitments, preparations, and implementation factors (Table 4).

Although he CSFs identified were not quantitatively ranked by the interviewees, some factors were described by the interviewees as very important for the successful adoption process. For example, it is suggested that technology vendors directly address safety issues in the models where at the current stage, OHS information is entered into the models through customisation actions taken by the construction companies. It is also suggested that technology vendors reduce the prices of their products so that these BIM tools are more attainable for smaller companies. Besides, it is suggested that government accelerate setting the BIM plans for construction OHS. Currently, the government has planned to implement BIM for OHS by 2023 and this plan only targets large-size projects.

Interviewees described contractors as the main drivers in the adoption process. This is due to the fact that they are liable for the construction accidents and at the same time they can benefit from improving construction OHS. Adoption of the BIM applications in the projects requires having people to operate the technology and process. As such, it is of importance to have site safety managers who have hands on skills to use BIM tools. Also, this requires sub-contractors to be educated to use such tools. Construction projects vary one from another and it is hard to find a fixed approach to implement these process and it requires a continuous monitoring of the process and revising it.

Clients, on the other hand, should look at the projects as life-time assets that require time to time maintenance activities. Therefore, spending some money in front to develop the building models capable of storing OHS information in the models can save lots of money during the maintenance phase by reducing a number of the accidents.

Designers are responsible to develop the building models and most of the developed BIM models at the current stage do not have a mechanism to store OHS information. Therefore, it makes contractors job harder to modify the model to be capable of safety management. Additionally, safety in design meetings are becoming part of the design process. BIM significantly improves the efficiency of these meeting and this requires allocation of additional time and effort from both parties of consultant and the contractor.

Table 4. CSFs for the adoption of BIM OHS applications in the construction projects

Commitments	Preparations	Implementation
• Clear safety goals set to achieve in the projects • Mutual trust among the parties involved in the projects to circulate required safety information in their BIM models • The commitment of contractors to use BIM models in their safety management • The commitment of the designers to develop BIM models with all safety features • Initiatives from large companies as the front-liners of the industry • Lower cost of the technology to be used in small and medium-size companies • Vendors develop software that address real on-site safety challenges • Scope definition of the safety management of the projects for their entire life-cycle	• Availability of the technical hardware and software in the companies • Allocation of additional time and budget for safety in design process • More automation in software tools • Creating new roles and responsibilities within the organisations for facilitating implementation of the BIM for safety management • Government mandating of using BIM models for safety management • Sub-contractors experience and competency in use of BIM • Mandating the use of digital models for safety in the contracts by the clients • Compatibility among the different software packages • Initiatives were taken by master builders associations • TAFE and universities initiatives in training safety managers to use BIM tools • Availability of safety managers with BIM knowledge • IP conflict resolving approaches for the developed models • The existence of financial incentives in the contracts for the use of BIM for safety management	• Continuous monitoring and modifying of the process of using BIM for safety management • Provision of the required safety information to the subcontractors • Liability of data inserted in the models for each of the parties involved • Developing comprehensive BIM models to cover safety information from the first drafts • Frequent updating of the safety information in the BIM models • Provision of the BIM models to the maintenance trade workers • The continuous collaboration of the designers and contractors on modifying the models • Having in place an effective communication and data exchange system among the people involved in the safety management process of the projects

5. CONCLUSION

As one of the first studies of its kind, the present study contributes to construction OHS using BIM in several ways. First, this study diagnoses accident causations in the construction projects of Australia. Findings show that the top contributors to the construction accidents are immediate supervision, workers unsafe actions and behaviours and risk management. Second, the study proposes a pool of CSFs for integration of BIM into project management practices on construction projects that are mainly developed for the Australian construction industry and it can be used as a model for global contexts as well. Among the 29 factors found from the interviews, contractors' capabilities in employing BIM for OHS, government initiatives, and vendors R&D activities found to be very important.

Findings reveal insights related to what are the focus areas of safety that required to be given higher attention and prevention of them could significantly reduce the number of fatal accidents. Although the sample investigated in this study considered fatal accidents, the findings also can be correct for non-fatal accidents that have resulted in extreme injuries. For practice, the findings of the study provide guidelines for policy-makers and companies' directors in Australia. That is, the findings enable them of identifying the most crucial areas for focusing their efforts and allocating resources efficiently in view of the outcomes of this study.

Nevertheless, the study findings should be considered with caution due to a number of limitations. That is, the CSFs found in this study may not be applicable to other contexts due to the socio-economic discrepancies between Australia and other countries. Moreover, the sample size was relatively small and the respondents mostly came from contractor companies and consultants. As such, the findings might not reflect the perceptions of government, clients and technology vendors. These limitations warrant further investigation by validating the model in other contexts and using larger samples that cover different sizes and various types of companies. Exploring the CSFs incorporating the viewpoints of a wider range of project stakeholders might add value to the findings presented here as another fertile ground for future research studies.

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INTEGRATION OF IOT AND BIM TECHNOLOGY TO IMPROVE INFORMATION SYSTEM FOR FIRE RESCUE AND ESCAPE

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ABSTRACT: *Fire is the most common disaster in everyday life. In Taiwan, about 100 firefighters die during fire rescues each year, primarily because they are unaware of the causes of the fire and unfamiliar with the location's environment. Meanwhile, evacuees often die in the panic. Therefore, in order to solve these problems, this research proposes a BIM-based visualization and warning system for fire rescue. By using a fire dynamics simulator (FDS) to simulate various conditions of fire disasters in conjunction with the visualization and integration properties of BIM, the results of the simulation such as temperature, carbon monoxide, visibility, etc. can be integrated and presented in the BIM model for briefing purposes before the fire rescue attempt. In addition, this research integrated Internet of Things (IoT) technology that allows for real-time situation monitoring. If there is a fire, then the BIM model will immediately display the situation of the fire scene, and control the LED escape route pointer according to the actual situation. The primary objective of this system is to provide useful information to firefighters such that they can be aware of the fire scene's environment and create an effective rescue plan. Moreover, the automated LED escape route pointer could assist the building's occupants to escape, provide the firefighters with valuable information, and allow them to discover the hazards in time so that the number of casualties could be minimized.*

KEYWORDS: *BIM, FDS, IoT, Visualization, Fire Rescue, Fire Escape*

1. INTRODUCTION

Structural fires are common urban disasters. According to the statistics of Taiwan's National Fire Agency, Ministry of the Interior, the incidence of fire accidents has increased annually over the last 5 years. Each year, about 1,153 accidents take place. Generally, the people involved in a structural fire can be classified into two groups: the evacuees and the firefighters. These two groups of people each have a distinct motive and goal. The goal of the former is to escape and save their own lives, while that of the latter is to assist the trapped occupants and execute rescue operations. The main reason why most evacuees die at a fire scene is that they have a poor sense of escape, encounter obstacles during evacuation (vigorous flames or blockage in the evacuation route), or lack sufficient time to escape (Cheng et al., 2016). On the other hand, firefighters often enter the fire scene merely based on their past experience, without full knowledge of the location or spatial configuration. This lack of information is one of the primary causes of death in firefighters (Kang et al., 2016). Summarizing the above, the most dangerous conditions in a fire scene for both groups of people are:

- Lack of information about the fire scene and spatial configuration, causing incorrect decision making when choosing the escape route (Li et al., 2014; Groner et al., 2012), and
- The ambiguity of changes in the fire scene, which can cause the occupants to spend too much time trying to escape (Lurz et al., 2017; Harris, 2013).

Based on the aforementioned reasons, this research developed a visualization and warning system based on Building Information Modeling (BIM). The system framework of this system is shown in Figure 1. This research utilizes the BIM model's capability to visualize and integrate information to provide the results of fire simulations and feedback from real-time information. This system will help the related personnel to escape or perform rescue operations. Hsu et al. reported that BIM can correct the deviations between 3D and 2D diagrams, visualize the building's surroundings and the positions of facilities in 3D, and improve discrepancies when using traditional 2D firefighting management tools(Hsu et al., 2014). Not only does BIM allow 3D visualization, but its model also contains building information such as the building materials and quantities. Fire trends are highly related to the building materials, and these parameters are crucial to the simulation. Different materials have different densities and physical attributes, so their burning rates also vary. The elemental properties of the material could be said to be one of the major factors governing the intensity of the fire (Shi et al., 2017). Hence, information from a BIM model could be inputted to a Fire Dynamics Simulator (FDS) for a more accurate prediction of the fire situation. An FDS primarily uses Computational Fluid Dynamics (CFD) to calculate and solve the fluid mechanics control equations created by fire scenes. Researchers who utilized FDS to re-enact a fire scene and compared the results with the actual investigative results of the fire scene reported that the heat dissipation rate and the smoke diffusion time were 80% similar to the real data (Shen et al., 2008). However, FDS software focuses on calculation, and the model is inadequate for the representation of the building information and 3D visualization. Hence, this study translates the simulation results into the BIM model so that users can obtain important information from a more user-friendly operating interface. The proposed system can create a time progression simulation according to the arrival time of firefighters at the fire scene. After the firefighters have retrieved the rescue information, they can assign teams and determine the flashover time based on the simulation result from FDS and the fire prediction from the BIM 3D model. The proposed system could replace the traditional rescue methodology and reduce casualties among firefighters.

The earlier the detection of the fire, the more time the occupants have to escape. Therefore, the conditions of the fire scene and real-time feedback are crucial to emergency evacuation. This research integrates Internet of Things (IoT) technology, which enables monitoring at the scene. In the event of the source of a fire being detected and also the environment reaching a certain temperature and CO concentration level, the BIM model will immediately display the situation and sound an alert that the building occupants should evacuate. Then the fire simulation results and the real-time situation can be used to control the escape pointers to guide evacuees along a safe escape route, increasing their chance of survival.

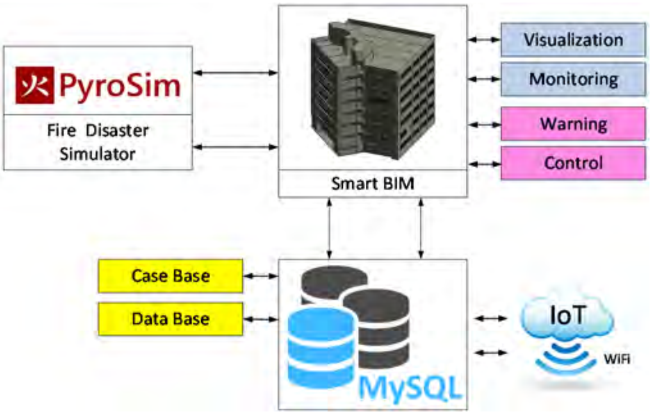


Fig. 1: System Framework for the BIM-based Visualization and Warning System.

2. FDS AND BIM INTEGRATION

This research uses a BIM model as its foundation, uses FDS to simulate structural fires, and sets the position of the fire source and simulation parameters according to different scenarios. The simulation results and the time are retained in a case database, from which the firefighters can retrieve a case similar to the current situation. The results of a case obtained from the simulation are translated into the BIM model and can be visualized in various ways (e.g., 1D text, 2D diagrams, 3D models) as the rescue basis for the firefighters. Figure 2 shows the concept of FDS and BIM Integration.

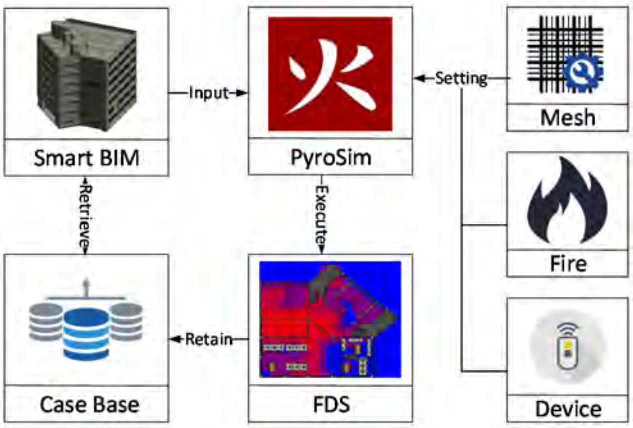


Fig. 2: The Concept of FDS and BIM Integration.

3. IOT AND BIM INTEGRATION

This research also integrates an IoT framework to propose a smart escape alert function. Environment sensors gather the building's physical factors, and then these physical factors are used to control the LED guide pointers to present danger alerts and evacuation guidance. The sensory data are stored in a cloud database, from which information is extracted for the BIM model. When the sensor value is anomalous, the BIM model will respond by visualizing the location of the detected abnormality and subsequently send out warning signals. This system, which both utilizes IoT technology to control the LED pointer to guide evacuees to escape and visualizes the result from the fire simulation, will inform fire rescuers about the fire scene prior to the commencement of rescue operations. This added information should reduce injury and death counts among firefighters while increasing the rescue rate of the evacuees. This concept is illustrated in Figure 3.

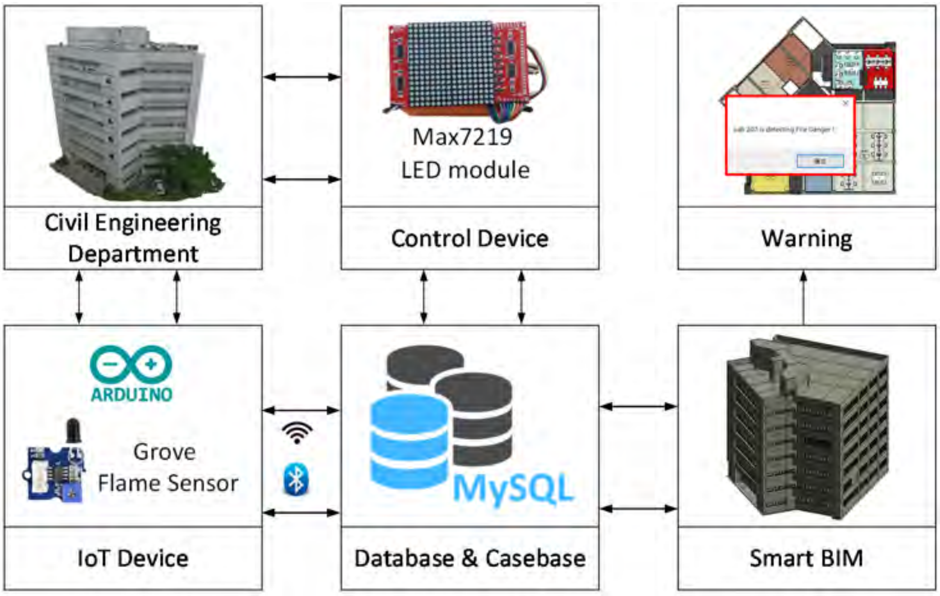
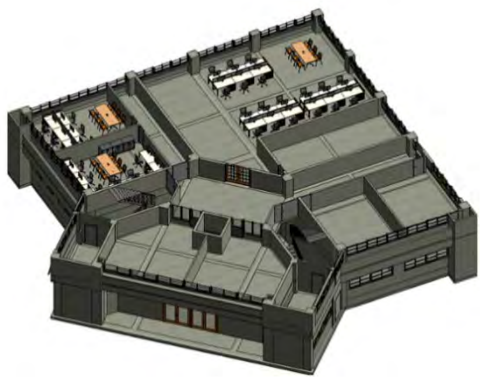


Fig. 3: The concept of IoT and BIM Integration.

4. DEMONSTRATION

The setting of this research was the Department of Civil Engineering at National Kaohsiung University of Science and Technology. First, a BIM model of a 7-storey building with a basement was constructed using Autodesk Revit for testing purposes, as depicted in Figure 4(a). This research uses PyroSim software to perform the fire disaster simulation as shown in Figure 4(b).



(a)3D Model in BIM

(b)3D Model in PyroSim

Fig. 4: 3D model example of Civil Engineering at National Kaohsiung University of Science and Technology.

4.1 Graphical User Interface

The fire rescue visualization and alerting system is constructed on the Autodesk Revit BIM software and uses Microsoft .Net C# to develop the API (Application Programming Interface) provided. As shown in Figure 5, users can choose 'Fire' in the Revit toolbar menu. This will display every functionality related to the fire rescue visualization and warning system.

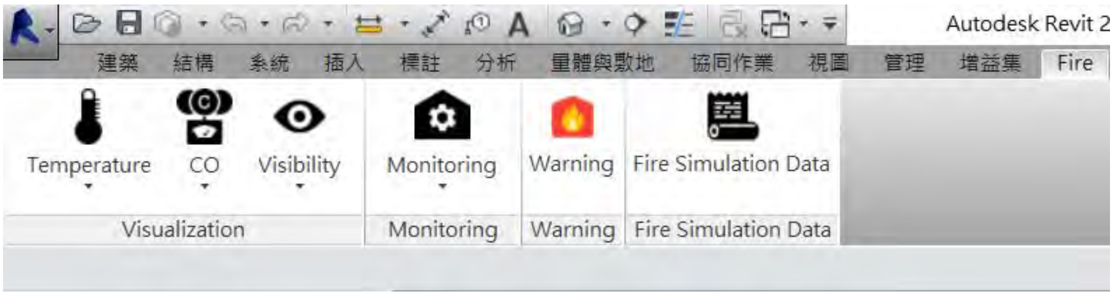


Fig. 5: The GUI of the BIM-based Visualization and Warning System for Fire Rescue.

4.2 Visualization for Fire Disaster Simulation

Fire simulation will generate data such as temperature, carbon monoxide concentration level, and the loss of visibility caused by smoke. The simulation results are shown in Figure 6-8. This study uses Autodesk Revit API to develop the functionality of information visualization by inputting these data to the BIM model. This will provide the firefighters with effective information to carry out the rescue operation.

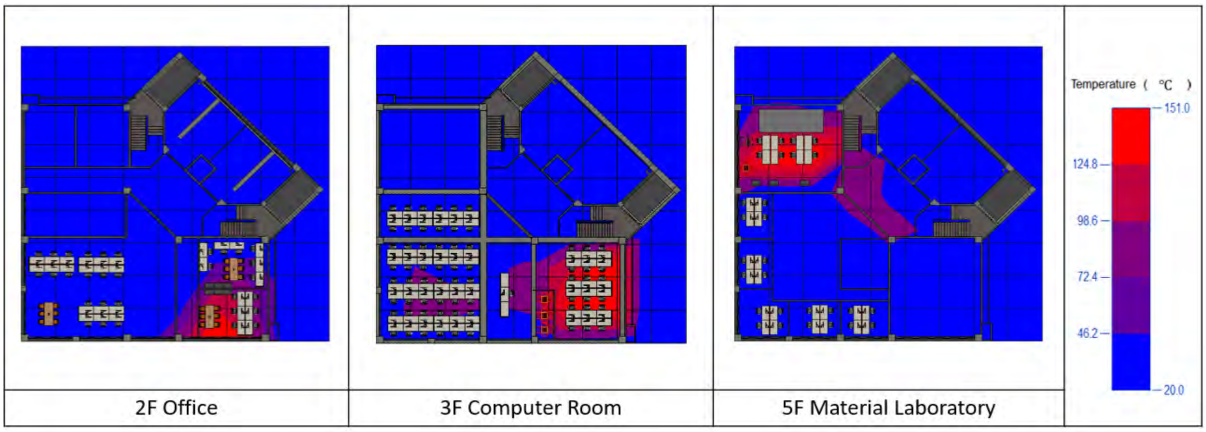


Fig. 6: Simulation Result for the Fire Scene's Temperature.

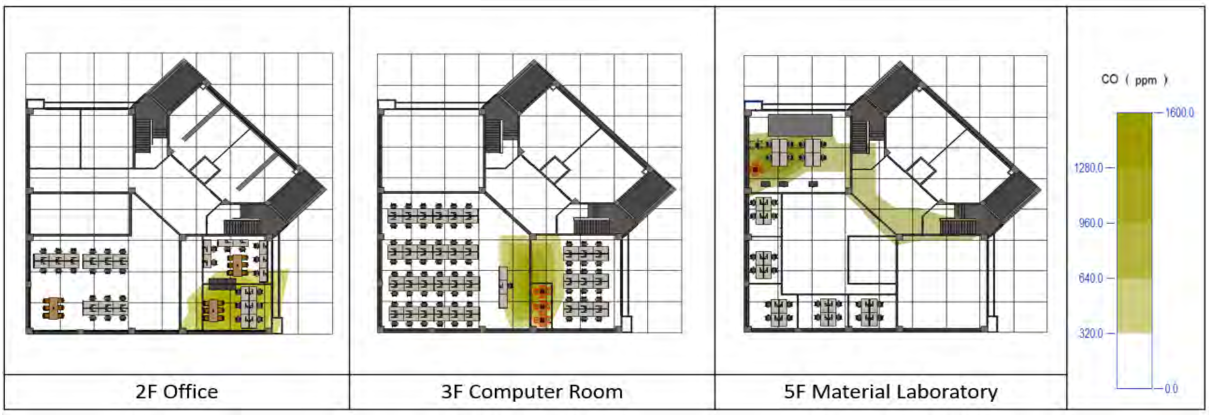


Fig. 7: Simulation Result of CO in Fire Scenes.

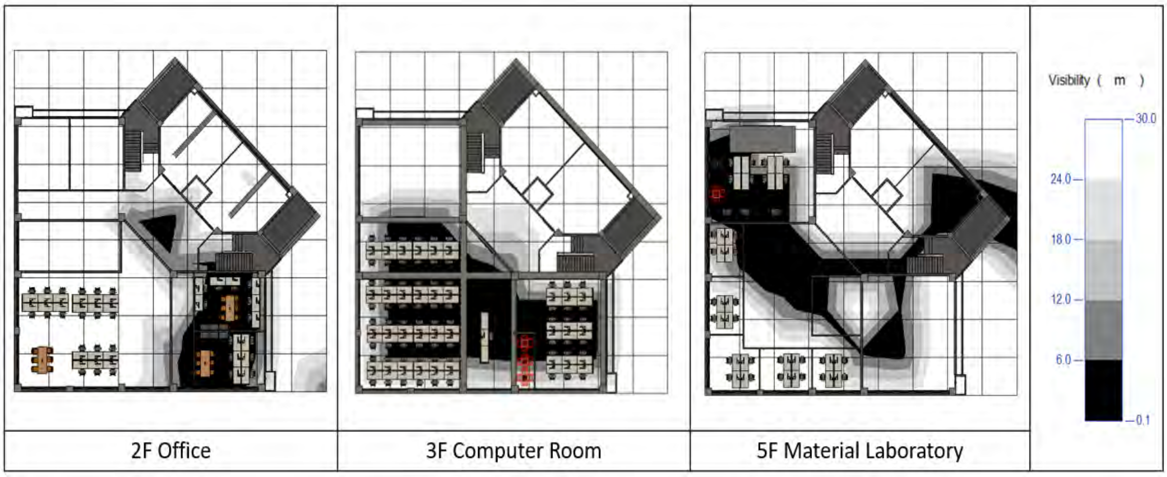


Fig. 8: Simulation Result of the Fire Scene Visibility.

4.3 Warning System

This research utilizes Revit API to allow the database to connect with the detectors and return the result to the BIM model. When the detectors detect a rise in temperature or the presence of a flame, the system will send out alerts and point out the position of the abnormality, as shown in Figure 9.

Fig. 9: Alert for the Position of Fire.

This study installs temperature and flame detectors at the exits and emergency exits. When a flame is detected, the door element in the BIM model will shine and display a warning, and the system will automatically switch the LED pointer to ‘no entry’, in order to prevent the evacuees accidentally opening the door of the emergency exit, which may create more casualties, as shown in Figure 10. Firefighters can evaluate the trend of the fire and control the LED guide pointer based on the simulation result and environmental monitoring data. This will help them to guide the building evacuees.

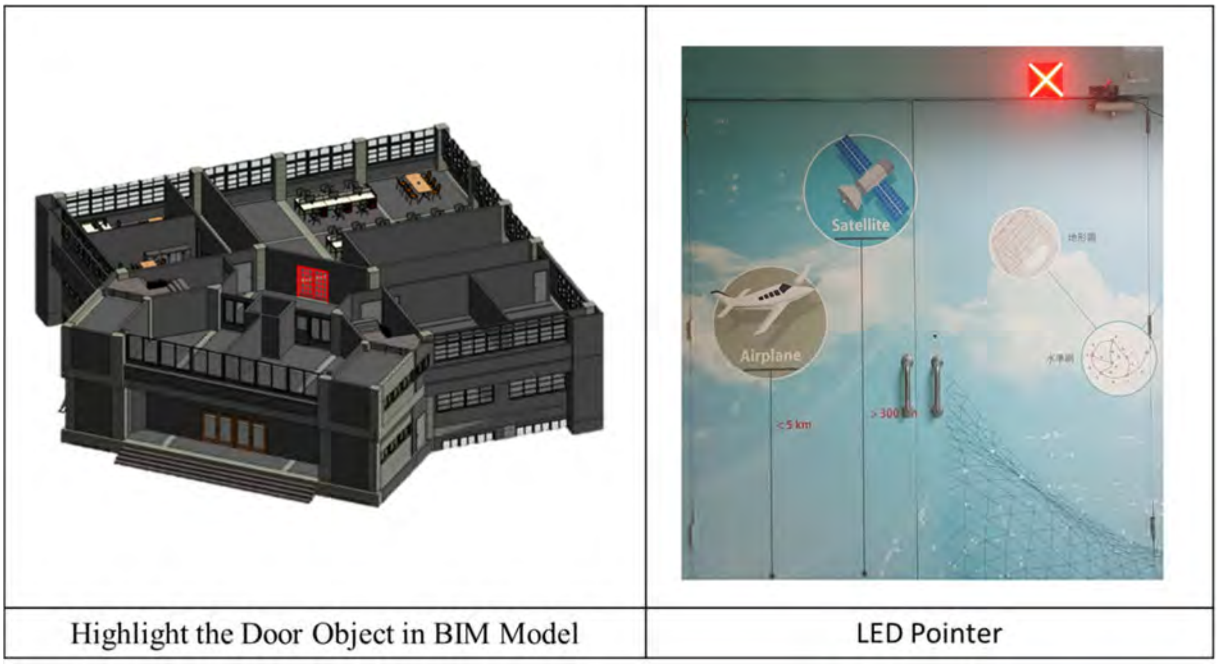


Fig. 10: LED Pointer Automation Control.

5. CONCLUSION

Casualties in a structural fire are mainly caused by uncertainties about the trend and size of the fire and unfamiliarity with the environment. Therefore, this research integrated three major research fields, namely, BIM, fire simulation, and IoT technology, to develop a structural fire visualization and warning system. It provides four major functions: visualization of the fire, environmental monitoring, fire alert, and pointer sign control. Prior to the fire, it is possible to simulate different fire scenarios by using FDS and visualize the results in a BIM model. This allows users to understand the possible hazards and circumstances that may occur in the environment during a fire. On the other hand, in the event of a structural fire, we can use IoT technology to return the real-time conditions and present them in the BIM model, while simultaneously providing a visual representation of the environment and a warning function for evaluation in rescue planning. In addition, the system can control the LED guide pointers according to the real-time situation to assist the occupants to escape, reducing the number of casualties. This research mainly solves the data integration problem of FDS, BIM, and IoT, and it provides accurate real-time data to the firefighters. This eliminates the lack of information inherent to traditional fire rescue, which can lead to casualties. Furthermore, automated guide pointers that provide correct instructions according to the simulation results of the live situation may reduce the number of casualties due to panic.

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A PLATFORM FOR STORING ROAD INSPECTION DATA BASED ON THE LOCAL GEOID WITH ITRF COORDINATE SYSTEM

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ABSTRACT: *Structures such as bridges, tunnels, road pavements, etc. are aging in most developed countries. Currently, various inspections are performed on these structures and inspection data will be accumulated every day. Three-dimensional models and information linkage are considered to utilize the data in each construction production cycle including planning, investigation, design and maintenance. In the future, it is highly possible that all data is accumulated in three dimensions, where the coordinate system which integrates all the three-dimensional models is required. Therefore, in this paper, we review coordinate systems and positioning technics and propose to utilize the International Terrestrial Reference Frame (ITRF) coordinate system. Specifically, the ITRF coordinate system, a three-dimensional orthogonal coordinate system capable of describing the entire earth, is applied as the world coordinate system, and the coordinate axis referring to the vertical direction obtained from the geoid is applied to the local coordinate system. We construct the ellipsoid, geoid and topographic surface on CAD, showing the effect of the geoid, and verify its applicability. Furthermore, we convert inspection data of road pavements to three-dimension to consider the effect of visualization and discuss the effectiveness of the coordinate system utilized in the construction production cycle.*

KEYWORDS: *large model, ITRF coordinate system, 3D model, BIM*

1. INTRODUCTION

In the field of Building Information Modeling (BIM), the study of three-dimensional annotated models (3DA) has been discussed. There has been an effort in standardization in the construction field such as IFC-Bridge, IFC-Road, IFC-Tunnel, etc., in buildingSMART International. In Japan, the use of 3D models has been considered even in the field of construction maintenance and management since the unexpected collapse of the Sasago tunnel in 2012 in Japan spread awareness of social issues. In Japan, the periodic (once every 5 years) inspection of all bridges and tunnels has been mandated since 2014 and more data has been accumulated, especially, considerable inspection data of road pavement. A dedicated survey vehicle acquires surface-continuous images and laser data, etc. of road pavement, and consolidated information is stored in units of evaluation sections of 20 m or 100 m into the database. The number of items per section is over 100 items including repair histories. In Japan, it is estimated that periodic inspections of 12,000 km of road, which is 1% of the total 1.2 million km, are conducted every year. About 600,000 records accompanying road surface images and laser data are stored every year. At present, the mechanization of inspection technology is advanced and it is common to acquire data in cooperation with Global Navigation Satellite System (GNSS) positioning. For example, GNSS sensors are also attached to survey vehicles of road pavements and position information is acquired at the same time.

In the field of maintenance and managing roads, there are studies on the automation of earthwork and maintenance (Skibniewski and Hendrickson, 1990, Seppä and Heikkilä, 2009), the construction of road paving sensing system (De Diego et al., 2011, Wu et al., 2016), the automatic detection of distress from photographed images and lasers, (Huang et al., 2014, Cubero-Fernandez et al., 2017, Ouma and Hahn, 2017), the measurement of tunnel lining and road delineate shape (Puente et al., 2016, Rodríguez-Cuenca et al., 2015), and the optimization of repair works or asset management (Hajek and Phang, 1989, Marttinen and Heikkilä, 2015, Reale et al., 2010). Also in research on handling wide area data, there are studies on the virtual globe of three-dimensional geographic information system (3D-GIS) (Nebiker et al., 2007, Brovelli et al., 2018) and the optimization of bridge management in multiscale (Lukas and Borrmann, 2012).

To use the 3D models, the smaller the gap between the real space and the virtual space, the easier for interference checking and comprehensive judgment. Among the problems of 3D models used in the civil engineering structure, the coordinate system is the one that is greatly different from the manufacturing industry. Given that roads sometimes cross regions and countries, it is necessary to consider the fact that the earth is spherical. Brovelli and colleagues (2018) built a virtual globe with NASA World Wind as the core engine for visualization of telecommunications data, but do not mention the shape of the earth and its coordinate system in detail. In this paper, we attempt to apply the coordinate system describing the shape of the earth to three-dimensional visualization for road pavement inspection data and examine the coordinate system in integrated environments.

2. GNSS POSITIONING AND COORDINATE SYSTEMS

2.1 Positioning technology

About the 2nd century BC the earth was proved to be spherical. Following the evolution of technics such as the Cartesian coordinate system and accurate observation methods of the crustal deformation and gravity, the method which accurately expresses the geoid has been established internationally. The current Japanese surveying law adopts the Earth-Centered, Earth-Fixed coordinate system (ECEF).

Due to active diastrophism in Japan and New Zealand, both governments have introduced semi-dynamic correction, which enables surveying to reflect the position information of reference points that keep changing over time. In addition, Quasi-Zenith Satellite System (QZSS) operated by the Japanese government began offering Centimeter Level Augmentation Service (CLAS) from April 2018, offering highly accurate position information in the construction production cycle.

2.2 Earth-Centered, Earth-Fixed coordinate system

ECEF is used as a coordinate system expressing a shape of the earth, where the center of gravity of the earth and the center of the earth ellipsoid are aligned. The earth ellipsoid is an ellipsoid approximating the geoid. The geoid is a shape of the earth and is one of an equipotential surface of the gravitational potential of the earth. It is the closest to the surface of Mean Sea Level in the world (Figure 1).

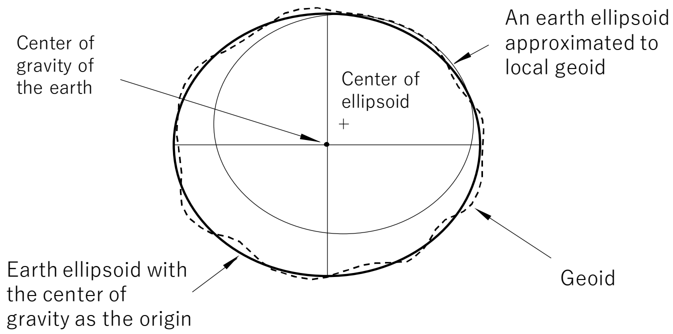

Fig. 1: Earth ellipsoids and geoid.

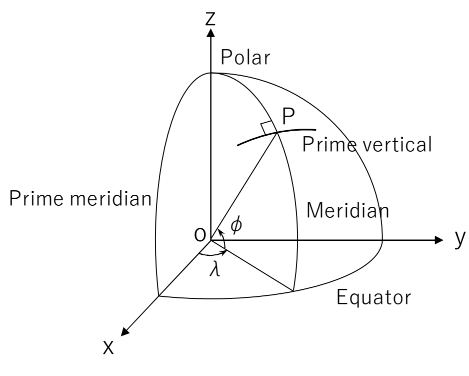

Fig. 2: Earth-Centered, Earth-Fixed coordinate system and prime vertical on point P.

ECEF coordinate system consists of three mutually orthogonal axes, of which origin is the center of gravity of the earth. The positive direction of x axis is the intersection of the equator and the Prime Meridian at longitude 0 degrees passing near the Greenwich astronomical observatory. The positive direction of y axis is the intersection of the equator and the meridian at 90 degrees east. The z axis coincides with the rotation axis where the north is positive (Fig. 2). The ITRF coordinate system is mainly used in the world.

2.3 ITRF coordinate system and WGS84 coordinate system

The International Terrestrial Reference Frame (ITRF) is specified by Cartesian ECEF (Earth-Centered, Earth-Fixed) coordinates X, Y, and Z. Its unit is the meter. The Geographical Survey Institute (GSI) of the Japanese government adopted ITRF2008 and adopted Geodetic Reference System 1980 (GRS80) ellipsoid for conversion to geographical coordinates (longitude, latitude and height). This ellipsoid has been adopted in most countries (Institut Géographique National, 2016).

Coordinates obtained by GNSS positioning such as smartphones and drones are based on World Geodetic System 1984(WGS84), where the earth ellipsoid is the WGS84 ellipsoid. The WGS84 coordinate system is independently managed by the United States. Originally it was the same ellipsoid as WGS 84 but due to the number of digits of calculation the leading radius is the same but the induction variable is somewhat different. The WGS 84 coordinate system is one of the coordinate systems which describes coordinates by longitude and latitude, driven by combining geographic coordinate systems (GCS) and vertical coordinate systems (VCS).

The epoch of the WGS84 coordinate system datum is 1984. Initially there was a difference between WGS85 and ITRF by around 70 cm. Through the revisions of 1994 and 1997, it became less than 10 cm compared to the ITRF coordinate system group. Note that technical differences would arise if you use the current coordinate system for the GPS measurement coordinates prior to 1997. As confirmed by ESRI's ArcGIS, no difference in position is confirmed between the ITRF system and the WGS 84 system.

2.4 Geographic coordinate system

In Japan, the current coordinate system used to express accumulated inspection data spatially is the Japanese plane rectangular coordinate system. This is a two-dimensional map coordinate system obtained by projecting the earth's surface approximated by the GRS80 ellipsoid onto the plane by the Gauss-Kruger Projection. The procedure to project a steep road onto the map is as follows: first, you project a steep road to the ellipsoid, and then project to the plane of orthogonal coordinate system. At this time, a scale factor depending on the longitude from the origin is set, so that the gap occurred in the process of the projection from the curved surface of the ellipsoid onto the plane is within 1 / 10,000.

In other words, depending on the distance from the meridian passing through the origin of the projection plane, the distance of 10km between two points on the projection plane differs from around -1 meter to 1 meter. Although the Japanese plane rectangular coordinate system is useful for calculating a distance and gradient compared to the geographic coordinate system, it requires us to pay attention in practice to the difference of the distance on the plane. Therefore, it is not necessarily suitable as an environment of the CLAS.

2.5 Large model

Comparing GCS + VCS to Cartesian ECEF coordinate systems as a coordinate system describing a 3D model which considers the shape of the earth, the Cartesian ECEF is preferable since its 3D model uses 3D coordinates. By adopting the ITRF, it is possible to integrate data with GNSS positioning results and easier to grasp the gap from the real world.

As a design reference plane of 3D models, the local ellipsoid or geoid surface which is assumed as being flat is conceivable. The vertical direction of the ellipsoid is the normal direction of the tangential plane at the point P on the ellipsoid, and the vertical direction of the geoid is the direction of gravity of the point P. Since gravity depends on the density distribution inside the earth, the geoid is an irregular surface with undulations on the ellipsoid. In construction sites, the geoid is preferable as the reference plane because it offers us information about the direction of gravity which is required in stress calculation and drainage planning.

Therefore, we define a small model as a 3D model where the design reference plane is the geoid and the area is sufficiently small so that the geoid can be assumed to be flat. In addition, we define a large model as a 3D model composed of two or more small models, such that it can be placed on the ITRF coordinate system where the geoid undulation is globally considered. Considering the continuity of the construction survey flow so far, the local coordinate system of construction sites is suitable as the coordinate system to be used in small models.

Large models and small models have their origin with ground control point (GCP) to place on the ITRF coordinates and a set of reference vectors to indicate the direction of the coordinate axes, and their vertical directions are the same as the normal direction of the geoid tangential plane (Fig. 3). As a result, the design space, which is a small model, can be placed in a large model that considers the geoid.

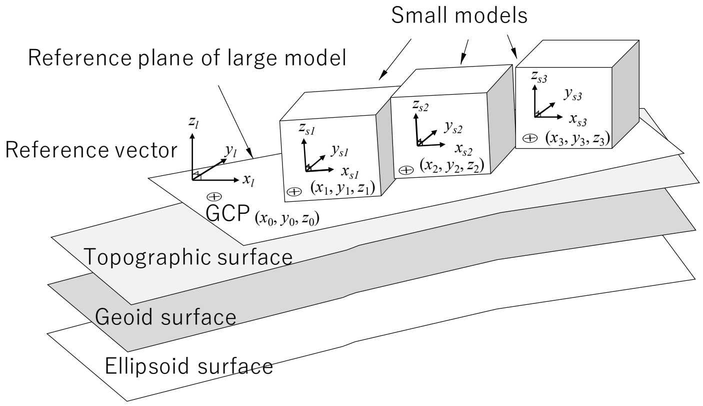

Fig. 3: Small Models placed in a Large Model.

3. AN APPLICATION OF LARGE MODEL

3.1 Conversion from geodetic coordinates into ECEF

Assuming that the equatorial radius is a and the polar radius is b, the formula of the ellipsoid is

$$\frac{x^2+y^2}{a^2}+\frac{z^2}{b^2}=1. \qquad (1)$$

When the geocentric latitude of the point P is ϕ, the geographical latitude is ϕ' (Fig. 4), and the radius of curvature in the prime vertical is N, coordinates (x, y, z) of the point P on the ellipsoid in ECEF coordinate system is expressed by following formulas (2)-(6) (Hofmann-Wellenhof and Moritz, 2006),

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} (N+h)\cos\varphi'\cos\lambda \\ (N+h)\cos\varphi'\sin\lambda \\ \{N(1-e^2)+h\}\sin\varphi' \end{pmatrix} \qquad (2)$$

$$N=\sqrt{\frac{a^2}{1-e^2\sin^2\varphi\prime}} \qquad (3)$$

$$\tan\varphi'=\frac{1}{1-e^2}\tan\varphi \qquad (4)$$

$$e^2=f(2-f) \qquad (5)$$

$$h=H+N_g, \qquad (6)$$

where a is the semi-major axis, f the inverse of flattening factor of the Earth, e the eccentricity, h the ellipsoidal height, H the elevation, and N_g the geoid height.

Parameters of GRS80 are in Table 1.

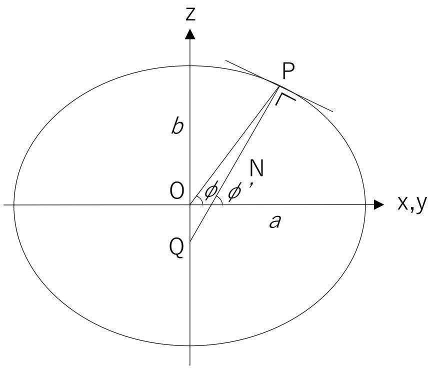

Fig. 4: Geodetic Latitude ϕ and Geocentric Latitude ϕ'.

Table 1: Parameter of GRS80.

Parameter	Notation	Value
Semi-major Axis	a	6,378,137m
Flattening Factor of the Earth	f	1/298.257222101

Using the above formulas and parameters, the major longitude and latitude points of the boundary lines, the coastlines and the oceans of the countries and regions of the world which are expressed in longitude and latitude were converted to the ITRF coordinate system. The validity of the conversion formula was confirmed (Fig. 5).

Fig. 5: View of world borders upon GRS80 surface using ECEF coordinate system.

3.2 Creating a 3D model of the earth's surface on ECEF

We took Fuchu City and Hino City which are approximately 40km west of Tokyo as an example to verify our method. The grid size was 3 seconds for latitude and 4.5 seconds for longitude, so that the cell size of raster data can be resampled as 100m in the Japanese plane rectangular coordinate system. The geoid height of this grid was acquired from the Geographical Survey Institute's "Japan Geoid 2011" (Ver. 2), and the elevation of the topographic surface was acquired from the numerical elevation model 10m mesh (elevation) (Fig. 6). From acquired values of longitude, latitude, height and the formulas (2) - (6), the xyz coordinate values of the three-dimensional orthogonal coordinate system of the ellipsoid surface, the geoid surface, and the topographic surface were calculated. From the calculated xyz coordinates, we created a three-dimensional surface model composed of triangle 3DFACE using AutoCAD Civil 3D 2017 (Fig. 7). In this figure, it can be confirmed that the geoid and the ellipsoidal surface are displayed behind the topographic surface, which expresses the unevenness of the terrain.

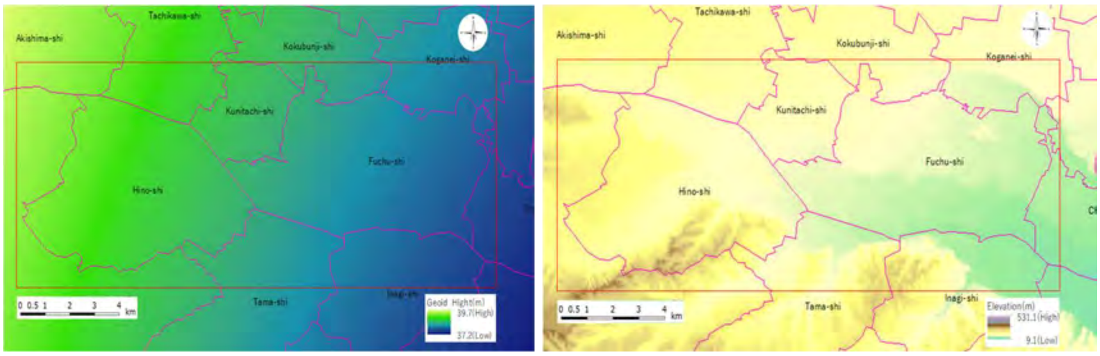

Fig. 6: Target area is surrounded by a red frame. Left map shows geoid height, right map shows elevation which means altitude above sea level.

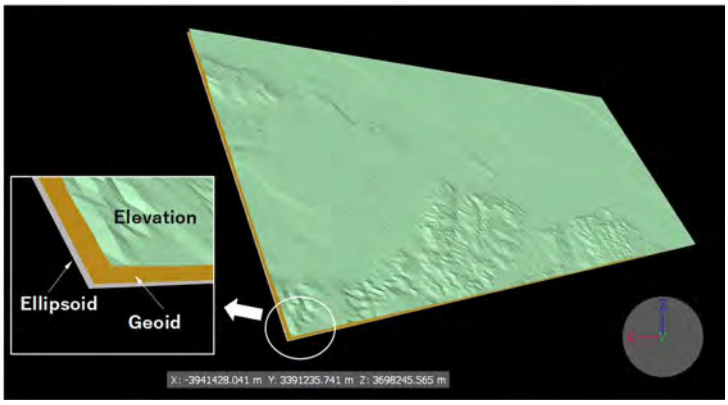

Fig. 7: View from y axis direction of created 3D model of earth surfaces.

3.3 Deviation between the geoid and ellipsoid in ITRF coordinate system

Here, we analyzed the effect of applying the normal direction of the geoid surface in the vertical direction of the small model, targeting the mentioned area. The 3DFACE's normal direction of the geoid can be estimated by the angle of the 3DFACE's normal direction of the earth ellipsoid surface. The variation of 3DFACE's normal direction is considered as the angle between the geoid and the ellipsoid surface. Taking the 3DFACE's normal direction of the geoid located in the most southwest as a reference, from the angle between reference normal direction and other 3DFACE, we can find that the angle increases as the distance between reference 3DFACE and other 3DFACE increases (Fig. 8). The distribution of the deviation between the normal direction of the geoid surface at the same place and the normal direction of the ellipsoidal surface was between 14.8 seconds and 27.1 seconds (Fig. 9). In a case of a deviation angle of 27 seconds, a building whose height is 300 meters will be 4 centimeters different from the position on the ellipsoidal surface.

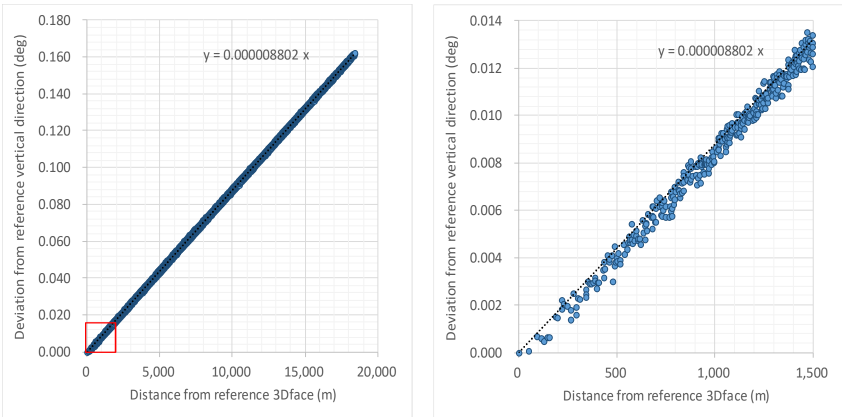

Fig. 8: Scatter plot of deviation of vertical direction and distance from reference 3DFACE. Right figure is enlarged of left figure in its range from 0 up to 1,500 meters with x-axis.

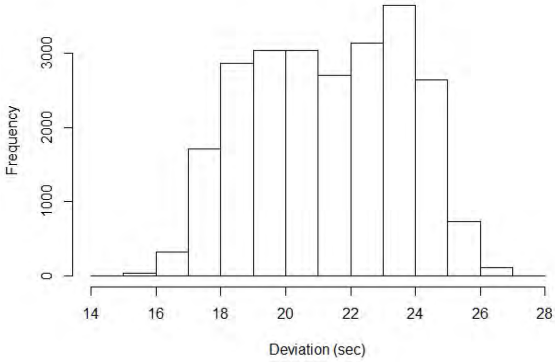

Fig. 9: Histogram of deviation of the normal direction of 3DFACE of geoid and earth ellipsoid.

When creating a digital mockup from design data or conducting a construction simulation, if the same vertical axis is applied to continuous small model groups, the difference will become larger for a large-scale structure. Also, the deviation between the geoid and ellipsoidal surface varies from place to place. It has been confirmed that the deviation was about twice as wide in a range of 15 km x 8 km in the target area. Thus, when considering geoids, it is necessary to use appropriate information.

3.4 Visualization of inspection data

When road managers maintain and manage road pavement, they will be required to grasp the damage tendency of the entire road pavement under management and determine the order of repair priorities. Therefore, we verified the effectiveness of the ITRF coordinate system in applying it to a whole project that took place in a mountainous area.

We displayed the crack ratio of road pavement on the road network considering the geoid in a mountainous area in a study area about 20 km × 30 km in size. We created ellipsoidal, geoidal and topographic surface as 3DFACE using AutoCAD Civil 3D in the same way mentioned above. The elevation range of the target area is about 1,500 meters. The height range of the road network is about 500 meters. The road network converted from GIS data, which was projected into two dimensions, to three-dimensional ITRF coordinates like the surface data. The color range of the road network is according to the crack ratio ranking of the road pavement. Since it is impossible to grasp the entire deteriorated situation of the road depending on its actual height and width, cylinders with a radius of 100 meters and a central axis based on the road center line were created and highlighted (Fig. 10). As shown in Figure 10, the crack ratio is relatively low in lowlands and the crack ratio is high in the mountainous area. In the section with a high crack ratio, the policy of not repairing the dead-end roads in mountainous area is visualized in three-dimensional views. Moreover, compared with conventional topographical information, our method can acquire more realistic topographical information. Therefore, for further cost reduction, it can be expected to be effective in determining the construction section and effectively optimizing materials procurement.

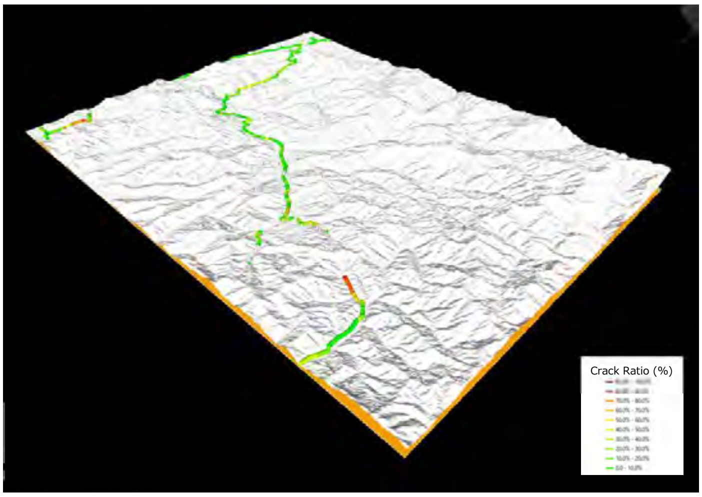

Fig. 10: Display of road network considering the geoid on ITRF coordinate system.

4. CONCLUSIONS

In this paper, we proposed to use ITRF coordinate system considering the geoid as a concept of a coordinate system for the maintenance and management of civil engineering structures in utilization of 3D model. Specifically, we divided the coordinate system between a large model and a small model, and further suggested that the vertical axis of the small model be the same as the normal direction of the geoid. In application to design data, we evaluated the effects considering the geoid by coordinate transformation from longitude and latitude notation to three-dimensional orthogonal coordinate system. Moreover, it verified the effectiveness of applying ITRF coordinate system to a maintenance management project.

Future tasks include cooperation with a database of inspection data, application of raster data, and cooperation with existing 3D GIS data. In the polar coordinate system, the south pole and the north pole cannot be expressed because of the divergence of coordinate values. But the ITRF coordinate system makes it possible to represent this position. In the future, we believe that a platform which can handle more global data and more precise data uniformly will become important.

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OPTIMAL PATH PLANNING OF UAV FOR AIRBORNE IMAGING OF OUTDOOR STRUCTURES

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ABSTRACT: *When we try to detect the degradation of bridges and tunnels by visual inspection, we have to make a scaffold temporarily and/or introduce a vehicle for high-place work. In addition, we sometimes need to regulate traffic. For avoiding such difficulties, unmanned aerial vehicles (UAV) have been used for photogrammetric inspection of outdoor structures recently. When we use a UAV for such a purpose, it has to visit all the inspecting points and take photos of them. Also, we have to make an efficient path for shortening the inspection time. Therefore, in this research, we propose a method for making a flight plan to take photos of target structures. In the proposed method, we first identify the optimal viewpoints which cover all the inspecting points and satisfy the overlap ratio of photos. This problem is formulated as a mathematical optimization problem and solved by an optimization solver. After that, we make a cyclic path which visits the optimal points and returns to the starting point. It is well known as the traveling salesman problem, so we can use various methods to solve it. Finally, we can obtain the optimal flight plan of UAV.*

KEYWORDS: *UAV, Path Planning, Airborne Imaging, Image Inspection, Mathematical Optimization.*

1. INTRODUCTION

Infrastructures—roads, bridges, tunnels, and so on—support countries' economic activities. Therefore, aging infrastructures should be maintained or renovated timely. For this goal, the periodical inspection of infrastructure is very important to understand the current status and detect the time for maintenance/renovation. Moreover, periodical inspection should be done efficiently for reducing capital and manpower cost. However, it is not the case now: for example, particular vehicles are needed for visual testing by inspectors at high altitude, and lane closure is also needed in many cases.

Because of these backgrounds, efficient and effective techniques for infrastructure inspection and monitoring have been developed. Especially, unmanned aerial vehicles (UAV) have got much attention recently for inspection at high altitude. If UAVs are introduced into on-site inspection, then inspectors can take photos of the target structures and examine their status. Also, inspectors can select places for hammering test by using the photos. Moreover, we can use UAVs for many purposes: surveying construction sites, monitoring the progress of construction, integrating as-built information, and so on (Metni and Hamel (2007), Siebert and Teizer (2014), Ham et al. (2016), Bang et al. (2017), Dupont et al. (2017), Qu et al. (2017), Kahloo et al. (2018)).

It is well known that UAVs can fly and take photos autonomously when they receive the GPS signal and the photographic subject is the surface of the ground. On the other hand, UAVs cannot receive the GPS signal when they fly in the mountain area or around the large-scale structures. In such cases, UAVs have to be controlled by an operator. Moreover, if targets are outdoor structures, for example, bridges, buildings, and so on, then an operator takes photos of targets manually. For such an operation, we have to make a flight plan in advance for taking photos which cover the targets with enough overlap.

On the other hand, the maximum flight time of UAVs is about 30 minutes. Also, an operator must avoid a crash by running out of battery. Thus an operator always keeps some allowance for battery. Therefore, practical flight time becomes shorter than the maximum flight time. It is difficult to make a flight plan of a UAV for taking photos of the targets under this time limitation.

In this research, we propose a method for making a flight plan to take photos of target structures. In the proposed method, we first identify the optimal viewpoints which cover all the inspecting points. For this goal, we make a mathematical optimization problem and solve it by an optimization solver. After that, we make a cyclic path which visits the optimal viewpoints and returns to the starting point. Finally, we can obtain the optimal flight plan of UAV.

2. PRELIMINARY: OPTIMAL SCAN PLANNING WITH MATHEMATICAL OPTIMIZATION

In this research, we propose a method for making the optimal flight path of a UAV for airborne imaging of outdoor structures. For this goal, we employ the method for optimal scan planning, which was proposed by Dan et al. (2010). For the self-containedness of this paper, we explain the outline of this method in this section.

2.1 Problem Settings

As you can imagine, 3D scanners cannot scan target structures from just one viewpoint: we have to set viewpoints to scan all the walls of them and merge the obtained data afterward. However, it is difficult to find the minimum number of viewpoints and where they are for covering all the walls of target structures. This difficulty is caused by self and mutual occlusion: we have to avoid occlusion for covering all the walls.

For this problem, Dan et al. (2010, 2011) proposed methods for making an optimal plan for scanning all the walls of target structures. In these methods, we first make a rough model of the target area in some way. After that, we solve mathematical optimization problems to find optimal viewpoints for scanning all the walls. The data of these problems are derived from the rough model mentioned above.

Dan et al. (2010) is based on a ground plan of the target area, and Dan et al. (2011) is based on a 3D mesh of the target structures and the surrounding environment. In this research, we apply the method proposed by Dan et al. (2010).

2.2 Mathematical Optimization Models

Dan et al. (2010) proposed two mathematical optimization models. In these problems, the following symbols are used:

[Set and Index]

- $i \in I$: candidate viewpoints for scanning,
- $j \in J$: walls of the target structures.

[Variable]

$$x_i := \begin{cases} 0, & \text{the candidate viewpoint } i \text{ is unadopted,} \\ 1, & \text{the candidate viewpoint } i \text{ is adopted.} \end{cases}$$

[Parameter]

$$d_{ij} := \begin{cases} 0, & \text{the wall } j \text{ is unmeasurable from the candidate viewpoint } i, \\ 1, & \text{the wall } j \text{ is measurable from the candidate viewpoint } i, \end{cases}$$

$$a_{ij} := \begin{cases} 0, & d_{ij} = 0, \\ \text{the angular distance of the wall } j \text{ from the candidate viewpoint } i, & d_{ij} = 1, \end{cases}$$

$$r := \text{ the upper bound of the number of the measurement.}$$

The angular distance (Fig. 1) is the angle of the wall from the viewpoint.

We can compute the value of parameters from a ground plan of the target area. The details of this computation were explained by Dan et al. (2010).

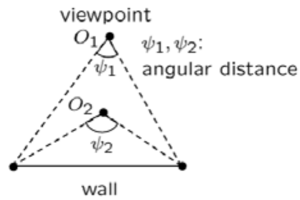

Fig. 1: Angular distance

Dan et al. (2010) proposed the following optimization models[1]:

$$\begin{array}{ll} \text{minimize} & \sum_{i \in I} x_i \\ \text{subject to} & \sum_{i \in I} d_{ij} x_i \geq 1 \quad (\forall j \in J), \\ & x_i \in \{0, 1\} \quad (\forall i \in I), \end{array} \qquad (1)$$

[1] In Dan et al. (2010), there are typos in the objective function of (2).

$$\begin{array}{ll} \text{maximize} & \sum_{i \in I, j \in J} a_{ij} x_i \\ \text{subject to} & \sum_{i \in I} d_{ij} x_i \geq 1 \quad (\forall j \in J), \\ & \sum_{i \in I} x_i \leq r, \\ & x_i \in \{0, 1\} \quad (\forall i \in I). \end{array} \tag{2}$$

The objective function of (1) is to minimize the number of viewpoints. Also, the term $d_{ij}x_i$ in the first constraint of (1) means as follows:

$$d_{ij}x_i := \begin{cases} 0, & \text{the candidate viewpoint i is unadopted } (x_i = 0) \\ & \text{or the wall j is unmeasurable from i } (d_{ij} = 0), \\ 1, & \text{the candidate viewpoint i is adopted } (x_i = 1) \\ & \text{and the wall j is measurable from i } (d_{ij} = 1). \end{cases}$$

Therefore, the first constraint of (1) means that all the walls are scanned from one viewpoint at least.

The term $a_{ij}x_i$ of the objective function of (2) means as follows:

$$a_{ij}x_i := \begin{cases} 0, & \text{the candidate viewpoint i is unadopted } (x_i = 0) \\ & \text{or the wall j is unmeasurable from i } (a_{ij} = 0), \\ a_{ij}, & \text{the candidate viewpoint i is adopted } (x_i = 1) \\ & \text{and the wall j is measurable from i } (a_{ij} > 0). \end{cases}$$

Therefore, the objective function of (2) is to maximize the sum of angular distances, that is, the density of scanning. Moreover, the second constraint of (2) is to restrict the number of measurement less than or equal to r.

3. DEFINITION OF PROBLEM

In this section, we define our problem considering in this paper.

As we explained in Section 1, it is useful for various applications to take images of the target outdoor structures by using a camera on a UAV. For this goal, we have to set the viewpoints and directions of a camera for covering all the walls of targets. Also, fewer viewpoints are desirable in view of the required time and cost. Therefore, we have to solve the following problem:

[Problem 1] How many viewpoints do we need to take photos of all the walls of the target structures?

Moreover, when we take photos practically by using a UAV, we have to control a UAV through the viewpoints, which are the optimal solution of the problem 1, without collision with the target objects and surrounding objects. Also, the flight path should be as short as it could be due to the limitation of battery capacity. Therefore, we also have to consider the following problem:

[Problem 2] How can we find the shortest path rounding the optimal viewpoints?

When we make an optimal path of UAV for airborne imaging, we have to consider a path in 3D space essentially. However, in this research, we consider a path in 2D space for preliminary study, that is to say, the vertical movement is ignored. It is equivalent to the case that we make an optimal path for vertical walls with the same height.

4. PROPOSED METHOD

In this section, we propose a method for solving the two problems in Section 3.

For the problem 1, we employ the method which was proposed by Dan et al. (2010). The goal of Dan et al. (2010) is to find the optimal viewpoints to scan all the walls of the target structures. It is similar to the problem 1: we want to take photos of all the walls of the target outdoor structures by a camera on a UAV. So we can apply the method of Dan et al. (2010) to this research. However, the difference cannot be ignored: we have to modify the optimization models in Section 2. In Section 4.1, we will explain the detail of our proposed method for finding the optimal viewpoints to take photos covering the walls.

On the other hand, Dan et al. (2010) did not consider a route through the optimal viewpoints. However, we need to make the flight path of a UAV in this research, because it is essential for on-site airborne imaging. This is corresponding to the problem 2 in Section 3. Thus, in Section 4.2, we will explain how to find the flight path through the optimal viewpoints which are found by the method in Section 4.1.

4.1 METHOD FOR FINDING OPTIMAL VIEWPOINTS BY UAV CAMERA

4.1.1 Optimization Model

In our proposed method, we solve a mathematical optimization problem to find the optimal viewpoints. In the optimization model, the following symbols are used:

[Set and Index]

- $i \in I$: candidate viewpoints and directions of a camera,
- $j \in J$: walls of the target structures.

[Variable]

$$x_i := \begin{cases} 0, & \text{the candidate viewpoint and direction of camera } i \text{ is unadopted,} \\ 1, & \text{the candidate viewpoint and direction of camera } i \text{ is adopted.} \end{cases}$$

[Parameter]

$$d_{ij} := \begin{cases} 0, & \text{the wall } j \text{ is invisible from the candidate viewpoint and direction of camera } i, \\ 1, & \text{the wall } j \text{ is visible from the candidate viewpoint and direction of camera } i, \end{cases}$$

$$a_{ij} := \begin{cases} 0, & d_{ij} = 0, \\ \text{the angular distance of the wall } j \text{ from the candidate viewpoint and direction of camera } i, & d_{ij} = 1, \end{cases}$$

$$b_j := \text{the lower bound of the sum of angular distances for the wall } j.$$

Some symbols are the same as the optimization model in Dan et al. (2010), which was shown in Section 2.2, but there are symbols which are different from the model.

In the optimization model in Dan et al. (2010), the index i means a candidate viewpoint for scanning. As you know, a 3D scanner can usually scan 360 degrees because a 3D scanner turns around while scanning. Therefore, the horizontal angle of view of a 3D scanner is not considered in Dan et al. (2010). On the other hand, in this research, we use a digital camera to take photos from a UAV, and a camera has its own angle of view. Therefore, we have to consider the direction of a camera on a UAV. In this research, we discretize the horizontal direction and deal with this problem. The detail will be discussed in Section 4.1.2.

Also, we introduced the new parameter b_j: it means the lower bound of the sum of angular distances for the wall j. When we use UAVs for airborne imaging, we have to consider the degree of overlap (Ajayi et al. (2017), Dandois et al. (2015), Leitão et al. (2016)). In this research, we consider the sum of angular distances for each wall instead of the degree of overlap.

We propose the following optimization model to find the optimal viewpoints and directions:

$$\begin{array}{ll} \text{minimize} & \sum_{i \in I} x_i \\ \text{subject to} & \sum_{i \in I} d_{ij} x_i \geq 1 \quad (\forall j \in J), \\ & \sum_{i \in I} a_{ij} x_i \geq b_j \quad (\forall j \in J), \\ & x_i \in \{0, 1\} \quad (\forall i \in I). \end{array} \tag{3}$$

The objective function of (3) is the same as that of (1): we would like to know the minimum number of adopted viewpoints and angles.

The first constraint of (3) has also emerged in (1) and (2): it means that the adopted viewpoints must cover all the walls of the target structures. Moreover, the second constraint of (3) means that each wall should be covered from the adopted viewpoints with the given lower bound of the sum of angular distances.

We can find the minimum number of viewpoints and directions by solving the optimization problem (3).

4.1.2 Values of Parameters

In this subsection, we discuss how to set the values of parameters which are used in the optimization problem (3).

First, we prepare the ground plan of the target structures (Fig. 2) and determine the elements of the sets I and J. The elements of the set I are the combinations of candidate viewpoints and candidate directions. In this research, we distribute candidate viewpoints like a lattice around the target structures (Fig. 3). Also, the direction of a camera on a UAV is discretized. We discretized 360 degrees into 8 directions uniformly (Fig. 4). Moreover, the elements of the set J are the walls of target structures. Especially, each wall is divided into an appropriate size and approximated by a line segment (Fig. 5).

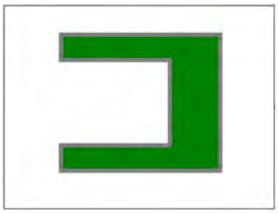

Fig. 2: Ground plan

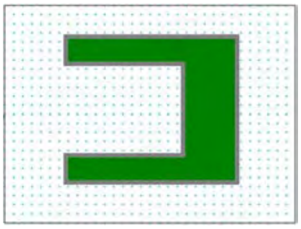

Fig. 3: Candidate viewpoints

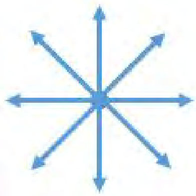

Fig. 4: Discretized directions

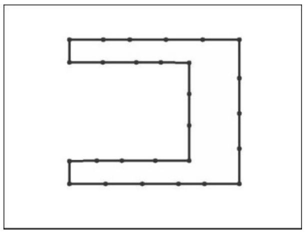

Fig. 5: Divided walls

Next, we compute the values of d_{ij} and a_{ij}. The 0-1 parameter d_{ij} shows the visibility of the wall j from the candidate viewpoint and direction i. Dan et al. (2010) proposed the method to examine whether a wall can be measurable from a viewpoint by a 3D scanner. This method inspects self and mutual occlusions and determines the visibility. In this research, we can apply it for examining the visibility. However, in addition to this, we have to consider another aspect of this research: the angle of view of a camera on UAV. As we explained above, a 3D scanner can scan 360 degrees because a 3D scanner turns around while scanning. On the other hand, a camera has its own angle of view, then we have to take into account it to determine the visibility (Fig. 6). We can examine it by easy geometric computation. If the wall j is not occluded and within the angle of view of a camera from a candidate point and direction i, then $d_{ij} = 1$. Otherwise, $d_{ij} = 0$. Moreover, we can compute the angular distance a_{ij} easily when $d_{ij} = 1$ holds (Fig. 6).

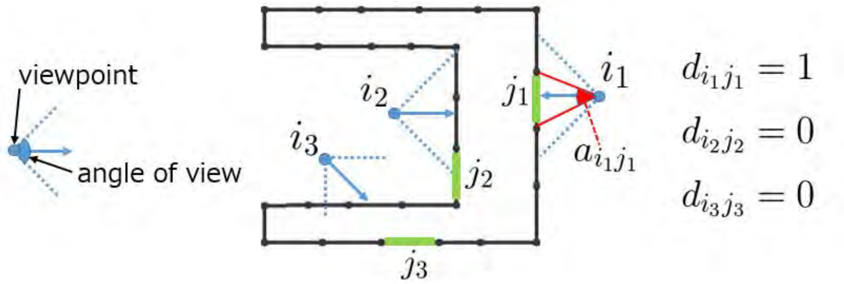

Fig. 6: Visibility of wall

4.1.3 Finding Optimal Viewpoints and Directions with Optimization Solver

Nowadays, we can employ optimization solvers to find an optimal solution of mathematical optimization problems. Now we prepared the optimization model (Section 4.1.1) and the data (Section 4.1.2), then we can find the optimal viewpoints and directions for airborne imaging of structures by using optimization solvers.

4.2 METHOD FOR OPTIMAL PATH PLANNING THROUGH VIEWPOINTS

In the previous section, we explained our proposed method for finding the optimal viewpoints and directions. However, it is not enough. A UAV flies continuously in the air, then we have to make a path through the optimal viewpoints for the on-site work.

In this research, we make the shortest tour through the optimal viewpoints as a UAV flight path. In fact, this problem is equivalent to the traveling salesman problem (Applegate et al. (2006), Cook (2012)), and we can use the proposed methods for solving it. In Section 4.2.2, we explain this approach. Moreover, for this approach, we need the data of the distance between the optimal viewpoints in advance. In Section 4.2.1, we explain how to compute it.

4.2.1 Shortest Paths between Optimal Viewpoints

First, we have to compute the shortest path between the optimal viewpoints. In this computation, we have to note that linear travel from one viewpoint to another is not allowed necessarily: a line segment between two viewpoints may be obstructed by the target structures and/or surrounding environment. For such a situation, we can use methods which have been proposed in the field of robot motion planning (Latombe (1991), de Berg et al. (2008), O'Rourke (1998)).

Consider the case that a robot is in a workspace with obstacles and a robot will move from a start point to a goal without collisions. For solving this problem, the visibility graph is useful. The visibility graph consists of the vertices in a workspace and the edges between these vertices (Fig. 7). However, we have to eliminate edges which collide with obstacles because a robot cannot move along such edges. If there exists a path from a start point to a goal, then a robot can go to the goal. Moreover, we can find the shortest path from a start point to a goal by using some methods. For example, the Dijkstra's method can find the shortest path.

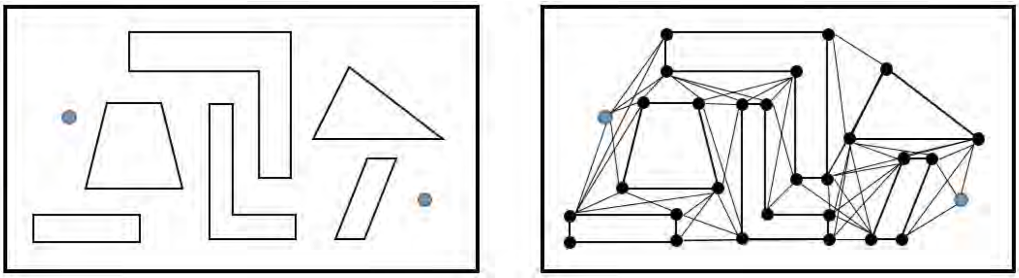

Fig. 7: Visibility graph

Practically, when we make a visibility graph, it is desirable that the target structures and obstacles in a workspace are enlarged uniformly (Fig. 8) (de Berg et al. (2008)). The size of a robot cannot be ignored in many cases. Thus we should ensure certain clearance for movement.

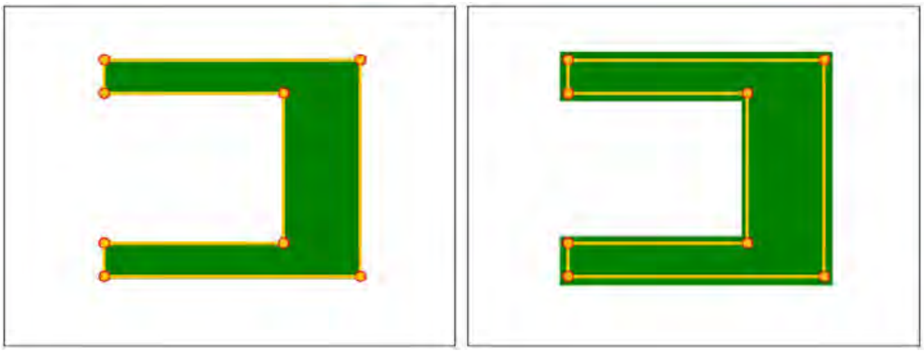

Fig. 8: Enlarged structures

After this process, we know the shortest paths between the optimal viewpoints which are obtained by the method in Section 4.1.

4.2.2 Shortest Tour through Optimal Viewpoints

Now we can find the shortest tour through the optimal viewpoints. As we wrote, this problem can be seen as the traveling salesman problem. The traveling salesman problem is a problem to find the shortest route that visits the given cities and returns to the origin city. This problem is NP-hard, then there is no polynomial time algorithm for this problem now. However, there are many practical algorithms and programs for this problem.

In this research, we employ the optimization model by Miller et al. (1960) and solve it by using an optimization solver. For the self-containedness of this paper, we show the model:

$$
\begin{array}{ll}
\text{minimize} & \sum_{i \neq j} d_{ij} z_{ij} \\
\text{subject to} & \sum_{j, j \neq i} z_{ij} = 1 \ \ (\forall i = 1, 2, \dots, n), \\
& \sum_{j, j \neq i} z_{ji} = 1 \ \ (\forall i = 1, 2, \dots, n), \\
& u_i + 1 - (n-1)(1 - z_{ij}) \leq u_j \ \ (\forall i = 1, 2, \dots, n; j = 2, 3, \dots, n; i \neq j), \\
& 1 \leq u_i \leq n - 1 \ \ (\forall i = 2, 3, \dots, n), \\
& z_{ij} \in \{0, 1\} \ \ (\forall i \neq j).
\end{array} \tag{4}
$$

In this model, the index i and j denote a city, the parameter d_{ij} is the distance between the city i and j, and the parameter n is the number of the cities. Also, the variable z_{ij} denotes the connectivity of the city i and j, that is, the salesman moves from the city i to j, and the variable u_i denotes the visiting order of the city i.

By using this formulation (4) and the data obtained by the method in Section 4.2.1, we can find the shortest tour through the optimal viewpoints. For this goal, we use some optimization solvers—the same approach as Section 4.1.3.

5. NUMERICAL EXPERIMENT

In this section, we show some numerical results by using our proposed method. Table 1 shows the computational environment of this experiment.

Table 1: Computational environment

OS	Microsoft Windows 10 Professional
CPU	Intel Core i7-3770 CPU @ 3.40GHz
Memory	8GB
Optimization Solver	GLPK 4.47

The target structure of this numerical experiment is a part of the Al Khamis Mosque in the Kingdom of Bahrain. Fig. 9 (left) is a bird's-eye view of the target area. In this experiment, we chose some walls of the Al Khamis Mosque and made the ground plan (Fig. 9, right).

Fig. 9: Target structures

First, as we wrote in Section 4.1.2, we set candidate viewpoints around the target walls and discretized directions. Also, we divided the walls of the target objects: in this experiment, the maximum length of divided walls is 180 pixels. After that, we solved the optimization problem (3) by using the optimization solver GLPK. In this experiment, the angle of view of a camera on a UAV is 90 (deg). Fig. 10, 11, and 12 show the optimal viewpoints when b_j = 10/15/25 (deg) holds for all j, respectively. We can observe that the more viewpoints are needed when the lower bound of the sum of angular distances becomes bigger.

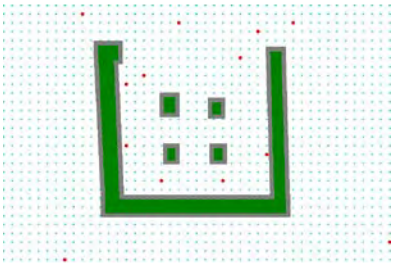

Fig. 10: Optimal viewpoints ($b_i = 10$ (deg), 13 viewpoints)

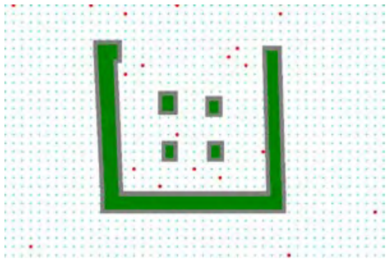

Fig. 11: Optimal viewpoints ($b_i = 15$ (deg), 19 viewpoints)

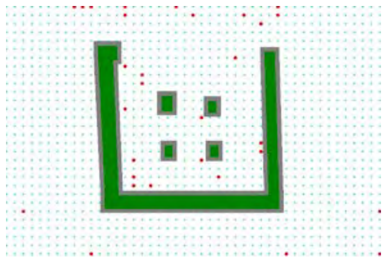

Fig. 12: Optimal viewpoints ($b_i = 25$ (deg), 30 viewpoints)

Next, we made the optimal tour through the obtained viewpoints as we wrote in Section 4.2. Fig. 13 shows the process of making the visibility graph ($b_j = 10$ (deg)). The line segments in Fig. 13 connect any two vertices: the blue line segments conflict with the (target) structures, and the red ones do not conflict. This figure was drawn by using OpenCV. Therefore, the red line segments make up the visibility graph. By using the data of the visibility graphs, we solved the optimization problem (4) to obtain the shortest tour through the optimal viewpoints (Fig. 14, 15, 16).

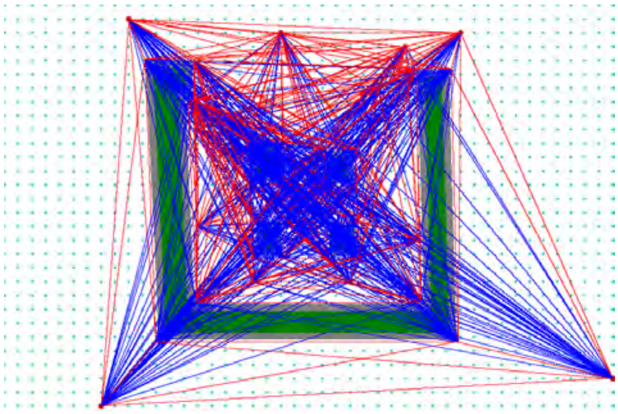

Fig. 13: Visibility graph

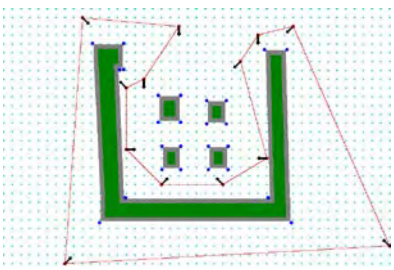

Fig. 14: Optimal tour ($b_i = 10$ (deg), 13 viewpoints)

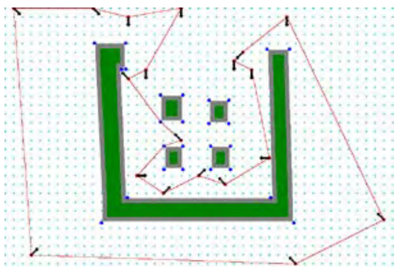

Fig. 15: Optimal tour ($b_i = 15$ (deg), 19 viewpoints)

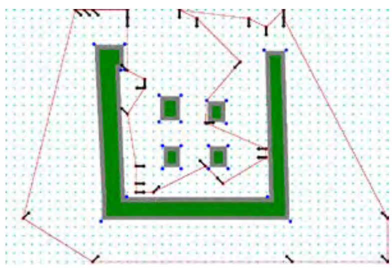

Fig. 16: Optimal tour ($b_i = 25$ (deg), 30 viewpoints)

6. DISCUSSIONS

In this research, we proposed a method for making the optimal path of UAVs for airborne imaging of structures. We assume that the movement of the vertical direction of UAVs is ignored. It is equivalent to the case that we make an optimal path for vertical walls with the same height.

First, our method finds the optimal viewpoint and direction for taking photos which cover all the walls and with sufficient angular distances. For this goal, we formulate this problem as a mathematical optimization model and solve it by using optimization solvers. Next, we make the shortest tour through the optimization viewpoints.

Actually, this problem is equivalent to the so-called the traveling salesman problem, then we can use various methods to solve it. In this research, we have employed the optimization solver "GLPK" to solve the optimization problem (4). We can download this solver (from https://www.gnu.org/software/glpk/glpk.html) without any charge and use it immediately. Also, there are many optimization solvers. They are designed for solving general optimization problems, including the problem (4), so we can use them for this research. Moreover, we can employ solvers which are specialized for the traveling salesman problem.

As we wrote, our current method assumes the level flight of a UAV while taking photos. So we would like to improve our method to be able to deal with the 3D movement of a UAV.

ACKNOWLEDGMENT

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RAPID 3D RECONSTRUCTION OF INDOOR ENVIRONMENTS TO GENERATE VIRTUAL REALITY SERIOUS GAMES SCENARIOS

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ABSTRACT: *Virtual Reality (VR) for Serious Games (SGs) is attracting increasing attention for training applications due to its potential to provide significantly enhanced learning to users. Some examples of the application of VR for SGs are complex training evacuation problems such as indoor earthquake evacuation or fire evacuation. The indoor 3D geometry of existing buildings can largely influence evacuees' behaviour, being instrumental in the design of VR SGs storylines and simulation scenarios. The VR scenarios of existing buildings can be generated from drawings and models. However, these data may not reflect the 'as-is' state of the indoor environment and may not be suitable to reflect dynamic changes of the system (e.g. Earthquakes), resulting in excessive development efforts to design credible and meaningful user experience.*

This paper explores several workflows for the rapid and effective reconstruction of 3D indoor environments of existing buildings that are suitable for earthquake simulations. These workflows start from Building Information Modelling (BIM), laser scanning and 360-degree panoramas. We evaluated the feasibility and efficiency of different approaches by using an earthquake-based case study developed for VR SGs.

KEYWORDS: 3D RECONSTRUCTION, VIRTUAL REALITY, SERIOUS GAMES, EARTHQUAKE SIMULATION

1. INTRODUCTION

Virtual Reality (VR)-based Serious Games (SGs) are becoming popular in recent years (Connolly et al. 2012). VR SGs have been applied widely for training and education purposes in different domains (Feng et al. 2018). One of the significant applications of training is emergency evacuation training such as fire evacuation (Duarte et al. 2014) and indoor earthquake evacuation (Lovreglio et al. 2018). These evacuation trainings aim to train building occupants in a virtual environment and equip them with the best evacuation practice, so that they can correctly behave and respond when facing such emergencies in their daily use buildings. In that respect, indoor 3D environments of existing buildings are instrumental in the design of VR SGs storylines and simulation scenarios, which can largely influence building occupants' behavior by providing a similar evacuation experience. Indoor 3D environments can be reconstructed from drawings and models. However, the modelling process may be time-consuming. Moreover, the generated data may not reflect the "as-is" state of the indoor environment and may not be suitable to reflect dynamic changes of the system (e.g., earthquakes), resulting in excessive development efforts to design credible and meaningful user experience. Therefore, there is a need to explore innovative approaches to overcome the limitations mentioned above. Such innovations should be able to rapidly reconstruct indoor 3D environments to become available in VR SGs. Therefore, this research examined and evaluated the effectiveness to rapidly create VR SG environments through three 3D reconstruction workflows, using Building Information Modelling (BIM), laser scanning, and 360-degree panoramas.

BIM can be defined as "a modelling technology and associated set of process to produce, communicate and analyze building models" (Eastman et al. 2011). BIM is able to produce building models enriched with massive amounts of information towards different analysis and management purposes. One of them is 3D visualizations, in which users can navigate freely to view each detail of the models. The models are composed of individual components representing different objects of buildings such as walls, doors, floors, and furniture. Resulting from that, objects in the models can be manipulated to make dynamic changes, thus, to generate VR SGs simulation. Rüppel and Schatz (2011) showed that BIM could be coupled with game engines to develop fire safety evacuation SGs. Loverglio et al. (2018) proposed a BIM-based VR SG for earthquake evacuation training.

Laser scanning is a surveying approach that can rapidly capture the "as-is" state of a facility with a laser scanner

(Xiong et al. 2013). The data obtained from laser scanning, which is a set of distance measurements and images of surfaces visible from the sensor's viewpoint, is represented as point clouds (Xiong et al. 2013). A laser scanner can be placed in various locations throughout a building so that the generated point clouds from each location can be clustered to obtain a complete point cloud model of building indoor environments. Thus, point cloud models have the potential to be applied as the gaming environment for VR SGs simulation representing the "as-is" state of building indoor environments. Bruno et al. (2010) illustrated a complete methodology to develop VR systems for cultural heritage using laser scanning data.

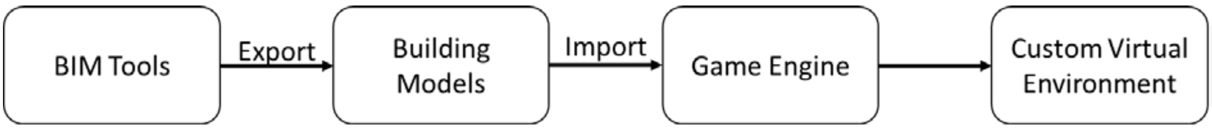
360-degree panorama captures an un-modeled view of the real environment (Pereira et al. 2017). 360-degree panoramas can be obtained by 360-degree panoramic cameras, providing unbroken views of the whole environment surrounding the cameras (Pereira et al. 2017). Then, 360-degree panoramas can be applied to develop a VR, which looks identical to the real world. Users can be immersed into such VR simulations given a "sense of presence, of being there" resulting from the realistic panoramic views (Bourke 2014). 360-degree panoramas have been applied in various VR applications. Pereira et al. (2017) developed an interactive panoramic scene of construction sites using panoramic photos and videos. Gheisari et al. (2016) showed that an augmented panorama could provide a location-independent VR experience.

The feasibility and efficiency of each technique for generating VR SGs scenarios are different due to the variety of original data formats and modelling processes. Each technique has different inherent abilities. For instance, BIM may facilitate a high level of dynamic changes while laser scanning may offer a high level of fidelity of virtual environments. Therefore, this study conducted a pilot case study to examine each workflow for the rapid and effective reconstruction of 3D indoor environments of existing buildings applied in earthquake simulations.

2. FROM BIM TO VR SG

Models generated by BIM consist of complete building components that make them suitable for virtual simulations (Bille et al. 2014). Such simulations can be developed by game engines. A game engine is a software development platform used for developing video games (Bille et al. 2014). One popular game engine is Unity (https://unity3d.com/). Unity is a cross-platform game engine whose primary purposes are developing 3D and 2D video games and simulations for different operation systems. Unity also has the capability of adding VR features to games and simulations, which makes it an ideal tool for VR SGs development. The general process from BIM to game engines to develop virtual simulations is illustrated by Bille et al. (2014) in Figure 1.

Fig. 1: General BIM to VR SGs process (Bille et al. 2014)



There are numbers of BIM tools available to generate building models. One of them is Autodesk Revit (www.autodesk.com), which is widely adopted by the architecture, engineering and construction (AEC) industry. Revit generates building models with parametric objects. These objects are individual with their own properties such as rendered materials, which offers the opportunity to set building models as the virtual environment for VR SGs.

Revit supports exporting models in various formats for use in other software. One fundamental format is FBX format, which stores information of polygonal mesh models. The FBX format contains geometric and material data and is directly readable by Unity and other 3D modelling software such as Autodesk 3ds Max (www.autodesk.com) or Blender (www.blender.org).

However, models exported from Revit in FBX format do not contain appropriate materials for representing textures in Unity. Revit exports FBX file with Autodesk materials while Unity can only read standard materials. Therefore, an additional process is required to convert Autodesk materials to standard materials (CIC Research Group 2016). Bille et al. (2014) suggested the conversion to be done by 3ds Max, given that there is a commercial script called Universal Material Converter (www.3dstudio.nl) which can directly convert Autodesk materials to standard materials. After the material conversion, the models are ready for developing VR SGs by game engines. The entire importation workflow is illustrated in Figure 2.

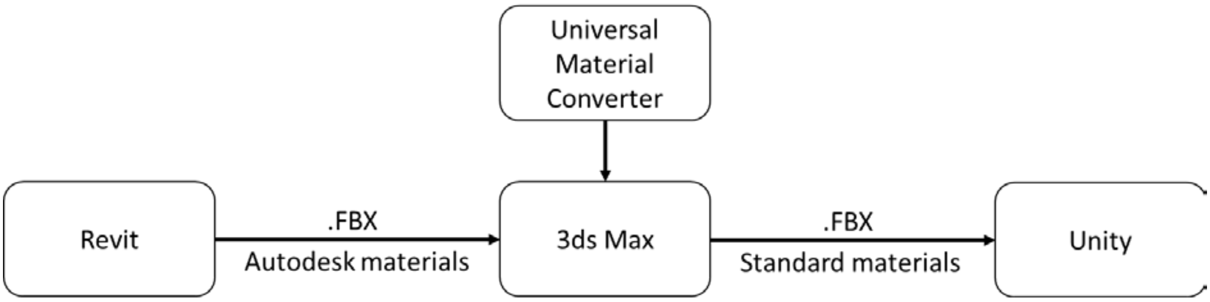


Fig. 2: Revit to Unity importation workflow (Bille et al. 2014)

Apart from that, there is also another free plugin called Walk-Through-3D (apps.autodesk.com) available for Revit, which can export 3D model geometry with standard materials from Revit to Unity directly.

Despite the straightforward importation workflow, BIM also has its limitations in terms of VR SGs development. One is that the models generated by BIM contain rich information and details which may be redundant for VR SGs, thus, reducing VR SGs development efficiency (Lovreglio et al. 2018). The cause of this issue is related to the essence of BIM as the native ability of BIM is for building design and management. For instance, a wall created by Revit includes multiple layers such as core structure, substrate, thermal layer, and finishing components. In addition, each layer has its own geometric data (e.g. thickness) and meta-data (e.g. material). Such rich information and details are not necessary for VR SGs development. A wall in a virtual environment can be simply represented as one single hexahedron with surface materials. However, the models converted from BIM with this rich information and details may become too heavy to be efficiently manipulated in game engines. Also, heavy models can reduce frame rate which may lead to an uncomfortable gaming experience (Johansson et al. 2014). Therefore, when developing VR SGs with a complex building model, acceleration techniques such as occlusion culling and hardware instancing need to be applied in game engines in order to improve performance (Johansson et al. 2014).

3. FROM LASER SCANNING TO VR SG

Laser scanning is adopted in the AEC industry for surveying, carried out by laser scanners. The initial output data of laser scanning is point clouds, which contained dense points with 3D measurements and images of the surface of a facility's "as-is" condition (Tang et al. 2010). Point clouds can represent indoor geometry with realistic colors of a building, which can be applied as gaming environment for VR SGs. In order to achieve that, a process is required to make point clouds data readable by game engines such as Unity.

One possible solution is to convert point clouds to mesh models in FBX format, which can be directly read by Unity. Lin et al. (2004) introduced an algorithm which can reconstruct a polygonal mesh from a given point cloud. The reconstructed mesh represents topologically correct surfaces of objects with numerous polygons. The initial polygonal mesh is in wireframe mode, which means only the points and lines are framed to describe the edges in a transparent drawing (Remondino 2003). To represent the images of surface in a facility, another process called texture mapping is required. Textures are mapped onto the polygon surface with the color at each pixel which is derived from the images (Remondino 2003). After texture mapping, the image-based mesh models converted from point clouds are ready for further applications such as game development. The general process from laser scanning to game engines to develop virtual simulations is illustrated in Figure 3.

Fig. 3: General laser scanning to VR SGs process

Point clouds generated from laser scans can be stored in an E57 format, which is designed to be an open standard for storing data produced by 3D imaging systems (Huber 2011). In order to convert point clouds to polygonal mesh models, one toolset called Autodesk ReCap Pro (www.autodesk.com) can be adopted, which is a "Reality Capture" program for working with native point clouds from laser scans. ReCap Pro includes two programs, one is ReCap, and another is ReCap photo. ReCap can read original point clouds data and generate image-based mesh models on Autodesk cloud servers. ReCap photo can read and edit the generated mesh models and save them in FBX format. Figure 4 illustrates the entire workflow.

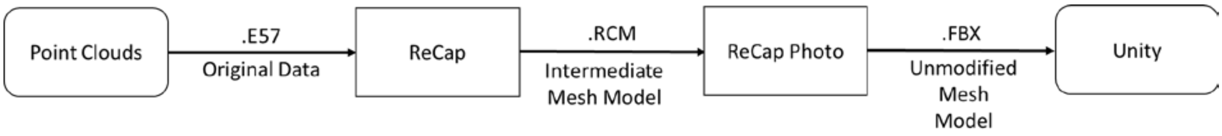


Fig. 4: Point clouds to Unity importation workflow

The converted mesh model is a single undivided mesh connecting all the objects captured by laser scanning. However, this is one of its limitations for VR SGs development. With a single mesh representing all the visible surfaces of objects, the capacity to manipulate each object in order to make dynamic changes is limited. One possible solution is to edit the entire single mesh in 3D modelling software in order to divide objects within the mesh. After that, the divided objects can be manipulated to perform dynamic changes. However, the main following issue is that once the divided objects being moved away from their original positions, there will be hollows left on the rest entire mesh since those places are invisible to laser scanners, thus, leaving no point clouds captured by laser scanning. Another possible solution is to provide an augmented virtual experience by adding additional virtual objects in game engines to perform dynamic changes, while the main mesh remains static as background environment.

Another limitation is that mesh models may contain large numbers of polygons (i.e., over millions of polygons), which can make computers inefficient to process, thus, reducing the frame rate and leading to an uncomfortable gaming experience (Papageorgiou, Platis 2015). In order to optimize performance, one possible solution is to reduce polygons in 3D modelling software with mesh simplification functions (Papageorgiou, Platis 2015). Another supplementary solution is to use acceleration techniques such as occlusion culling and hardware instancing as we suggested in the previous BIM workflow (Johansson et al. 2014).

4. FROM 360-DEGREE PANORAMAS TO VR SG

360-degree panoramas can provide immersive visualizations of the real world (Gheisari et al. 2016). 360-degree panoramas can be created by stitching multiple photos taken from a rotating robotic camera (Peleg, Ben-Ezra 1999). With current new technologies, 360-degree panoramas can also be generated by panoramic cameras with fish-eye lens in few seconds without manual process. Panoramic cameras capture a complete scene as a single image that can be viewed by rotating about a single central position (Wikipedia 2018). 360-degree panoramas are ideal to be applied for VR. The general process from 360-degree panoramas to game engines to develop virtual simulations is illustrated in Figure 5.

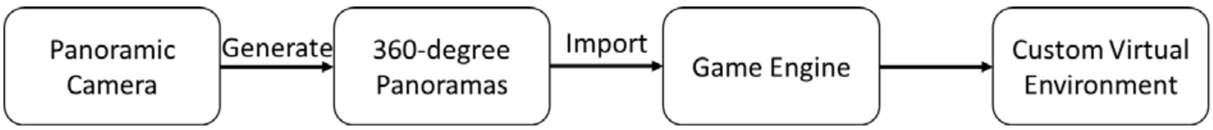


Fig. 5: General 360-degree panoramas to VR SGs process

360-degree panoramas taken by panoramic cameras are usually in JPG format which can be directly read by game engines such as Unity. There is no additional process required to convert the original data. Figure 6 illustrates the importation workflow.

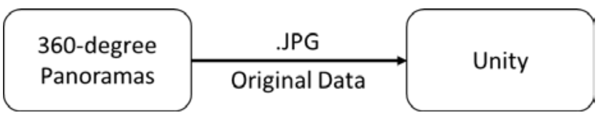


Fig. 6: 360-degree panoramas to Unity importation workflow

However, 360-degree panoramas also have limitations to be extended to VR SGs. One is that panoramas are only planar images without depth so that participants are not able to navigate “inside” the images. Another is that objects are captured as static 2D pictures in panoramas which make them impossible to be manipulated in game engines to make dynamic changes.

In order to overcome the navigation limitation, one possible solution is to take a series of panoramas on the potential navigation path and teleport users from one point to another (Pereira et al. 2017). One famous application of this solution is Google Street View (map.google.com), which teleports users to move forward and backward. Sequential panoramas on the navigation path can be connected by scripts in game engines to implement teleportation.

Regarding the limitation of dynamic changes, one possible solution is to add additional layers of information on static panoramas (Gheisari et al. 2016). In other words, objects in panoramas remain in an "as-is" state while virtual objects and information can be added to augment virtual experiences. Such augmented information can be created and manipulated in game engines. As a result, users can still receive a perception of simulated scenarios which are delivered by augmented information.

5. EVALUATION OF 3D RECONSTRUCTION APPROACHES USING A PILOT STUDY

This research aims to compare and evaluate the different 3D reconstruction workflows mentioned above towards the rapid development for VR SGs. The feasibility and efficiency of different workflows were examined by using an earthquake-based pilot case study developed for VR SGs.

5.1 Research subject

An area of the Engineering VR/AR Lab of the University of Auckland was selected as the reconstruction object. The floor area is approximately 6m x 5m, and the clearance height is approximately 2.6m. The lab includes various objects such as desk, chairs, computers, drawers, partition walls, and cardboard boxes. The photo showing the actual state of the lab is illustrated in Figure 7(a).

5.2 Apparatus

Three different reconstruction workflows, namely BIM, laser scanning, and 360-degree panoramas, were adopted to reconstruct the 3D indoor environment of the Engineering VR/AR lab.

The PC we used to run the VR SGs earthquake scenarios is equipped with 16GB of RAM, a Nvidia GTX 980m graphic card with 8GB of memory, and a 2.60GHz Intel i7-6700HQ processor. The VR headset we used is Oculus Rift (www.oculus.com). Oculus Rift is a consumer-grade VR headset with 1080x1200 resolution per eye, and a 110-degree field of view.

The BIM workflow was carried out on the same PC as mentioned above. Cameras and measure tapes were adopted to run a simple survey as no plan drawings were available.

The laser scanner we used is FARO Focus3D X 330 (www.faro.com). The scanner can scan objects up to 330 meters away and in direct sunlight, providing precise 3D models in a photo-realistic style.

The 360-degree panoramic camera we used is Nikon KeyMission 360 (www.nikon.co.nz). This camera is equipped with two fish-eye lenses that can directly capture panoramas with no manipulation from users. The camera captures a complete 360-degree panorama with a single shot. The output resolution is 4k.

5.3 Research design

Each workflow was applied individually to capture data, reconstruct 3D environment, and develop earthquake scenarios for VR SGs. As a result, a total of three earthquake scenarios were developed based on the virtual environments generated from each reconstruction workflow. The detailed development process will be described in section 5.4.

Tang et al. (2010) proposed performance measures for modelling as-built BIMs, which can be catogrized into three aspects: 1) measures of algorithm design; 2) measures of environmental conditions; 3) measures of modelling performance. Inspired by these measures, we formulated six performance dimensions to evaluate the feasibility and efficiency of each workflow. Table 1 shows the detailed description and assessment criteria of each performance dimension. Each workflow in each performance dimension was compared with each other and ranked from low to high level with a score ranged from 1 to 3, where 1 stands for low ranking, 3 stands for high ranking. The score is a relative value which is only to show different rankings of each workflow in each performance dimension.

Table 1: Performance dimensions of different 3D reconstruction workflows

Performance Dimension	Description	Score Criteria	Measurement Type
Level of fidelity **(static environment, before earthquakes)**	How close is the static virtual environment to the "as-is" state of the real world?	3 stands for the highest fidelity	Subjective assessment with qualitative measure
Level of fidelity **(dynamic environment, during earthquakes)**	How realistic is the earthquake simulation?	3 stands for the highest fidelity	Subjective assessment with qualitative measure
Level of dynamic capability	To what extend can dynamic changes be performed in the virtual environment?	3 stands for the highest dynamic capability	Subjective assessment with qualitative measure.
Time requirement	How much time is consumed for completing the entire approach?	3 stands for the least time consumption	Subjective assessment with quantitative measure
Model complexity	How many polygons does the virtual environment have?	3 stands for the lowest polygons	Objective assessment with quantitative measure
Computational complexity	How many frame rates per second (FPS) does the virtual environment achieve when running earthquake simulation in VR headset?	3 stands for the highest FPS	Objective assessment with quantitative measure

The first two performance dimensions namely level of fidelity (static) and level of fidelity (dynamic) were examined subjectively by five undergraduate students. Firstly, each student was asked to experience three static environments (before earthquakes) in order to compare them with the real world to rank the level of fidelity (static) of each workflow, where the highest fidelity was given 3 score and the lowest got 1 score. As a result, mean values of each workflow were calculated and used to rank each workflow accordingly. Secondly, each student was asked to experience three dynamic environments (during earthquakes) in order to rank the level of fidelity (dynamic) of each workflow, where the highest fidelity was given 3 score and the lowest got 1. As before, each workflow was ranked based on the mean values.

Level of dynamic capability and time requirement were examined subjectively by the researcher who developed these three earthquake scenarios. Each workflow was evaluated and ranked with the capability to perform dynamic changes. As for time requirement, the time consumed for developing the complete VR scenarios by each workflow was recorded and used as indicators to rank each workflow.

The last two performance dimensions namely model complexity and computational complexity were examined objectively by comparing the performance data recorded by the computer running the virtual scenarios. The total number of polygons of each virtual environment was used as indicators of model complexity, while the frame rates per second (FPS) of each virtual environment running earthquake simulation in VR headset was used as indicators of computational complexity.

5.4 Procedure

A BIM model of the lab including furniture was developed by a researcher skilled in Revit. However, there were no plan drawings available so that the geometry information was obtained from a simple field survey. Then the 3D model was imported from Revit into Unity by the plugin called Walk-Through-3D. Figure 7(b) shows the BIM-based virtual environment in Unity. After that, the earthquake simulation was developed in Unity by using C# script enabling physics engine to shake and bring down objects in the lab. A cloud of dust (virtual particle system) was also added to the simulation. The VR function was enabled supporting Oculus Rift in Unity. Figure 7(c) shows the BIM-based post-earthquake environment.

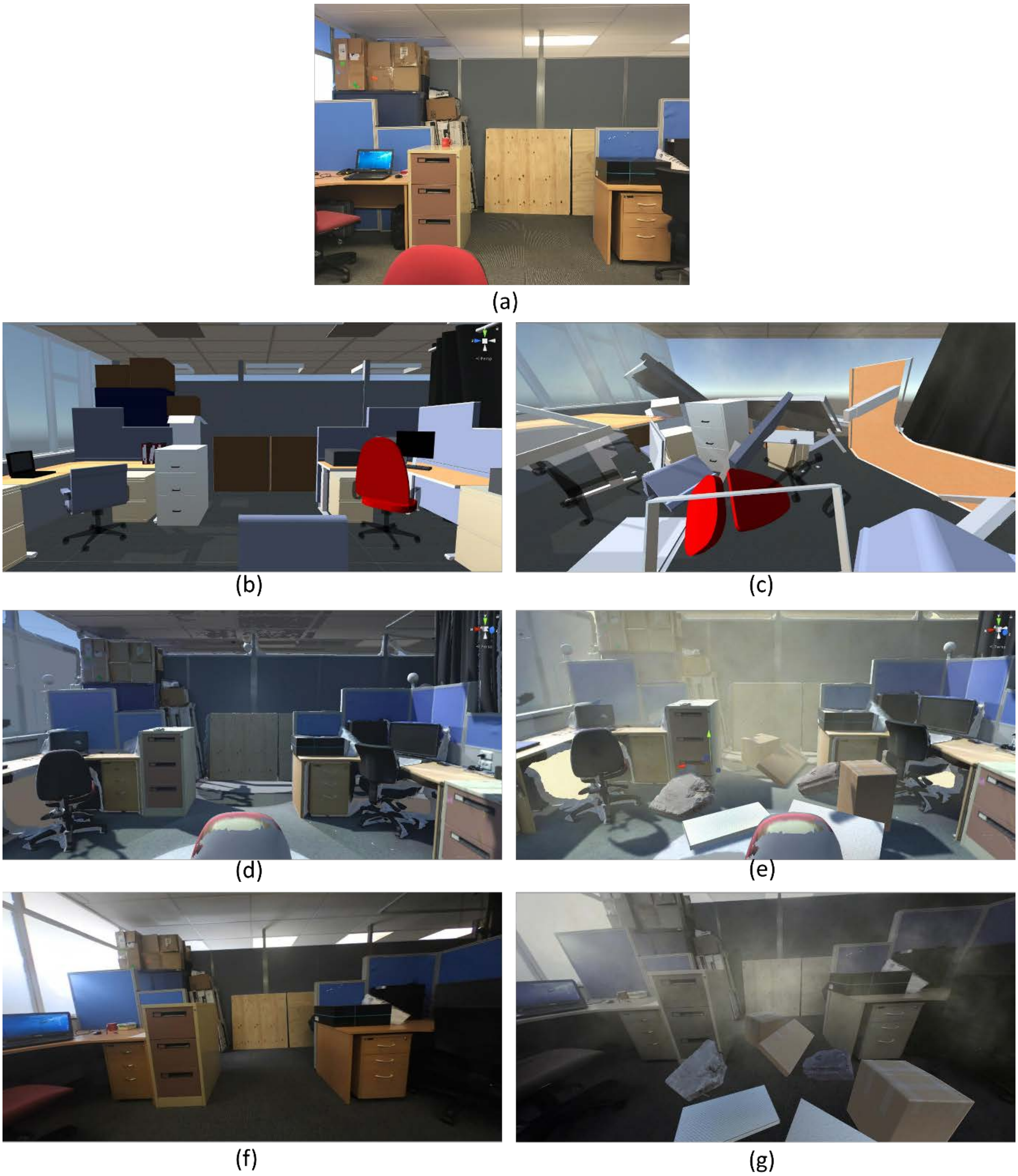


Fig. 7: (a) Actual state of the lab, (b) BIM-based 3D environment, (c) BIM-based post-earthquake environment, (d) Laser scanning-based 3D environment, (e) Laser scanning-based post-earthquake environment, (f) 360-degree panorama-based 3D environment, (g) 360-degree panorama-based post-earthquake environment

Two laser scans were produced by the laser scanner in two positions in the lab in order to get maximum coverage of the environment. Two scans were registered and clustered in Faro Scene and exported as point clouds in E57 file format. ReCap was used to convert point clouds to a polygonal mesh model in FBX format. Then the mesh model was imported to Unity. Figure 7(d) shows the laser scanning-based virtual environment in Unity. After that, additional layers of information were added in Unity to augment the earthquake simulation including falling objects (virtual 3D objects with materials) and a cloud of dust (virtual particle system). The main camera was shaken in Unity by using C# script in order to provide a perception of shaking experience as earthquakes. The VR function was enabled supporting Oculus Rift in Unity. Figure 7(e) shows the laser scanning-based post-earthquake environment.

One 360-degree panorama was taken by the panoramic camera. The panorama was directly imported to Unity. Figure 7(f) shows the 360-degree panorama-based virtual environment in Unity. Additional layers of information were added in Unity to augment the earthquake simulation including falling objects (virtual cubes with materials), flickering lights (change brightness of panorama), and a cloud of dust (virtual particle system). The main camera was shaken in Unity by using C# script in order to provide a perception of shaking experience as earthquakes. The VR function was enabled supporting Oculus Rift in Unity. Figure 7(g) shows the 360-degree panorama-based post-earthquake environment.

5.5 Results

Three earthquake simulations were developed for VR SGs based on three different virtual environments. Mean values of rankings for levels of fidelity are shown in Table 2. Time consumed to complete each workflow was recorded in Table 3. Polygons and FPS of each simulation at runtime, where the former stands for model complexity and the latter stands for computational complexity, were obtained from statistics provided by Unity and recorded in Table 4. Based on these results, each workflow was ranked in performance dimensions listed in Table 1, which are shown in Table 5.

Table 2 Mean values of rankings for each workflow in terms of level of fidelity

	BIM	**Laser Scanning**	**360-Degree Panorama**
Level of fidelity (static)	1.6	2.6	1.8
Level of fidelity (dynamic)	2.6	1.8	1.6

Table 3 Time consumed to complete each workflow

	BIM	**Laser Scanning**	**360-Degree Panorama**
Survey time (optional)	0.5 hour	0	0
Model creation time	7 hours	1 hour	0.1 hour
Model treatment time (conversion)	1 hour	2 hours	0
Simulation development time	1.5 hours	1.5 hours	1.5 hours
Total time	10 hours	4.5 hours	1.6 hours

Table 4 Model and computational complexity of each simulation

	BIM	**Laser Scanning**	**360-Degree Panorama**
Polygons	2.1 million	13.6 million	35.5 thousand
FPS	46.1	42.3	86.3

Table 5 Performance rankings of each workflow

Performance Dimension	BIM	Laser Scanning	360-Degree Panorama
Level of fidelity (static)	1	3	2
Level of fidelity (dynamic)	3	2	1
Level of dynamic capability	3	2	1
Time requirement	1	2	3
Model complexity	2	1	3
Computational complexity	2	1	3

6. CONCLUSIONS AND DISCUSSIONS

This research examined three 3D reconstruction workflows for indoor environments suited to VR SGs. The results indicated that each workflow has its unique advantages and limitations.

BIM is a comprehensive approach to reconstruct indoor environments due to the nature of its modelling ability and process. This workflow can be time-consuming if it is for a large building with large amounts of objects. Besides, BIM may not represent the “as-is” state of buildings if the modelling is based on old drawings. When modelling, it is also difficult to get the objects similar to the ones in the real world. In this research, we spent hours to get the objects as close as possible to the real ones. Even though, the reconstructed model still misses some details which make it different to the “as-is” state of the indoor environment. Apart from that, the heavy model with rich information can lead to a low development efficiency of VR SGs in game engines and a low runtime performance. However, BIM also shows the advantage in terms of dynamic ability. BIM is able to perform a high level of dynamic changes given that all the objects in models are individual, which offers BIM high extensibility to game engines for further manipulation and development (Bille et al. 2014).

Laser scanning is a faster 3D reconstruction approach compared to BIM. It also provides a higher level of fidelity which can reflect the “as-is” state of the indoor environment. Even though the objects are not able to be manipulated in an individual basis, laser scanning-based virtual environment still shows a certain capability to be extended to VR SGs by enhancing dynamic changes through additional virtual objects as augmentation. However, the major limitation is that the mesh model converted from point clouds contain massive numbers of polygons, which largely depends on the complexity and regulation of original geometry. This issue can lead to a relatively low runtime performance. An additional process is required to reduce polygon numbers before importing mesh model into Unity.

Regarding 360-degree panorama, it is the fastest approach with the least computational complexity. And it is interesting to find that even though 360-degree panorama provides an un-modeled view of surroundings, it gives a weaker perception in terms of level of fidelity of static environment. Besides, the major limitation is that limited dynamic changes and interaction can be made for VR SGs. In this research, 360-degree panoramas showed limited ability to be extended to earthquake scenarios due to only few earthquake damages can be represented and such dynamic representation has a relatively low level of fidelity. However, 360-degree panoramas may have better performance in other fields that require less dynamic changes such as fire simulation (can be augmented by flame and smoke mainly) or construction management (Pereira et al. 2017).

This research also has some limitations. One is that the experiment was limited to a situation where there was no navigation through the virtual environments. Each workflow may require different navigation solutions, which can largely influence user experience. Another limitation is that due to different data formats and modelling processes, each earthquake scenarios was generated using different algorithms and visual effects, which leads to the comparison of each workflow is not rigorous.

This research provides an insight of each workflow based on the evaluation of feasibility and efficiency. It is difficult to draw a conclusion that which workflow is the best towards VR SGs. Selection criteria and actual performance depend on various aspects. For instance, for large and complex buildings, time consumption of BIM can increase exponentially due to models need to be created manually, while computational complexity of laser scanning can increase exponentially due to numerous of polygons for complex geometry. Besides, different algorithms and visual and sound effects applied for VR SGs can also influence the performance. Possible future research could be to establish a framework mixing multiple workflows in order to take the advantages of each approach, for instance, using laser scanning and photogrammetry to create an "as-is" BIM model for VR SGs development.

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AUTOMATING CHANGE REQUEST VALIDATION USING INDUSTRY FOUNDATION CLASSES AND NATURAL LANGUAGE PROCESSING

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ABSTRACT: *Construction projects generate massive amounts of information from initial feasibility study to decommissioning of facilities. Such information needs to be updated on a daily basis and is often stored in multiple incompatible file formats.*

Unplanned changes and mismanagement of information cause delays and costly mistakes. To alleviate such issues, this paper investigates the possibility of using Industry Foundation Classes (IFC) data model and Natural Language Processing (NLP) to validate and visually identify the result of change requests. The approach builds upon a web-based platform capable of generating reports and visual previews, highlighting the differences between IFC files throughout the design processes.

The paper presents a web-based system prototype that allows users to compare different versions (old and new for example) of IFC design models in terms of: additions, modifications and deletions. The system uses NLP to intelligently identity the changes that have been made as it compares newer and older versions of the same model, making this information available to designers and 3D modellers.

Prospective work will focus on the application of artificial intelligence to automate the implementation of changes within the construction models.

KEYWORDS: *3D models, IFC, NLP, AI, Web Services*

1. INTRODUCTION AND RATIONALE

The BIM revolution has played a lead role in the process of collaborative design involving multi-disciplinary designers and experts including architects, structural engineers, electrical and HVAC engineers. For each discipline, there is a need to make design changes, and consequently, these changes will have a knock-on effect on the other disciplines. Ultimately, any undetected design changes (either a change not carried out, carried out incorrectly or design mistakes not being correctly identified) will result in extra financial costs of reworks and project overruns during the construction phase.

The cost of errors and reworks in construction varies widely by project. The financial and economic impact of these errors can account for up to 80% of the project costs (GIRI, 2016). Reworks resulting from clients' design changes or design consultant errors have been identified as the primary factor contributing to time and cost overruns (McDonald, 2015). Furthermore, Love et al. (2008) reported that 70% of the total amount of rework experienced in the construction and engineering mainly contributed to design induced reworks. However, with the emergence of building/project, information modelling and clash detections identifying errors and design changes became easier, thus reducing reworks. Therefore, it is paramount that any changes or modifications within the multi-disciplinary design team are well tracked and managed.

Much of the research is focused on clash detection and conflicts between different objects from different disciplinary building information models. With the emergence of a number of software tools such as Solibri Model Checker, Navisworks and Tekla BIMsight these issues can be detected (Volk et al., 2014).

Other research work is in the area of code compliance checking in the AECO (Architecture Engineering Construction Operation) domain and with the emergence of widely accepted IFC (Industry Foundation Classes) open standards for Building Information Modelling (BIM) data interchange, this has been made possible to resolve. Despite interest in this area, there is still a lack of holistic approaches to address the problem of automating compliance checking (Dimyadi and Solihin, 2016). Further research work conducted by Zada et al. (2014) tackles the challenges of integrating object versioning through IFC extensions to represent the history of changes in any object in the model.

Our current research describes the development of a tool (under the working-title Elwynn) which is designed to aid in the problems of change management by providing users with a way to easily track changes and generate reports across building/IFC model versions throughout development. This paper aims to present the developed system to support automated change request validation. The paper introduces new features building on the core Elwynn system that explores the automatic validation of change requests using natural language and IFC files. This concept is explored using examples of changing objects within a building. Natural Language Processing (NLP) is included as a core component of the system to provide a fluid interface for change requirement entry. Additionally, change request information has the potential to come from a variety of sources such as: email, memos and formal requirement documents. Allowing input in natural language supports all of these inputs and reduces the burden of a user having to parse information manually.

2. The Elwynn Change Management System

The Elwynn system is a web-based application currently in development. It is designed to aid users working on construction projects by automating the identification of changes between different versions of the same building model. The interface of the system allows users to set up a new Elwynn project (representing one construction project) to which they can then upload different versions of building models as IFC files, generate file previews and produce a list of changes between any two model versions.

The system is developed using a combination of the Angular framework for front-end development with the server component being developed using C♯ and ASP.NET. The server component makes use of the xBIM library (Lockley, et al., 2017) to interact with IFC files. This allows the system to work with native IFC objects directly, benefiting from implicit semantic information. The xBIM library features allow IFC models to be viewed directly in the web browser. The application was designed to be an accessible web-based system allowing users access from as many devices as possible to use the application without needing to install any local software.

One of the key features of the system is being able to generate a report of changes between IFC file versions. This is achieved by leveraging features provided by xBIM. Also, using the library, objects and object properties can be extracted from an IFC file and compared to those extracted from another IFC file to provide a list of objects that have been added, deleted or changed between the two IFC file versions. This is compiled into a report that users can view showing the individual object changes and associated properties. Combinations of Global Object Identifiers and other unique markers are used to keep track of objects between IFC file versions.

The details of IFC file comparisons are stored, which saves time in re-generating the changes on every viewing and allows the details to quickly be reused in other areas of the system, such as validating change requests. The collected information includes details of objects, type of change applied to them (added, deleted or modified) along with semantic information such as properties, coordinates and any associated spaces or levels.

Figure 1 shows an overview of the main Elwynn user interface with the “File Comparison” tab selected. Figure 1:1 displays a list of user-created projects (used to group related IFC files and comparisons). Tabs highlighted in Figure 1:2 allow users to switch between generated comparisons and uploaded IFC files. The area in Figure 1:3 lists generated comparisons - clicking on a comparison will take users to a detailed report showing objects that have been deleted, added or changed (grouped by level). Clicking the preview button (Figure 1:4) will display a 3D model in the browser highlighting changes. Figure 1:5 shows an example comparison between two building versions, colours are used to designate the type of change that has occurred to objects (red for deleted, green for added or blue for changed).

The preview shown in Figure 1:5 the ability of the system to generate a 3D comparison model as a companion to the detailed report of object changes that is also generated. Comparison models are generated by combining geometry from two IFC files highlighting the changes. Any existing colours of the model not part of the changes are recoloured to white, avoiding any confusion and further highlighting the elements that have been changed. The preview is intended to provide users with a quick comparison while the detailed report is more useful for seeing the list of individual object changes. To combine these features a preview button is included next to each object in the report. This allows users to see a specific object directly on the model itself.

The remainder of this paper will focus on the extensions made to the Elwynn system to improve the change

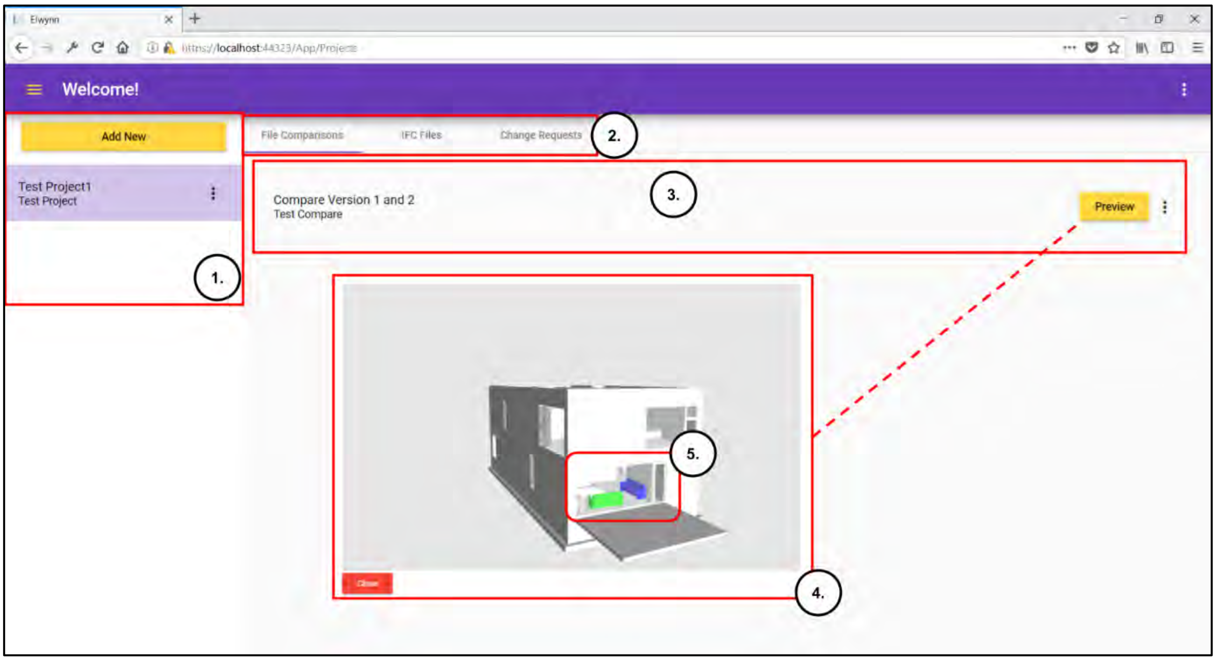

Figure 1: Annotated screenshot from the prototype Elwynn software showing an overview of the main Elwynn interface with the "File Comparisons" tab selected. Screen capture taken from the prototype Elwynn user interface.

management process. Change management is a large area of research that outlines processes for handling changes within a project, aiming to improve the changes by creating a detailed record of the requests and their output (Crnkovic, et al., 2003). An example methodology that incorporates change management is PRINCE2 (Bentley, 2012). Within these processes, a change request is a formal record of the description of the change, usually including information such as: who raised the change and if it has been completed. In software engineering, a common example of this is bug tracking software which is used to track issues in a software system; an example of such software is FogBugz.

The extensions that have been developed for Elwynn aim to provide a way of capturing change requests as part of the overall change management process and provide an automatic method of validating their completion. While change request could potentially come from multiple sources and be completed by many individuals attached to a project, we outline the core concept with a specific use case. The use case we have focused on in this paper is as follows:

1. An architect develops an initial model, uploaded to Elwynn as IFC
2. The architect then identifies changes that need to be made submitting a new change request to Elwynn and expecting the work to be completed by a contractor
3. The contractor then completes the changes and uploads a new version of the model to Elwynn as IFC
4. The architect can then use the Elwynn system to automatically validate if changes have been made
5. The architect then makes the final decision on the changes, e.g. approve changes, request more changes, etc.

An overview of this process is presented in Figure 2. This figure highlights the use case process and is designed to illustrate how users can interact through the Elwynn system. It also highlights the flow of information, where automated processing takes place and the information used as part of automated processing. On this figure, Elwynn is allocated two swim lanes one for documents and one for processing tasks, in reality, these tasks are closely tied together but have been separated here to provide additional clarity.

3. Change Request Creation

Automating change request creation builds upon the foundations provided by the Elwynn change management system through integration of a natural language component to automate the extraction of change request information from free text input. The system then uses this information to determine if requirements have been met. Users can enter free text into the system; key information is then extracted and formalised into a change request object-structure (Minsky, 1974). The change request object structure contains properties such as: the type

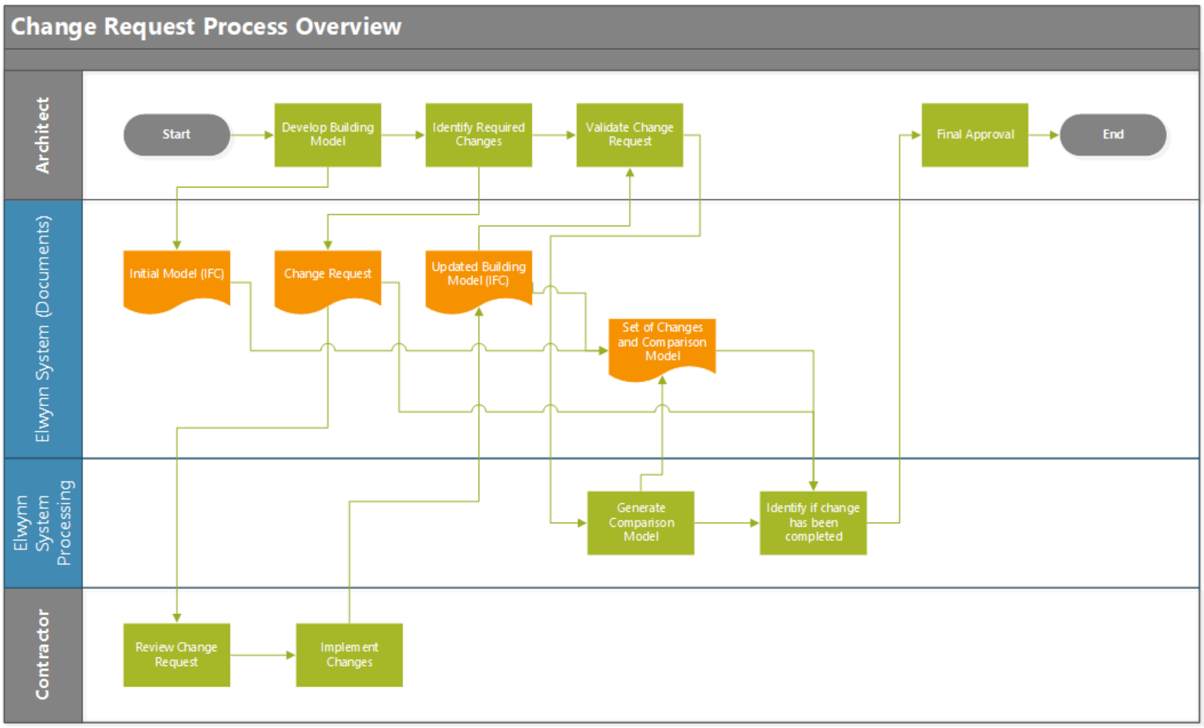

Figure 2: Example change request process overview, showing changes between an architect and contractor while interacting with the Elwynn system.

of change request; the object associated with the change request and the location associated with the object (although this can easily be expanded and changed in future iterations). The system adopts a user-in-the-loop approach, allowing the user to edit any extracted information manually, potentially correcting any errors. For the current version of change request validation, a focus was placed on requests that refer to objects within a building, although, the plan is to consider larger structural changes in future iterations.

3.1 Natural Language Processing Approach

The first step in the approach is to extract as much information as possible from the input text. To achieve this, shallow Natural Language Processing (NLP) is leveraged, which is effective at extracting domain-specific information (Zhang & El-Gohary, 2017; Åkerberg, et al., 2003; Georg & Jaulent, 2007). In contrast with deep NLP techniques,

shallow processing aims to provide a pragmatic approach, extracting key information without a deep understanding of the text. Finite State Transition Networks (FSTN) are used to analyse text, an approach inspired by the FASTUS system (Hobbs, et al., 1997) which illustrated how series of FSTN applied in succession can be used to extract increasingly detailed and complex information from text.

One of the major downsides to using shallow natural language processing is that the approach can sometimes lead to brittle rules for extracting information, causing errors or extracting information that is not relevant. For this reason, leveraging the advances in statistical processing, CoreNLP (Manning, et al., 2014) is incorporated into the system. CoreNLP provides a feature called TokensRegex (Chang & Manning, 2014), which allows developers to integrate solutions that make use of FSTN. The implementation provides an interface that looks very similar to standard Regular Expressions but allows access to information provided by CoreNLP such as: Part-Of-Speech (POS) Tags or word lemmatisations. This can greatly aid development as it allows FSTN to be described at a much higher level than pure lexical matches. The TokensRegex feature of CoreNLP was used to develop SUTime (Chang & Manning, 2012) library to normalise temporal expressions, which was also inspired by the FASTUS system.

Figure 3 shows an overview of the NLP approach. Successive FSTN are applied and used to annotate the input sentence with domain-specific named entities. Each stage builds on the previous: first, the nouns in the sentence are classified as objects, the type of request can then be identified using the pattern: "*verb <object>*". The starting and ending locations for the object can be classified using the patterns: "*from <object> to*" and "*to <object>*" respectively. The result of this analysis is a sentence where the words are annotated with semantic information

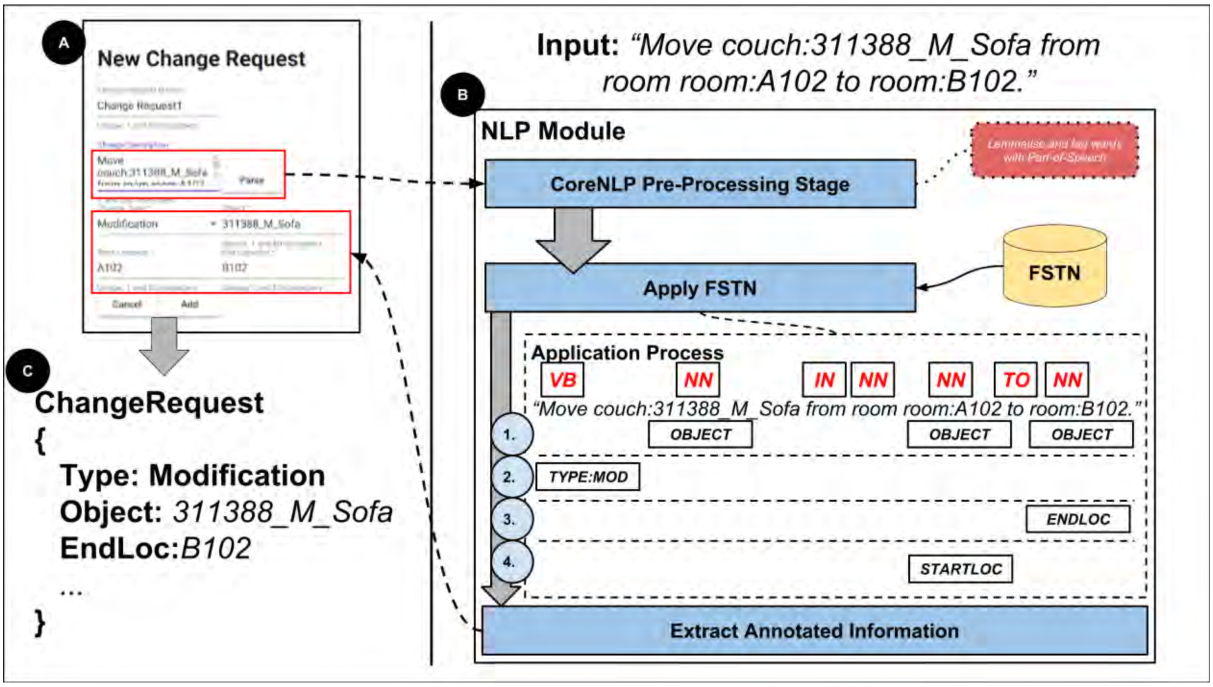

Figure 3: A) Example input as accessed form from the web-based user interface; B) Overview of the language processing component; C) Change request object extracted from input text that is also shown on the form (A) once analysis is completed

such as: the type of request, object and locations. This information is then used to populate fields in the change request form that can be used to create change requests. In the use case shown in Figure 1, this would correspond to the architect creating a new change request as part of the task "Identify Required Changes".

3.1.1 FSTN Scope

A set of FSTN have been developed on input that users are expected to provide. The benefits of building this system in such a way is the ability to refine the system in the future based directly on user input and feedback.

Table 1- Table illustrating example synonyms encode for different modification types shows an example of the synonyms encoded within the FSTN that are used to recognise the different types of change requests, based on the three high-level types of requests that can be recognised by the system. The change request type must match one of the synonyms shown in the table and also be recognised as a verb by CoreNLP.

Table 1- Table illustrating example synonyms encode for different modification types

Modification Type	Synonyms
Addition	Add, Create, Insert, Incorporate, Include
Modification	Alter, Adjust, Change, Refine, Revise, Move, Relocate
Deletion	Delete, Remove, Erase

To expand the FSTN in the future while still maintaining a robust system the following methodology is applied:

1. Analyse new input sentences provided by users, identify instances where change requests generated from the raw input text do not match the details of the change requests submitted by users.
2. Use concordance analysis to identify new patterns that would cause the FSTN set to recognise the input as defined by the user
3. Add such new patterns to the existing set of FSTN
4. Run unit tests against existing patterns to make sure new patterns have not introduced errors

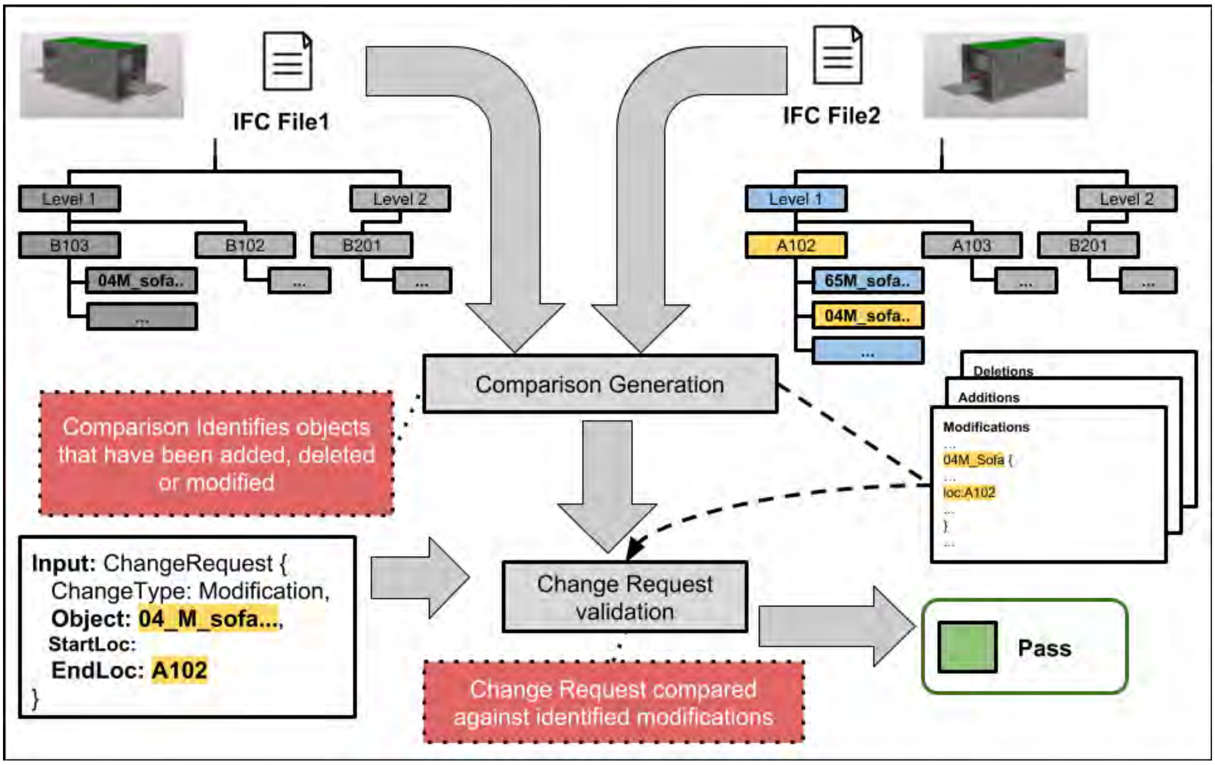

Figure 4: An overview of the change validation process that incorporates a comparison between two IFC files

5. If errors have been introduced, either find an alternative way of integrating the new patterns or delete them

This approach leverages the benefits of software engineering methodologies, integrating automated tests to ensure the system remains as error-free as possible even as potentially many new patterns are added to the system.

3.2 Validating a Change Request

3.2.1 Validating deletions and modifications

Once a change request has been created the next step is to validate the change request, analysing if the change has been completed. To achieve this, the change request is compared to a set of changes generated by Elwynn from two building models that have been uploaded in IFC format. From the perspective of a user, change requests are presented as a list under a tab within the main project view (shown in Figure 1:1). This allows users to see and manage existing change requests along with testing if the changes have been validated. Figure 4 shows an overview of the change validation process, highlighting a modification example. Validating a change request corresponds to the Elwynn System Processing task "Identify if a change has been completed" shown in Figure 2. The user interface is updated to alert the users if changes are valid or not. A prototype implementation of this interface is shown in Figure 5 A) shows the details of the change request; B) allows the user to select the IFC files to validate the change request; C) runs through the validation procedure; D) visually indicates the results of the test; E) allows the user to edit or delete the change request. Submitting a change request can be initiated by a user of the Elwynn system. In the use case outlined in Figure 1, this corresponds to an architect validating a change request as part of the "Validate Change Request" task.

The validation procedure builds on the foundations of the comparison generation feature that was previously implemented. This allows the system to search the comparison details between two IFC files (which are saved after the initial comparison is generated) as we include locations of objects (as an *IfcSpace,* if available). Such a subset of information is all that is needed to validate a change in many cases. Another benefit of re-using our ability to generate comparison information is that property information for objects is extracted as part of the comparison generation process. Object properties are not currently supported within change requests, but this system will be expanded in the future.

For deletions, the process consists of searching the set of deleted objects between two IFC files for the unique object identifiers. If the object(s) cannot be found in the deletions the change request will fail, else it will pass. The

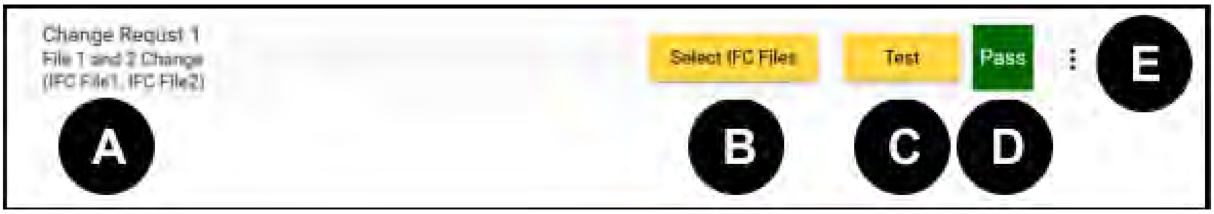

Figure 5: Overview of change validation interface as viewed within the Elwynn interface.

starting location can be optionally included as part of the change request - this prevents any IFC file that did not originally contain the object from asserting that the change request has been completed.

For modifications, the initial procedure is largely the same: the set of changes is queried for the unique object identifier; the change request will fail to be validated if the object cannot be found. If the object is found, however, an additional step is needed. Exploiting the semantic information available in the IFC we include the space in which the object is located (if available). Currently, if a space is specified in the change request but the object location cannot be found in the IFC file – for example, not being semantically associated with a space – the change request will fail. If the start location was available, it can also be used to make sure that the object was originally located in a given space.

A problem that exists in validating change requests - resolving an object entered in plain text to an object in the 3D building model - is a non-trivial problem. For example, in the sentence: "Move the couch to the upstairs bedroom." The system would need to identify both the couch and bedroom, resolving these to one instance each if multiple instances exist. In text-to-scene systems, this problem is called *grounding* (Chang, et al., 2015). While this problem is very difficult to solve through completely automated means, a pragmatic approach can be used that allows users to enter unique object identifiers into a change request easily.

The system can use object information extracted from IFC files to provide users with a list of object names and unique identifiers. These can be inserted into the change request directly, prefixed with plain English followed a colon, to improve the readability of the actual text. This allows change requests to contain the precise information needed for automated validation, without users having to enter unique object identifiers by hand.

3.2.2 Validating additions

Validating objects that have been added is more challenging, as a unique identifier will not be available at the point a change request is added, making the grounding problem unavoidable. This is the core problem in validating additions: identifying an object in the set of changes between two IFC files that matches the object specified in the change request. These features are still being implemented, but this section will outline the methodology. The semantic information included with objects in IFC files such as the name of an object is used to match them to objects in generated comparisons – to simplify processing it is assumed that the location stated in the change request exists in the previous IFC file, avoiding the problem of having to identify a new location and a new object at the same time, although this will be an area to build upon in future versions.

The examples used to develop this methodology uses object names as those contained in the IFC reference the object type. Names of objects added in the generated change request are mapped to the names of objects in the change request, this involves splitting the name into individual words such as: "m_sofa_new-edition" becoming "m", "sofa", "new" and "edition", this can then be checked for instances of the object in the change request (or synonyms for the object). Objects with the highest number of instances will be identified as matches.

For instances where multiple objects are being added to the same space, the number of objects can be included. For example, if there were two new objects of the same type and only one change request for a new object of that type, the change request will still pass. Likewise, if there was only one new object and two individual change requests they would both still pass. To avoid these situations, the user can incorporate the quantity as part of an addition change request.

Figure 6 shows an overview of the process used to match a change request object to the set of objects that have been added. The example shows an instance where the change request will match against two objects due to the quantity being specified. To test our methodology, a small set of object synonyms covering the duplex model was developed. This allows instances where a change request used a synonym for an object to still match against objects in the change set. In the future iterations of the system, resource such as WordNet (Miller, 1995) could be used to look-up synonyms without having to add them to the system manually.

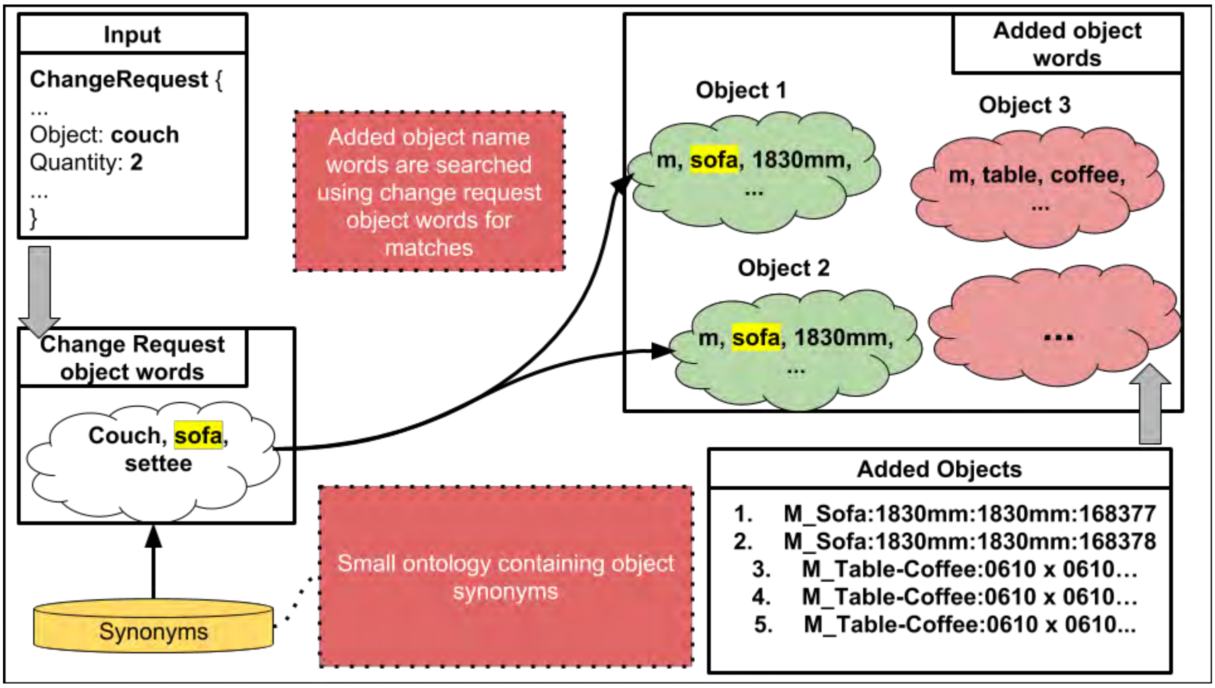

Figure 6: Overview of mapping change request objects to added objects

4. Discussion

The tools that are being developed aim to solve real-world issues within the construction domain. We are targeting a web-based application, inclusion of natural language and use of IFC as an input format to reduce the barrier to adoption. Currently, the system is focused on allowing users to compare IFC models and create change requests that can act as rules validating a change.

Validation of change requests could be used to reduce the time in checking changes (and potentially improve quality) when multiple developers are working on the same project. However, assuming these requests are kept up-to-date, they can also be used to validate that future models are still meeting the requirements, essentially acting as Unit Tests (Jorgensen, 2002) for a project.

Evaluating individual components (such as the performance of the NLP component in extracting information) is currently a challenge due to the variations in workflow between organisations, no standardised procedure for change requests and the limited freely available data. However, our work started collaborating directly with the potential customers of the system, and additional interested industry end users are being sought. Feedback from such collaborations will be directly incorporated into future development. This should lead to the generation of enough data to effectively evaluate the natural language component of the system, which can also be improved over time by comparing the raw text-input with the user-refined form input. Once the system is available to customers, a method of providing general feedback will also be provided.

5. Conclusions and Future Work

The current work represents a prototype application that aims to improve automation on construction projects. Automatic change validation provides a framework that allows users to define custom rules to help users ensure consistency and quality from projects.

A potential to expand the change request system to incorporate more general criteria exists, e.g. when all rooms should contain a specific piece of furniture, rooms should meet specific size requirements, etc. This could lead to a system that incorporates many of the automated testing methods used in the software industry (Jorgensen, 2002; Gamma & Beck, 2006; Smart, 2011), greatly reducing the time developers need to spend manually inspecting changes.

In the short-term the goal will be to develop the change request system further, e.g. overcoming the situations when an object is not in the specified start location which would cause a change request to fail. Resolving such issues would lead to a more granular system that provides warnings when the results may be unclear to the user or even indicates an error with the change request itself.

The goal would also be to expand the natural language processing approach, with an end result to expand this approach even further to automatically extracting rules from an input specification. For this, we could leverage the use of deontic verbs, which have been shown to mark key construction information and would integrate well with our NLP system (Georg & Jaulent, 2007). Deontic verbs in English usually present the model verbs must, could, should, etc. They describe behaviour as it should be carried out and are common across many types of documents including medical, legal and guidelines.

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FROM BIM TO VR: DEFINING A LEVEL OF DETAIL TO GUIDE VIRTUAL REALITY NARRATIVES

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ABSTRACT: *From July 2013 to August 2018,* the *Carleton Immersive Media Studio (CIMS) worked in association with Public Services and Procurement Canada to develop a building information model (BIM) of the Parliament Buildings National Historic Site of Canada. The model was created to facilitate a multi-year rehabilitation of the site and was developed using both historical records and highly detailed geo-referenced point cloud data. In the process of planning the model, CIMS developed a unique Level of Detail (LOD) specification for existing and heritage buildings that linked aspects of BIM detail to cultural value. As the rehabilitation project unfolded, the possibility of using the BIM for public engagement through the creation of virtual reality (VR) experiences was proposed. In this paper, we discuss the transferal of CIMS' LOD from a BIM to a virtual reality environment arguing that BIM LOD is consistent with virtual reality LOD in that it can be used to guide participants through a virtual reality narrative by inferring that areas of higher fidelity have greater value.*

KEYWORDS: *Virtual Reality, Building Information Modelling, Level of Detail, Narrative, Storytelling*

1. INTRODUCTION

In 2019, the Centre Block of Parliament Buildings National Historic Site of Canada will close to the public for a multi-year rehabilitation project. Carleton Immersive Media Studio (CIMS), a research unit associated with the Azrieli School of Architecture and Urbanism at Carleton University in Ottawa, Canada, has had the opportunity to be involved in the documentation and modelling of the existing conditions of the site to prepare for the rehabilitation since 2013. CIMS is now helping to leverage this data for public engagement through various digitally assisted storytelling projects — including active and passive virtual reality (VR). To help manage the assets within the virtual experiences and maintain a file size appropriate for current VR functionality, strict protocols have been developed for the level of detail (LOD) of assets within the scene.

CIMS created an LOD system for VR based on the system used in-house for heritage building information models (BIM), called the CIMS LODIA (Graham, 2018). Unlike standard BIM LOD classification systems that focus on the level of development in new construction, the CIMS BIM classification system provides a higher LOD status for assets of greater cultural significance. When transferring this LOD schema to VR, the assets within the virtual experience modelled at a high LOD are those important to the narrative of the story and heritage significance of the space. CIMS created a classification system for the LOD within VR to help identify which spaces and assets are of high importance/value for the narrative of the heritage environment.

This paper will examine how the CIMS LODIA is unique to heritage BIM and will demonstrate how its key principles are translated into a LOD classification for heritage spaces in VR. We will also compare CIMS LODIA for BIM and VR to existing standards in the construction and computer graphics industries. Using our work on the Parliament Hill National Historic Site, we will provide examples, that demonstrate the effectiveness of our LOD system for heritage spaces in VR — both in helping to define a narrative and in evoking the cultural value of a space.

1.1 History of the Parliament Hill National Historic Site Rehabilitation Project

Construction of the Parliament Hill National Historic Site — comprised of the Library of Parliament, Centre Block, West Block, East Block, and grounds — began in 1859. It quickly became a symbol of Canadian parliamentary democracy and admired for its exemplary Gothic Revival style. In 1916, a fire destroyed the original Centre Block. A ten-year reconstruction began in 1917 following the new design of John A. Pearson and Jean Omer Marchand. The new building showcased cutting edge technologies for construction at the time — such as a new steel structural system — while retaining the ornamental gothic revival quality of the other buildings still standing within the campus.

A comprehensive rehabilitation project began on Parliament Hill in 2002 with the intention of repairing the historic fabric, modernizing services, and addressing changes in its functional program. Rehabilitation began with the Library of Parliament and moved on to the West Block in 2011, with completion planned for 2018. The Centre Block program of work is scheduled to begin late 2018, and the East Block will follow shortly thereafter. Tours of the Centre Block will be suspended for the duration of construction. Alternate means of engaging with the public, both on site and remotely, are being studied. These include virtual reality and other digitally assisted storytelling methods.

1.2 The documentation and modelling by CIMS

Beginning in 2013, on behalf of the Parliamentary Precinct Branch (PPB) of Public Services and Procurement Canada (PSPC) and in preparation for the rehabilitation, CIMS worked with Heritage Conservation Services (HCS) — also a division of PSPC — to document the grounds and buildings of the Parliament Hill National Historic Site. The recording process was completed using a combination of terrestrial laser scanning and photogrammetry.

Terrestrial laser scanning employed Leica C10 and P40 scanners for exterior and large interior spaces and a Faro Focus for small to mid-sized interior spaces. The point cloud data was used as the primary source in the BIM because of the accuracy of the information and the capacity to capture material deviation and structural deflection in the building elements. More than 2000 individual scan stations captured 3 terabytes of data. In spaces of high heritage value — to add higher resolution colour to the point clouds — 360-degree photography was completed at each scan station. The coloured point cloud data was also used for the virtual reality experiences to provide texturing of some elements.

All significant heritage spaces in the Centre Block, such as the House of Commons and Senate Chamber, were documented using photogrammetry by HCS while additional smaller assets such as carvings were captured by CIMS on request. Photogrammetry uses the combination of multiple photographs of an object to extract measurements and create an accurate three-dimensional digital model. The photogrammetric model created is limited to only include what was captured by the camera. If a portion is missed in documentation, such as the top or small crevice in a corner, the model will contain inaccuracies; however, if captured in entirety, the model can offer a high fidelity digital replica of the physical asset.

The data acquired through laser scanning and photogrammetry, in addition to historic construction drawings and photographs from Library and Archives Canada, were used by CIMS to create a highly detailed Building Information Model (BIM) of the site in Autodesk Revit (figure 1). The purpose of the documentation and model was to assist in the design and construction management of the rehabilitation project and serve as an historical record of the iconic heritage buildings.

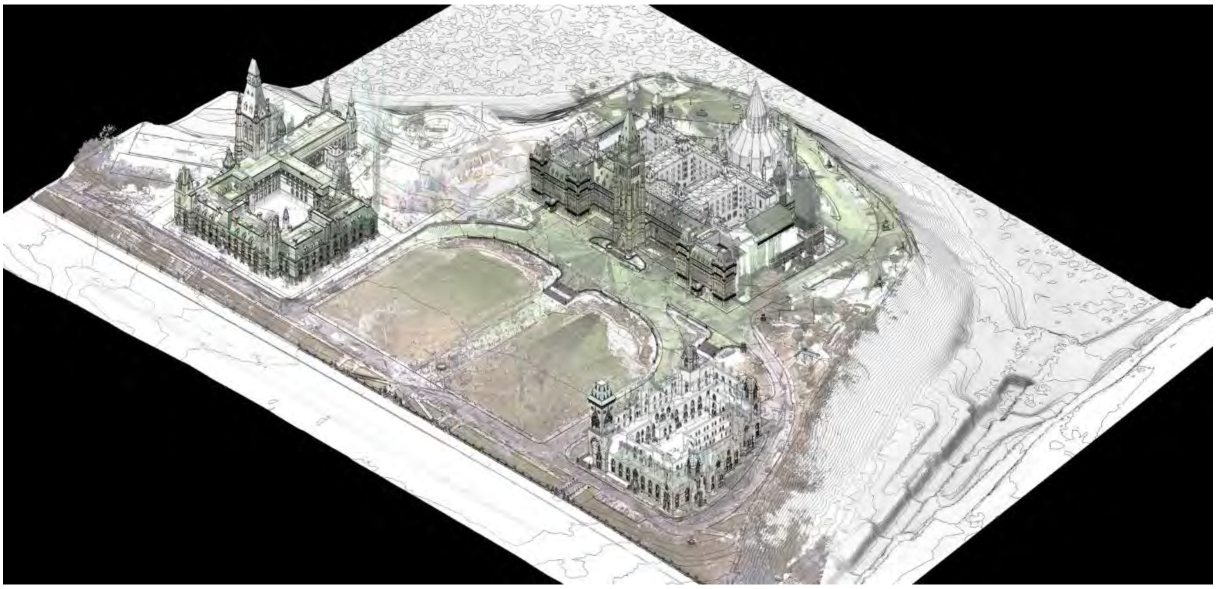

Figure 1: The BIM of the Parliament Hill National Historic Site with point cloud overlaid.

1.3 Dissemination Through Digitally Assisted Storytelling

Working with PPB and others, CIMS has had the opportunity to leverage the digital recording and modelling of the Parliament Hill National Historic Site for digitally assisted narratives that are directed at partner and public engagement with the rehabilitation project. These narratives have been developed for a wide range of media including: web, mobile, in-situ, and augmented reality. We have also developed both passive and active virtual reality experiences. The first passive 360 experiences were made available to the public in 2017, through an on-site installation — the VR Kiosk (figure 2) — in Ottawa, Canada. Experiments into active experiences using the BIM, point cloud data, and photogrammetry of the Canadian Parliament buildings are ongoing.

Figure 2: The VR Kiosk at the Capital Information Kiosk across from Parliament Hill allowed visitors to explore passive VR. Photo by Chris Roussakis.

Within the passive 360 experiences of the VR Kiosk, visual assets included a combination of panoramic photography, point cloud data, BIM, and historical photos to create a hybrid visualization. Careful selection of visual stimuli was made and overlaid with a soundtrack and narrative that helped to draw the viewer's attention to key elements of the scene. The storyline within the 360 experiences were linear with the careful control of what was visible and how the story unfolded.

In active VR, the sense of agency — the feeling of control experienced by the user over the outcome of the story — is greater, with the viewer able to move around more freely and interact with the virtual environment. This enhanced sense of agency comes with increasing demands on hardware, software, and narrative development. In the passive VR experiences the viewer remains stationary while the scene unfolds around them. The rendered scene of the passive 360 experience, outputted as a video file, is less effected by the limitations of workstation performance and the game engine platform as is the active experience. Within the passive experiences, the narrative is controlled by the linear flow of the video and the reduced agency of the user. The active experiences allow for greater agency and therefore less control of the narrative outcome; therefore, methods to control where the user's attention is drawn should be implemented. CIMS determined that the gaze of the participant can be controlled by creating specific assets within the space with a higher level of detail. These elements would be important to the narrative due to their heritage and architectural significance. To help define the new LOD system for virtual reality, CIMS took elements from its own classification system for BIM — LODIA — that defines the architectural elements of high heritage significance to be of higher fidelity than less important elements. The CIMS LODIA and the new LOD for VR system benefited from research of existing classification systems.

2. EXISTING LEVEL OF DETAIL SYSTEMS

2.1 Level of Detail/Development Systems for New Construction BIM

In the Architecture, Engineering and Construction (AEC) industry, BIM is intended as a communications tool for stakeholders and therefore needs to follow guidelines or standards — like a level of detail or development classification system — to maintain a consistent language among those stakeholders. A number of international BIM organizations have developed guidelines, such as *The Level of Development Specification* created by BIMFORUM in the United States and *PAS 1192-2013,* developed in the United Kingdom by the British Standards Institution (BSI). These standards are created primarily for new construction and focus on requirements for different phases of a new-build project such as concept, design, construction, and operation — with little or no discussion of as-found modelling.

These existing guidelines hold commonalities between them such as the progression from a simplified place holder object as the lowest LOD level to a highly graphically detailed object with all imbedded information such as materiality and manufacturer on the high end. The classification systems define both the graphical representation and imbedded information related to the representation; however, a metric for identifying and quantifying disparity between geometric information and non-geometric information is lacking.

For heritage buildings, these LOD systems are flawed in that they do not offer guidelines — among other shortfalls — for recording the current phase of development, the cultural interpretation of the found condition, or identifying assets of greater or lesser heritage significance.

2.2 CIMS Level of Detail/ Information / Accuracy (LODIA)

To address the lack of BIM guidelines or standards for existing and heritage buildings, CIMS began developing internal guidelines in 2015. The three tier, five category level of development system borrows from AEC industry standards and guidelines and maps level of detail (LOD), level of information (LOI), and level of accuracy (LOA)—LODIA—for each element type.

The level of detail (LOD) describes the graphical representation of the model and follows the existing standards referenced from symbolic placeholder to detailed model in the categories LOD 0 to LOD 4 (figure 3). The choice of a specific level of detail is determined by available reference material and the purpose of the model.

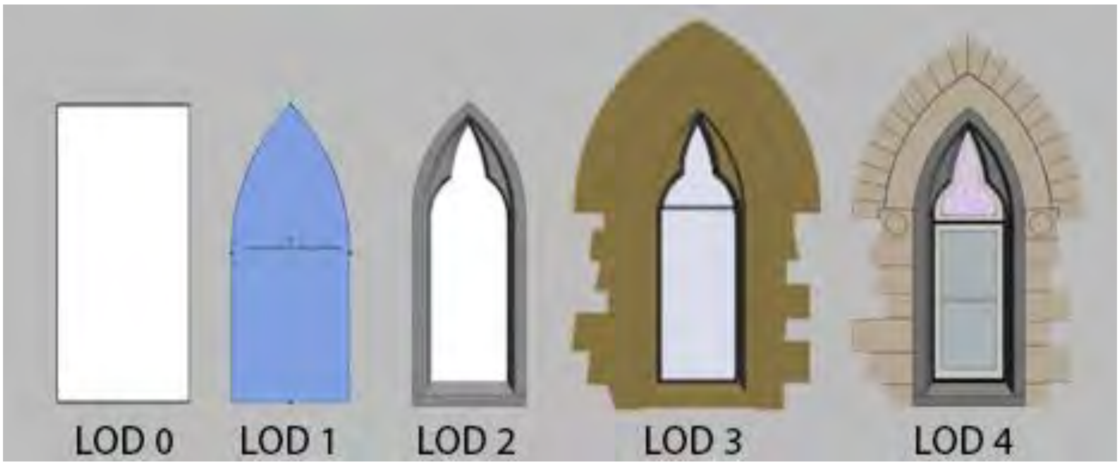

Figure 3: CIMS Level of Detail 0 to 4 of a window

The level of information (LOI) is the imbedded information that BIM elements contain. This may include material, manufacturer, source data, or additional resources. The level of information is often determined by the data available. Unlike a new-build — where the material and assembly of a wall are known — a BIM of an existing or heritage building relies on existing drawings, specification documents, and onsite investigation to determine structure, material, etc. In some cases, only onsite documentation and observation are available.

Level of accuracy (LOA) is a category added when it became clear that the deviation found in elements through documentation should be categorized outside of the level of detail. In the context of the CIMS LODIA protocol, LOA determines the level that the deflection and deviation of the building element are illustrated in the BIM. Separating the level of accuracy and level of detail allows for the model to properly reflect different sources of information.

Unlike existing classification systems that focus on the construction phases of a project, the CIMS LODIA creates a BIM that acknowledges both existing and future conditions and models uses. For example, the Centre Block

BIM was prepared in anticipation of an extensive rehabilitation project and as a heritage record of the building prior to that rehabilitation. For the rehabilitation, the LOI was underdeveloped since onsite investigations were limited. LOA and LOD were developed to a high level based on available point cloud information. The next phase in our research was to study the possible adaptation of CIMS LODIA for virtual reality.

2.3 Existing LOD Systems for Computer Graphics

While LOD systems for digital spaces are well established, they lack any attempt at an industry standard related to content. Rather, they are typically used to optimize polygon count and processor speed. First introduced in 1976 by James H. Clark in *Hierarchical Geometric Models for Visible Surface Algorithms,* the guidelines proposed that objects farther away from the camera should be at a lower level of detail than those closer to the camera. As Clark explains, the eyes of a human figure in the distance would require minimal representation whereas seen close up would require more detail. What can be represented as a black speck at one distance must have visible distinction between iris and retina at another. By looking at the proximity of objects within a scene as a hierarchy and modelling only "…the minimal information needed to convey the meaning of what is being viewed…" *(Clarke, 548)*, the geometric complexity and polygon count of the scene can be carefully maintained to meet industry standards.

This concept of proximity based LOD was used in developing the passive VR experiences of the VR Kiosk. Objects in the distance were simplified while those in the foreground were rendered at a higher resolution. For example, in the experience, *From Yesterday to Today: Discover the Hill*, lower resolution historic photography comprised the buildings in the distance, while the camera was situated on a more detailed terrain model with high-resolution images populating the scene between the viewer and the background (figure 4). Essentially, object resolution was dictated by the distance from the camera.

Figure 4: Screenshot from the VR Kiosk experience, *From Yesterday to Today: Discover the Hill*.

Unlike the passive scenes of the VR Kiosk — where objects are rendered at chosen LODs and placed in relation to a fixed camera — typical scenes in video games and active virtual experiences allow the participant and objects to move around, creating the need for the objects of the scene to change between different LODs relative to proximity. Three common frameworks are currently used to identify LODs within a scene: discrete, continuous, and view-dependent.

The Discrete LOD framework is the method that Clark proposed in his 1976 paper. Multiple versions of an object are created at predefined LODs. During the real-time play of the experience, the different versions are loaded in based off the proximity of the participant to the object (Luebke, 9). For example, if the asset is a sphere, from a distance it will be modelled as the simplified dodecahedron. As the object gets closer, through movement of the participant or the scene, the digital form will be replaced with more complex shapes until it appears as the poly-heavy sphere (Clarke, 548).

Continuous LOD, also known as Progressive LOD, creates a complex data structure that contains multiple LODs within it. During run-time, the appropriate LOD is pulled out and additional details are left unloaded. This framework creates better granularity and fidelity due to the smooth transition between LODs pulled from one source and not dictated by a predetermined set (Luebke, 10).

The final LOD framework, View-Dependent LOD, allows for an object to be simplified anisotropically relative to the distance or point of view of the camera. For example, a large field, such as a landscape, will have the portion currently being viewed by the camera shown at a high LOD while the distant edges would be modelled with less detail. Similarly, only the portion of an object being viewed — for instance, an object with a front and back — will only be partially visible, allowing fthe back — or the side not currently in the camera — to be reduced (Luebke, 11).

Again, Level of Detail in computer graphics has not been systematically developed for the development of narrative content and is primarily a method for communicating degrees of modelling complexity in a virtual scene to minimize polygon count and optimize processing speed.

3. AN LOD FOR VR NARRATIVES OF HISTORIC SPACES

When creating active virtual reality experiences of heritage spaces, the important assets to the heritage quality or narrative of the space must first be identified. Although the computer graphics LOD systems are helpful when relating model complexity to proximity and to optimize processor speed, for heritage spaces, certain assets in the room are integral to the overall heritage significance of the space while others are not. A VR LOD classification for a heritage space should reflect both the proximity of existing standards and the historical significance to aid in the general narrative of the space.

3.1 Lessons Learned from the CIMS LODIA

To help define a VR LOD for heritage spaces, we considered the lessons learned from the creation of CIMS LODIA for BIM. At a fundamental level, assets within the spaces that are of minimal historical and cultural significance are either omitted or represented at the lowest LOD. Whereas assets of high heritage value are represented at the highest LOD. The objective is to draw the eye to the areas of higher LOD and to highlight the significance of the heritage asset. Further, this LOD system is not exclusive and can complement existing proximity based LODs for computer graphics.

The CIMS LODIA allows for the graphical detail (LOD), imbedded information (LOI), and deformation accuracy (LOA) to be independently valued for each modelled element. This allows the BIM to be accurately categorized based off the available documentation. With heritage buildings, the knowledge of what can be modelled is based on the documentation provided, sometimes limited to what is visible in a space. When translating the heritage spaces into VR experiences, the LOI is removed and the LOD is the primary requirement. The LOI has no influence on the aesthetic quality of the model and therefore does not translate to the requirements of the virtual environment. Including the LOA in a VR experience needs to be evaluated on a case-by-case basis to determine if the ideal or the actual condition of the space is needed. The LOA will show all deformations that are greater than 25mm, however, showing these modifications in the VR experience will greatly increase the polygon count and slow processing speed. For accuracy, the BIM has repeated elements — such as columns and wood paneling — treated as unique geometries modelled to the point cloud data. The unique elements transferred to the virtual environment have a negative effect on performance due to the increased processor speed. To improve this performance, the unique elements can be converted to repeated geometries that are instanced within the virtual environment. Only one geometry is loaded within the space and then repeated, reducing the processing time of the experience. For most elements, the ideal condition found in the repeated elements will not affect the heritage aesthetic of the environment, however, if the narrative requires attention to the variances, the unique geometry will need to be used.

As discussed above, for a heritage BIM, the LOD is higher for spaces of cultural significance. For example, within the Centre Block of Parliament Hill BIM, the hallways and attic space are modelled at an LOD of 200 while the Senate Chamber is modelled at an LOD of 350. (figure 5) Effort was placed in ensuring the wood and stone detailing within the Senate Chamber were modelled while the hallway and attic was left with minimal graphical representation. The correlation between higher LOD and if an element or space contains cultural and heritage significance is key to both the BIM and VR standards when showcasing heritage buildings. For VR, the elements of significance will help with the narrative flow of the space and therefore must be shown at a higher LOD than the elements of lesser importance.

Figure 5: The Senate Chamber and Foyer modelled at LOD 350.

When the LOD is linked to the heritage significance of the space, the classification system becomes the orchestrator of the narrative, applying greater importance to assets with a higher LOD. This concept found in the BIM LODIA classification system was created to help with creating an historic record of the as found condition and be used in visualizations. Through applying these concepts to a LOD system for virtual reality assets, a new categorization system that focuses on drawing the narrative to historically significant assets can be created.

3.2 LOD VR for Heritage Spaces Classification

The LOD VR classification system (figure 6) for heritage spaces that CIMS has developed uses a three-tier system that focuses on the graphic quality of assets. On the low end of the spectrum is LOD 1 with a clean mesh that uses normal maps for complex geometries and generic texturing. LOD 1.5 expands on LOD 1 by texturing the model with photogrammetry, photography, or point cloud data. LOD 2 replaces the built mesh with an optimized photogrammetric model to ensure all details are represented and the heritage asset is highlighted. LOD 2 is intended to only be used for assets of high importance and interest due to their high polygon count. Below is a greater breakdown of each LOD.

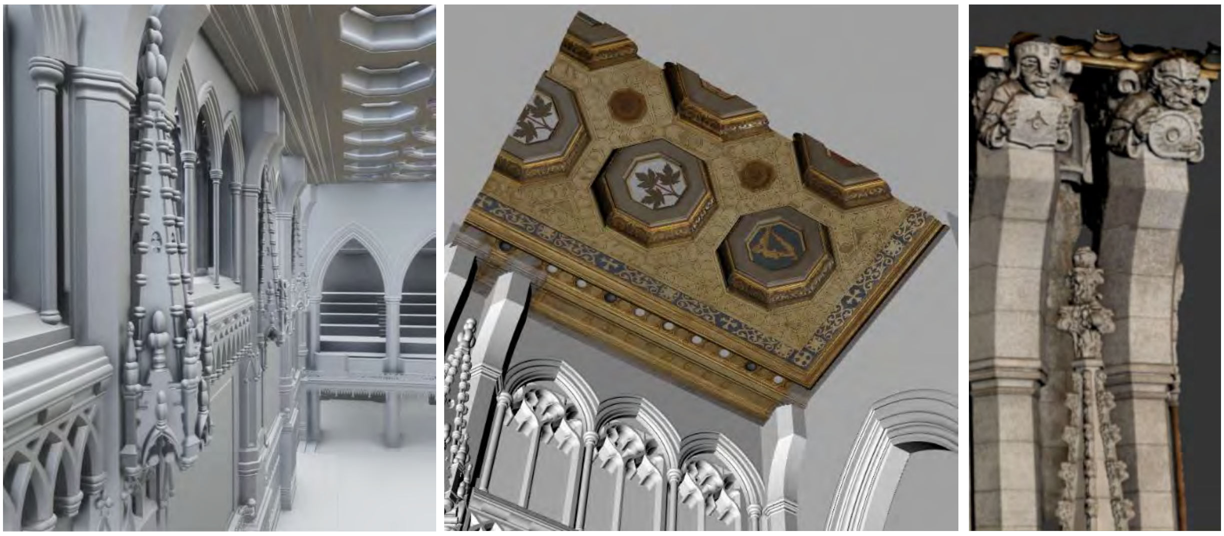

Figure 6: From left to right, LOD 1 of the senate chamber direct from the BIM, LOD 1.5 of the Senate ceiling textured with point cloud data, and LOD 2 of the double columns created from photogrammetry.

3.2.1 LOD 1

The lowest LOD classification is LOD 1, which consists of a mesh with either generic textures or none at all. In the CIMS workflow, the mesh is created by converting an LOD 350 BIM model into an optimized mesh using the computer modelling software Rhinoceros. The use of the BIM to create the virtual reality assets takes advantage of the digital assets CIMS has previously created as well as ensures an accurate representation of the space. Details within the BIM are converted into normal maps and applied to the newly created mesh. Textures from a generic texture library can be applied to give the assets a sense of materiality, however, the textures are not custom or unique to the space. The polygon count of an LOD 1 mesh remains relatively low. The LOD 1 assets help give context to the heritage space and provide a backdrop to more significant components without drawing attention to themselves.

3.2.2 LOD 1.5

LOD 1.5 uses the LOD 1 mesh and applies a texture created with site-specific information. Point cloud data from terrestrial laser scanning, photogrammetry, or photography can be used to help generate textures for chosen assets. The polygon count of the mesh remains equal to LOD 1 with any additional visible detail appearing as a property of the texture. Unfortunately, the quality of the LOD 1.5 model is dependent on the quality of the colour data and requires time to acquire, process, and convert into a viable texture. LOD 1.5 is best used on areas that are of cultural or heritage significance but will either remain at a distance or is secondary to the specific narrative of the experience.

3.2.3 LOD 2

LOD 2 is a textured mesh that is created directly from metric data recorded with laser scanning or photogrammetry. This third and final category of the LOD system for heritage spaces in VR offers highly detailed geometry and photo-realistic colour. It is, however, labour intensive and results in a higher polygon count. Even if steps are taken to reduce the polygon count through optimization, current technology will not support a virtual environment composed entirely of LOD 2 elements due to polygon count and load-times. The LOD 2 elements can be extremely intricate in detail — showing details through a combination of a complex meshes, normal maps generated, and correct texturing of the assets with the texture generated from the photogrammetry or point cloud. Using LOD 2 heritage assets can be examined in close detail with a full sense of their materiality and intricacy. LOD 2 elements should be used for assets that are of highest significance in the space. Through using them exclusively for the areas that are of significance to the space and therefore the narrative, the user's gaze will naturally drawn to them.

3.3 Strategies for Using the LOD for VR of Heritage Spaces

A heritage space can have multiple and diverse assets that contribute to its heritage value. When creating a representation of these spaces in VR, it is important to manage the level of detail to not overwhelm the participant's field of view and to manage the size and performance of the experience. The combination of the three LODs will help highlight areas of interest to the participant and ensure the experience runs smoothly with an optimized polygon count and processing speed.

Careful classification of the LODs is required to not only control the narrative or gaze of the participant, but also to help manage available data. Due to the nature of documentation through laser scanning and photogrammetry, only elements visible to the lens of the laser scanner or camera can be captured. This may cause limitations and problems to how assets in the space are represented. If the back or top side of artifacts are not in the field of view of the documentation device, then those surfaces will be missing in the generated meshes. When requiring a high LOD within the virtual space, the documentation will need to be inclusive of all important aspects, adding greater time and planning in the documentation process.

Within a given virtual heritage space, the division between LODs to help with the narrative can be seen as 5% or approximately 2-5 assets at LOD2, 25% at LOD 1.5, and the remainder at LOD 1. This division is based off balancing points of interest, appropriate file size, modelling effort, and availability of data. The Senate Chamber in the Centre Block of the Parliament Buildings of Canada will be used to examine this concept further.

Within the Senate Chamber, the gothic revival style resonates in the ornate detailing found in the walls, columns, ceiling, and sculptures. The heritage impact is felt in the small details of the wood paneling to the ornate complexity of the canopies within the column detail. Converting the Senate Chamber into a virtual experience will require careful consideration of LODs to help reduce overall size and complexity of space, reduce modelling time, and ensure that the narrative of space is visible to the participant. Without the careful selection of the higher LODs, the participant will see all heritage assets as equal and will not direct their gaze to the intended elements.

Within the chamber, the elements that will be modelled at LOD 2 will be the key heritage assets to the narrative or elements that will negatively impact the virtual space if simplified. The space will include approximately 2-5 assets at LOD 2. LOD 1.5 elements will consist of assets that are significant to the heritage impact of the space but not key to the narrative or will only be seen at a distance. All remaining elements will be at LOD 1.

To determine the division, the room is examined at the main location of the participant. If the participant is to be standing by the entrance of the chamber, the divider between the chamber and the ante-chamber will need to be at a greater LOD to ensure its ornate wood detailing is visible. The grotesques carved in the wood above the door will need to be clearly represented. If, however, the participant will be in the middle of the room, the divider will be at a great distance and will be reduced to an LOD 1. The grotesques may be omitted since they will not be visible from the chosen point of view. In this manner, traditional LOD for computer graphics principles are transferable to the LOD for VR of heritage spaces.

Assuming a participant location of the centre of the room, the side walls of the chamber can be broken down into a division of LODs based off the mentioned principles to discuss further. The wall is divided horizontally into three segments – wood paneling, stone, and windows. Intricate wood and stone details are present. Vertically, the wall is divided into four portions by double stone columns with an ornate canopy and carved stone figures at the capitals. Each divided wall portion contains a culturally significant painting of World War 1. Through an examination of these elements, the stone columns with ornate canopies and stone figures is analyzed to have a high heritage significance and therefore will be important to the heritage narrative of the space. These elements will be necessary to be included at LOD 2. On the contrary, the wood paneling and stone wall, although containing unique details, can be reduced to LOD 1 to not distract the participant from the more significant assets. Figure 7 demonstrates the wood panelling of the wall as an LOD 1 and an LOD 2 asset. The paintings will be portrayed as LOD 1.5 since it is important that they are represented with correct colouring, however, they do not need a complex geometry. Other aspects that will be included at LOD 1.5 are the ceiling and detailed stone band behind the senate speaker's chair platform. These assets contain heritage significance that cannot be left out of the narrative, however, they are not the main components of the space. They can be reduced to LOD 1.5 and appear flat in contrast to the LOD 2 elements. This allows the select LOD 2 elements to be highlighted and draw the eye of the virtual participant.

Figure 7: The wood paneling of the Senate Chamber wall shown as LOD 1 (left) and LOD 2 (right).

At times, the LOD can be used to carefully control the gaze of the viewer and force a strict narrative. If the narrative of the experience is to focus solely on the Senate Speaker's chair, the LOD may be defined to have only the Speaker's Chair at LOD 2 with all other assets divided between LOD 1.5 and LOD 1. Although there may be other elements that are significant to the heritage qualities of the space, they can be reduced to a lower LOD to ensure the focus is on the one highlighted item that will appear in greater detail. In addition to helping control the narrative, a careful selection of higher LODs helps reduce overall production time and ensures a lower polygon count and optimal processor speed.

4. CONCLUSION

Within virtual worlds and games, careful attention must be spent on ensuring a reduced polygon count for optimal processing speed and high fidelity. Level of detail techniques have been created to help define methods for reducing mesh complexities based off proximity. Discreet, continuous, and view-dependent methods have allowed for an object to appear in high detail when in close range and greatly reduced when at a distance. This technique, although transferable to the representation of heritage spaces, does not help manage the representation of large quantities of ornate detailing in a space that may all be seen at an equal distance. To help define a new LOD for the representation of heritage spaces in VR, the example of a BIM categorization system created by CIMS called the CIMS LODIA can be used. This system applies a higher value to elements of heritage significance, providing them with a higher LOD. In the virtual experience, the elements of high heritage significance should be valued at a higher LOD than those not as important. Additionally, the narrative of the scene can help dictate what elements are of more heritage significance within the space and should be represented at the highest LOD. When there is a greater contrast between the LODs, the gaze of the participant will focus on the elements that are at the higher LOD. The VR LOD for Heritage Spaces therefore defines elements of greatest heritage and narrative significance at the highest LOD, LOD 2.

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CONSERVATION OF MODERNIST ARCHITECTURE THROUGH THE PREDICTIVE SIMULATION OF PHYSICAL DECAY – A CONTRIBUTION TO FACILITIES MANAGEMENT IN HBIM

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ABSTRACT: *Most modernist architecture in Brazil have experienced some degree of decay. The conservation of our national architectural heritage is constantly threatened by the inefficiency, or even lack of, conservation, maintenance and restoration programmes, as well as the imminent end of the projected lifespan for the first modernist constructions. There have recently been great advances with regards to Historical Building Information Modelling (HBIM) and, as such, we will attempt to demonstrate how predictive simulation can contribute to the decision-making process for Historical Facilities Management. The merging of these three areas – the ross-heidecke formula in heritage management, decision support in facilities management and the visualization of building information modelling – will allow us to not only register current and proceeding heritage status, but predict the impact of future management decisions. By mapping a section of the University of Brasilia Central Science Institute according to degradation factors, it should be possible to visually identify key elements and predict the outcome of maintenance decisions. In order to do so, we will represent a myriad of scenarios both mathematically and visually, concerning the advance and progression of a combination of building elements' physical decay by means of the Ross-Heidecke formula and its ensuing manipulations with the aid of 3D and parametric computer programmes and a use case of the University of Brasilia Central Science Institute. These scenarios, in turn, can benefit conservation decision making process through the predictive simulation of pathology progress and physical decay as a result of the variation of the formula's physical parameters, such as lifespan and depreciation status, and the estimation of maintenance priorities. By doing do, we should also be able to precisely determine the cost difference of executing preventive maintenance now and reparative maintenance in the future.*

KEYWORDS: *predictive simulation; HBIM; depreciation status; decision support; Ross-Heidecke model; FM practices.*

1. INTRODUCTION

The growing concern for architectural heritage preservation and conservation in Brazil has recently generated a series of studies regarding its service life, degradation status and pathologies (Associação Brasileira de Norma Técnica, 2013). Modernist architectural heritage has been specially affected by the short service life of reinforced concrete and non-existent governmental maintenance budgets. Most modernist construction in Brazil has already reached sixty years of existence, many without appropriate periodic maintenance. However, it is well known that building operations and maintenance costs during service life can extend to many times higher the construction cost (Becerik-Gerber *et al.*, 2012), making it critical to influence decision-makers to see the importance of regular conservation processes as well as demonstrate the monetary consequences of postponing decisions.

Recent research has indicated Historic Building Information Modelling (HBIM) and Facilities Management (FM) as important tools in achieving this process. Although heavily used during modelling and constructions stages, Becerik-Gerber *et al* (2012) indicates that the use of Building Information Modelling (BIM) can "support and enhance other functions of FM through its advanced visualization and analysis capabilities". However, we do not yet have a total understanding "as to where BIM can provide benefits to FM practices, what some of the challenges are, and what the expected value is".

Volk, Stengel and Schultmann (2014) indicate that FM practices are still focusing on recently completed constructions with existing BIM models, as opposed to developing an as-built model for existing structures. While buildings with existing BIM models face a number of challenges regarding data standardization and system compatibility, heritage FM requires a complete as-built analysis and data migration into open BIM or FM systems (Patacas, Dawood and Kassem, 2015).

With regards to HBIM, despite the fact that considerable advances have been developed concerning documentation strategy through modelling techniques (Fai and Rafeiro, 2014, and Banfi, Fai and Brumana, 2017), data-acquisition (Cheng, Yang and Yen, 2015), and maintenance information integration (Motawa and Almarshad, 2013), existing buildings concerns such as deterioration modelling, condition assessment systems, and failure modelling in HBIM, are still at the very early stages (Motamedi, Hammad and Asen, 2014).

1.1 Field Contributions

In order to satisfy the need for decision-making tools, the merger of these three areas was needed. While BIM practices can provide a visual record of current and future degradation states, the Ross-Heidecke formula used in heritage management can provide FM the necessary prediction tools for effective decision making. By visualizing critical areas and precisely determining the cost difference of executing preventive maintenance now and reparative maintenance in the future, it is possible to predict the consequences of different maintenance decisions and decide on the best one according to its cost-benefit ratio.

We believe that recent developments of the Ross-Heidecke depreciation cost evaluation model, such as Pimenta (2011) and Pereira (2013), can be used to graphically simulate building depreciation according to a number of chosen parameters (such as structure and infrastructure). FM personnel can then perform what-if analysis according to different scenarios and possible maintenance decisions. This scenario analysis helps the conservation decision-making process by demonstrating the consequences of maintenance decisions, or lack thereof.

This research use case encompasses a section of the University of Brasilia Central Science Institute, which was built from 1963 to 1975 with a precast-prestressed isostatic structure. Five parameters were chosen to calculate general degradation: pillars, beams, rainwater drainage system, window frames and slab. The formulas were manipulated according to maintenance decisions to develop predictive scenarios by using graphic parametric software, such as *Rhino 3D* and *Grasshopper*.

1.2 Methods

We have attempted to identify the possible uses of the proposed developments of the Ross-Heidecke formula within growing HBIM and FM applications and contributions to heritage conservation based initially on the Pimenta (2011) and Pereira (2013) thesis papers. In order to do so, we carried out a non-exhaustive literature review of the project involving heritage and FM in BIM over the last six years through scholastic web search engines and citation indexing services, such as Web of Science, Google Scholar and the Brazilian Capes Periódicos. A section of the University of Brasilia Central Science Institute was chosen as the main case study as we had recently participated in its complete inspection, according to which, we were able to assign individual depreciation state factors to each of the following construction elements: pillars, beams, slabs, window frames and rain gutters. We were also able to quantify certain characteristic qualities, such as execution, use, interior environment and maintenance along with the building's history and plans. The building was then modelled in a computer-aided design application software (*McNeel's Rhinoceros 3D*), after which a graphical algorithm editor (*McNeel's Grasshopper 3D*) was used to associate different construction elements to the initial formulas and generate a parametric visualization of individual and global depreciation status through a gradient of green to red.

2. HISTORICAL CONSIDERATIONS

The preservation and conservation fields in Brazil are still being developed. The Artistic and Historical Heritage National Service (SPHAN) was created in 1937 by Gustavo Capanema, former Minister of Education, and Mario de Andrade, a modernist architect, in order to "promote, nationally and permanently, the protection, conservation, enrichment and information of historical and artistic national heritage" (Brazil, 1937).

At this time, many modernist architects worked within SPHAN, writing legislative texts, formulating guidelines and overall management. The task of acknowledging and confiscating that which could be considered part of the national cultural identity fell to architects such as Lucio Costa, Rodrigo Melo Franco de Andrade, Paulo Santos, José de Souza Reis, Renato Soeiro and Alcides da Rocha Miranda. According to Silva (2012), not only were they responsible for encouraging national heritage preoccupation, the proximity of the modernist movement to the SPHAN made it possible to determine and preserve that which should personify as national monuments.

The São Francisco de Assis Church and the MESP (Education and Public Health Ministry) building were the first modernist constructions to be registered as Cultural Heritage. The São Francisco de Assis Church was registered in 1947, four years after its inauguration, and the MESP building was registered in 1948 three years after its inauguration. Although newly finished, these works already constituted the creation of a national image and therefore were apt to be considered national heritage. Nevertheless, it should be noted that despite the importance of these monuments, the lack of temporal distance between Modernist production and its registration as national heritage has had severe consequences due to the advanced deterioration of reinforced concrete (Silva, 2012).

The use of reinforced concrete structures was largely responsible for the beauty and delicacy of modernist buildings. On account of it being a new and very malleable material, it became possible to decorate the urban space with innovative curves, which, according to Niemeyer (1978), resembled the curves of the female body. However, at the time, reinforced concrete was thought to compare to stone constructions, eternal and immutable, immune to deterioration. However, the inevitable appearance of degradation processes in most of the reinforced concrete constructions led scholars to inquire about its service life, performance and durability (Boldo, 2002).

After years of experience with reinforced concrete, a series of technical standards were developed to ensure construction quality. The NBR 15,575 of 2013 defines service life as the "period of time in which a building and its systems support the activities for which they were designed and constructed, meeting expected performance levels." When taking into account the minimum structure service life established in the aforementioned standard of 50 years, or even the more comprehensive 100 years suggested by Pimenta (2011), it is possible to understand the fragility of assigning heritage status to modernist constructions. These national and international symbols of the Modernist Movement are perishable and, therefore, are in need of constant maintenance and conservation programmes.

2.1 University of Brasilia Central Science Institute

Access to information was a critical factor in determining a use case. The chosen test subject is a section of the University of Brasilia's Central Science Institute (ICC). It which was constructed from 1962 to 1975 and is the first university building in Brazil to integrate several science institutes under one roof, in accordance to the University's pedagogical plan, where university students could have access to a number of fields even without being directly affiliated to them. The 720-meter-long construction represents a juxtaposition of uses, functions and its harmonization to users. (Alberto, 2009)

The construction is also considered a milestone for pre-fabricated concrete construction in Brazil. It is composed of two elongated parallel constructions, each 720 meters in length, separated by an open garden space of 16.5 meters in length, as seen on Figure 1. The western construction is 29.6 meters wide and houses the auditoriums. However, for this case study, we chose the 26.6-meter-wide section of the eastern construction, that houses the Architecture College. The entire building is isostatic with pre-fabricated reinforced concrete pillars and pre-stressed beams and slabs. (Fonseca, 2007)

Fig. 1: ICC view from above.

The building axes pass through the smallest section and are numbered from south to north with pillars at every 3 meters. There are seven colleges throughout and the Architecture College is comprised of a 120-meter section of the eastern bloc, starting at meter 474 and ending at 594, as shown on Fig. 1.

3. STRUCTURAL PERFORMANCE

There is a large fraction of modernist structures in a state of physical depreciation and threatened structural performance. For this reason, scenario simulation has become essential through the precise record of the construction's current status, the qualitative and quantitative physical depreciation evaluation, and the pathological progression prediction. Amongst physical depreciation causes are: aging, wear, obsolescence, function alteration, interaction between different materials, and even natural disaster. The building's financial value is, therefore, intrinsically linked to the study of its physical depreciation factor.

The methods, or criteria, used to calculate physical depreciation abound. However, according to Pereira (2013), the one that is most in use is the linear depreciation method where the value loss is constant through its service life. Notwithstanding, evidence suggests that identical constructions may not decay in similar manners, making it necessary to develop different methods which take into account additional variables, such as conservation status, projected lifespan, service life, construction quality and maintenance regularity. The Brazilian Institute of Engineering Inspection and Evaluation has chosen to use the Ross-Heidecke as its standard evaluation model, which, along with its later development and expansion by Pimenta (2011) and Pereira (2013), will be the basis of our programme.

The Ross-Heidecke Model is based on the relation between age and conservation status. According to this method, maintenance and restoration are not fully capable of completely recuperating construction value as it only prolongs service life, thus well-maintained properties depreciate more slowly than poorly-maintained ones (Pereira, 2013).

Pimenta (2011) expanded the Ross-Heidecke Model by calculating physical depreciation for each construction element and then using the weighted average to determine total depreciation. Each element, or parameter, is weighted according to its cost percentage during initial construction and then multiplied by the depreciation factor attributed by a specialist. The number of parameters analysed does not have to encompass the entire construction, as long as it is possible to determine the cost percentage of each individual parameter in relation to the sum.

Initially, we gathered information about the building: the type of building; the history of the construction and whether there had been maintenance or repairs. Subsequently, we defined cost structure, in order to attribute a weight to each parameter and the percentage they represented within the total structure (Ei) according to estimation of initial costs. We then established the current age of the different parameter (AGE) by taking into consideration if it had received maintenance or repairs, and defined their estimated service life (ESL). The following step was the definition of each parameter's depreciation status (DSi). In this case, the evaluator's experience is of upmost importance, so as to adequately quantify the property's physical depreciation. In the Ross-Heidecke model, the conservation status is defined for the entire property, wherein with Pimenta's model, we define the status for each parameter separately.

$$k_i = \frac{1}{2}\left[\frac{AGE}{ELS} + \left(\frac{AGE}{ESL}\right)^2\right] + \left[1 - \frac{1}{2}\left[\frac{AGE}{ESL} + \left(\frac{AGE}{ESL}\right)^2\right]\right] \times DS_i$$

Once we have defined the value for each parameter, we can calculate the physical depreciation factor of each element (ki) with the previous formula.

From the cost structure, we then established the individual depreciation factors (ki) and their percentage of relative cost to the global property (Ei). With these integers, it is then possible to calculate the global depreciation factor, kg, according to the subsequent formula, where i represents the parameter and j the number of parameters analysed.

$$k_g = \sum_{i=1}^{j} [k_i \times E_i]$$

Further expansion by Pereira (2013) suggests manipulating the variable with the greatest degree of influence on the final result, the service life, to which he applies a factorial method based on seven quality characteristics of each parameter, namely: material quality, project quality, execution quality, internal environment quality, external environment quality, operation quality and maintenance quality. A factor from 0.8 to 1.2 is assigned to each characteristic (ISO, 2011) according to quality level and then multiplied by standard service life to obtain the estimated service life.

It is possible to establish a behavioural history of depreciation systems and predict consequences to status changes (such as maintenance, reinforcement, restoration, and even natural disasters) by manipulating models attributes (such as service life, conservation status and age), and formulating predictive simulations for decision making and conservation programs.

4. PREDICTIVE SIMULATION

This article is part of an ongoing research programme at the University of Brasilia where the Ross-Heidecke formula is currently being explored. The pathology progress and depreciation simulation was initially represented only with charts and numbers. Oliveira, Pantoja and Santoro (2017) show, mathematically, how the various manipulation of this formula can impact degradation calculation. This article goes one step further and takes calculations into HBIM formats and makes attributions to FM. Since this research is ongoing, our intention is to share its current progress.

Two powerful tools were involved in the process used to visually represent physical depreciation of a construction element. First, the building elements were modelled in a computer-aided design application software, *McNeel's Rhinoceros 3D*. Second, a graphical algorithm editor, *McNeel's Grasshopper 3D*, was used to script Pimenta's (2011) and Pereira's (2013) formulas. A *shader* from green to red was then added to the final result, representing the lowest to highest physical depreciation factor (ki) respectively.

The University of Brasilia's Central Science Institute (ICC) is subdivided into seven colleges and we chose the Architecture College as our test subject. It is comprised of a 120-meter section of the eastern bloc, starting at meter 474 and ending at 594. Five construction elements were chosen – pillars, beams, slab, window frames and rainwater gutters. Each element was then subdivided and manually mapped and modelled according to damage level, as shown for beams on Figure 2. The restrictive colour spreading represented here is due to element grouping, however, further development includes more precise damage mapping. Considering current progress of laser scanning data acquisition, automated inspection, mapping and modelling is a possibility for future study.

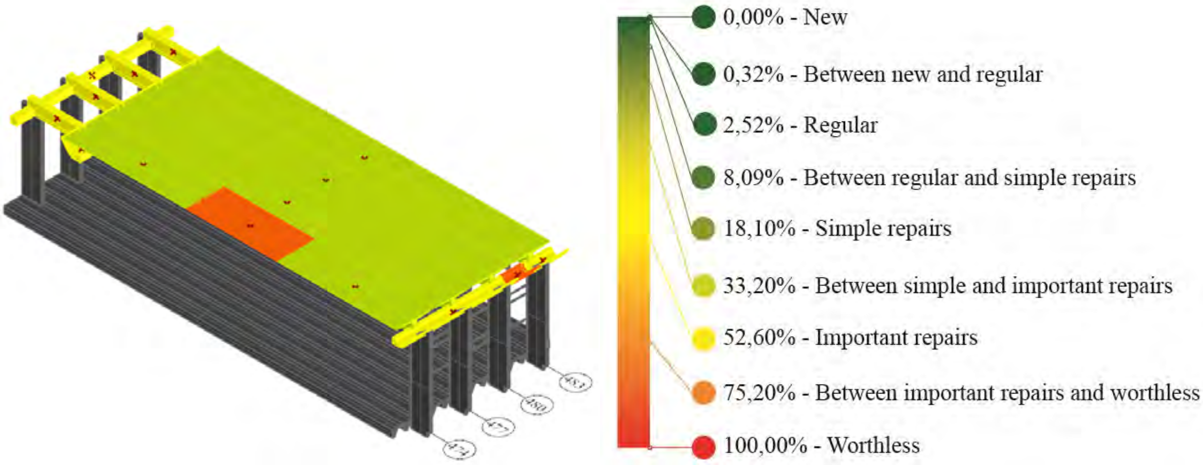

Fig. 2: Local damage (ki) map of beams from meter 474 to 483.

On-site physical inspection and historical research allowed us to roughly quantify Pereira's (2013) characteristic's quality for each chosen parameter. Based on the factorial method proposed by ISO 15.686, Pereira argues that it is necessary to assign a factor from 0.8 (non-existent or very bad) to 1.2 (excellent), and multiply it by the Standard Service Life (SSL) to establish the Estimated Service Life (ESL).

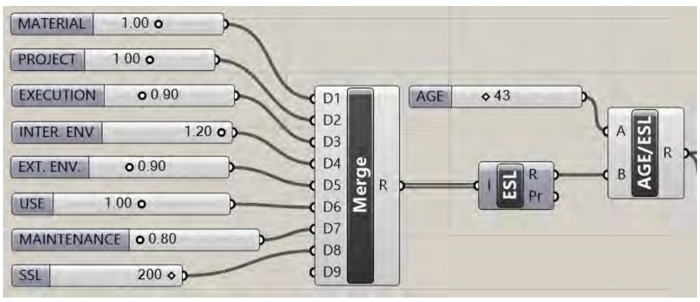

Fig. 3: Pereira's contribution to the Ross-Heidecke method programmed in Grasshopper.

We then programmed the initial Ross-Heidecke formula into Grasshopper, however attributing separate a

Depreciation Status according to damage level, as shown on Figure 4. The damaged sections were given a 75% depreciation status (DS), as they are in need of urgent repairs. The regular T beams are in the best shape, only needing simple repairs and both the curved and thinner horizontal beams are in a state of simple to important repairs. The result of each section's depreciation factor (ki) was then assigned a gradient from green to red identifying its individual depreciation status, green being new and red worthless

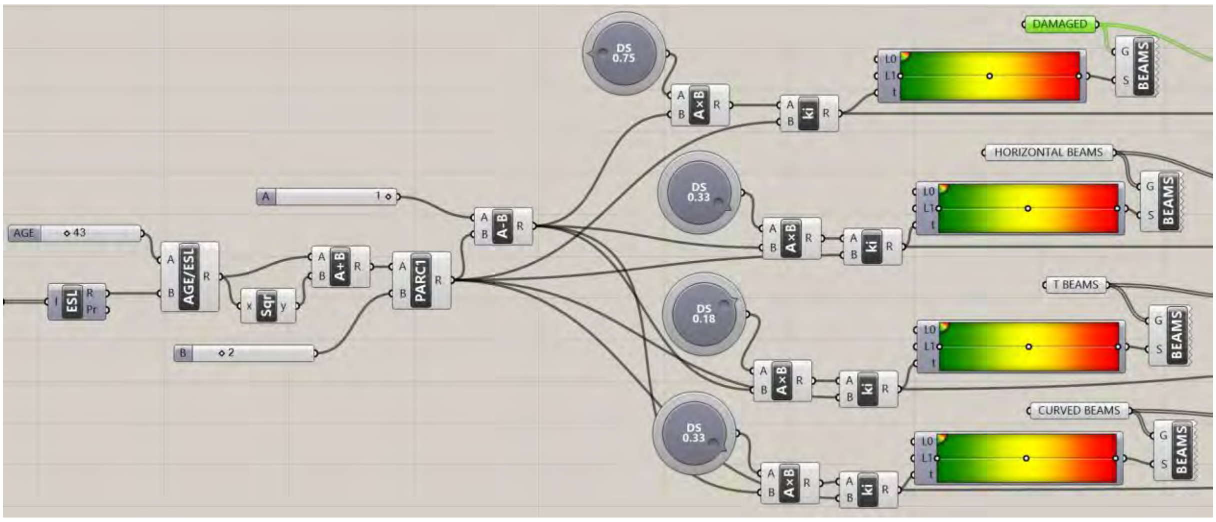

Fig. 3: Ross-Heidecke method programmed in Grasshopper for different beam damage levels.

Grasshopper was then programed to calculate the weight of each section according to the relation between each individual volume to the total volume, which, according to Pimenta's (2011) attribution (Figure 4), which gave us a global depreciation factor (kg) of 37% for all inspected beams.

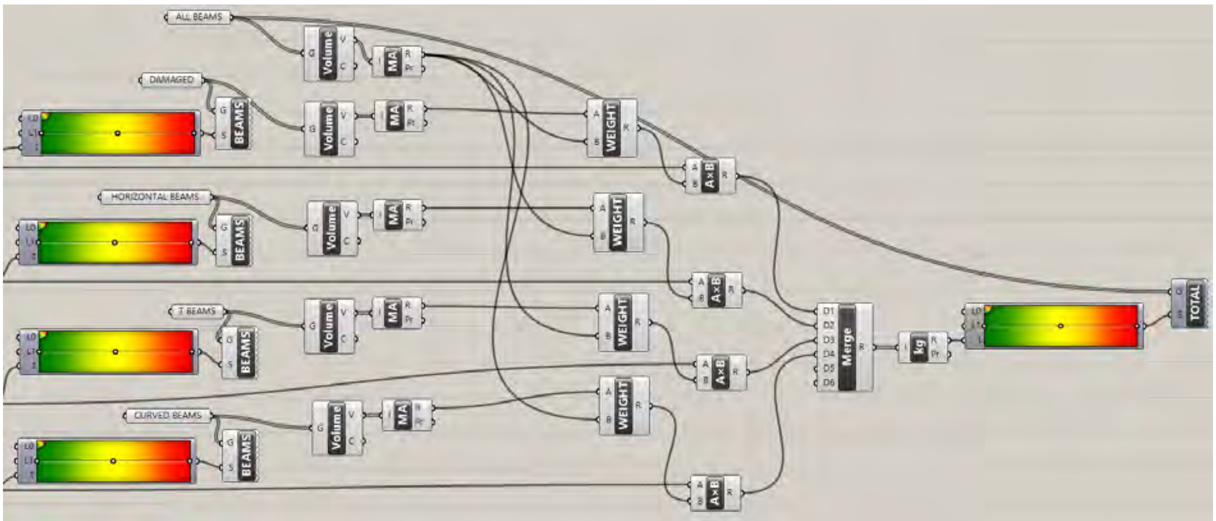

Fig. 4: Pimenta's attribution to the Ross-Heidecke method programmed in Grasshopper.

4.1 Ensuing Development

Initial test simulations have been performed considering element groups. As you can see, elements with shorter service life are the most depreciated, followed by the most exposed building elements – roof beams and pillars. The slab, by being in an inside environment, is the least affected. Different depreciation statuses (DS) were given to each element as a group: 52,6% to pillars, 33,2% to beams, 0,32% to slabs, and 75,2% to both the rain gutters and the windows (Figure 5). After processing in the Ross-Heidecke formula with Pereira's attribution, the individual factors (ki) found were 0,631 for pillars, 0,445 for beams, 0,132 for slabs, and 1 for both window frames and rain gutters, amounting to a global depreciation factor (kg) of 0,452. The global depreciation status was determined according to the weighted average of the five individual depreciation factors with the initial cost of each construction element with regards to all five elements.

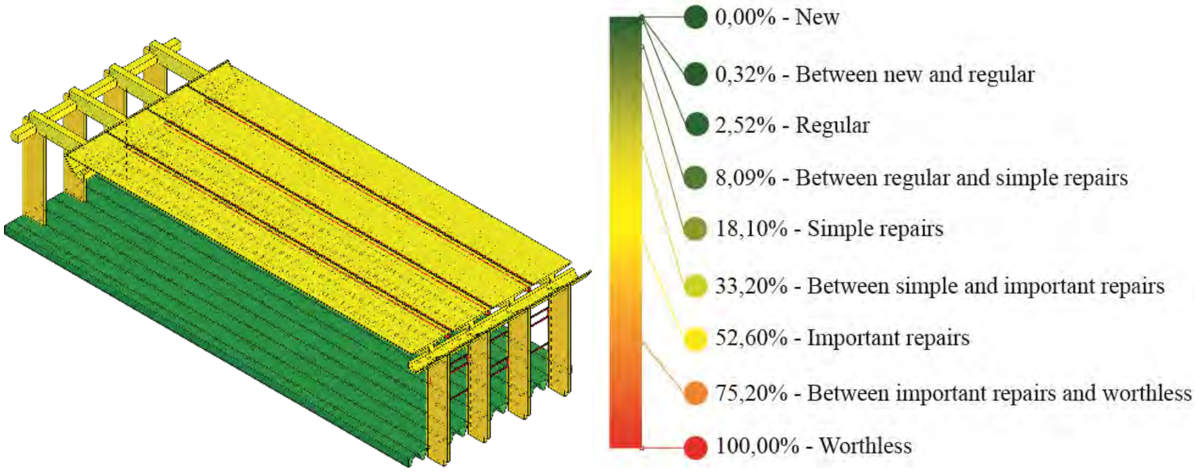

Fig. 5: Pimenta's attribution to the Ross-Heidecke method programmed in Grasshopper.

Three simulation scenarios were initially chosen to represent the project's potential. The first scenario depicts the impact of proper preventive maintenance on service life. The global depreciation factor, by increasing maintenance quality to its maximum (scenario 01), was 0,406. The impact of replacing both the window frames and the rain gutters with new and high efficiency materials (scenario 02) decreases the global depreciation factor to 0,349. Performing both of the previous operations (scenario 03) would result in a global depreciation (kg) of only 0,315 (Figure 6).

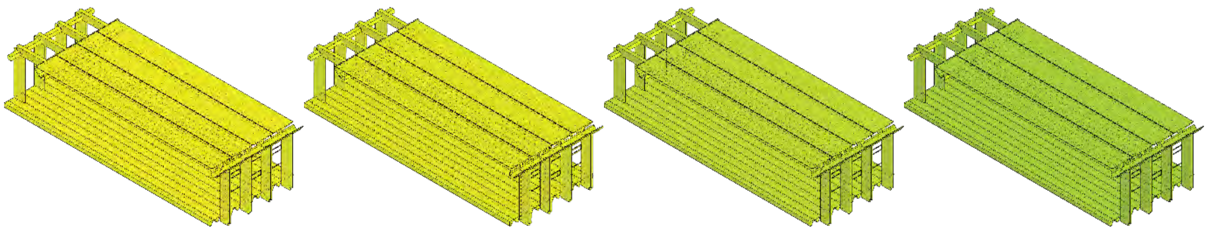

Fig. 6: In order from left to right: current depreciation status, scenario 01, scenario 02 and scenario 03.

Following the complete and precise damage mapping for the Architecture College, we intend to try to predict not only the consequences of different maintenance decisions, but how different pathologies will expand when no maintenance is performed. By manipulating input data in Grasshopper we will attempt to predict how much the building will be depreciated in 10 years' time with or without maintenance operations. We should also be able to precisely determine the cost difference of executing preventive maintenance now and reparative maintenance in the future.

5. CONCLUSION

Reinforced concrete is a concatenated engineered material, and as such, does not last forever. FM practices are, therefore, essential to modernist architectural heritage, as it is mainly made from reinforced concrete. However, in Brazil, modernist architectural heritage is government-managed and, as such, its conservation is prey to endless bureaucracy, which hinder all maintenance and causes further degradation. Governmental maintenance budget for architectural heritage is non-existent. It has become evident that governmental FM decision-makers lack the necessary tools to envision and understand the consequences of either their decisions, or lack thereof.

We feel that this line of research may contribute to understanding some of the benefits that BIM can provide to FM practices, such as deterioration modelling and conditions assessment systems. The advanced visualization and analytic capabilities of depreciative predictive simulation can support decision makers in determining conservation priorities, especially regarding architectural heritage.

Even though our research continues, it is essential that we share the findings accomplished so far. By simulating the consequences of different maintenance decisions on service life, such as replacing window frames and rainwater gutters or providing regular and appropriate maintenance, it is possible to see the impact on the depreciation of heritage buildings. While at its current status, our case study subject has depreciated 45%, if the necessary actions had been taken, it would have depreciated only 31%.

Nonetheless, there are many challenges that would benefit from further study. The Depreciation State and the qualities that influence the Estimated Service Life are still very subjective, determined mainly by field experts through visual inspection, and as such, may be the most benefited by the advances in laser scanning and data-acquisition, as they hold the highest potential for standardization. Visualization and data sharing methods are also in want of further development.

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AUTOMATED COLLABORATION FRAMEWORK OF UAV AND UGV FOR 3D VISUALIZATION OF CONSTRUCTION SITES

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ABSTRACT: Unmanned aerial/ground vehicles (UAV/UGV) can be a useful means of obtaining 3D geographic data of complex construction sites because of their superior advantages of site accessibility and remote controllability. However, both technologies have individual disadvantages caused by their limited field of view. Especially, the accuracy of vertical elements in the 3D point cloud built by UAV's images is relatively poor because of the obliqueness of the incident angles of the rays. Similarly, UGV cannot perceive point clouds of horizontal surfaces of objects which are taller than UGV. To mitigate the drawbacks of both systems, this study presents a cooperative operating method of UAV and UGV with a gradient and occupancy map-based path planner. In addition, this study proposes an automatic point cloud registration method for UAV and UGV point clouds using 2D image features. To validate the proposed methods, this study conducted an outdoor field test and obtained the promising results: (1) autonomous scan position generation for UGV which minimizes occlusions in scan data and (2) automatic point clouds registration with high registration accuracy. It is highly expected that the proposed methods can significantly reduce human intervention and time in collecting and processing site data at construction sites.

KEYWORDS: *UGV, mobile robot, UAV, drone, path planning, data pairing, point cloud registration*

1. INTRODUCTION

As a means of acquiring 3D geometric data of construction sites, unmanned aerial vehicle (UAV) and unmanned ground vehicle (UGV) are two of the most promising technologies because they can automatically collect the geometric data without human intervention and risk (Dupont, Chua, Tashrif, & Abbott, 2017; Kim, Chen, & Cho, 2018). However, both unmanned technologies have distinct disadvantages caused by their limited data collection ability due to the restricted field of view. Since UAVs take pictures of objects from the air, they are vulnerable to occlusions under the roof-level (e.g., eaves). In contrast, UGVs equipped with a laser scanner face occlusions behind objects and above a roof level because they typically scan the line-of-sight vertical surface of objects from the ground level. Moreover, the accuracy of vertical elements in a 3D point cloud built by UAV's images is relatively poor because of the obliqueness of the incident angles of the rays (Templin, Popielarczyk, & Kosecki, 2017). To overcome each other's weaknesses, several researchers have performed studies on operation both technologies simultaneously for collecting geometric data. However, most of the studies have only focused on automating a particular process such as UGV path planning using UAV maps (Jung, 2013) and integrating UAV and UGV 3D point cloud data (Gawel et al., 2017). Furthermore, few studies have investigated ways to collaborate both UAV and UGV to collect 3D geometric data of construction sites where the ground condition is uneven and geometric shape is complicated. This study, therefore, proposes a framework for automated collaboration process of UAV and UGV from data path planning to data pairing for effective 3D visualization of construction sites.

2. RELATED WORKS

In this study, the automated framework of UAV and UGV for collecting 3D geometric data is divided into two sections: (i) path planning, and (ii) data integration. This section shows the results of literature reviews on automatic path planning for UGV and data integration of UAV and UGV.

2.1 Path planning for UGV

To generate an optimal path of UGV for field scanning, the optimum scan positions must be determined first. A proper scan position is a location where data collection time is minimized while capturing all required geometric information. Latimer et al. (2004) performed a study to automate laser scan planning with the concept of sensor configuration space, which is a 3D volume with specific geometric features called an "informational goal" displayed on the imaging sensor. Some studies have shown that scan planning problems can be solved using an as-designed model (Pito, 1996). The conventional laser scan planning focuses on a single fixed object (Lee, Park and Son, 2001; Plantinga and Dyer, 1990; Son, Park and Lee, 2002). However, it has limitations for the environments with multiple objects or targets. In the field of mechanical engineering, researchers have also created an automated process planning system based on a visibility analysis that includes free-form surfaces (Fernández, Rico, Álvarez, Valiño, & Mateos, 2008). However, few researchers have focused on the scan planning issue in as-is cluttered environments (e.g., construction, disaster sites). Therefore, there is a strong need to improve the methodology of laser-scan planning in cluttered environments.

2.2 Automatic UAV and UGV data integration

Most of the automatic point cloud registration approaches commonly use the iterative closest point (ICP) algorithm (Besl & McKay, 1992). The main disadvantage of the ICP-based approaches is that ICP requires a significantly overlapped zones between two point-cloud sets to achieve a precise registration (Holz, Ichim, Tombari, Rusu, & Behnke, 2015; Kim, Chen, & Cho, 2018). For the automatic initial alignment, many studies have proposed several methods using 3D features in point clouds. Surmann et al. (2017) present a point-cloud registration method performed by matching planar segments that are extracted from the point clouds generated by UAV and UGV. Cheng et al. (2013) also propose an automatic point cloud registration using extracted building corners. In addition, Gawel et al. (2017) show the methods using several 3D feature descriptors such as fast point feature histogram (FPFH), unique signatures of histograms for local surface description (SHOT), and ensemble of shape functions (ESF). Most of the studies have roughly aligned the point clouds through the 3D feature point matching algorithms and then finely tuned the point clouds with ICP. However, the 3D feature-based point cloud registration methods require a globally scaled UAV point cloud. This can be critical in the areas where it is difficult to use ground targets or global positioning system (GPS) because structure from motion (SfM) cannot generate an absolute-scale point cloud set unless camera position information for each image is provided through GPS or kwon targets. Although UAV images may have GPS information in most cases, the accuracy of the GPS on a UAV varies depending on the surrounding environment (Kamarudin & Tahar, 2016). This study, therefore, proposes an automatic point cloud registration method using 2D features in images taken from UAV and UGV. The 2D feature-based registration method does not require scaled point clouds, but the challenges of image matching due to significant viewpoint differences between UAV and UGV should be addressed.

3. RESEARCH OBJECTIVE

The main objective of this study is to develop a framework for the automated method of registering UAV and UGV data for 3D visualization of construction sites. To operate both unmanned systems effectively, a complementary cooperation method is required from the planning stage of data collection. For this purpose, this study presents an automatic path planning method for UGV using a 3D point cloud generated by UAV. Moreover, this study also proposes the automatic point cloud registration method using 2D features in images taken from UAV and UGV. Figure 1 shows the overall framework for the automated collaboration of UAV and UGV.

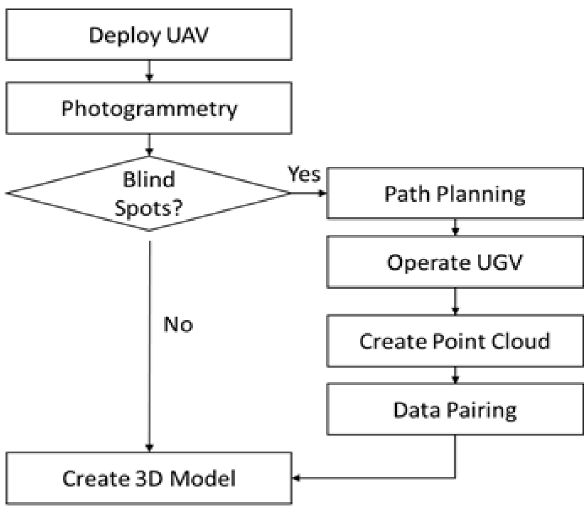


Fig. 1: Framework for the automated collaboration for UAV and UGV

4. METHODOLOGY

4.1 UAV-assisted path planning for UGV

In this research, the path planning process for UGV is divided into two steps: finding appropriate scan positions and generating an optimal path that links the scan positions. To find the best scan positions, this study generates a 3D gradient ground surface map with the point cloud created by UAV images. With the gradient map, this study also builds an occupancy map to choose candidates for scan positions. The candidates for scan positions are selected in the movable and flat area by setting a gradient threshold value. After that, the proposed method simulates the line of sight visibility in the candidates with the ray tracing algorithm (Lichti & Eng, 2017). This simulation constructs a list of the scan locations where it can acquire the maximum number of points from the laser scanner with the minimum number of occlusions. With the simulation results, this study finally determines the scan locations on the point cloud of ground generated from UAV images. Figure 2 depicts the proposed process for finding scan positions. Once the scan positions are decided, the proposed method finds the optimal travel path. The optimal path is selected by finding the shortest path with a low slope where UGV can travel. In addition, this study also utilizes the simultaneous localization and mapping (SLAM) technique for traveling to a next scan position and combining point clouds obtained from each scan location(Kim, Chen, Kim, & Cho, 2018).

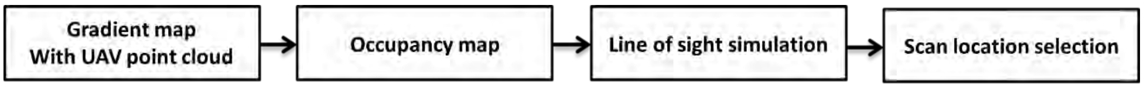


Fig. 2: The process for finding scan positions

4.2 2D image feature-based point cloud registration

To automatically integrate geometric data of construction sites acquired by UAV and UGV without ground targets, this study modifies and adapts the 2D image feature-based automatic point cloud registration method. The 2D image feature based-registration has the advantage that that several matching points can be detected even if a point-cloud scale is quite a different from each other. Moreover, this method is independent of the GPS signal reception because this method detects the matching points in the images taken from UAV and UGV and adjusts the scale of the UAV point cloud based on the UGV's absolute-scale point cloud. Figure 3 describes the pipeline of the proposed point cloud registration method. The basic idea of this method is derived from the fact that both UGV and UAV cameras take pictures to create a colored point cloud. The images taken from UAV generate a colored dense point cloud through the SfM process. UGV also takes pictures to create textured-RGB on the point cloud generated by laser scanners.

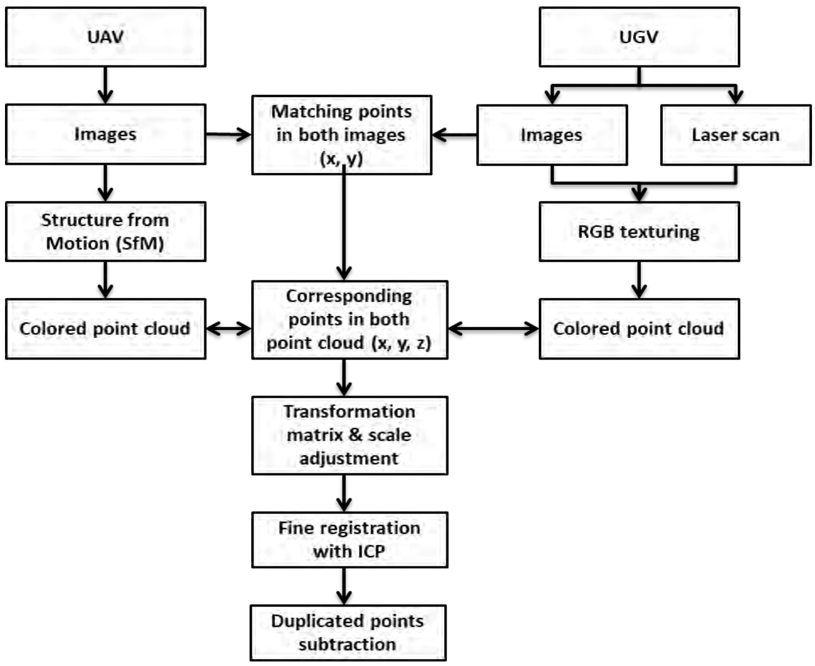


Fig. 3: The pipeline of the 2D image features-based automatic point cloud registration

To realize this method, the problem with image matching caused by different viewpoints between UAV and UGV needs to be addressed. For this purpose, this study adopted the matching on demand with view synthesis (MODS) algorithm because the algorithm can match images taken at extremely different viewpoints, which may not be feasibly matched with scale-invariant feature transform (SIFT) and affine SIFT (ASIFT) matcher (Mishkin, Matas, & Perdoch, 2015). Furthermore, this study found that when using the panorama images generated from UGV, the MODS algorithm detects more matching points. Figure 4 shows the difference in image matching when using panoramic images vs. regular images taken by UGV. For this reason, this study embraced the MODS algorithm as a 2D feature point matcher and used UGV's panoramic images.

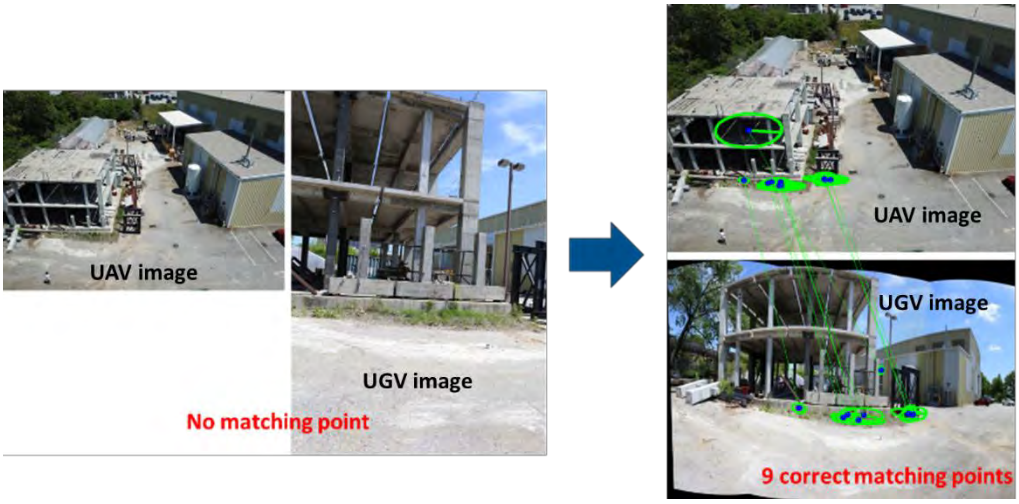


Fig. 4: Matching points between UAV and UGV images with regular images (left) vs. a panoramic image (right)

The automatic point cloud registration process proposed in this study is divided into three stages:1) initial alignment with corresponding points; 2) fine registration with ICP process; and 3) duplicated points subtraction with the k-nearest neighbors (k-NN) algorithm. In the initial alignment stage, the transformation matrix and scale adjustment value are computed with the corresponding points in both UAV and UGV point clouds. The roughly aligned point clouds are registered in the fine registration stage with ICP. In this stage, both point clouds are finely tuned with the transformation matrix calculated from the ICP process. Finally, the proposed method subtracts the overlapped points in the registered point clouds set to reduce redundant data for efficient post data processing and measurement accuracy. Because the measurement accuracy of the UGV point cloud is relatively higher than that of UAV point cloud, this method removes the UAV points that are close to the UGV points using the K-NN algorithm.

5. FIELD TEST

5.1 Overview of the field test

The field test was conducted in the structure and materials lab at the Georgia Institute of Technology in the U.S. Similar to an actual construction site, there were various construction materials and structures. The area of the site was about 3,000 m^2 (30m×100m), and a two-story concrete structure was built on the site as shown in Figure 5.

Fig. 5: The aerial views of the testing field

5.2 Test equipment

5.2.1 UAV

This study used a quadcopter drone (i.e., DJI Mavic Pro) equipped with a 1/2.3" complementary metal-oxide semiconductor (CMOS) sensor with a resolution of 4000×3000 pix. The camera is stabilized by a 3-axis mechanical gimbal and localized by a GPS, a compass, and an inertial measurement unit (IMU) sensor in the UAV. Figure 6 (left) shows the UAV used in this study. In this test, we used a commercial drone path planner to set the flight height of 20m, the camera angle of 30 degrees and 90 degrees, and the overlapping ratio of 90%. The total flight time was about six minutes to collect 60 images of the test field. The UAV first collected images with a camera angle of 90 degrees to generate a 3D point cloud which can be used for UGV path planning. After that, the UAV collected images with a camera angle of 30 degrees to acquire images that can be better matched with the UGV images. With the combined images taken at 30 degrees and 90 degrees, a dense point cloud was built through the SfM process. The SfM process was conducted by VisualSFM and CMPMVS, which are open source software for point cloud generation.

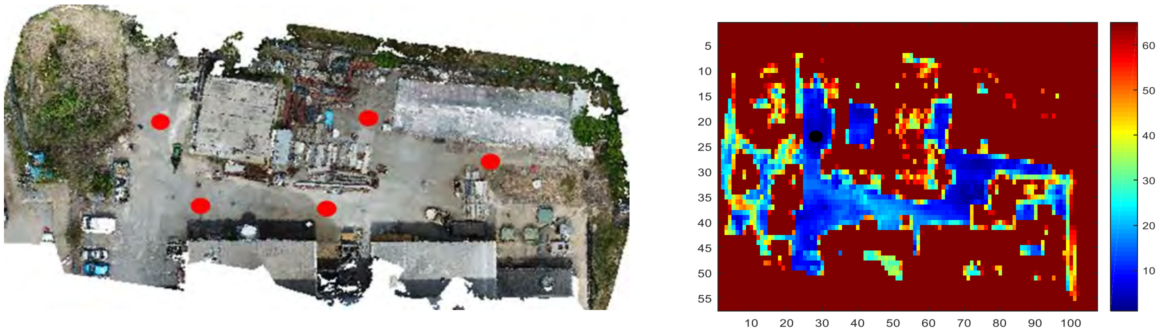
Fig. 6: The DJI Mavic Pro (left) and UGV (right) used in this research

5.2.2 UGV

The UGV used in this study is an all-wheel terrain mobile robot, Ground Robot of Mapping Infrastructure (GRoMI), which is a custom-built mobile robot with SLAM capability (Kim et al. 2018). The GRoMI is composed of two major parts: a laser scanning system and an autonomous mobile robot platform, as shown in Figure 6 (right). The upper laser scanning part, which is for collecting 3D mapping information, consists of five SICK 2D laser scanners as well as a built-in digital camera. The lower mobile robot part, which is for collecting localization data, has four wheels with encoders, object avoidance sensors, an inertial measurement unit (IMU), and a navigation camera. The characteristics of this system are: 1) data acquisition is possible while the robot is moving; 2) RGB-mapped high-resolution point cloud can be obtained through the digital single-lens reflex (DSLR) camera, and 3) robot navigation and data collection can be carried out remotely or autonomously. The resolution of each line laser used in this test was 0.25 degrees in the vertical direction and 0.1 degrees in the horizontal direction. The digital camera captures sixteen pictures per 360º scan to obtain the RGB information of the construction site.

5.3 UAV-assisted UGV path planning for UGV

With the initial 3D map generated by UAV, the proposed scan planning method generated the 2D gradient map with a 1m × 1m grid as shown in Figure 7 (right). The gradient-based map is used to plan a series of environment views for the UGV scanning system, and all scan locations in this initial phase are planned in advance before the robot does any data acquisition. The main objective of scan planning is to find good scan locations by evaluating the candidate scan locations with a line-of-sight simulation of a 3D laser scanner. The requirements for the scan locations chosen are 1) a large field-of-view of the surrounding with minimal obstructions, 2) a flat surface, 3) low overlapped areas between scans, and 4) no missing areas that are not scanned on the job site. The evaluation criteria are the quantity of point cloud data and amount of occlusion, which differ depending on the scan location. Based on these criteria, the goal of this method is to minimize the number of scans and time while maintaining similar coverage and level of detail. From the field test, this method found five scan locations based on the above criteria shown as the red dots in Figure 7 (a). The gradient map shown in Figure 7 (b) was created by computing the gradient between neighbor cells based on the first scan position. It can be used to visualize which cells are flat, tilted, or occupied by obstacles. The blue colored zones have potentially good spots for moving and scanning. Based on the gradient map, the proposed method drew an occupancy map with the gradient threshold to find the candidates for scan positions. The movable area used for path planning is shown in Figure 8 (left) while the flat area used for the initial candidate scan locations is shown in Figure 8 (right).



(a) (b)

Fig. 7: 3D point cloud map generated by UAV (a) and 2D gradient map (b)

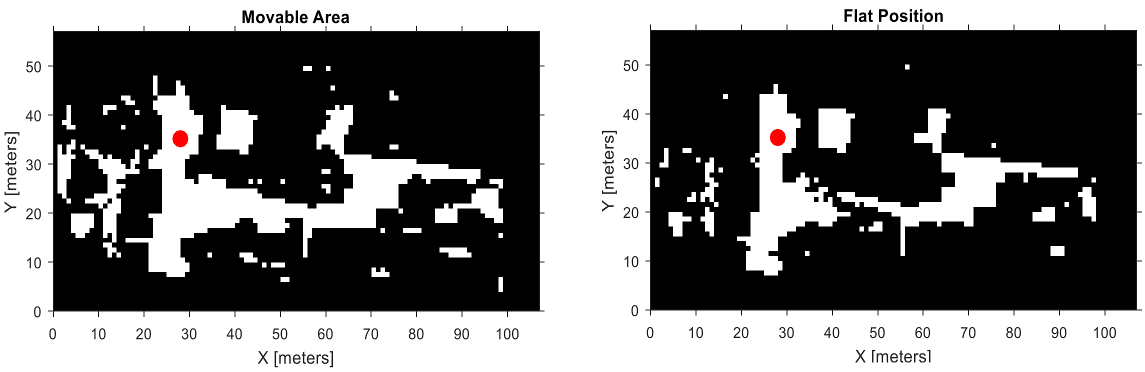


Fig. 8: Occupancy map for the movable area (left) and flat position (right)

5.4 UAV and UGV data integration

5.4.1 Image matching with MODS

To detect the matching points between the UAV and UGV images, this study adopted the MODS algorithm. Moreover, this study also used panoramic images made with UGV images to make the scale similar to UAV images taken from the air. Figure 9 depicts the examples of the image matching results with MODS. In Figure 9, the upper images are the UAV images taken at a camera angle of 30 degrees, and the lower ones are panoramic images generated from the UGV images. The feature matching points are linked with green lines. The algorithm detected 313 true positive matching points and 40 false positive matching points in a total of 200 image pairs (20 UAV images × 10 UGV panoramic images).

Fig. 9: Examples of the image matching results between UAV(upper) and UGV (lower) images

5.4.2 2D image features-based automatic point cloud registration

With the pixel coordinates of the matched 2D points in both image sets, the proposed registration method found corresponding 3D points in both UAV and UGV point clouds. Figure 10 represents the scale difference between UAV and UGV point clouds. Since this research did not use the GPS information of UAV, the point cloud built by UAV images did not have an absolute scale. For this reason, the proposed automatic registration method computed a transformation matrix and scale adjustment values with the coordinates of the corresponding points in both point clouds. The results of the initial alignment using the corresponding points are shown in Table 1.

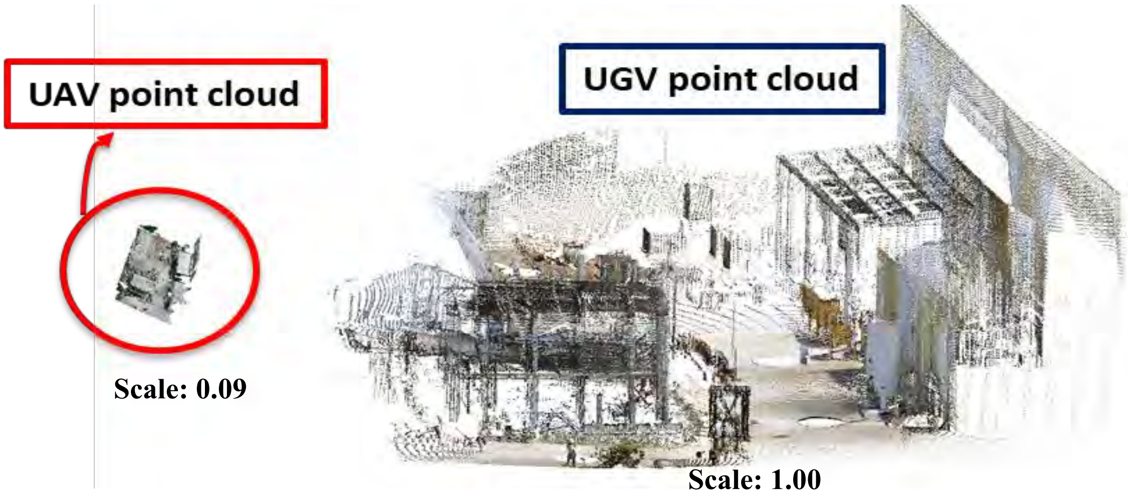


Fig. 10: Relative scale of UAV point cloud (left) compared to UGV's point cloud (right)

The proposed method aligned both point clouds with the computed transformation matrix and scale adjustment values. After the point clouds are aligned roughly, this method finally registers both point clouds with ICP. Table 1 and Figure 11 show the results of the 2D image-based initial point clouds registration. In Figure 11, the false-colored point cloud is the UGV point cloud, and the true-colored point cloud is the UAV point cloud. As shown in Table 1, the mean distance of both point clouds was 0.264m by the initial alignment, and it became 0.116m in the final registration stage.

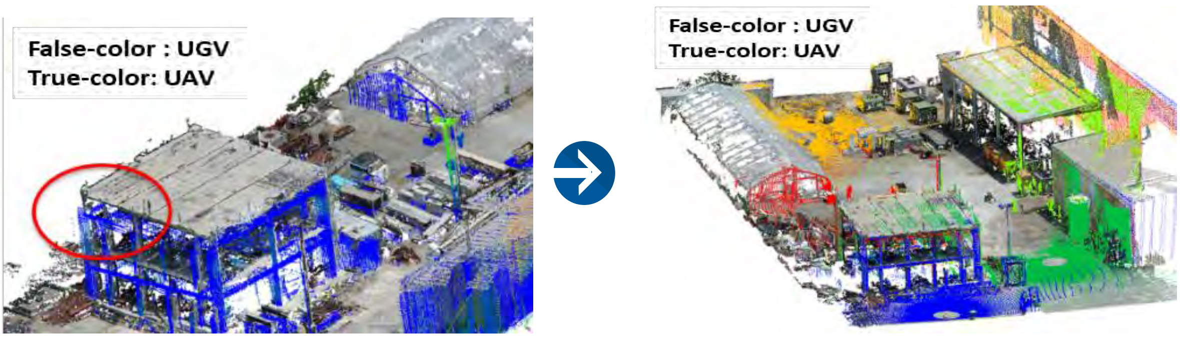


Fig. 11: Initially aligned point clouds (left) and fine-tuned point clouds with ICP (right)

Table. 1: The results of the 2D image feature-based automatic registration

Index	Initial alignment	Final registration (ICP)
Average of point distance (m)	0.264	0.116
RMS of point distance (m)	0.595	0.133
Scale adjustment	× 10.528	× 0.993

6. CONCLUSION

A framework was introduced in this study which can enhance the efficiency of construction progress monitoring by fully automating the 3D geometric data acquisition and visualization process utilizing UAV and UGV. Typically, UAV has weakness in vertical surface data collection, and UGV has weakness in elevated horizontal surface data collection; thus they can supplement each other's weakness when both data are combined. The proposed framework is divided into two main stages: UAV-assisted path planning for UGV, and automated point cloud registration using 2D features in images taken from both UAV and UGV. In the path planning stage, a path planner first determined multiple scan positions having a maximum number of points and a minimum number of occlusions through a line of sight simulation based on a 3D point cloud map created from UAV images. With the identified scan positions, the path planner determined the shortest travel path with a low slope where the UGV can navigate. For the automatic data integration, this study presented a 2D feature-based point cloud registration method. The proposed method initially aligned both point clouds generated by UAV and UGV with common feature points on the images. Then, the initially aligned point clouds were finely tuned with ICP. The main purpose of combining UAV and UGV point clouds is to fill several occlusions that exist in each of UAV and UGV point clouds; thus, a complete scan of the whole site can be made. It is highly expected that the proposed framework will significantly reduce the time and risk for a field manager to inspect a construction site because the proposed method can collect and visualize site data in detail autonomously, which significantly reduces human intervention. For future work, the research team will validate the developed unmanned-system approach further at various real-world construction or post-disaster sites.

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KNOWLEDGE-BASED APPROACH FOR FAÇADE RETROFIT: A STRATEGY FOR ADDING ARCHITECTURAL VALUES TO INDUSTRIALIZSED FAÇADE CONFIGURATION

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ABSTRACT: *Shifting the focus from construction to offsite manufacturing has emerged as an ongoing area of discussion for renovating facades. This is followed by a controlled and cost-effective automated system in which Building Information Modelling (BIM) combined with integrated processes facilitated the industrialization of the whole construction chain. However, in relation to façade retrofit, due to the high level of customer involvement as well as the necessity of facade adaptation to different locations and functions, problems are project-specific and solutions need to be separately customized for each case. This has been considered as a barrier to harnessing the benefits of offsite manufacturing due to the considerable extra costs for customization of architectural products.*

The idea of Design for Manufacturing and Assembly (DFMA) claims to change this through using parametric design for customization of solutions already being used by other industries to become feasible in construction. Integrating engineering knowledge and manufacturability data earlier than usual into the design process, these solutions provide an opportunity for efficiently adding architectural values to industrialized design configuration. Therefore, this study aims to chart a new course for contemporary façade modernization to investigate customization of architectural products with a manufacturability approach through what this study calls DFMA_ parametric design.

KEYWORDS: *BIM, Knowledge-based design, façade retrofit design, customization, Integrated Project Delivery (IPD), offsite manufacturing (OSM), Design for Manufacture and Assembly (DFMA).*

1. INTRODUCTION

The process of project delivery in Off-Site Manufacturing (OSM) has been criticized for being inefficient. The issue has contributed to the fragmentation in the construction industry, meaning the isolation of disciplines, lack of coordination between design and construction leading to time delays, additional requests for information onsite, and production of waste (Nawi et al., 2011a, Kamar et al., 2003).To overcome the fragmentation issue, many industry-led reports, such as the Strategic Forum for Construction (2003), and studies by Egan (1998) and Latham (1994),have mentioned the need for a transition within the industry from traditional modus operandi to innovation and integration in process and product development in OSM projects. If implemented properly, integrated practice is capable of delivering predictable results to clients, increased quality, cutting waste, and lowering cost (Nawi et al., 2014). However, this transition has proved to be slow and minimal (Hill, 2001).

To support integrated product and process development in the construction industry, also known as a ‗mind shift revolution' (Miller et al., 2009), many approaches have been introduced to the industry, including concurrent engineering (Anumba et al, 1998; Love and Gunasekaran, 1997), knowledge management (Anumba et al, 2008; Alshawi& Ingirige, 2003), BIM (Eastman et al., 2008; Sacks et. al., 2010; Howard and Bjork, 2007) and Integrated Project Delivery. In 2007, California Council suggested that IPD with the use of BIM could alleviate the fragmentation in the construction process. IPD refers to an approach in the design, execution, and delivery of buildings, suitable for complex projects, implemented by collaborative teams consisting of key participants in AEC (Architecture, Engineering, and Construction) such as client, architect, contractor and manufacturer (Anderson, 2010). This concept has been the source of inspiration for various alternative delivery models across the world, the most notably being the Project Alliance method which has been successfully implemented in Australia and New Zealand on more than 50% of infrastructure projects within the last 15 years.

Despite alliancing within some projects in New Zealand, the productivity rate in the AEC sector has decreased recently due to a lack of process and product innovation. This can be attributed to the fact that the alliance approach is mainly focused on contractual and organizational parts with little focus on process improvement and knowledge management strategies in the AEC sector (Vilasini, 2014). The construction industry plays a predominant role in New Zealand‘s economic structure. It is rated as New Zealand's fifth largest sector, accounting for 8% of the total economy, and it is the most influential domain in making up the country‘s infrastructure stock which is the foundation of productivity and economic growth (PWC, 2011).

The retrofit project environment is common to the construction sector in that operations are constrained by clients‘ needs for continuous manufacturing activity and the compressed design to the assembly program, the process of which is changing due to the adoption of BIM-IPD. Being a determining factor in cost and energy efficiency, buildings‘ facades play a fundamental role in the success of retrofit projects. The significant growth of OSM combined with the implementation of BIM and IPD approaches, especially for complex projects such as building retrofit will inevitably affect the nature of façade retrofit design and construction. While there has been a surge of interest in improving the productivity of the AEC sector, most research has narrowly focused on new buildings. Moreover, although extensive research has been carried out on BIM and IPD, there exists little research that gauges the impact of the aforementioned transition on architecture itself, especially in the context of façade retrofit. Along with this paradigm shift, many architects, as one of the main contributors to the industry, acknowledge there are issues with productivity, ubiquitous waste, and quality assurance in the construction process, and propose a new method of architecture suitable for OSM projects that would help them to become part of the solution. Anderson, (2010), states that BIM and IPD are more about alternative ways of doing things than technologies. The Wikipedia page on BIM describes this as follows:

―BIM goes far beyond switching to new software. It requires changes to the definition of traditional architectural phases and more data sharing than most architects and engineers are used to.” (Anderson, 2010)

Therefore, this study aims to explore an alternative architectural design methodology suited to OSM and IPD within the context of retrofitted façades, taking advantage of process improvement and knowledge management strategies. Because of the increasing adoption of BIM and IPD in the AEC sector, architecture design will unavoidably undergo a change. Architects will no longer be the only arbiters of design at both macro and detailed levels. On the contrary, design will become the outcome of a process in which a series of considerations, such as manufacturability, installation and delivery methods, inserted by a team of knowledgeable professionals influence the resultant configurations. Certainly, architects will still be looked to for design leadership, but their roles will also be extended to cover IPD process improvement and knowledge management methods during the different design phases through which the pre-construction activities will be carried out.

2. RESEARCH BACKGROUND

Over the last two decades, there has been a surge of interest by studies regarding productivity improvement in OSM. In the context of New Zealand, the construction industry has a significant impact on the economy accounting for 4.3% of the gross domestic product (GPD) and currently, about 177,000 people are working in the sector representing 8% of the NZ workforce (Department of Building and Housing, 2010). The New Zealand economy, therefore, would benefit greatly from productivity improvements through a growth in GPD (Vilasini, 2014).

The New Zealand construction industry council reported a number of issues that the construction sector is facing, including being slow to adopt new technology, focusing on cost over value, limited innovation, and more recently (2009), issues with the procurement method of projects1 (Department of Building and Housing,2009). Current procurement methods, especially traditional contract such as ‗Design-Bid-Build‘2, fail to encourage product and process innovation (Blayse et al., 2004). This is due to the fact that as buildings become more complex, the AEC sector becomes more specialized, fragmenting a process that was formerly directed by one builder‘s leadership.This contributes to adversarial relations, fragmentation in the industry(Vilasini, 2014) and increased design changes costs (ABADI, 2015). The issue of fragmentation typically stems from two areas: the separation of the design and construction phases, and the structure of the construction itself (Nawi et al., 2011). To reduce fragmentation while producing value in complex and high- risk projects, such as multi-story façade retrofit buildings, alliancing has been widely used in Australia (Clifton et al., 2006). This improves working relationships among participants, leading to significant benefit over the traditional system of contracts. The second highest alliance user in the South Pacific area is New Zealand, with investments worth $4.25 billion between 2001 and 2010. However, New Zealand‘s alliancing focus is mainly on the contractual and organizational domains through encouraging collaboration, which concerns the strategic level of projects while the traditional Design-Bid-Build method is still dominant (Vilasini, 2014). Significant improvement in integrated project delivery and construction is highly unlikely to be achieved merely through contractual and organizational domains (Grynbaum, 2004). The key issue, therefore, is to alter the way works are done at the scale of projects (Singleton, 2011).

Consequently, there is an increasing interest in combining approaches, such as collaborative project delivery, with process management methods to improve the procurement system in OSM projects. Vilasini, (2014), studied different process management methods to improve alliancing projects and identified lean construction as a suitable technique for alliances (Vilasini, 2014). Lean construction refers to a manufacturing theory termed the Toyota Production system which stems from the Toyota Motor Company. The main objective behind lean construction is globally summarized as a process improvement method in which the main focus is on the elimination of waste and increasing value to the next customer downstream at the product level in the manufacturing system (Cribbs, 2016). There are three distinct roles that form the value chain of alliancing projects: implementation, management, and governance. While lean theory operates on implementation, the alliance principles cover the remaining roles. As a result, the main focus of alliancing is on efficacy and effectiveness aiming at setting the right objectives and doing the right things while lean construction mainly focuses on efficiency with the objective to do things in the value chain in a right way (Vilasini, 2014)

Traditional contracts are regarded as inadequate and unable to provide efficiency in complex projects (Sakal, 2005; ABADI, 2015; Vilasini, 2014; Nawi et al., 2011a; Kent, 2010). Retrofit projects consist of working on existing structures with additional constraints at the initial phases of the design process. This makes the projects more complex compared to new buildings, while inducing technical limitations such as analysing existing conditions and capabilities (Cribbs, 2016). In such projects, procurement methods need to comply with the interest of project participants to decrease fragmentation while increasing value. As a result, alliancing is commonly used in complex projects where scope changes are high, risks are unpredictable, and stakeholders‘ issues put pressure on schedules to be tight (Colledge, 2005).

Through increasing design efforts at the early stage of the projects, integrated project delivery decreases the design change costs to their lowest level. This highlights the importance of design itself and the role of designers in alliancing projects. Figure 1 shows the relation between time and the ability to affect the cost of design changes. The most effort is made in the detailed design of IPD projects when the cost of design changes is low. This compares with traditional methods where more efforts are made when the changes are costly. Compared to IPD, traditional procurement methods are no longer favourable since the period of applying changes has passed (ABADI, 2015).

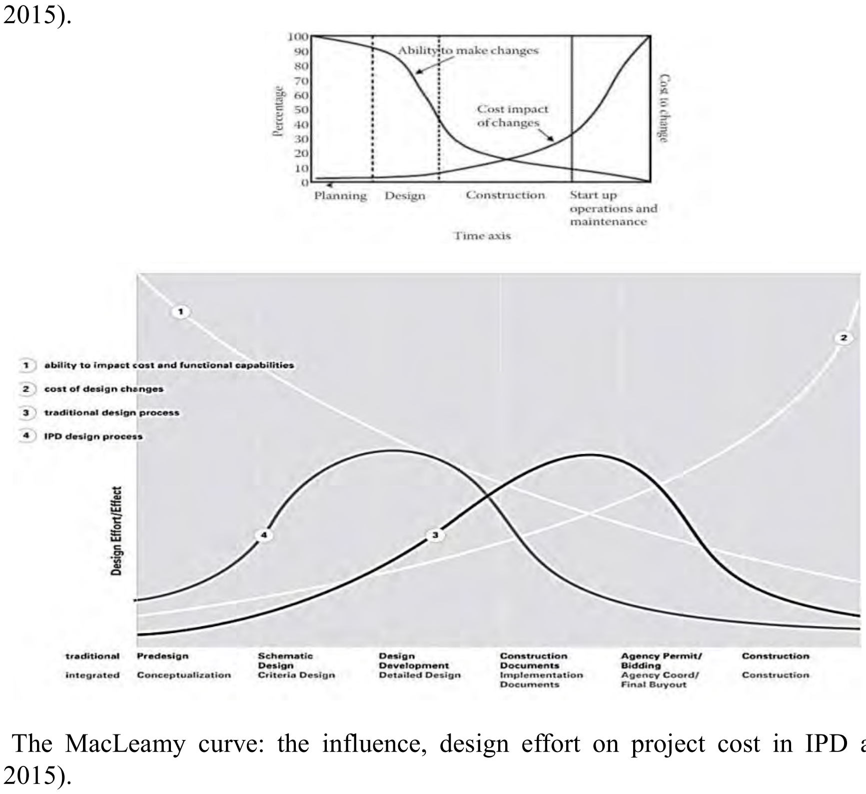

Figure 1; The MacLeamy curve: the influence, design effort on project cost in IPD and Design-Bid Build (ABADI, 2015).

Architects select and assemble manufacturing components while the value of a project‘s wasted resources can make up to 25% of the total investment, mainly wasted in façade design and the manufacturing and installation sectors. This is primarily because architects who design façades tend to avoid a single manufacturer‘s products in order help the contractor bid for alternatives. This leads to a lack of coordination between the architect‘s and the manufacturer‘s shop drawings until construction has started , leading to much expert knowledge being missed and a break in the data chain from design to manufacturing and assembly. Poor collaboration in problem-solving has an adverse impact on the industrialization of the façades. Changing architects‘ design 3D models by architects re-developing the detailed façade design and creating new fabrication drawings, cause a significant waste due to design changes and reworks (CABR, 2015). The IPD system, on the other hand, is induced to decrease the adversarial relationship between participants, to optimize resource consumption and to elevate the labor productivity through taking BIM technologies and lean thinking. Alliancing, therefore, is considered as a way of overcoming these issues and creating a more suitable delivery system for façade retrofit design.

The transition from the fragmented toward an integrated building design and construction process includes many transforming keys such as lean thinking, BIM, relational contracting, OSM, performance-based design and early collaboration to lower cost, eliminate waste, increase quality and productivity in the AEC sector (Miller et al., 2009). Although most BIM-IPD research has targeted the attitude of other disciplines such as building project management, and civil and environmental engineering(Vilasini, 2014; Nawi et al., 2011a; Bahar et al., 2013; Schlueter et al., 2018; Guo et al., 2016), there remain limited understanding about the issues underpinning architectural design. Rather than a technology, BIM and IPD are associated with efficient methods of doing things, which inevitably influences the AEC sections including architectural design. Therefore, the question of what alternative design methodologies can be used to help architects become part of the transition from a fragmented industry to an integrated one, still remains. The following sections of the literature aim to fill the gap by studying the shortcomings of architectural design in terms of OSM projects.

3. ARCHITECTURE AND MANUFACTURING COMPONENTS

Historically, manufacturing components as elements of tectonic integrity between the wall and façade in which the exterior enclosure is supported by panels have been demonstrated in the works of architects such as Prouve; in the Buc Pavilion-at the Roland Garros Flying Club,(1939)- and have changed the attitude toward framing, resulting in the overall appearance of the building being formed by the quality of the manufactured panels themselves(Katz, 2014).Being commensurate with building structure, the dimensional coordination of the surface follows a module as an element of both prefabricated panels and measures in which dimensions are derived from spacing between posts. The design of a façade is more similar to that of car and shipbuilding in that a cladding system such as this unitizes the enclosure. According to Prouve, (1971), a designer is not an architect if he/she fails to work according to the demands of industrial construction. However, a designer in the aviation, shipbuilding and car industries could be called architect. Prouve suggests that it would be better if an architect was an engineer and, therefore, for a façade designer to be a façade engineer. However, unlike manufacturing in other industries such as shipbuilding and car in which engineers define the design of all components with certainty before an order is confirmed, architecture is both project and customer specific; meaning that architects are employed to deliver patterns of buildings which incorporate specific functionality for specific customers (Fox, 2001). Consequently, there are extensive differences between the roles of engineers in other industries compared with those of architects.

For many new buildings, façade design is hybrid (standard subassemblies with bespoke interfaces); that is, as irregular boundaries need to be satisfied, bespoke interfaces are required to install standard sub-assemblies. Moreover, due to tolerance for construction operations that cause extensive differences between actual and virtual building dimensions, bespoke component interfaces are also needed. In terms of retrofit, façade refurbishment is bespoke since bespoke interfaces are the only solution to achieve a unitized appearance between the new elements and the existing surface. This can be seen as the conformity of prefabricated components with the existing sub-structures as well as the façade typologies. Therefore, customization becomes critical not only from an aesthetic perspective, but also from a functional point of view in that the careful consideration of interfaces that happens during the design process is fundamental to the success of a project (Larsen et al., 2011; Fox, 2001; Zuhaib et al., 2016). Nonetheless, the manufacturing industry has needed to continuously deal with two issues related to customization: firstly, the need to evaluate a product to check if it is customizable according to manufacturing codes and regulations; and secondly, the need to develop an integrated delivery model in which designers and manufacturers communicate at an effective level while considering the end customer and transforming their needs into set of quantifiable solutions (Mohamed et al., 2017). On the architect side, Luo et al., (2017), relate the problem with customization to the way of doing design; they argue that although customization in architecture is unavoidable, as a design activity it is trapped in the traditional thinking pattern in which architects still tend to highlight their own personal talents. Therefore, no matter how much architects seek to use manufacturing knowledge in architectural design, they still adhere to this mode of practice which supports their lead design position.

In response to these challenges, an increasing number of investigations into new material and methods of fabrication and assembly have been developed over the years. Blismas et al., (2011), identified two constraints in the use of OSM in the construction industry; Knowledge related issues and; the fact that methods by which expertise in OSM evaluation, manufacture, and use are generated, obtained, and disseminated are fragmented and underachieving due to the lack of industry investment in research and development (R&D). Luo et al., (2017), conducted a case-study research of the shortcomings that hamper architects' implementation of OSM in China and included interviews with professionals in the industry. The findings demonstrated that rather than being a matter of how to build or obtain information, the current challenge of OSM is associated with how to use cooperative practice, for example, by using BIM as a tool for information management, and enabling every sector to access the same digital information on the same platform. These findings align with those of Blismas and Wakefield, (2011), who asserted that design and construction need to be part of a streamlined process in which there is a continuity between process and program (Luo et al., 2017).

4. IS BIM REUNITING ARCHITECTURE DESIGN INTENTION AND DELIVERY?

To bridge the gap between architects' design intention and project delivery, the construction industry has explored ways to reunite design and construction. The objective was not based on single-designer or single-manufacturer, but on a different method of information sharing in which many actors participate in a design process; although, they remain separate, but use the same digital file from the start to the end. This form of information sharing is considered as an integrated building design process versus fragmented design which has been introduced to OSM as a methodology to coordinate the whole industrialization process from design to manufacturing and installation. It is also known as a consistent methodology to guide designers on how to use preferred design strategies and suitable digital workflows for different situations _and façade typologies_ with economic feasibility .In recent years, such collaborative system thinking and managerial approach have merged with an avant-garde new generation of digitally intelligent designers under the name of BIM Level 2. The implementation of BIM Level 2 on all public projects by 2016 is mandated by some countries such as the UK. This requires digital models to be shared between all the disciplines involved in the AEC sector to provide 3D spatial coordination based on BS1192:2007(British Standard) (Abrishami et al., 2015).

Carpo identifies two crucial examples that shape the modern architecture:

- The humanistic idea of building as the similar replication of an author's concept which was proposed by Leon Battista Alberti in the fifteenth century;
- Identical duplication of mechanical master models, matrixes and molds which were manufactured in mass production in nineteenth and twentieth centuries.

This participatory way of constructing proposes a mode of delivery in which authorship is no longer a privilege for traditional designer; meaning that more participants may in turn lead the design and construction process while leaving out the humanistic mode of Albertian design by notation. The utopian dream of communal construction similar to that of medieval art and craft which was appealing to Victorian Romantics such as John Ruskin may be revived through the idea of reuniting design and making on a collaborative BIM environment; but according to Garber, 2014, this may result in the end of design itself:

―Designers did not exist before the Renaissance, and if we revert to a digitally re-enacted mode of design by making, we usher in the obsolescence and disappearance of design itself or at least design in the humanist and modern sense of term." (Garber, 2014, P.13)

Moreover, Vicente, 1999, stated that there are some limitations to the participatory way of design including hampering the possibilities of new technologies, the utilization of incomplete design methods such as scenarios and leaving a purposeful analysis of the design's progression unexplored (Vicente, 1999).To alleviate these deficiencies, a hybrid approach was presented by Bødker and Iversen, 2002, where the designer envision a strategy for the entire process. The strategy should develop itself based on the participants, situation and the progress of the design activity, but the designer's intervention is necessary to ensure its success (Bødker and

Iversen, 2002). Garber, 2014, suggests that using the potential of BIM to the full can be merged with the traditional humanistic notion of design. He proposed the construction sequencing and simulating part manufacture while changing the shop drawing review process to have a sense of perspective upon the design phases (Garber, 2014, P.13).Therefore, this research hypothesize that some shortcoming of participatory design can be leveled out if instead of using the old concept of ―file-to-factory", architects adopt the idea of ―file-for-factory".

5. DFMA AS A DESIGN CONCEPT

Architectural design has been recognized as having a significant influence on construction productivity and quality from at least the early 1960s following the widely reported failure of AEC deliverables in meeting the requirements of structural integrity, sustainability and aesthetics. Fragmentation of design and construction was distinguished as being a determining factor for the aforementioned failure. The failure led the Construction Industry Research and Information Association to define the term buildability as ―the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building." Constructability and buildability have been used interchangeably for many years. Having a broader scope, constructability includes buildability as a design-phase and method to bring construction knowledge into the design stage (Kifokeris et al., 2017). Fox, (2001), points out that integrating production-related information into design can improve productivity and quality at the same time. Thus, attempts to bring construction knowledge, and later manufacturability and installation information through DFMA method, into the design phase have a long history.

The integrated approach to construction follows the concept of lean thinking, the principles of which are derived from the production system at Toyota including teamwork, effective collaboration, elimination of waste, and efficient use of materials. Lean thinking has a philosophy that is built around respect, communication, and mutual trust, enabling self-organization and candour by assuming that everyone who brings value not only has a stake in the outcome, but also an equal voice in taking direction in projects; the expected result is to achieve minimal waste and maximum value(Miller et al., 2009).

DFMA as an approach that facilitates better OSM is a combination of two design methodologies: design for ease of manufacture of components and parts (DFM), and design of the product for ease of assembly (DFA). Due to standardization, the former decreases the need for taking many steps during the manufacturing process, while the latter reduces the time of assembly. It is claimed that DFMA contributes to harnessing the benefits of OSM and will aid in reaching the long-term horizon of lower carbon emission and energy demand by 2050. It also accounts for a 20%-60% reduction in construction time, 20%- 40% reduction in construction cost and 70% reduction in onsite labour (RIBA, 2013a). As such, DFMA is seen not only as an adjunct to lean, but also as a bona fides practice of lean theory. The process consists of three major components: digital design tools which involve a computer aided design (CAD) system; digital manufacturing tools using a computer aided manufacturing system (CAM) to realize how the digital model is manufactured, and a computer numerical control (CNC) to manufacture (Machado et al., 2016). The DFMA characteristics are defined as component driven, a likely degree of repetition, modularity, and standardization approach.

In the delivery process of facades, every time that a product is requested by clients the process starts from the design stage. These products are known as ETO products, the production of which is notoriously costly (Montali et al., 2018). The early design stage of façades is the fundamental phase in which about 20% of the design decisions are made (decisions such as material, geometry, and assembly). Subsequently the early design stage influencing 80% of all design decisions and the overall cost of construction (Voss & Overend, 2012). Consequently, the façade sector is considered to have a great potential to benefit from the DFMA methodology (Fox et al., 2001).

4.1. BIM implementation to streamline design to manufacture and installation

The precise and integrated design that BIM has to offer through monitoring lifecycle data, leads to a lean process that minimizes waste at all stages of design to manufacturing and installation (Rubrich, 2012).The product development process in DFMA is a structured sequence of design activities to transform technical and design requirements into product specification through adapting them to corresponding geometric models. However, the designers' ability to make design knowledge explicit contributes to the resultant component configuration.

4.1.1. BIM project execution planning

Properly executing BIM in a project requires extensive BIM project execution planning (BIM PxP), the framework of which exists in many forms in the industry such as an international consensus standard for information exchange, namely the Information Delivery Manual (IDM). IDM is used by BIM participants to document information in a readable form (Anderson, 2010). The content of IDM is a process map, which has an instantly recognizable visual style in which the processes involved in the designing and constructing of a system are re-arranged through a hierarchy of chunking and labeling to produce a more efficient way of undertaking the design and construction process. Most large organizations in the manufacturing industry use a process map to assist them in delivery insurances within budget, and time and of the right quality. Using Business Process Model and Notation (BPMN) tools, a process map shows the following three elements: activities which represent the specific tasks of a use case (address an exchange scenario between roles for a certain purpose during a specific phase of a project lifecycle, in this study façade designer, façade engineer and the façade constructor); activities which are linked by information flows shown as arrows or dashed lines; information exchange which shows the information packets exchanged between activities (Venugopal et al., 2012). It is originally a method of data visualization adopted from Knowledge Based Engineering (KBE).

The purpose of KBE is to automate repetitive tasks such as the design automation problem, and knowledge reuse and to support product cost estimation purposes in a multidisciplinary environment so that the design effort will be reduced. In other words, various forms of knowledge such as cost data, manufacturability constraints, and rule-of-thumb can be encapsulated through KBE. Placed at the core of KBE is Information mapping, which is a research-based method for writing clear and user focused information. Founded in 1967 by Robert Horn _ a researcher at Harvard and Columbia Universities _ information mapping methodology was firstly used to explore the way people learn and to develop methods for analysing, organizing and presenting the learnt information. The methodology‘s presentation mode is process mapping in which a framework of interrelated tasks such as engineering products and the relevant knowledge are presented in a graphical style with a digital format (Aouad et al., 1999). Information mapping is now a familiar method in the AEC sector for capturing, reusing, and managing project knowledge, aiming to achieve an improved performance, efficiency, and project delivery. The KBE is also considered as ‗a means to prevent the reinvention-of-the-wheel for every new project‘ (Kamara et al., 2014). Motawa et al., (2013), used a process map to study the KBE-BIM _based system in building maintenance ;Voss et al.,(2013), represented a façade design and construction process map to study the activities of façade consultants and contractors from commencement of their participation to the end of their involvements(Voss et al., 2013).A process map developed for the purpose of defining and illustrating actors, processes ,and information exchange, was used by Venugopal et al., (2013), to study the precast architectural concept model.

The vision of BIM PxP aims at identifying reasons for the use of BIM on a project, connecting the utilizations to project phases, and understanding various responsibilities for completing the components. As for building façades, execution plans are a useful foundation to study how the pre-construction phases will be approached, managed, and implemented. A BIM execution plan matrix for façade design includes information regarding the design review process, the model approval process, roles and responsibilities, information exchange, level of detail required for BIM, project specific goals, the collaboration process, and BIM enabled software (Birrell, 2014).

Use of BIM as an object driven tool with an integrated collaborative environment benefits the progression of DFMA (BCA, 2016; Machado et al., 2016). The BIM guide line for DFMA developed by the Royal Institute of British Architects (RIBA, 2013a) can be used as a framework to support façade design. The main goal of RIBA is to create a document to support the standardization of BIM that assists in the adoption of DFMA. The typical conceptual/developed/ detail workflow is followed within the process in which the levels of complexity increase as the design progresses from the early stage geometric components definition, (e.g., window to wall ratio), to the detailed information, (e.g., interface management of façade elements), for production and installation (RIBA, 2013a; Montali et al., 2018; Cribbs, 2016).

4.1.2. BIM geometrical information for DFMA

A BIM object is detailed information that defines a product‘s geometry with descriptive information regarding physical characteristics. BIM‘s objects are stored in a library as components within installation folders or contained externally through different store systems. At least 150 BIM software tools have been listed by Building smart (http://www.buildingsmart-tech.org/) that are currently used in the AEC sector. The most common are BIM software packages such as Revit, Bentley, ArchiCAD, and Inventor Professional. Objects are in their original file formats, but some are able to be exchanged in a recommended format such as IFC (Abanda et al., 2017). The current approach to digitally supporting façade design is available through BIM and IFC. The former supports information regarding geometrical features and materials while the latter contains data in the form of text that can be imported into common BIM software, supporting the digitalization of knowledge (Montali et al., 2018).

DFMA rules in other industries such as car and shipbuilding are structured in a step-by-step pattern in which designers can follow knowledge regarding manufacturability guides in each steps of the design (Lahtinen, 2011). There have been studies exploring methods to formulize DFMA rules for construction activity (Stamatiadis et al., 2017; Jiang et al., 2014). For example, Build-Offsite property Assurance Scheme, demonstrated a set of guidelines in relation to the rules. This includes a sequential chain of orders for construction supply lines such as Actavo Steel Framed Modular Solution and Closed panel structural timber system (Luo et al., 2017). In North America, existing prefabrication strategies are established on an inline ―wiki-prefab” platform to engage the participants in the AEC industry toward a library of hybrid and ready to used components for architectural design. Aiming for an advanced level of customization, the Marmol Radziner Architects proposed a web interface where the customers choose a predefined model and re arrange it with multiple alternatives. Tailoring the design to pre-set personalized options, each alternative modifies the overall cost in real time project. Mass customization, therefore, becomes feasible depends on an option-controlled standardization (Carbone et al., 2017).

Opportunities to integrate DFMA into the design process as well as the buildability requirements need to be considered at the stage of concept. Data structure in the form of design rules, parametric design and object modelling are embedded into BIM in the form of knowledge-based BIM. For effective automation, congruent computational support throughout the project life cycle is required. Using a mathematical formula for dimensions while defining numeric relationships between various parameters, parametric building information modelling allows the creation of flexible geometric models that can be adjusted through manipulating primary parameters. There are three major advantages in utilizing parametric design as opposed to rigid traditional CAD geometry: automatic change is applied to all models; there is a re-use of predefined components and geometries; and there is embedding knowledge regarding design/manufacturability- such as minimum bend radiuses for cast design- and geometry (Gembarski et al., 2017).

The DFMA is presented as an alternative design methodology based on architects‘ future roles in construction industry which transforms the architectural design mode to a building product design mode through morphing architects into product engineers. This transition may be an alternative mindset suited to architects‘ future roles which would probably be connected to interdisciplinary engineers and designers to manufacturers.

6. CONSLUSION AND FUTURE WORK

In recent years, a change of understanding in the construction industry has happened, a mind shift revolution, which has transformed the fragmented industry toward an integrated construction system. This has been a holistic transition with major transforming keys such as lean thinking, BIM, relational contracting, OSM, performance-based design, and early collaboration. This transitional mind shift will inevitably affect architecture-related fields including the façade retrofit design process. At the heart of this mind shift revolution, IPD-BIM for OSM projects has become an increasing area of focus in the industry. There is a gap in the research as well as in the industry regarding the alternative design methodologies that support architects during this transition.

This research identified DFMA as an alternative design approach and architectural mindset suited to IPD-BIM. Several studies have been undertaken to address the DFMA method in building manufacturing, including studies by Salford University, ―Implementing BIM to streamline a design, manufacture, and fitting workflow” (Machado et al., 2016) and China Council &The University of Newcastle Joint Funding Program on ―New industrialised construction technology of indemnificatory housing” (Luo et al., 2017); However, none of these studies have explored this methodology from an architectural perspective. The necessity of examining DFMA from this angle is that the process of design to assembly requires the involvement of both product design and process design simultaneously (Venkatachalam et al., 1993). This means that the decision taken during the design of a product will have an impact on the decision taken during the design of the process that produces that product. This implies that the steps to design a façade as an ETO product will affect the manufacturing and assembly process design; thus, the importance of exploring and re-interpreting the methodology from an architectural point of view is an area which is worth researching.

DFMA offers various research opportunities from the perspective of developing alternative design methodologies which support architects‘ design mindset suited to OSM and IPD_BIM. This may help to bridge the gap between architects‘ intention and product delivery while help architects to keep pace with the ongoing change in the AEC sector. This concept will further be developed by the author through answering what computational or process support for DFMA design methodology can help designers to improve design freedom in facade retrofit design. The pressure on all participants of the AEC sector including Architects to keep up with the IPD trend in the industry creates the need to constantly update new processes and design methodologies which require new skills to implement it accordingly. Taking the DFMA approach, façade also has to keep pace with new requirements, manufacturability and installation knowledge for new products and services to suit the necessary criteria. Creativity when using DFMA design methodology would be a different kind of creativity, with more constraints on various design phases. Therefore, the study‘s future aim would be to discover, when DFMA is adopted in a façade retrofit environment how is the architecture design process from both a creative artistic and an engineering design perspective altered.

Kieran et al., 2003, explains the way complex manufacturing industries like car and shipbuilding benefited greatly from focusing on the process of design to manufacturing of parts that are further assembled together, thus, have progressed over the years (Kieran et al., 2003).The advanced design process is the major difference between construction industry and other industrial sections which guides the use and reuse of product components during the design process. A clear analysis of the façade design phases is, thus, needed to analyse the knowledge and skills to be incorporated in the design and for the assembly issues to be solved (Vaz et al., 2008; Voss et al., 2013;). Examining this concept as an architectural solution to facilitate the transition in the AEC sector from a fragmented toward an integrated industry is a significant contribution which this research would have to offer. To address the identified question, a research design within the category of qualitative research in the context of Auckland, New Zealand will be carried out. This involves an exploratory study to create a process map of all phases of model development and data requirement in BIM for façade design retrofit (as-is process mapping), proposing a new alternative process map more suited to DFMA based on semi-structured interviews with Architects, cladding specialists and façade engineers; then validating that alternative process-map in case-study focus groups. The resultant process map will serve to assess to what extent the current industry process is different from the outcome of the research project and whether it would be useful to modify the ongoing façade design retrofit steps. In addition, the information gathered through process map will shed light on how parametric object modeling could provide support for a component final manufacturing and installation.

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POTENTIAL FOR VIRTUAL REALITY AND HAPTIC FEEDBACK TO ENHANCE LEARNING OUTCOMES AMONG CONSTRUCTION WORKERS

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ABSTRACT: *The construction industry involves highly hazardous working conditions, where workers need to identify and assess a litany of risks on jobsites resulting from the varied high-energy work being performed around them. Research suggests that, while the traditional training approaches offer value, they do not sufficiently prepare workers to eliminate preventable injuries. Emerging technologies offer opportunities to leverage immersive virtual environments to train construction personnel about safe practices. This research reviews the uneven literature across various domains and examines how virtual technologies and haptic feedback has been used for targeted training experiences. The results of this work illustrate that there are many different learning advantages reported for VR and haptic environments for various fields. There is also evidence to suggest synergies between the two technologies justify the exploration of both in conjunction with one another for adult learning applications. The authors use the findings reported in these prior studies to theorize potential learning benefits that the construction industry could gain by adopting immersive simulation-based training environments. The effort here also identifies how immersive training environments can generate targeted emotional arousal and increase situational interest to meet safety-related learning objectives while also promoting risk-averse decisions.*

KEYWORDS: *Virtual Reality, haptic technology, training, and construction safety.*

1. INTRODUCTION

The U.S. construction industry makes up 6% of the U.S. GDP and accounts for $1 trillion in annual spending (Huesman et al., 2015) and 9 million American jobs (Dong et al., 2014). However, the industry has struggled with productivity and wastes of about $15.8 billion annually due to inoperability (Gallaher et al., 2004) and another $15 billion in direct costs stemming from occupational fatalities and injuries.

Recent studies have highlighted that the current format of skill and safety training sessions are not engaging and often present information in a manner that cannot be easily retained by adult learners (Albert and Hallowell 2013). From a safety training context, Albert et al. (2014) showed that workers are engaging in unsafe behavior perhaps unwittingly because the conventional safety training programs are ineffective at improving their hazard recognition skills. This incompetency is the result of the framework of these safety training programs that uses child-focused pedagogical principles (Albert and Hallowell, 2013) which makes them not only ineffective in promoting learning, also leads to instilling a negative outlook towards learning among workers (Haslam et al. 2005). *This 'teacher-student' passive learning framework for training is not conducive to positive learning environment for construction workers.* Furthermore, it would be fair to hypothesize that there is going to be a massive influx of semi-skilled workers to address the critical labor shortages facing the industry right now (Wang et al., 2010). Thus, the industry could benefit significantly by revolutionizing the design and delivery of the various training programs to encourage workers to engage within the learning environment and also enhance their long-term knowledge retention.

Researchers have started to explore the efficacy of using virtual reality (VR) technology within construction safety training contexts to create immersive environments to test hazard recognition (Tang et al., 2009), risk assessment (Tixier et al., 2014), and decision-making (Bhandari et al., 2018) skills. The use of high-fidelity VR environments allows researchers to expose individuals to risks without causing actual harm. Similarly, haptic feedback has been used within the construction context to provide error feedback and defect management for workers (Dong et al., 2009; Kosch et al., 2016). While VR environments have been successfully used to measure skill and decision-making abilities, studies have not explored if these immersive environments and feedbacks can enhance learning outcomes among workers. Specifically, it is unclear if providing experiential learning on construction projects can translate to enhanced skills and safer practices on the construction site. The purpose of this paper is to review literature from other domains and propose how use of VR and haptic technology can potentially further learning outcomes among construction workers and identify critical gaps in body of knowledge for future research endeavors.

2. OVERVIEW / BACKGROUND

In the section below, we examine the relevant literature related to using VR and haptic feedback for training and education purposes across diverse domains and how the use of these technologies can instigate and sustain primary psychological precursors to learning. The established theory presented here will be used to ground our discussion on the potential benefits the construction industry can receive by adopting these immersive technologies.

2.1 Psychological Antecedents to Learning

Emotional arousal and interest are strong and immediate precursors to intense learning experiences. Both are key learning agents as they generate and mediate a learner's cognitive functioning (Renninger, 2000), motivation (Pekrun et al., 2011), attention (Hidi et al., 2004), commitment to learning (Schiefele, 1999) and knowledge retention (Brown and Kulik, 1977).

Emotional arousal is a fundamental component to experiential learning. Experiencing an emotional response in a learning environment can motivate learners to pursue or continue to engage with the information being provided by heightening curiosity or instill a need to improve performance (Konradt et al., 2003). Studies have found that students who experience emotional arousal in a learning environment are more likely to recall and remember the information (Chung et al., 2015). Furthermore, Brown and Kulik's (1977) flash-bulb theory suggests that events with strong emotional impact can remain well-preserved in our long-term memory. This implies that training sessions that provide information with relevant and impactful emotional cues would be less likely to be corroded easily from memory, thereby improving long-term retention of knowledge.

Both positive and negative emotions can enhance learning experiences. Positive emotions promote intrinsic motivation and creative thinking (Bless et al., 1996) whereas, negative emotions can generate extrinsic motivation and promote a more cautious and detail-oriented approach to problem solving (Pekrun et al., 2002). Appropriate emotional responses within learning environment can aid learners to adequately assess, categorize, and value the information being presented. These findings underscore the importance of experiential learning (Chung et al., 2015) since sensory experiences and active learning techniques yield greater emotional arousal than passive lectures and presentations (Bell and Kozlowski, 2008; Um et al., 2012). Moreover, emotional arousal during training environments can also be used to influence risk-taking behavior and safety decisions (Tixier et al. 2014).

Additionally, interest experienced by a learner in a subject has been noted by researchers as a critical driver of long-term engagement with learning as well (Hidi and Renninger, 2006). There are two primary forms of interest: *individual* and *situational* where individual interest has been characterized as a deep and enduring personal connection with subject matter whereas situational interest is immediate and fleeting experience where interest is associated with stimulus within the environment in that moment (Hidi and Renninger, 2006). Situational interest is a strong predictor of willingness to apply cognitive resources to acquire and apply knowledge (Ainley et al., 2002). This paper focuses on situational interest because it is more relevant to consider immediate and short-term reactions to training environments however, Hidi and Renninger (2006)'s interest model suggests that a pervasive learning environment that sustains situational interest can develop into meaningful and well-developed individual interest. Because current safety training frameworks can often be mundane and do not incorporate adult learning principles (Albert and Hallowell, 2013), a focus on generating situational interest can yield not just a more cognitively motivated workforce, but also one that is emotionally and behaviorally engaged (Sun and Rueda, 2012).

Therefore, in summary training programs need to provide active learning environments with agents to generate both situational interest and targeted emotional arousal to improve engagement, enhance knowledge retention, influence behavior, and address the negative outlook towards training in the workforce.

2.2 Use of VR for Learning and Training Purposes

VR simulation can be characterized as computer-generated synthetic immersive environment that allows a person to interact with reality (Briggs, 1996). These immersive environments are often used by researchers to study an individual's perceptions and behavioral tendencies by simulating reality without incurring significant costs and within certain experimental contexts, circumventing the need to place someone in real danger. VR environments have received significant attention from the research community and its efficacy within learning (Merchant et al., 2014; Youngblut, 1998) and training (Lateef, 2010) contexts across various domains has been rigorously validated.

Immersive VR environments can be effective in enhancing attention (Cho et al., 2002) and reducing cognitive demand for improved learning experiences (Wetzel et al., 1994). Seymor et al. (2002) conducted a double-blind study on surgical residents and found that the participants with VR training took less time and made fewer errors compared to non-trained participants. Similarly, a plethora of studies have replicated these findings confirming the utility of VR training in improving performance in operating rooms (Grantcharov et al., 2004). Use of VR training can provide learners the opportunity to constantly and consistently train without utilizing significant resources each time (Gallagher and Cates, 2004) and trainers or supervisors can monitor an individual's learning curve (Gallagher and Satava, 2002). Similarly, construction workers also deal with significant time pressure and work in an environment that is dynamic and the risks are ever-changing, thus placing them in VR simulation can serve as a high-fidelity experiential learning tool that can heighten their situational awareness by engaging their visual and auditory sensory experience.

As VR technology continues to increase in fidelity, users will continue report increased *presence* in the environment. The degree of immersion, interactivity, novelty, and challenge by using this technology can yield proportional motivation and mindful engagement (Malone and Lepper, 1987) and self-directed learning (Pantelidis, 1993; Standen and Low, 1996). The level of immersion in a VR environment also generates emotional arousal (Riva et al., 2007), while Edwards and Gangadharbatla (2001) proposed that 3D modalities should increase situational interest. Thus, VR can be an effective tool for training construction workers on technical skills and level of immersion can generate targeted emotional arousal that can enhance learning outcomes and risk-averse decision-making.

2.3 Use of Haptic Technology for Learning and Training Purposes

Just like visual and auditory cues, our sense of touch can influence attitudes, behavior, and judgments (Ernst and Banks, 2002; Peck and Childers, 2003). Haptic feedback is essentially sensory feedback that is generated from kinesthetic and tactile receptors (Botden et al., 2008). The feedback can guide individuals on the speed and direction of necessary movement thereby improving tactile skill (Pantelidis, 1993). Haptic feedback technologies allow a user to interact mechanically with remote environments without being exposed to the risks (Hatzfeld and Thorsten, 2014). This form of feedback has been found to be highly beneficial and is widely used in the medical field to aid in improving skill among residents and patients to improve performance of surgery (Mayer et al., 2007; Okamura, 2004) and improve motor-skills (Jiang et al., 2009) respectively.

Even in other domains, haptic feedback has been used to enhance the transfer of technical skills. Marchal-Crespo et al. (2010) found that haptic training improved car steering performance among all age groups. Primary reason that feedback from haptic devices improves performance could be attributed to gaining physical representation through "feel" of knowledge that learners cannot access in a traditional learning environment (Reiner, 1999). Reiner (1999) also suggests that the gain of such knowledge promotes construction of accurate mental models that learners can easily access. Even under high cognitive load, haptics can improve the speed and accuracy in task performance (Cao et al., 2007).

Like VR being proven to instigate emotional responses, there is evidence that haptic feedback could intrinsically impact emotional arousal (Olausson et al., 2002). A study by Jones et al. (2003) showed that students who received haptic feedback had an overall positive emotional experience in the learning environment and reported more meaningful engagement and interest with the subject matter. These studies suggest that haptic feedback can mediate emotional arousal and the experience of interest among learners that could be used by teachers, facilitators, and managers to enhance learning outcomes.

2.4 Use of Haptic Technology in conjunction with VR

While VR technologies and haptic feedback have been utilized across various domains, their use has been mostly mutually exclusive of each other. But sparse and preliminary evidence suggests that providing haptic feedback within VR environment can be used *further* heighten user presence and sense of realism (Weiss et al. 2009).

Use of haptic feedback with VR technology has aided both sighted and blind people with development of cognitive models and spatial knowledge (Colwell et al., 1998; Jansson et al., 1998). A study by Jacobs et al. (2007) found that, compared to the traditional use of only visual feedback, a combination of haptic and visual feedback can improve an individual's productivity by significantly reducing their task completion times while also reducing the number of errors they commit.

Combining the two technologies has also been shown to improve the transference of the virtual experience to real-world skills (Council et al., 1995) as it improves users ability to make personal connections with subject matter (Jones et al., 2006). Use of haptic feedback within VR environment has been shown to improve the range of motion and speed of hand movement among patients who have suffered a stroke even at chronic stages (Merians et al., 2002). Within learning contexts, the combination of visual and auditory cues from the VR environment and sense of touch from haptic feedback allows learners to utilize multiple channels to process information, build more accurate mental models, and improve retention of knowledge (Baddeley, 1992). Furthermore, the cutaneous sensations alongside visual and auditory information improves memory capacity (Killi 2005; Sweller, 1988; Wickens, 2002) while the novelty of the experience improves curiosity and interest (Richard et al. 1996).

So far within the construction domain, VR technology and haptic devices for feedback have been used independently and sparingly. However, VR environments have only been used as tools to measure skill and behavior but rarely to provide training. Haptic feedback on the other hand, has received nearly no attention from researchers and industry stakeholders within the construction domain. The research that has been conducted is mostly qualitative and speculative in nature (Wang et al., 2007). There is a need to conduct empirically driven exploration to examine if providing high fidelity information from immersive environments improves or hinders acquisition of skill and knowledge among workers.

3. DISCUSSION

The literature review above shows that VR environments and haptic feedback are being commonly used in the various domains to transfer technical skills, enhance learning, and study users' perceptions and behavior when interacting with real-world simulations. Within the construction industry, most training programs use either passive settings (Albert and Hallowell, 2013) or a multimedia learning environment, which includes physical simulations and narration (e.g., Bhandari and Hallowell, 2017) that can be interactive but not immersive in nature. The following section uses the findings presented above to interpolate the theoretical benefits the construction industry can derive by adopting VR+ haptic feedback training format. Furthermore, the authors also identify potential avenues for future researchers to further the current body of knowledge.

3.1 Implications

Research shows that witnessing or sustaining an injury creates a deeper experience and consequently leaves the experiencer with a long-lasting lesson learned (Hallowell, 2010). It is fair to hypothesize that placing workers in a VR simulation and allowing them to make mistakes and deal with the consequences can lower their overall risk tolerance and heighten their situational awareness on actual worksite. This is the reason training programs especially within construction domain need to focus on fostering experiential learning environments (Bhandari and Hallowell, 2017).

Adult learners interact with learning environments differently and their needs are very different compared to children. Passive learning environments generally ignore relevant life-experiences and their cultural backgrounds (Hollins and King, 1994; Merriam, 2004). VR technology and haptic feedback can promote self-directed learning among adults by giving them autonomy to interact with simulated reality. Adult learners are context-driven and truly engage with learning environments if they see information relevant to their everyday life (Lindeman, 1956). Furthermore, real-time feedback can allow the workers to enrich pre-existing knowledge, while gaining new knowledge. Passive learning environments are framed to not allow self-directed learning which adults prefer (Specht and Sandlin, 1991) and coercion experienced in those learning environments (Boyatzis, 2002) could explain the negative outlook towards safety training among construction workers.

To make training a fun and interesting experience, it needs to be unique and interactive. A VR training environment may be perceived as both novel and immersive, which are key factors to triggering situational interest among learners (Hidi 1990). Factors such as engaging narrative, humor, and belongingness (Bergin, 1999) can be easily incorporated in a virtual training environment to sustain that interest of workers. For the construction industry, this coupled with the findings from previous studies showing the use of VR technology and haptic feedback can make individuals more productive, which can address crippling costs incurred due to interoperability and injuries mentioned above. Finally, as mentioned before, emotional arousal can influence not only our learning outcomes, but also our behavior and decision-making abilities. It can be used to control risk-taking behavior and heighten perception of risk (Loewenstein et al. 2001). Specifically, negative emotions can reduce risk-taking behavior by lowering false optimism (Taylor and Brown, 1988) and reduce appraisal of safety (Izard, 1977). Within the construction context, Tixier et al. (2014) showed in a controlled experiment that participants induced with negative emotions showed higher risk-perception when assessing construction hazards compared to participants induced with positive emotions and control group. Similarly, Bhandari and Hallowell (2017) showed that multimedia simulation-based training environments can be used to generate targeted emotional arousal among construction workers. As noted before although typically, positive learning environments are favored, negative emotions can generate extrinsic motivation to avoid failure (Pekrun, 2002) and make learners more detail-oriented and cautious (Bless et al., 1996) which in safety context is more desirable. Table 1 shows that training environments that use both VR and haptic feedback can theoretically enable more learning agents over the more traditional learning environments.

Table 1: Crosswalk table comparing VR and Haptic training combination against other training formats

	Emotional Arousal	Self-directed Learning	Immersive Interaction	Physical Interaction	Experiential Learning	Novelty
VR + Haptic Feedback	X Reiner 1999, Taylor & Brown 1998	X Okamura 2004, Schiefele 1999	X Cho et al. 2002	X Gallager and Sataya 2002	X Gallager and Kates, Gallager and Sataya 2002	X Bergin 1999, Hidi 1990, Malone and Leper 1987
VR	X Reiner 1999, Schiefele 1999	X Okamura 2004, Schiefele 1999	X Cho et al. 2002		X Gallager and Kates, Gallager and Sataya 2002	X Bergin 1999, Hidi 1990, Malone and Leper 1987
Haptic Feedback	X Merriam 2004	X Chien et al. 2010		X Gallager and Sataya 2002	X Kosch et al. 2016	X Bergin 1999, Hidi 1990, Malone and Leper 1987
Multimedia Learning Environment	X Bhandari et al. 2017	X Bhandari et al. 2017		X Bhandari et al. 2017	X Bhandari et al. 2017	
Passive Learning Environment	X Perry & Dickens 1984					

In sum, VR + haptic feedback-based training may be able to be used as tools to induce targeted emotional arousal to manipulate risk perception and promote risk-averse decision-making among construction workers. Furthermore, the incorporation of self-directed learning framework with active learning environment may generate meaningful interest among workers to persevere with learning and dedicate cognitive resources. Finally, realistic and immersive simulations of hazards, risks, and injuries can act as experiential learning components for workers that should lower their risk tolerance and heighten situational awareness. Figure 1 shows the pathways that can lead to these potential improvements in learning outcomes, productivity, and risk-taking behavior.

3.2 Gaps in Knowledge and Future Directions

It has been established that the current methods of safety training are woefully inadequate (Albert et al., 2014) and the use of VR technologies and haptic feedback has been largely successful in other domains. This paper posits that the use of VR technologies with haptic feedback could overcome the shortcomings of the current child-focused pedagogical principles-based training modules currently used on construction sites. However, the implications discussed above have not been empirically tested and need validation.

The qualitative assertions of potential gains that the industry could gain are derived primarily from studies conducted in the medical domain focused on resident surgical training. These findings need to be validated in a construction setting as construction jobsites are much more dynamic in nature (Rozenfeld et al., 2010) and the nature of hazards and risk can vary on each jobsite. There is a need to study if the higher fidelity training systems can improve situational awareness and work performance among the adult learners over the traditional methods of training. Specifically, while we theorize that VR environments and haptic feedback may reduce errors and improve hazard recognition skills, the degree of the improvement that can be expected remains completely nebulous. Finally, it is unclear if the realistic simulations of accidents and injuries resulting from their poor decisions (i.e., experiential learning) would indeed be effective in reducing risk-tolerance levels and attitude towards safety among workers. Addressing these gaps by conducting empirically driven experiments in a controlled laboratory setting would provide more context to the understanding of whether the cost of adopting VR + haptic feedback training is justified or not.

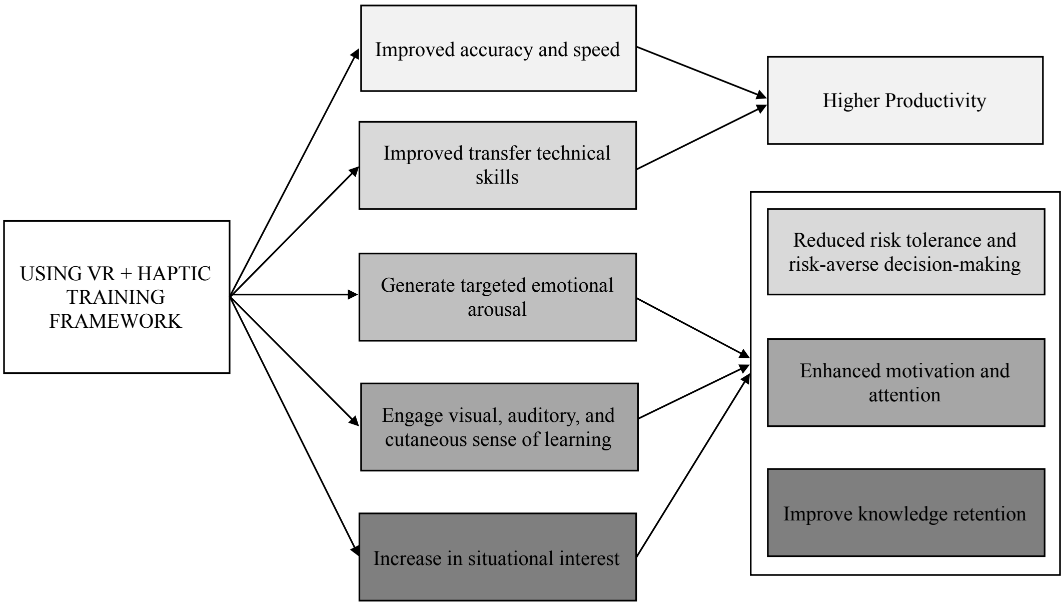

Figure 1: Pathways to potential gains from adopting VR + haptic training framework

From a psychological context, while researchers agree that VR and haptic technologies can be used to generate emotional arousal, there is uncertainty regarding their pervasive nature. In other words, it is unclear if these technologies generate more intense *and* sustained emotional experiences over the traditional media, and if those experiential emotions mediate learning and decision-making among adult learners. Such knowledge would not only benefit construction community, but also learning and psychology community as adult learners are often neglected and the learning agents in occupational training environment have not been rigorously examined.

There are indeed some practical challenges that need to be explored as well. The construction industry shows significant resistance when it comes to adopting and adapting to new technologies. It is not clear how often this type of training would need to be provided and how could it be integrated with current safety training methods such as Occupational Safety and Health Administration 10-hour training, safety inductions, and hazard checklist (e.g., jobsite hazard analysis) as it is possible that former may not effectively address each task and site-specific challenges. Finally, there is also no comprehensive study that could be identified to understand what challenges workers may have while interfacing with new and sophisticated technology. If these practical challenges are not addressed adequately, it could impede the industry adoption on a wide-scale, regardless of the proposed or empirically validated benefits.

4. CONCLUSION

While there has been significant research within the safety domain, safety training itself in the construction industry has hardly changed over the past few decades. It has not evolved to address the advancements in the field of adult learning, nor has it been very accepting of new technologies for various reasons (e.g., first costs, skepticism and reluctance due to lack of existing users, and scaling issues). These reasons have been published in industry reports (KPMG International 2016), however they have not been empirically validated by the research community. Restructuring the training programs from the ground up could address critical competency needed in the largest single-service industry in U.S., which is about to see an influx of new workers to address the crippling workforce shortages. The purpose of this paper was to highlight theoretical learning and behavioral gains that the industry could reap by adopting VR and haptic technology-based learning environments and also to identify key gaps in the current body of knowledge. Although VR based training with haptic feedback may require more upfront resources, the authors posit that workers who are given training in immersive experiential learning environments would be more productive, retain knowledge better, and make appropriate risk-averse decisions.

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A NEW APPROACH TO TESTING AUGMENTED- AND VIRTUAL-REALITY TO SUPPORT TACIT KNOWLEDGE GENERATION IN DESIGN ASSESSMENT

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ABSTRACT: *Professional expertise in the architecture, engineering and construction (AEC) industry is typically developed through years of field experience. The knowledge obtained during this time consists of both explicit knowledge and tacit knowledge. Educators typically focus on presenting content to develop explicit knowledge, but both forms are required for novice students to become expert practitioners. Part of the challenge with developing tacit knowledge is that actual project experiences can be difficult to replicate in academic environments. Emerging augmented reality (AR) and virtual reality (VR) technologies may offer new abilities to provide experience that mimics on-site experiences for students. Other fields of research have developed educational approaches to support experiences that may enable tacit knowledge generation, including the Carnegie Foundation's Three Apprenticeships Model, which states that the most comprehensive learning experiences must include an emphasis on cognitive understanding, practical skills, and moral dimensions. Therefore, this paper proposes a methodology that will enable researchers to use this model as a guide in order to test the impact of AR- and VR-enabled learning in the AEC domain. This methodology includes three main parts: expert focus group interviews, VR/AR experiences with data collection throughout, and pre-post analysis to assess the impact of the technology intervention.*

KEYWORDS: *Augmented Reality, Virtual Reality, Three Apprenticeships Model, Design Assessment, Tacit Knowledge*

1. INTRODUCTION

1.1 Industry Concerns About Shortage of Skilled Workforce

In the coming decades, the architecture, engineering and construction (AEC) industry is expected to see substantial growth with labor demands growing upwards of twenty percent nationally (Henderson 2015). Although the growth is projected to increase revenues, the AEC industry as a whole is projected to struggle with meeting this demand as it continues to grapple with criticism of poor productivity (Goodrum et al. 2011; Teicholz et al. 2001) and wasted money due to interoperability issues (Chohan et al. 2007; Hwang et al. 2009; Love et al 2011). The severity of these issues are compounded by the challenges associated with entering a "labor-cliff". A labor cliff is defined as the state at which project performance is significantly affected by one or more workforce issues: labor, quantity or quality (Albattah et al. 2015). The median age of construction professionals has risen to 42.6 years of age and design professionals' median age is now 44 years old (Bureau of Labor Statistics 2017), and the lack of new professionals entering this industry is not offsetting those retiring (Gamble 2013). The confluence of these trends means the industry will continue to face challenges of training new professionals rapidly to meeting the growing workforce needs (Arditi & Mochtar, 2000; Dubois & Gadde, 2002; Schwatka, Butler, & Rosecrance, 2012).

This loss of knowledge and expertise will pose a major challenge to the AEC industry in the coming years. Knowledge is generally broken into two categories: explicit and tacit knowledge (Pathirage et al. 2008). Explicit knowledge is related to the information that can be accessed, articulated, and communicated easily. This information is typically conveyed in the form of textbooks or detailed examples (Collins 2010; Maravilhas & Martins 2018; Pathirage et al. 2008). In the AEC industry, this form of knowledge is generally taught and retained through manuals or standard operating procedures (Hizar Md Khuzaimah & Hassan 2012). However, due to the growing complexity of projects and the diverse nature of project scope within the AEC industry, a growing interest in tacit knowledge has emerged in order to better train project team members (Hizar Md Khuzaimah & Hassan 2012; Woo et al. 2004).

Unlike explicit knowledge, tacit knowledge is defined as the understanding, capabilities, skills and the experiences of individuals; often expressed in human actions in the form of thoughts, points of view, evaluation and advice (Collins 2010; Nonaka & Takeuchi 1995; Pathirage et al. 2008). Tacit knowledge has been identified as a critical element within the AEC industry and can be subcategorized further into cognitive knowledge (mental beliefs or hunches) and technical knowledge (the know-how and skills) (D'Eredita & Barreto 2006; Hizar Md Khuzaimah & Hassan 2012). By its nature, this form of knowledge is difficult to record and therefore challenging to teach to new industry members that have not had the opportunity to experience an active project jobsite in a particular situation. Typically, it is gained through years of project site experience, but the time required for this tacit knowledge generation is not conducive to meeting the industry's growing labor demands. With the current labor shortage, the industry needs a means of educating new individuals more rapidly to gain this tacit knowledge.

1.2 Potential of Emerging Technology

In the past, educators have leveraged physical design and construction projects (i.e Solar Decathlon) to enable students to attain both explicit and tacit knowledge. While this type of hands-on education may be highly valuable to the students, it is extremely time and resource intensive, which means that not all students can have this type of practical experience prior to graduation. This limits access to experience that can enable tacit knowledge generation. Augmented Reality (AR) and Virtual Reality (VR) environments may facilitate this type of education by replicating construction or design environments in a classroom setting with relatively low costs in materials. Figure 1 presents a conceptual graphic illustrating how this technology may enable similar experiences to physical presence.

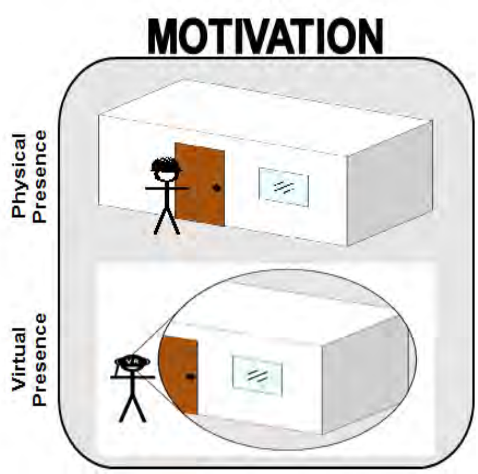

Fig. 1: Graphical representation of motivation to research

Augmented Reality (AR) and Virtual Reality (VR) environments have been suggested to provide value by allowing project teams and educators to replicate construction or design environments in a classroom setting with relatively low costs in materials (Alsafouri et al. 2017; Alsafouri & Ayer 2017; Frank & Kapila 2017; Wu et al. 2013). AR is the incorporation of both the tangible elements of the physical environment with that of the modeled virtual environment displayed simultaneously (Milgram & Kishino 1994). VR environments are where the sensation of presence is conveyed by minimizing the contact of the user with the physical world, thus differentiating from web-based VR application that are normally manipulated through a mouse and the PC display (Marini et al. 2012). AR has been identified to provide value in the early stages of a construction project by supporting decision making processes (Alsafouri et al. 2017). In addition, VR has been previously found to enable users to visualize and recognize complex workplace situations, from which the knowledge of procedures and skills could be built, and tasks in a safe and forgiving environment be carried out (Li et al. 2018). These environments are intended to simulate experiences that could only be achieved otherwise through physical experiences (Alsafouri et al. 2017; Gupta 2012; Hughes et al. 2005; Milgram & Fumio 1994). This immersion in the experience motivates the researchers to explore the extent to which these visualization environments may be able to replicate the type of tacit knowledge generation that is typically developed through years of onsite experience. Thus, the interactions with these environments lead researchers to question whether or not AR and VR can be leveraged to facilitate tacit knowledge generation.

While AR and VR offer theoretical potential to students' development of tacit knowledge, there is not currently an understanding of how tacit knowledge should be evaluated in the design and construction education domain. The Three Apprenticeships Theory offers a framework that outlines three critical components that must be embraced in order to facilitate tacit knowledge generation: head, heart, and hand (Shulman 2005). Other fields of education such as nursing have found success in the application of this learning theory in the development of better-prepared medical professionals (Taylor & Care 1999). It is possible that this same approach to learning may benefit design and construction education as well, but currently there is a lack of understanding of how it should be applied to this specific domain. Therefore, this paper aims to fill this knowledge gap by addressing the following questions: 1) *What methodological decisions facilitate the appropriate application of the Three Apprenticeships learning theory using AR/VR intervened cyberlearning environments to enable tacit knowledge generation relevant to design and construction education?* 2) *And what data should be collected during AR/VR learning activities to inform the development of relevant learning assessments in this new genre of cyberlearning?* This paper contributes a methodology to test design- and construction-related tacit knowledge generation through AR and VR-enhanced cyberlearning environments. The remainder of this paper will include a summary of the learning theory supporting the proposed methodology, along with the three-step methodology itself.

2. THEORETICAL UNDERPINNINGS

2.1 The Three Apprenticeships Model

The "Three Apprenticeships Model" provides the theoretical underpinnings for the proposed methodology of this paper. The results of a multi-year, multi-institutional study conducted by the Carnegie Foundation for the Advancement of Teaching (2007) describe the current state of undergraduate engineering education in the U.S. and provide recommendations for improving curriculum to align with the professional demands of the field. The study found that within engineering fields, curricula are primarily focused on the technical or explicit knowledge within the related field, though there is a need for more integrated learning experiences that involve knowledge (Head), skills (Hand), and professional judgment (Heart) (Sheppard et al. 2009). In theory, these experiences should provide a more well-rounded approach to facilitating the development of more robust forms of explicit and tacit knowledge among new professionals.

The Three Apprenticeships approach is informed by the insights of many contributors. John Dewey, a professor and education researcher, argued that teachers not only need to be educated on theory, but also practical application (Shulman 2004). Later, Shulman expanded on Dewey's theory with his perspective on the three apprenticeships. Shulman theorized that professional education is composed of three apprenticeships: cognitive, practical, and moral (Shulman 2005). The cognitive dimension focuses on the knowledge professionals should possess, the practical dimension focuses on the skills a professional must exhibit, and the moral dimension focuses on the attitudes, values, and ethics that are commonly associated with the profession of interest. Following this line of research, the Transformative Sustainable Learning (TSL) theory was created to ensure that certain values were imparted in education to ensure a sustainable future that will continue to progress our society (Sipos et al. 2008). Sipos and colleagues (2008) echoed the sentiments of Dewey and Shulman through their work, and continued to argue that the head, hand, and heart should be implemented into inter- and trans-disciplinary education. While the combination of the three constructs are interchangeably referred to as both Transformative Sustainable Learning and Three Apprenticeships in existing scholarship, the authors will refer to them as the "Three Apprenticeships" in this paper for continuity. The proposed methodology of this paper aims to address the need for more diverse learning integration in design curricula through the application of a Three Apprenticeships approach to educating future design and construction professionals.

3. PROPOSED METHODOLOGY

The proposed methodology involves a three-step procedure based on the Three Apprenticeships theory to test design- and construction-related tacit knowledge generation through AR and VR environments. The intention of this methodological approach is to provide researchers and educators a method to test tacit knowledge generation with visualization technologies so that they may be able to understand the extent each technology may be used to recreate experiences that elicit behaviors relating to tacit knowledge gain. The first step of the methodology includes expert interviews to identify particular use cases and desired research questions that need to be addressed in relation to the targeted apprenticeship. The second step involves the development of pre- and post-learning activity assessments that will help educational researchers to evaluate the impacts of technology interventions. The third step involves the development of the actual AR/VR-enabled learning experience based on the targeted learning outcomes. These steps are outlined in Figure 2 and detailed in the subsequent sections.

Figure 2: Graphical Overview of Proposed Methodology

3.1 Expert Interviews

Different forms of assessment allow for gathering evidence of different forms of knowledge. Thus, in order to evaluate each of the three apprenticeships in relation to design assessment, educators and researchers must strategically target each apprenticeship using a variety of forms of data collection and analysis. Although tacit knowledge is gained through the combination of the three apprenticeships, by separating each apprenticeship into separate evaluations, it allows researchers to identify specific characteristics of each apprenticeship that may be manipulated to promote greater tacit knowledge gain. Once a targeted apprenticeship is established amongst the research team, the first step within the methodology would be to identify which experiences would best replicate career situations within the industry that call for that particular apprenticeship. To do this the research team must first gain insights about the real world situations faced throughout the design industry and the associated decision processes industry professionals take to be successful in each situation. To establish this understanding and provide a framework for replicating an experience in a testing environment, researchers should first conduct interviews with subject matter experts targeted at understanding the decision processes or elements of knowledge they dwell upon when coming up with solutions. Subject matter experts are those assumed to have prolific working experience within the industry or a content expert in an academic setting.

To obtain the most beneficial commentary amongst industry professionals, it is suggested to develop an interview protocol specifically focusing on how experts and novices differ in their processes for acquiring knowledge and how they represent knowledge (e.g., domain-specific vs. general knowledge) (Popovic 2000). Interview questions should be based upon the working knowledge and work experience each expert faces in their careers. The questions should allow for open-ended discussion from the interviewee to reflect upon previous experiences and decision-making processes that were used to remedy the discussed situation. Dependent upon which apprenticeship is targeted, interview questions should be refined to accommodate each dimension in order to encourage interviewees to have more attuned perspectives and answers to the apprenticeship. For example, sample questions developed for application with the heart dimension or moral apprenticeship are provided in Table 1. Through these interviews, researchers should be able to identify specific career experiences in relation to design assessment that can be recreated in a virtual and/or augmented environment. Each interview protocol should be piloted and refined as necessary in order to allow researchers to target meaningful responses from interviewees.

Table 1: Sample Expert Interview Protocol Questions

1	Tell me a little about how long you have worked in this industry and what you currently do.
2	Based on the following four options, which phase do you have the most impact on as part of your day-to-day job: planning, design, build, or operate?
3	Can you give me example of a time when you needed to design or build a facility (or component) for individuals with needs different from your own? Please keep this example in mind throughout the rest of the interview.
4	What is your approach for designing/constructing a facility that is mindful of a diverse group of individuals (e.g., age, disability/ability, etc.)?
5	How do you evaluate different design/construction options to support the group of individuals? (Prompt: What information is useful for completing this evaluation?)

3.2 Technological Intervention

Once an experience can be identified through the situational content provided by the expert interviewees, researchers can then address how to best recreate the experience through visualization technologies. Table 2 presents examples of defined career experiences and the associated targeted apprenticeship. In order to target a particular apprenticeship, it is necessary to develop a strategy for replicating, recording, and analyzing tacit knowledge generation for the intended career experience researchers would like to evaluate.

Table 2: Example Experiences Associated With Each Apprenticeship

Apprenticeships:	Example Experience Use-Case:	Experience Justification:
Cognitive (Head)	Building Code Evaluation	To test industry specific knowledge participants should possess through the use current building codes required for a space
Moral (Heart)	Handicap Accessibility	To generate empathy among participant by placing them in a design scenario requiring of a user with different needs than their own
Practical (Hand)	Window Frame Assembly	To challenge participants use of skills by defining a set of means and methods that can be built by hand

Assuming that a physical experience is not available for assessment on an active project that would exactly replicate the identified situation or experience, researchers must artificially create this experience. For this, a technological intervention may be able to facilitate the environment. The authors of this paper have refrained from explicitly detailing development strategies for the technological intervention. The intent of this methodological approach is to have a wide applicability to test tacit knowledge across various construction use-cases or career experiences of which researchers and educators may require different development needs in creating the immersive experience. Therefore, general guidelines and suggestions are presented in order to develop the technological intervention to be tested. The technological intervention to create this environment should represent the intended career experience in a manner that conveys enough detail and immersion so that it is comparable to the physical world experiences that students would face in their eventual career. From previous work, visualization technologies such as AR and VR have been identified to be effective means of communication and creating immersive environments that mimic the physical world. AR and VR have been reported to support better decision-making that traditionally had only been reported through physical mock-ups or experience (Alsafouri et al. 2017). AR allows for the users to physically walk around or interact with a space while simultaneously interacting with the developed virtual model. Where physical exploration of a virtual space is not required, VR can be used to allow participants to be fully immersed in a developed virtual model. The close approximation of experience through the use of these technologies may provide users enough of an immersive experience to facilitate tacit knowledge generation

3.2.1 Data Collection Methods & Analysis

As tacit knowledge is gained through experience, researchers are interested in both the verbal and non-verbal behaviors demonstrated within the modeled experience and how that may relate to the decisions of professionals. In order to evaluate the user within the modeled experience and test the possible tacit knowledge gain in relation to the targeted apprenticeship, it is necessary to record the interaction both visually and audibly. This data can be used to conduct future behavioral analysis. Researchers are interested in both expert demonstrated behaviors within the modeled experience as well as novice behaviors. By having both expert and novice behavioral data, statistical comparisons (i.e. one-sample t-tests) to evaluate the ability of novices to meet the standard set forth by experts.

Multiple video and an audio recording devices are suggested to collect this information. The use of multiple video camcorders allows researchers to fix the cameras in key locations and different angles around the experiment to record all physical interaction with the modeled experience. An audio recording device can be fixed on or near the test subject to record user’s answers to posed scenarios and communication while interacting with the modeled experience. Assuming the testing space is sufficiently small, video camcorders can be used alone to record the interaction if background noise is of no concern.

To facilitate verbal communication of participants, it is suggested that researchers develop a think-aloud protocol to lead subjects through the experience and inquire about the subject’s decision-making process without bias. A think-aloud protocol is a tool typically used in psychology and cognitive human factors fields that has been suggested to be one of the most effective ways to assess higher level thinking processes which involve working memory (Joe et al. 2015; Olson 1983). It is a tool used to establish verbal communication of the problem-solving strategies of participants (Joe et al. 2015). The protocol should first sufficiently introduce the test subject to the experience or use case they are virtually being placed into and establish the task the user is to complete. Researchers should avoid the use of prompting test subjects past the point of introducing the experience as to not introduce bias. During the experiment, researchers should attune the think-aloud protocol to have little to no involvement by the research team and only use open ended questions with regard to the experience or use case. The questions should not suggest a right or wrong answer, but rather ask "how" and "why" the participant made the decisions they did. The answers to the questions can be later used for video behavioral analysis and qualitative analysis.

Once the video and audio data are collected, a behavioral coding scheme can be developed to identify and quantitatively evaluate the verbalized answers and key physical interactions. By assigning codes to each identified answer or interaction, researchers are able to assign a numeric value to the interactions the users are demonstrating that can later be used for statistical analysis (Alsafouri et al. 2017; Liston et al 2001). This can be done in numerous types of video analysis software such as BORIS. The coding scheme is dependent upon the experience and apprenticeship the research team is targeting within the experiment. Depending on which data points are of most interest to analyze or provide the greatest value with regard to meaningful inference, the coding scheme can be rearranged as necessary to accommodate the experiment. Example codes are provided below in Table 3 for an experiment in relation to handicap design assessment. Behavioral codes can be assigned to collect different information from the experiment. Time and duration information can be collected by monitoring the beginning, end, or time stamp of a certain interaction or communication. This information can be used to conduct productivity statistics of participants and identify the order of which information is identified. Counted instances of coded elements can be used for rubric-based evaluation or for comparison against different sampled groups (i.e. novice and expert).

Table 3: Example Behavioral Codes for Video Analysis

Code:	Behavior:	Data Collected for Statistical Analysis:
Begin Assessment	Moment when participant acknowledges the start of their assessment or when the first comment is given	Duration : Beginning timestamp of activity
End Assessment	Moment when participant acknowledges the end of their assessment or when participant states they have no additional comment	Duration : Ending timestamp of activity
Countertop Height	Participant comment stating the height of any countertop needs to be adjusted to fit the height of someone in a wheelchair	Point : Counted event
Movement Through Model	Active movement in wheelchair by participant in model	Duration & Point: Can assign start/ stop codes to collect timestamps or counted event

3.3 Perceptual Analysis – Pre & Post Questionnaires

To understand and evaluate the impacts of intervention on participants before and after the modeled experience, a pair of pre and post-test surveys (known more generally as a repeated-measures design) can be used to collect quantitative data (Dugard & Todman 1995). The perceptual content gathered can be used for statistical analysis (e.g. one-sample t-test) to determine if there is any significant change in perception and/or knowledge due to the introduction of the intervention. A main advantage of using pre- and post-test design is that the associated repeated-measures statistical analyses tend to be more powerful, and thus require considerably smaller sample sizes than other types of analyses (Brogan & Kutner 2012).

The pre- and post-test surveys aim to collect quantitative data, in addition to the qualitative data collected using the think-aloud protocol, to address the following research questions:

I. How do participants respond to the technology intervention itself, including the experience and potential knowledge gains?
II. How do participants perform in the experiment, i.e. conducting design and constructability review, in the technology-intervened environment?
III. How other factors, including the demographics (e.g. prior working knowledge and experience) of the participants and the two different visualization technology (i.e. VR and AR), may influence their performance in the modeled experience?

3.3.1 Pre & Post Activity Questionnaire Design

The pre-test survey questionnaire should collect the demographics information of the participants, including their prior working knowledge and experience with: 1) design and constructability review; and 2) visualization technology (VR & AR) used in the research activity. Perceptions and expectations towards performing the tasks in the experiment with different visualization technology are also measured using 5-point Likert-type scales. The post-test survey questionnaire collects data on participants' perceived experience with the design and constructability review activities in both VR and AR intervened environments. To help understand the usability difference perceived by participants in the two environments should integrated into the questionnaires as well. The ten-item attitude Likert scales, i.e. the System Usability Scales (SUS) developed by Brooke (1996), are suggested to be used to quantify this information. In order to keep data consistent, the questionnaires should be linked via the use of identifier questions to allow direct comparison of responses by the same participants before and after the activity. In order to limit bias, identifying questions should be prompted in a fashion that does not directly identify the participant within the activity. The medium of which the questionnaire is distributed, whether it be a paper or electronic questionnaire, is not important. Though in order to allow participants to have the best recall of the activity, it is imperative that the pre-questionnaire be given immediately before the activity and the post questionnaire immediately after the activity.

Corresponding to the research questions, the following analyses can be performed:

I. Comparing the usability of the two visualization technology-intervened environments, using one-sample t-test;
II. Comparing the expected with experienced results of design and constructability review in the VR- and AR-intervened environments using one-sample t-test; and
III. Evaluating if the above analyses are dependent on prior working knowledge and experience (i.e. novice vs. experts) using Pearson's chi-square test.

4. LIMITATIONS & DISCUSSION

The authors provide a methodological approach to test new and emerging technological interventions' impacts on tacit knowledge generation based on the Three Apprenticeships model. While the methodology has a theoretical basis, it has not yet been empirically tested, so the authors cannot claim the extent to which this mode of education impacts student learning.

As the proposed methodology does not call for an evenly distributed sampling of expert interviewees, generalizability among diverse population may be limited. The experiences and replicated environments in AR or VR are based on the situational content provided by expert interviews which are assumed to be regionally centered in experience. This may lead to developed experiences that may not be practical for replication in other research or curricula.

The authors aim to create this methodology to support learning experiences enabled by AR or VR technologies. It is possible that other researchers will want to explore the impacts of different technologies. If so, they may find that certain aspects of the proposed methodology must be changed to accommodate the different technology. It is likely that this would only impact the technological intervention data collection activities, but the authors recognize the potential limitation that this poses to broad application of this methodology.

5. CONCLUSION

This research presents a methodological approach for testing and assessing tacit knowledge generation for design and construction education according to the Three Apprenticeships model. The specific methodology developed aims to provide a means for assessing tacit knowledge generation through the use of AR- and VR-intervened cyberlearning environments. The use of video and audio recordings of users in simulated environments translated into coded information allows researchers to objectively compare both student novices and practitioner experts to understand the similarities or differences in the behaviors related to tacit knowledge. This work contributes to the current body of knowledge by providing an approach that allows researchers to perform objective and empirical future work to test the applicability of using these technologies to facilitate experiences that would otherwise be difficult or impossible to replicate in a classroom setting.

If the methodology provided is leveraged by other researchers, it may provide an effective way for educators to develop a more comprehensive understanding of how the Three Apprenticeships learning theory supports design and construction education. This will not only advance the theoretical understanding of cyberlearning for the AEC domain, but it may also allow educators and practitioners to train new individuals to more rapidly develop the critical tacit knowledge that traditionally has required years to develop. This would provide a mechanism to address some of the pressing needs for skilled workforce in the AEC industry while supporting the personal development of the future industry leaders.

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COMPARING PERCEPTIONS OF OCCUPANT FLOW AND SPACE FUNCTIONALITY IN A VIRTUAL REALITY AND AN ACTUAL SPACE

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ABSTRACT: *As virtual reality (VR) transitions into an everyday tool, there is a need to study how the technology influences decisions during building design. This paper presents an approach to evaluate the reliability and benefits of adopting VR when assessing occupancy flow and space functionality issues. We present findings from a pilot study of 56 subjects. All are students with a background in Building Science. The subjects were guided through a VR walkthrough of the building space and completed a survey about flow and functionality. Then subjects related the value of VR versus the real space. Results indicate a strong positive response regarding the VR experience compared to the actual walkthrough. Other findings provide glimpses of where limitations exist within the VR experience. As an example, the survey results show evidence that subjects could detect differences in the quality of a design but did not perceive a significant difference in flow obstruction risks, when in reality, one corridor is prone to congestion. Most importantly the study provides direction for more comprehensive work. For instance, scaling of objects and the scene in the VR experience has also been identified as a key factor that may affect the decision-making process.*

KEYWORDS: *Virtual reality, BIM, Design Review , Space Functionality, Virtual Design and Construction*

1. Introduction

Visual aids are used to assist collaborative designs and communications in the Architecture, Engineering and Construction (AEC) Industry. As one of the most advanced visual aid technologies, Virtual Reality (VR) is gaining popularity in geometry creations and design reviews with its rapid development and integration with Building Information Modeling (BIM) (Xie et al, 2011).

1.1 Background

A VR experience is defined as "any in which the user is effectively immersed in a responsive virtual world" (Brooks, 1999). By interacting with virtual models in an immersed environment, users can understand the functionality of the space, detect potential design errors and therefore make better design decisions. VR also provides the opportunity to better understand the client’s design requirements, as virtual mock-ups can create a “better sense of realism” and “have been used to provide a better understanding of a project to end-users and stakeholders, resulting in improved communication” (Heydarian et al, 2015, p. 117).

With that said, comprehensive analysis of VR as a design tool and the extent of its benefit and limitations is still needed. For VR to be widely adopted as a legitimate design-assist tool, it will be likely for the industry to understand these aspects so it is not simply perceived as a gimmick to excite the owner.

1.2 Problem Statement

The work described in this paper is the beginning of a longer line of inquiry. In short, the broader research is targeted at better understanding how VR can help design reviews. Generally, one might assume after seeing a design in VR that it is definitely useful, but there is not much clarity as to how useful, when it is useful, and how good the VR needs to be in order to be useful.

This specific work evaluates perceptions within a VR experience and compares the VR experience to the real space. The assumption is made that seeing the actual space would be the best way to assess the design. Thus this study, in part, aims to see if the VR perceptions are comparable to the actual space. If the two experiences elicit similar perceptions, then the assumption that VR helps make good design decisions may be justified. It is preliminary and exploratory, but still some valuable insights were gained and will be reported upon.

The problem scope for this initial and preliminary work assumes an early schematic design without detailed lighting or materials and with lower Levels of Development (LOD) of the BIM model. The design review is specifically focused on space functionality and occupant flow issues rather than being a general purpose evaluation. The reviewers are meant to be people who have some familiarity with buildings but who are not necessarily adept at evaluating a design.

The specific questions being addressed are:

- To what degree do the subjects believe VR is going to be useful as a design review tool?
- Can subjects decipher design issues in the VR experience?

2. Literature Review

The literature review focuses on two general themes: conventional design review methods and on use of VR in design reviews.

2.1 Conventional Design Review Methods

Regular design reviews in design phases are important for successful project deliveries. According to the Design Council (2013, p.6), design review is "is an independent and impartial evaluation process in which a panel of experts on the built environment assess the design of a proposal". Designers often neglect the holistic view of a project and perceive design scopes with independent visualizations, which may lead to unanticipated continuous cycle of design revisions (Mujumdar & Maheswari, 2018). A good design review procedure will reduce the amount of rework and promote innovative constructions (Soibelman et al, 2003), as well as improving the communications between different disciplines in design and construction phases (CFM, 2009).

Design reviews are typically conducted by expert practitioners in design and development, including lead designers, contractors, clients, and external consultants, etc. (Design Council, 2013) Soibelman et al (2003) developed DrChecks (an online design review checking system) and Corporate Lessons Learned (CLL) system to capture / reuse corporate lessons learned and provide ongoing supports for design review processes. Ping et al (2011) presented a case study of Hong Kong MTR Corporation Projects and demonstrated a systematic design review process in an integrated multi-disciplinary design environment. A Mixed Reality (MR)-based design review prototype was proposed by Wang & Dunston (2013) to improve remote design review collaborations. In 2014, the Facilities Planning & Design Review (FPDR) team at The George Washington University introduced an integrated process made up of 11 teams to the university's design review process (FPDR, 2014).

2.2 Use of VR in Design Reviews

Information fragmentation and redundancies have been challenging the AEC Industry in recent years, and Building Information Modeling (BIM) is being widely adopted to foster collaborations and communications (Campbell, 2007). BIM acts as an integrated platform for team members to share and exchange project information through comprehensive object-oriented building models (Eastman et al 2011; Liu et al 2013). Based on BIM models, virtual models are built to integrate BIM and Virtual Reality (VR) technologies and are mainly implemented in pre-construction phases (Xie et al 2011). BIM-enriched Virtual Reality enhances optimization experiences and communications, and helps team members and stakeholders understand project plans and sequences (Dunston et al, 2007; Xie et al, 2011).

Kreutzberg (2015) conducted a study to explore non-specialist user experiences of viewing and navigating a BIM VR model with a head mounted display (HMD). The study indicated that real-time rendered BIM VR models can convey architectural space requirements to non-specialist users with reasonable good results. VR has been proved to be cost-effective and efficient to facilitate design reviews for health care projects. Dunston et al (2007) explored the use of VR to identify how design and physical elements impact processes and safety, and suggested the use of VR to create a database of quantitative and qualitative building elements to help decision-making processes in hospital design. VR was also used with Radio Frequency Identification (RFID) to automate data collections and help the AEC team with construction sequence optimization, site logistics and trade coordination (Xie et al, 2011). To solve the problem that VR headsets mostly provide a solo experience insteading of promoting collaborations in design reviews, Soluis developed a portable immersive system that offers interactive VR experiences for groups without the need for headsets (Innovate UK, 2016). In addition, game engines have been used to enhance VR experiences in design phases. A VR design review system was developed by Shiratuddin and Thabet (2003) using Unreal Tournament (UT) 3D Game Engine to enable real-time manipulation and modification of graphical information. A similar VR application, developed by Cárcamo et al (2017) using BIM models and Unity Game Engine, demonstrated the benefits of using VR in design review processes.

3. Methodology

The aim of the study is to investigate whether users' perceptions about a three-dimensional space in a VR environment are similar as their perceptions about the actual space. Gaining a better understanding of user perceptions in the VR environment will be useful to evaluate the efficacy and accuracy of using VR for design reviews.

The methodology section is organized into three parts and follows the research process outline in Figure 1. With the research problem already defined, the first section will highlight the model development and questionnaires. First, data collection process is identified. Then data analysis strategies are discussed. Lastly the VR experience development process is summarized. Figure 1 documents the research process for this study with particular focus on steps taken during the VR experience and space walkthrough. Make note that the team recognized the importance of a quick acclimation period for the subjects, since at the time of the study, most subjects had not used a VR headset before.

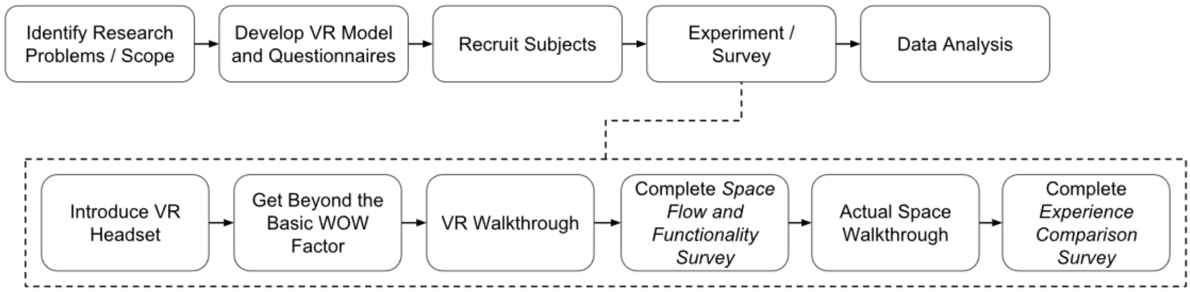

Fig. 1: Flow chart of research steps

3.1 Model Development

The VR experience takes place in a study lounge and occupant corridor found within Katherine Harper Hall on Appalachian State University's campus. The site was originally chosen due to some known issues that were impediments to occupant flow and overall functionality.

The space seen in Figure 2 is composed of two occupant flow corridors, a central workspace, entries to faculty office suites and restrooms, and a food prep station. The space being examined is roughly 560 square feet and is a heavily traffic space to the lower level of the building.

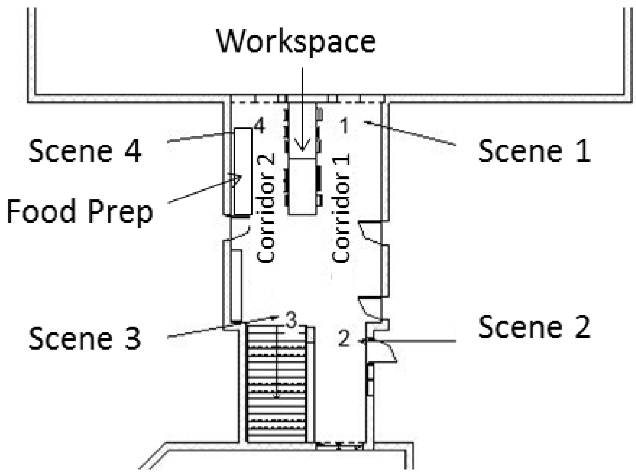

Fig. 2: Floorplan view of the building space used for the study

The consumer version of Oculus Rift (a VR headset) was used as the VR environment platform, and a space model was developed in Autodesk Revit 2017 and 3DS MAX and integrated with the headset through Unreal Game Engine 4. The Oculus Rift system has two motion sensors to track the user's locations and simulate the movements in the VR environment (Oculus, 2018).

Several methods of presenting the VR experience were considered. The primary decision was based on how the subjects will move about the space. The team decided free movement with a controller posed to many risks of user disorientation, dizziness, and nausea. A teleport scheme was chosen for periods where subjects were allowed to move around the space, but even this posed too much risk for distraction. The team settled on creating four scenes in the game engine. The locations are shown in Figure 2. Subjects can still move freely to the extent of the Oculus Rift tether. This scene approach, the team felt, would keep the user on task while experiencing a very novel technology.

To develop the VR environment, the team built a 3D model in Revit, exported it as an FBX file into 3DS MAX, updated some material and lighting elements, exported this updated version as a new FBX file, and finally loaded the file into the Unreal Engine platform. From there, the team wrote a few small scripts and created the different scenes of the study.

Figure 3 shows a view from the VR scene and the actual space. Only basic materials and lighting were incorporated to represent an early stage of the design. *Note*: At the time of this project, simplified methods that currently exist to bring a BIM model into the game engine were not available.

3.2 Questionnaire Description

Two surveys were developed for this study. Both surveys primarily used Likert scale rankings. A small selection of preliminary baseline questions were incorporated to ensure a consistent sample pool used in the assessment.

The *Flow and Functionality Survey* consists of two preliminary questions and ten design review questions. There were three sets of parallel questions related to the design of corridor 1 and 2. The themes of these question included:

- Overall design effectiveness for occupant flow and space functionality (Q3 and Q6);
- Specific assessment of occupant flow potential (Q4 and Q7); and
- Identification of obstructions as a problem (Q5 and Q8).

The other four questions asked about specific objectives to the space, including:

- Overall occupant flow capacity (Q9);
- Workspace design (Q10);
- Electrical outlet quantity placement (Q11); and
- Food prep station design and placement (Q12).

Note: question numbers are represented by Q#.

Fig. 3: Shows a comparison of the geometry between the VR experience and the actual space.

The *Experience Comparison Survey* was composed of four questions (as shown below). They asked about how the VR experience compared to the actual walkthrough of the space.

- *When using the virtual reality headset, I had a clear understanding of the space and expected uses of the space in corridor one.*
- *The virtual reality experience was just as good as walking through the real space for understanding potential problems.*
- *My perception of the functionality of the virtual space was the same as the real space.*
- *The virtual reality experience was confusing.*

The four questions were intended to be combined to provide an opportunity to make use of parametric statistics in quantifying the quality of the VR experience.

3.3 Data Collection Process

A sample of 56 participants was recruited from the students taking Building Science courses in the Department of Sustainable Technology and the Built Environment at Appalachian State University. Each subject was introduced to the VR headset with a script read by the investigator. After the introduction, subjects took a guided VR walk through based on the four scenes of the model and another script read by the investigator. After the VR walk through experience, subjects took the *Flow and Functionality Survey*. Upon completion of this survey, the subject was guided up to the actual space where they were guided through the same four scenes and script from the VR experience. Upon seeing the space in person, the subject then took the *Experience Comparison Survey*.

The 56 individual walkthroughs were delivered over the course of two weeks. Half way through the experiment, a protective face guard was incorporated into the VR headset.

3.4 Analysis Strategies

A combination of descriptive and comparative strategies was used to make initial assessments from the data. In general, when comparing data, the Mann-Whitney statistical test was employed.

3.4.1 Experience Comparison Survey

The primary purpose of the *Experience Comparison Survey* was to give subjects an opportunity to compare the VR walkthrough experience to the actual walkthrough experience. The Experience Survey was composed of four questions, all with a 7-point Likert scale.

With the data, basic descriptive statistics is primarily used to characterize the general consensus of the population. A summative assessment of the four Experience Survey questions allows for parametric analysis outputs describing the general feeling of the sampled population.

3.4.2 Flow and Functionality Survey

The *Flow and Functionality Survey* was the primary tool used to address how well subjects could decipher and interpret design issues from the VR experience. A few lines of inquiry will be presented from the survey. First, design quality is treated as an independent variable and Corridor 1 and 2 are treated as different groups. A series of parallel questions [Q3 with Q6; Q4 with Q7; Q5 with Q8] were used to understand what the subjects noticed. The Mann-Whitney statistical test was used to check if there was any statistical difference in the sample's perception of design issues between the two corridors.

Q11 in the survey was originally meant to assess if subjects could identify a known problem related to electrical outlet placement within the space, but before the project was conducted, the space was altered to resolve the issue. In response, question 11 still asks about the electrical outlets, but no outlets were shown in the actual VR experience. The question was then used to gauge how people might respond if there was nothing to actually respond to in the VR experience.

Q11 was then compared to other questions (Q10 and Q12) from the survey to assess if there was any statistical difference in how the subjects responded. The Kruskal-Wallis test was used for this assessment.

3.4.3 Headgear Treatments

An opportunity arose to explore whether a protective face guard altered a subject's response to the VR experience. This was possible because roughly half of the subjects (25 out of 56) participated by directly wearing the VR headset, while the other half put on a face guard before wearing the VR headset. The face guard is meant to prevent potential health risks due to direct contact between the headset and subjects' faces.

As such, a comparative test was conducted to assess whether there was any statistical difference between treatment 1 and treatment 2. Again, Mann-Whitney tests were performed on a subset of questions from both surveys to see if there was any variation between the two treatments. Subjects 1-25 and 30-55 composed the pre and post treatment samples respectively.

4. Results and Analysis

The results and analysis will be broken into three sections. The Experience Comparison survey, Flow and Functionality Survey and the headgear treatments will be discussed separately.

4.1 Experience Comparison Survey

After subjects conducted both the virtual and physical walkthrough of the space, they were asked to compare their experiences. Figure 4 highlight how the subjects generally felt very positively that the VR experience was equivalent. Using a summative Likert scale, the results strongly indicate that the subjects believed the VR experience was very similar to the real walkthrough with over 88% indicating either agree or strongly agree.

4.2 Flow and Functionality Survey

The results from the *Flow and Functionality Survey* begin to shed light on what people experience in the VR

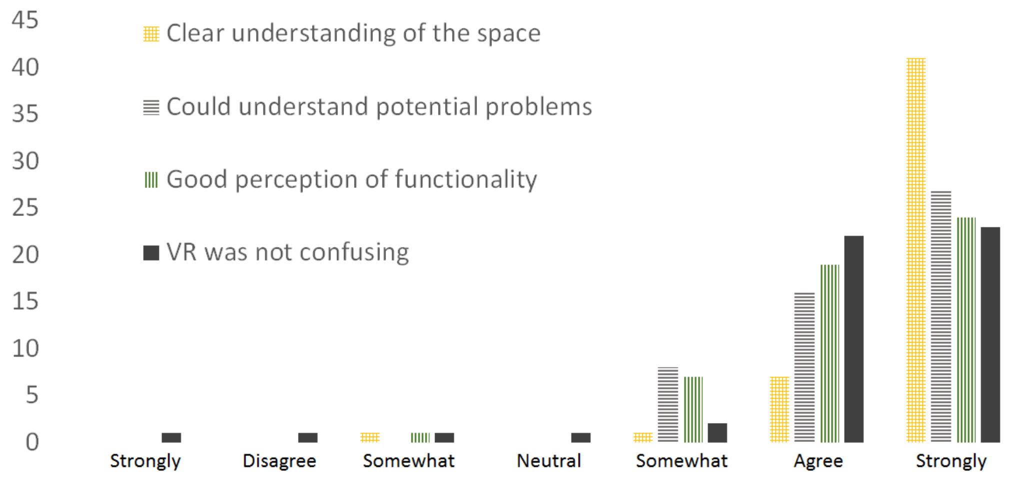

Fig. 4: Adjusted results from the experience survey

setting and if they can distinguish issues or not. These result are preliminary with some significant limitations that will be discussed, but they should still be useful in guiding future work.

4.2.1 Comparison of Corridor Design Issues

Results shown in Figure 5, to a modest degree, indicate that the subjects felt Corridor 1 was better than Corridor 2 in regards to occupant flow. Questions relating to overall design effectiveness (Q3 and Q6) and design for occupant flow (Q4 and Q7) both indicated a significant difference with p-values of 0.00013 and 0.0054 respectively. With that said, Q5 and Q8 asked if the corridors were prone to obstructions, and in this case, responses were not significantly different with a p-value of 0.60.

Note: Q6 had to be normalized from a 5 point to a 7 point scale, as such those result should only be seen as preliminary indicators. These results may suggest that subjects can detect a difference in design quality. Based on the obstructions question though, perhaps limitations exist when it comes to pinpointing the problem.

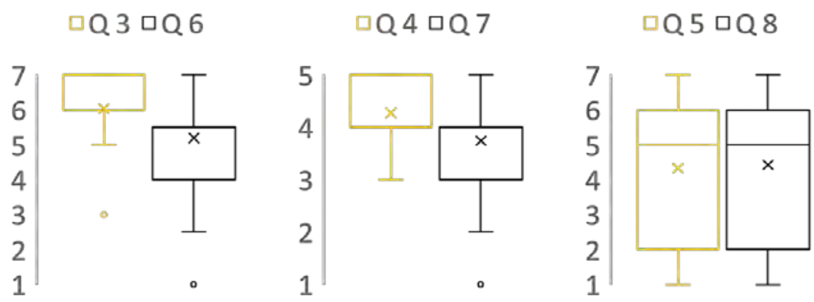

Fig 5: These box plots highlight the variation in response regarding the two walking corridors in the study. Q3, Q4, and Q5 were in regards to Corridor 1. Q6, Q7, and Q8 were in regards to Corridor 2.

4.2.2 Electrical Outlet Responses and Other Design Elements

As was previously indicated, there were no electrical outlets shown in the VR experience, but the subjects still indicated that the outlet position and quantity were sufficient. Figure 6 show the distribution from this question. A few possible reasons for this response profile include:

- Confusion about the question;
- Responding to the novelty of the VR experience; and/or
- Leveraging prior experience with the space.

When comparing this response profile to Q10 and Q12, there is no statistical difference in how the sample responded to the different questions, resulting in a p-value of 0.423. Additional thoughts on this observation are offered in the Discussion and Conclusions section.

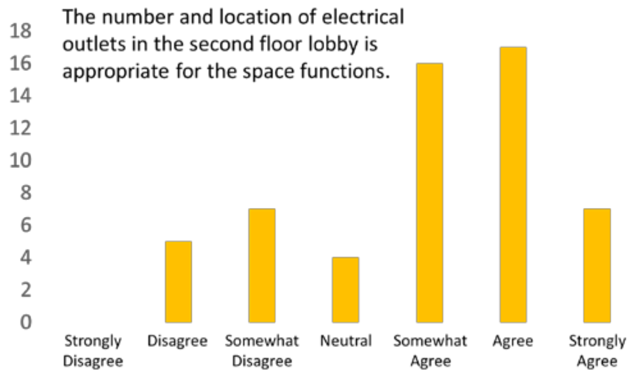

Fig. 6: Responses from Q11 when no electrical outlets were present

4.3 Headgear Treatments

Face guards were used half way through the project, offering an opportunity to compare responses between the two treatments. Results indicate that there was no significant difference in how subjects responded to the VR experience or in their comparison between the VR vs real walkthrough. No result had a p-value lower than 0.40 based on the two treatments of the VR experience.

5. Discussion and Conclusions

This work is preliminary and primarily meant to shed light on the development of more comprehensive studies that will contribute toward our understanding of how and to what extent VR design reviews can improve building design decisions. The hope is that the technology will result in users coming to the same conclusions that they would come to by actually walking through and interacting with the eventual space.

5.1 Limitations

As this study was a small-scale pilot project, there were some limitations. Due to time and resources, the breadth of the subject pool was restricted to only students taking classes from the Building Science program at Appalachian State University. This limits the generality of the conclusions, but is useful for defining qualities about this specific population, which might be of value for future work.

The survey instrument did not go through a thorough process of validating questions, and was intentionally kept to less than 20 questions to help the investigators carry out the project for the 56 subjects. As such, conclusions cannot be made from all of the questions.

The space selected for the VR experience was chosen in large part because there were very significant issues with electrical cords being draped in the corridors for computers in the study area. Between the selection of this space and when the survey was delivered, electricity was rerun on the workspace table, eliminating the issue. This altered how the electrical outlet question was used.

One issue that restricts the conclusions to the flow and functionality survey is that all of the subjects had some prior familiarity with the space chosen for the VR experience. In future work, it will be important to select subjects that do not have this prior knowledge and potential bias. For the current study, it is impossible to know if the subjects were responding purely to the VR experience or if their prior knowledge influenced their responses to the *Flow and Functionality Survey*.

On the other hand, this prior knowledge may strengthen the *Experience Comparison Survey* because the subjects knew what the space does look like, and one could reason that the subjects would have noticed any significant issues.

5.2 Conclusions and Future Work

For at least while VR is new to its users, the results from the protective mask analysis provide some level of assurance that it will not be a negative factor when delivering future studies in the VR environment. With that said, the newness of the tech may allow subjects to forgive the inconvenience of a protective mask, but perhaps in the future, this could become a distraction.

The VR experience had very real issues that made it different from the actual space. For example, scaling of certain objects like the microwave was not correct. Despite these inconsistencies, the results overwhelmingly suggest that the subjects felt the VR experience was a strong and useful match to the actual walkthrough.

A few questions arise:

- To what degree does scale matter for the overall scene and for objects within the scene in the context of a design review?
- Can people draw conclusions that are the same as being in the real space if there are scaling issues in the VR experience?
- What are the scaling tolerance levels for VR scene developers when making an experience to assist in design reviews?

Current and future work look to provide more evidence into these elements of VR for design reviews.

6. Acknowledgements

The authors would like to recognize Appalachian State's University Research Council for providing the seed funding for this project. Additionally, special recognition goes out to Abraham Somers and Landon Coleman for developing the VR scenes and conducting the survey procedures. Chris Schoonover provided valuable advice for developing the VR scenes and writing scripts.

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CONSTRUCTION OF POINT CLOUD DATA FOR ROAD MAINTENANCE

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ABSTRACT: *In road maintenance, it is necessary to construct an environment that manages three-dimensional data and maintenance information. A road management system comprises functions for planning, design, construction, maintenance, and rehabilitation of roads. A fundamental requirement of such a system is the ability to support the modeling and management of design and construction information, and to enable the exchange of such information among different project disciplines in an effective and efficient manner.*

The primary objective of this research project is to support road maintenance work using three-dimensional point cloud data by combining terrestrial laser scanning (TLS) and unmanned aerial vehicles with photogrammetry. TLS and photogrammetry technologies are used to survey road structures. Three-dimensional data for the Shiraito Highland Way in Japan are constructed using point cloud data generated by TLS. Shiraito Highland Way is approximately 10 km in length, and its elevation varies between 1000 m and 1400 m. The measuring range of TLS on a road varies from approximately 10 m to 100 m. Point cloud data are combined using coordinate points. In addition, the data are used for road maintenance, taking into consideration data size and accuracy. Road maintenance information can be referenced at any three-dimensional point in the point cloud data. Coordinates of the three-dimensional data are constructed on the basis of the structure from motion (SfM) range-imaging technique of photogrammetry using video camera data. PhotoScan Professional is used for SfM. This paper evaluates the accuracy of the point cloud data of laser scanning and photogrammetry for road maintenance.

KEYWORDS: *Point Cloud Data, Terrestrial Laser Scanning, Unmanned Aerial Vehicle, Road Maintenance*

1. INTRODUCTION

Roads must be safe and maintained in good condition. Maintenance management is an essential operation that must be carried out effectively for maintaining, repairing, and rehabilitating roads. If large-scale damage occurs to a road in an urban area and it cannot be used, many aspects of life may be affected. Thus, it is important to protect roads from large-scale damage and to carry out road maintenance in order to maintain services for the public. In addition, it is necessary to accumulate information produced during the entire life cycle of a road in order to analyze problems and solutions within a temporal sequence and to maintain roads strategically and effectively. In Japan, much road infrastructure was built over fifty years ago. Due to progressive deterioration in road infrastructure, ensuring proper maintenance of overall facilities to avoid potential problems is currently an important issue. In particular, in order to avoid or reduce substantial loss, deal with an emergency, prevent damage, perform emergency disaster control, and carry out disaster recovery, road administrators must maintain roads more efficiently. In current maintenance work, road administration facilities are represented on a two-dimensional map, which is not suitable for pothole repair, inspection, or annual overhaul. Locating and analyzing a position can be difficult when using such a map.

In road maintenance, it is necessary to construct an environment that manages three-dimensional data and maintenance information. A road management system comprises functions for planning, design, construction, maintenance, and rehabilitation of roads. A fundamental requirement of such a system is the ability to support the modeling and management of design and construction information, and to enable the exchange of such information among different project disciplines in an effective and efficient manner.

Engineers should be able to use three-dimensional data not only for virtually reviewing the design of a facility, but also for analyzing building operations and performance. Three-dimensional data tend to be applied to a particular phase of a construction project. Using three-dimensional data will thus improve the efficiency of operations and maintenance.

The primary objective of this research project is to propose a road maintenance framework using three-dimensional point cloud data. A point cloud is a collection of data points defined by a given coordinate system. In a three-dimensional coordinate system, for example, a point cloud may define the shape of some real or created physical system. Terrestrial laser scanning (TLS) (Tanaka, 2016a; Tanaka, 2016b; Tien, 2018) and photogrammetry technologies (Vosselman,2000) are used to survey road structures. In road maintenance work, a mobile mapping system (MMS) is used, which generates point cloud data. In this research project, TLS and photogrammetry by an unmanned aerial vehicle (UAV) are used. Three-dimensional data for the Shiraito Highland Way in Japan are constructed using point cloud data generated by TLS. Shiraito Highland Way is approximately 10 km in length, and its elevation varies between 1000 m and 1400 m. The measuring range of TLS on a road varies from approximately 10 m to 100 m. Point cloud data are combined using coordinate points. In addition, the data are used for road maintenance, taking into consideration data size and accuracy. Road maintenance information can be referenced at any three-dimensional point in the point cloud data. Coordinates of the three-dimensional data are constructed on the basis of the Structure from Motion (SfM) range-imaging technique of photogrammetry using video camera data. PhotoScan Professional (Agisoft) is used for SfM. This paper evaluates the accuracy of the usage of point cloud data by laser scanning and photogrammetry for road maintenance. For example, this method can be used to check potholes and surface irregularities on pavement that can be easily and quickly confirmed by management.

2. USAGE OF TERRESTRIAL LASER SCANNER AND PHOTOGRAMMETRY OF UAV CAMERA

There are a number of survey methods for constructing three-dimensional data using laser imaging detection and ranging (Lidar; laser profiler), laser-based photogrammetry, MMS, TLS, and photogrammetry using a camera by UAV. Combining these survey methods according to site situations and structures enables surveys of civil infrastructure and construction of three-dimensional point cloud data. It is necessary to understand the characteristics and specifications of the specific measurement instruments and choose suitable point cloud data for a use case for a road maintenance site. In this research project, TLS and UAV-based photogrammetry are used.

Table 1. Characteristics of point cloud data by measurement instrument.

	TLS	UAV photogrammetry
Survey Cost (time)	Expensive, but portable	Less expensive and small size, but have to consider weather and wind speeds
Measurement range	Narrow area	Wide area
Visible Area	Visible area from point of TLS setting	UAV flight area
Invisible Area	Superior surface cannot be measured	Overhang area cannot be measured
Accuracy	A few millimeter	Depends on SfM software
Density of points	Extremely high	High
Distribution	Non-uniform. Distribution is higher for area close to an object of surveying	Depends on SfM software
Angle	Between 10 to 90 degrees	Approximately 90 degrees
Measurement of Edge	Exactly	Potentially inaccurate
Measurement of Surface	Including noise	Including noise
Measurement of Structure	Side surface can be measured	All surfaces can be measured
Noise due to Structure, Vegetation, and Mobility	Including noise	Including noise
Reflected Data	*xyz* coordinates value of local coordinate system, reflected intensity, and luminance value	*xyz* coordinates value of plane rectangular coordinate system Using reference point and luminance value

(1) Usage of TLS

A terrestrial laser scanner is set on a ground surface, and the laser component illuminates objects. A laser beam is reflected, and a return-beam detection device records two-way travel time, calculating the distance between the scanner and the object. As a result, point cloud data for an observed object are generated. When using TLS, it is important to choose a location where the instrument can be set up easily. It is usually advantageous to overlook and survey the location when setting up the instrument.

(2) UAV platform camera

Point cloud data are generated by aerial photogrammetry using photographs or a video-output camera on a UAV. The data are generated using an SfM process (Kubota, 2016; Kubota, 2017; Tanaka, 2017).

The characteristics of TLS and UAV photogrammetry are represented in Table 1. They are analyzed with respect to time cost, measurement range, visible area, invisible area, accuracy, density, distribution, angle, measurement of edge, ground, and structure, noise, and enabled data.

3. CONSIDERATION OF INFORMATION SYSTEM FOR ROAD MAINTENANCE

An information system for road maintenance is proposed in this research project. This chapter discusses the information system, which uses point cloud data based on the definition of an information system.

By definition, an information system collects, processes, transfers, and utilizes information in its own domain. Fig. 1 depicts the definition of a road maintenance information system using point cloud data.

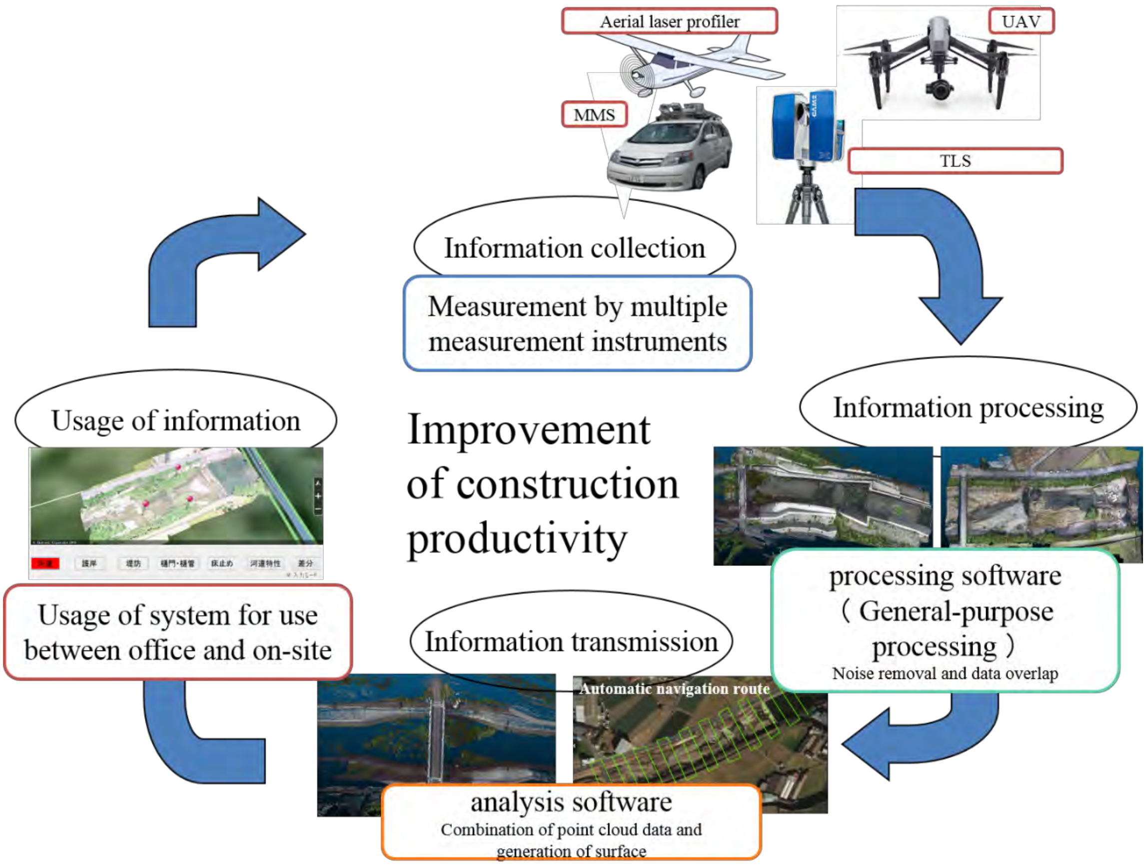

Fig. 1: Definition of road maintenance system.

(1) Information collection

Point cloud data for road infrastructure are collected using TLS and UAV-based photogrammetry. In addition, maintenance and operation data, such as for inspection, rehabilitation, and repair, are collected on-site for the system.

(2) Information processing

Point cloud data generated by TLS contain noise data concerning trees and vegetation on a road. In information processing, such objects should be removed in order to represent road structures accurately. TLS's survey range is confined to the visible range and the scan range of the scanner; therefore, it contains blind spots that are not represented by the point cloud data cloud. Accordingly, surveyors need to move the scanner to multiple locations across a number of points in time.

UAVs can acquire photographs or videos in-flight. Such visual records are used for SfM software and translated point cloud data. In addition, the point cloud data are colorized for visualization.

(3) Information transmission

TLS and UAV-based photogrammetry each have distinct characteristics with respect to survey time cost, scan range, and accuracy. Wide area and high precision point cloud data are generated by combining each set of data units. In addition, in this process, structural members and surface data, such as a triangulated irregular network, are extracted and generated in accordance with the purpose of usage. Furthermore, it is also possible to compare two different temporal data units for analysis.

(4) Usage of information

In this research project, instead of a surface model, point cloud data are used for road maintenance. A road maintenance information system is proposed, which has functions for detecting cracks and superimposing photographs based on point cloud data. In addition, a function is needed for reflecting inspection and repair events that have been represented on a two-dimensional map displayed on a smart device onto three-dimensional point cloud data on-site.

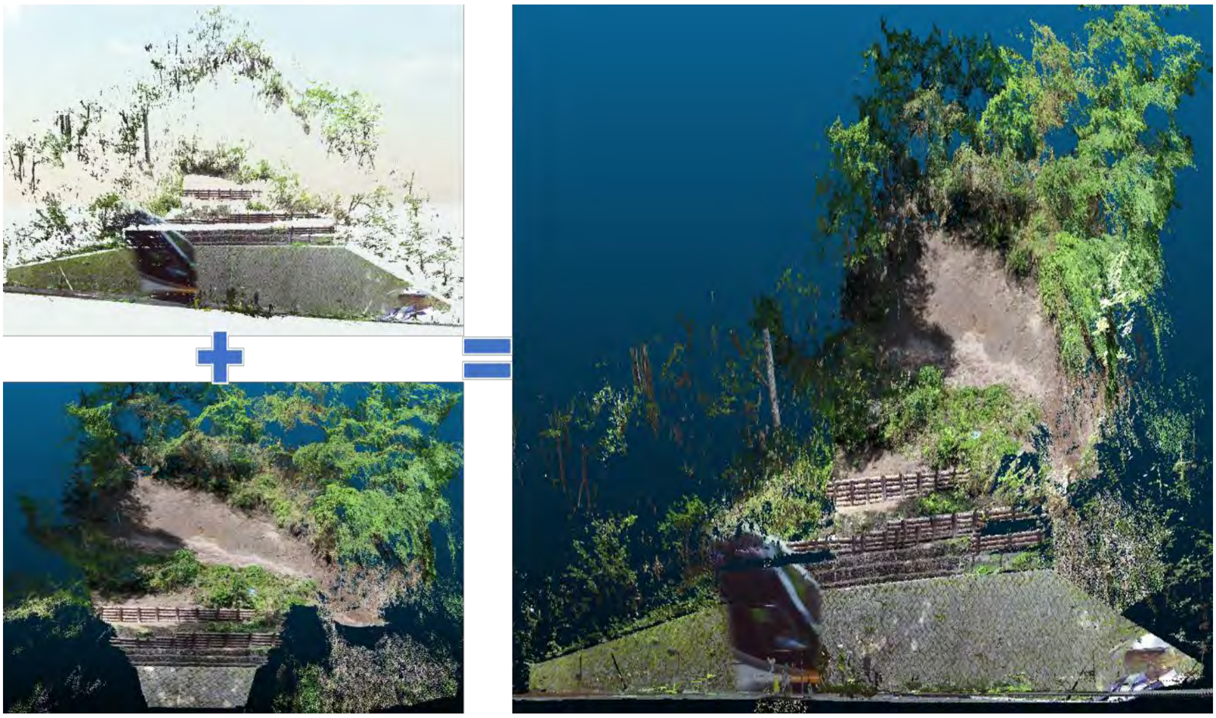

Fig. 2: Fusion of three-dimensional point cloud data acquired by TLS and UAV photogrammetry on slope.

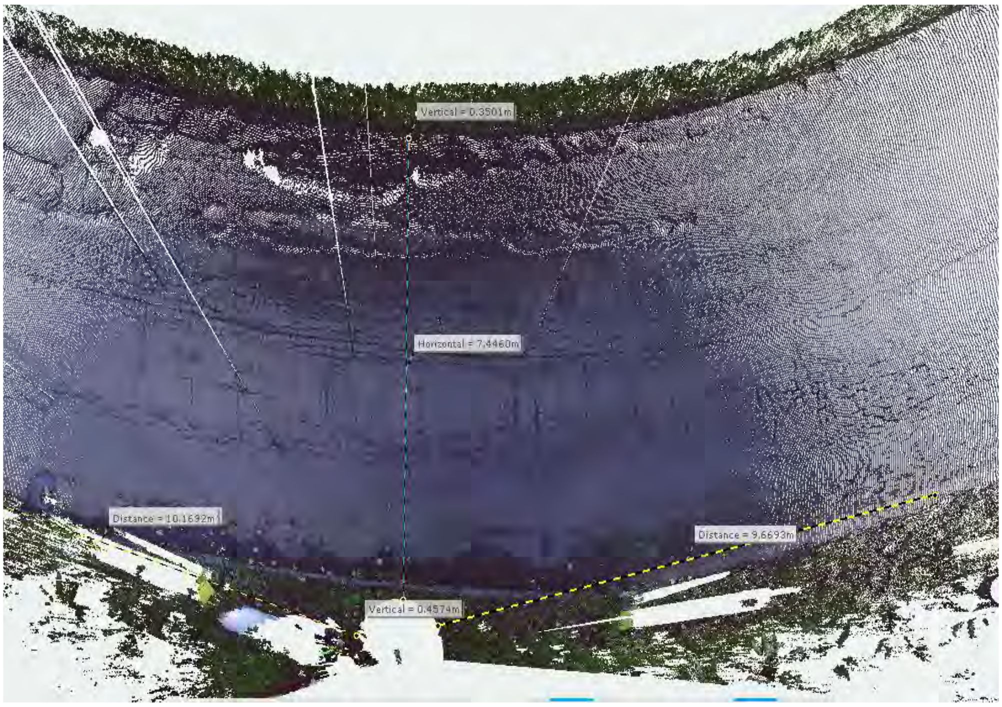

Fig. 3: Point group data on road surface.

4. SURVEY AND GENERATION OF POINT CLOUD DATA

TLS and UAV photogrammetry technologies are used to survey and generate road structures. Three-dimensional point cloud data for the Shiraito Highland Way in Karuizawa Village, Kitasaku County, Nagano Prefecture, Japan, are used.

In this paper, usage of point cloud data for road maintenance is proposed. If a road administrator possesses point cloud data for a MMS, the data are used for road maintenance. Usage of TLS is more efficient for surveying narrow areas to check for cracks and holes in the pavement of a road. In the case of a landslide on the side of a road, using TLS to survey the upside of a slope can be difficult. The reason is that TLS has limitations for measuring the upside of a landform or slope occluded by such objects as trees or other vegetation and by the angle of incidence of the scanner. Therefore, the upside of a slope or a landform is surveyed using a camera mounted on a UAV. Point cloud data for such objects are constructed using photographs employing SfM technology. Fig. 2 depicts SfM data and laser scanning data for a slope. The point cloud data are constructed by combining SfM data with laser scanning data corresponding to 5000 random points between those data, as depicted in Fig. 2.

According to the results of an on-site survey, limitations have been discovered. The first limitation is based on site circumstances. Passengers and cars pass by on the road being surveyed during measurement. There are few berms and little space for setting a TLS, given the high slope on the Shiraito Highland Way. In addition, locations where instruments can be set are limited. Therefore, it is difficult to perform a number of measurements for acquiring point cloud data. It is necessary to pay attention to surveyors and instruments, and to determine measurement range and accuracy for the set of circumstances.

The second limitation is measurement range, given the specifications of instrument functionality for pavement surveys. According to experimental results, high-density measurement range is restricted to within an approximately 10-m radius, as depicted in Fig. 3. It is necessary to perform a number of plural measurements for surveying wide-range pavement data.

In the road maintenance system described in Chapter 3, the inspection result and repair information can be linked with three-dimensional point cloud data and displayed, stored, and referenced. It is easy to detect road cracks and spots in need of repair, as depicted in Fig. 3. In addition, it is possible to determine changes in shape and damage using temporal management of point cloud data. Figs. 4 and 5 depict examples of data fusion of TLS and SfM data acquired by a UAV using the same method as described above.

Fig. 4: Data fusion of TLS and UAV in road and river space.

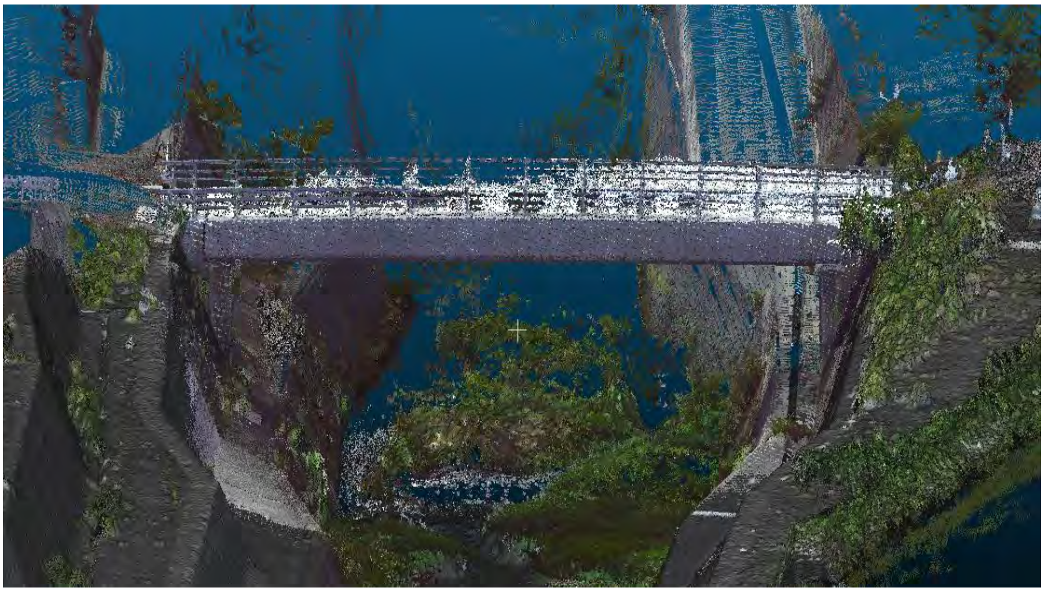

Fig. 5: Data fusion of TLS and UAV on a bridge.

5. MEASUREMENT AND ACCURACY EVALUATION OF BRIDGES

To construct the three-dimensional data for the upper and lower part of bridges, UAV aerial photogrammetry and TLS measurements were performed for the Kashii River (Izumisano City) and Kimyuji River (Sennan City) in the south of Osaka Prefecture in November 2017. During the UAV aerial photogrammetry, the UAV flew at an altitude of 30 m, the movie was converted into pictures, and SfM processing was performed with PhotoScan to construct the three-dimensional data. The accuracy of SfM data in the river space of the Kashii River was evaluated by assigning absolute coordinates from the global navigation satellite system survey to the three target points as reference points, and four verification points were used. The root mean square error was 0.272 m in the *xy* direction and 0.261 m in the *z* direction (Table 2). Because the wind was strong at the time of the measurements, the fact that the aircraft and the camera were not stable affected the accuracy. For the TLS, we targeted the Megata Bridge in Kashigawa River and the Warazuhata Bridge in Kinyuji River, the feature points of multiple-point group data measured from six places bridges from five places were matched, and thinning processing was applied to obtain one data point.

Table 2. Accuracy verification results for SfM data.

Accuracy verification result of SfM data		
Inaccuracy(m)	*xy* Direction	*z* Direction
Verification points	0.199	0.349
Verification points	0.232	0.082
Verification points	0.414	0.211
Verification points	0.185	0.120
Average	0.258	0.191
Root mean square error	0.272	0.216

The three-dimensional point cloud data obtained by SfM are measured from the air, and SfM data and TLS data are combined because three-dimensional data for bridge sides and lower works cannot be constructed. The accuracy of TLS data is higher than that of SfM data, and therefore duplicate SfM data are deleted before combining. According to Cloud Compare, we can combine 50,000 characteristic points for each type of data with reference to each other type of data and describe the side and bottom works of bridges that could not be acquired by UAV aerial photogrammetry as three-dimensional data. To evaluate the accuracy of three-dimensional data, we compare the point cloud data of the Warazuhata Bridge with its design conditions. The bridge length is 22.20 m and its width is 4.00 m, whereas the bridge length from the point cloud data is 22.212 m and its width is 4.019 m. Therefore, the inaccuracy for the bridge is an effective length of 12 mm and an effective width of 19 mm (Fig. 6) and the three-dimensional point cloud data describes the structure of the bridge with high accuracy.

The three-dimensional point cloud data for the road pavement surface and the bridge could be used to develop a road maintenance management system that accumulates data and refers to the inspection results and repair information in three dimensions.

6. CONCLUSION

In this research project, point cloud data for road infrastructure have been surveyed using TLS and UAV photogrammetry for road maintenance. For on-site surveying, the limitations of these methods have been clarified. The first limitation is based on site circumstances. Passengers and cars use the road being surveyed during measurements. There are few berms and little space for setting a TLS, given the high slope on the road. In addition, locations where instruments can be placed are limited. Therefore, it is difficult to perform the number of measurements necessary for acquiring point cloud data. The surveyors, instruments, and measurement range and accuracy of the conditions should be considered. The second limitation is the measurement range, given the specifications of the instrument functionality for pavement surveys. The experimental results indicate that the high-density measurement range is restricted to within an approximately 10-m radius. Thus, multiple measurements must be taken for surveying wide-range pavement data. Based on these limitations, in this work, the upside of a slope or a landform is surveyed using a camera mounted on a UAV. Point cloud data for these objects are constructed using photographs with SfM technology. SfM data and laser scanning data are used for slopes. The point cloud data are constructed by combining SfM data with laser scanning data corresponding to 5000 random points between these data.

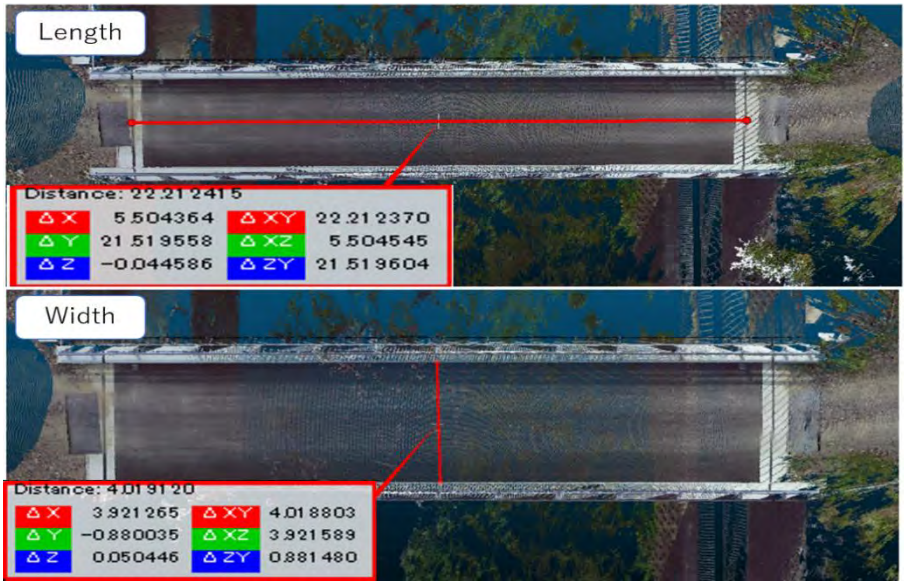

Fig. 6: Length and width based on the combined point cloud data for Warazuhata Bridge.

A road maintenance system was considered based on the definitions within an information system. The road maintenance system can link inspection results and recondition information with the point cloud data for display, storage, and reference, facilitating the management of road cracks and areas for repair. In future work, point cloud data will be used to identify changes in the shape and condition of damage through spatial and temporal management (Fig. 7).

Fig. 7: Repair information linked with three-dimensional point cloud data.

7. ACKNOWLEDGMENTS

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INFORMATION DELIVERY MANUAL (IDM) CONFIGURATOR: PREVIOUS EFFORTS AND FUTURE WORK

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ABSTRACT: *This study reviews a variety of previous efforts to support the development of the information delivery manual (IDM) configurator to satisfy a digital construction environment. Due to requirements for submitting a BIM execution plan (BEP), including employer's information requirements (EIRs) by the UK government, the need to develop an updated IDM and model view definition (MVD) is increasing. However, currently developed IDMs and MVDs are hard to share and modify for reuse. Moreover, neither a system nor a standard exists to globally share and manage IDMs and MVDs. In this paper, this study reviews significant previous efforts that can potentially be part of an IDM configurator or a global IDM server. These efforts can be categorized into three groups: (1) software development, (2) IDM framework development, and (3) MVD development. To conclude, we identify current challenges and future work to fill the gaps between the present status and goals of the IDM configurator. The existing efforts discussed in this paper will serve as a fundamental basis for realizing the IDM configurator.*

KEYWORDS: *Information delivery manual (IDM), employer's information requirements (EIRs), BIM execution plan (BEP), model view definition (MVD)*

1. INTRODUCTION

As more and more regions mandate building information modeling (BIM), information requirements at each stage of a project are becoming more specific, and criteria for managing projects are also becoming more stringent. Most prominently, the UK began requiring that all government procurement contracts be certified as BIM Level 2 from April 2016. The British Standards Institution (BSI) describes BIM Level 2 as a collaborative work environment based on a common data environment with fully exchangeable BIM models (BSI, 2010, BSI, 2007). To establish the digital construction platform, both employers and contractors must demonstrate their information requirements and corresponding BIM capabilities on the basis of the international standard. BSI produced a series of standards to support the adoption of BIM Level 2, such as BS 1192-2007, which describes the collaborative production of architectural, engineering, and construction information (BSI, 2007). At the early stage of BIM projects, the most significant submissions are the specification of information requirements and the entire plan for BIM implementation to meet the project's goals. The information requirements are called the employer's information requirements (EIRs).

EIR is one of the key documents defining what employers want to know as delivered by a project team. The PAS1192-2:2013, a standard for information management at the capital and delivery phase of the projects, defines what information should be contained in the EIRs (BSI, 2013). The structure of the EIRs consists of three parts: technical, management, and commercial aspects of the required information. The information includes, for example, software specifications, exchange format, level of detail for the BIM model, responsibility and security of each task and roles, scheduling and procurement documents, and the overall content of project deliverables. During a project, various decision-making processes occur at each stage, and the employer can make reasonable decisions based on a clear set of information provided by verified documents. This is one of the most important roles of the information provided by the EIRs.

As a response to the EIRs, the project team and relevant bidders must supply a BIM execution plan (BEP) in accordance with the requirements. The BEP is developed in both pre- and post- types. The pre-BEP is made by prospective suppliers to demonstrate the possibilities of their proposal at the tender stage, while the post-BEP is made by the winning supplier to confirm their real project plan and capabilities. While the pre-contract BEP is a relatively simple document showing the project implementation plan and feasibility of the project's goal, the post-contract BEP should describe from a detailed perspective the specific plans and strategies for delivering the required EIRs. The post-BEP deals with, for example, roles and responsibilities, a master information delivery plan (MIDP) specifying relevant protocols and procedures, and software and exchange formats for supporting technical aspects. The core contents of the BEP should be developed based on the EIRs and should include all of the agreed-upon elements as outlined in the EIRs and contract documents. Considering the interaction between the EIRs and the BEP, the most important strategy for satisfying the information exchange requirements at each stage of the project is to define who the information is for, how it will be delivered, and what it will contain.

Because of the close relationship between the EIRs and the BEP, it is necessary to define clear exchange requirements for corresponding information throughout logically connected business processes. Most employers, however, cannot specifically define what they need to know or how they can successfully achieve their goals using the BIM model during their project. Even if the employer submits the EIRs to the project team, it is still hard to publish a set of documents for the BEP because the project-planning teams have neither a detailed plan nor a data exchange process. Although great efforts have been made to develop BIM authoring tools to support BIM modeling, there has been less investment in developing BIM execution processes.

The information delivery manual (IDM) was proposed to establish a methodology for capturing a business process and information exchange requirement across the entire life-cycle of a built asset (Wix, 2005). Nevertheless, most IDMs developed since first being proposed in 2005 are still difficult to search and use. For instance, over 100 previously developed IDMs and MVDs are posted on the buildingSMART website; however, almost all of them are invalid for practical use (Karlshøj, 2011). Current IDMs and MVDs cannot be fully developed, shared, or reused for several reasons:

- The IDM development process is a complex and laborious method that demands substantial time and cost. For instance, an IDM requires abundant metadata, such as task type, descriptions, and a change log, making it too difficult to input all the information in each step of the development process.
- There is no standard format for exchanging information between an IDM and an MVD. To share and reuse existing IDMs and MVDs, an information exchange standard data format, such as an eXtensible markup language (XML) schema that defines IDM information systematically, is required.
- The current tools have limitations regarding the integrated development process, from digitally mapping information between the EIRs and the BEP to automated quality checks for the IDM and the MVD. Also, there is no official criteria or approved process for quality assurance.
- It is difficult to share and reuse the developed IDMs and MVDs because of a lack of physical shared servers and the absence of an administrator.

Because of these problems, project participants repeat potentially the same laborious and complicated IDM development process followed in past projects. Thus, an additional data standard is needed for exchanging information, as well as some tools for making IDM development easier and simpler using existing IDMs and MVDs.

To resolve these issues, Lee et al. (2016) proposed the IDM configurator in 2016. The IDM Configurator is an integrated framework, which includes a platform, a set of tools, and international standards, to enable users to define, share, and reuse EIRs, BEPs, IDMs, and MVDs. Many individual efforts that can be potentially become a component of the IDM configurator have been made even before the IDM configurator was proposed. This paper introduces the IDM configurator, reviews the previous efforts related to the IDM configurator, and analyzes the obstacles to realizing it by reviewing previous efforts related to IDM development.

The next section introduces the goals and needs of the IDM configurator and addresses the expected benefits. Section 3 reviews existing efforts to develop the IDM configurator in terms of three subjects. Section 4 concludes by discussing obstacles to meeting the goals and the future direction of the IDM configurator.

2. INTRODUCTION TO THE IDM CONFIGURATOR

2.1 Goals and Needs of the IDM Configurator

The goal of the IDM configurator is to provide an integrated environment that links various individual software applications to enable users to develop, share, and reuse BEPs, EIRs, IDMs, and MVDs. Fig.1 shows the framework of the IDM configurator. Once an employer specifies and distributes EIRs to potential project teams as part of an Invitation-To-Bidding (ITB) package, the project teams submit a BEP report and Master and Task Information Plans as a response to the ITB. An IDM report specified by ISO 29481 can be used to define EIRs and Master and Task Information Plans.

An IDM describes the logical procedure for and a detailed description of the information that should be exchanged between participants at a specific point in the project. The IDM has become an international standard, ISO 29481(ISO, 2010), with the second edition published in 2016 (ISO, 2016). According to the revision of ISO 29481-1:2016, an IDM consists of process maps (PMs), exchange requirements (ERs), and model view definitions (MVDs). An ER is a document that specifies which information is requested and exchanged, which is the same concept as in the EIRs. In general, PMs and ERs do not contain IFC information but instead define the process and scope of data exchange as a human-readable document. Each ER can be linked to a subset of the industry foundation classes (IFC) schema. A collection of the IFC subsets for an IDM is called MVD. The MVD is usually defined by EXPRESS or mvdXML.

This EIR, BEP, IDM, and MVD specification process is very complex and time consuming. Fortunately, the same ERs and MVDs specified for an IDM can be reused in other IDMs. Also many elements in an BEP overlap with those in the other BEPs. Nevertheless, as described in the introduction section, lack of standards and a platform to share EIRs, BEPs, IDMs, and MVDs makes it very difficult to reuse them. As a result, the IDM/MVD development speed is very slow.

The ultimate goals of the IDM configurator are:

- to develop an international standard data schema to integrate the IDM and the MVD and to support the information exchange of IDMs in the global IDM server.
- to establish a global platform (called the IDM server) based on the above standard wherein all existing IDMs and MVDs can be stored, shared, and reused for other IDM/MVD/BEP/EIR development.

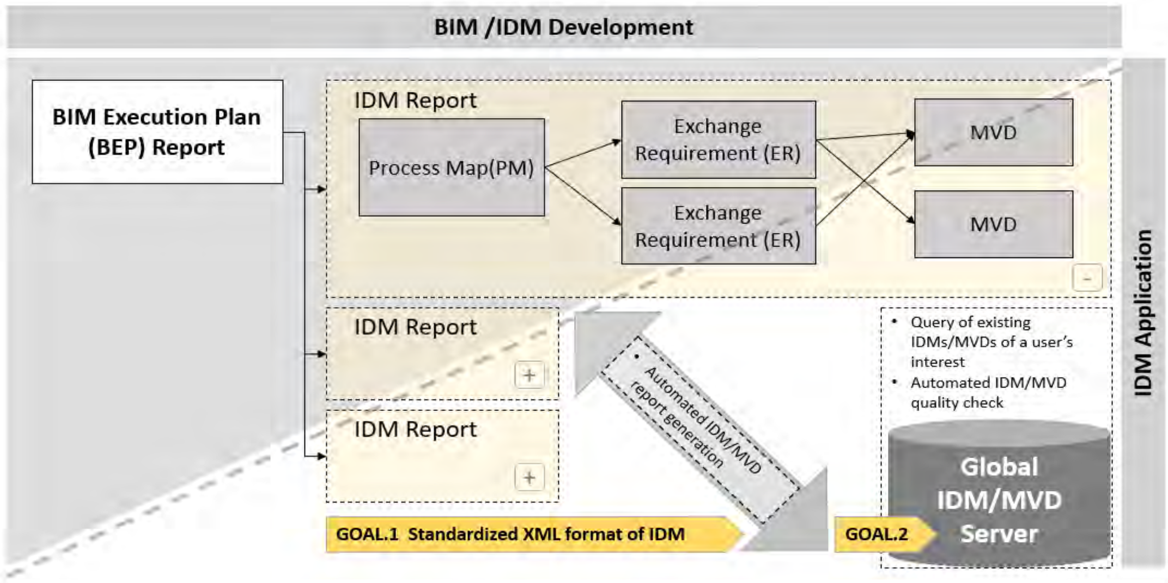

Fig. 1. The IDM configurator framework.

2.2 Benefits

If the above goals are achieved, every new IDM document can be published in a standard format and stored and shared in the global IDM server and the tracking and management of the relationships between PMs, ERs, and MVDs will become possible. If the new IDM was developed and saved using the standard format, tentatively named idmXML, then it will be easier to exchange and share the information among data sources.

Another benefit is the development of new IDMs and MVDs by reusing and modifying existing documents. Anyone wishing to develop a new IDM and MVD can search the existing references and reuse or customize them for their own project. Users of the IDM configurator can find an IDM specification that closely matches the set of information from their own projects. Moreover, the PMs and ERs can be modified and reused to make a new IDM to meet users' needs. It will be also possible to automate IDM and MVD report generation based on a standard data schema.

The seamless development of PMs, ERs, and MVDs for EIRs will become possible by developing a software engineering tool to support the development process using the IDM configurator as a platform and the standard IDM format. The information requirements can be maintained and reused across all component development phases using the standard IDM format.

As a result, fast and reliable IDM and MVD development will be achieved. When information constraints, such as level of detail specifications, are added to the MVDs, this combination can be used to validate the data from existing models and documents. Individually developed MVDs can also be used as a filter to identify information in software tools for a specific exchange requirement. This means there is no need to develop different IFC exporters for different use cases in one process.

3. EXISTING EFFORTS

The IDM configurator effort is not totally new, but built based on existing efforts. The need for an integrated platform to support both information requirement management and BIM implementation is increasing, and a number of existing studies and solutions have already been developed. This section reviews existing efforts from three aspects. First, commercial tools for BEP development were reviewed. Then, the previous studies that considered methodologies for the integrated development of IDMs and MVDs were reviewed. Lastly, existing efforts to develop MVDs were reviewed. Table 1 summarizes the previous efforts that this section will review.

Table 1. Previous Efforts toward an IDM Configurator

Supporting tools	IDM frameworks	MVD development
NBS BIM Toolkit	Lee et al. (2006), Lee et al. (2007)	Weise et al. (2003)
BIMQ by AEC3	Eastman et al. (2010),	Yang and Eastman (2007)
MODELSPACE by Gravicon Oy	Eastman and Sacks (2010)	Lee (2009)
BIM Execution Plan Generator by BIM Supporters B.V	Lee et al. (2013)	Zhang et al. (2014)
	Mondrup et al. (2014)	Weise et al. (2016)

3.1 Supporting Tools for Developing a BIM Execution Plan

The National Building Specification (NBS) is an organization that provides various solutions and regulations for digital construction environments in the UK. The NBS BIM Toolkit is one of the major solutions for supporting the BIM platform (NBS, 2016). According to the UK government's construction strategy, the NBS BIM Toolkit was developed as part of the BIM Level 2 package, and it is performed based on the digital project's lifecycle as defined by PAS1192-2:2013. At the first stage of the project in the NSB BIM Toolkit, each task content and role's responsible who is involved in can be defined and edited to meet the EIRs. The proper multi-disciplinary templates were provided, and the user can refer to examples of existing projects when every stage of the new project is created. Then, the deliverable information can be defined by specifying the level of detail and responsible party for that deliverable. All deliverable information can be arranged by a unified classification system called Uniclass 2015*,* which covers all construction sectors in UK industry. The NBS BIM Toolkit also supports a collaborative work platform that enables interactive communication between project participants online. Moreover, manufacturer product specifications and free-to-use BIM objects are provided so that project teams can easily access the construction manufacturer in the early stages of detailed design. Verification of deliverables is only provided on a limited basis such as COBie data format, which is a list of information required for facility management. The validation is possible through using an open source xBIM software development kit. Data validation is the most significant function for identifying the correctly classified objects and checking their properties to verify the existence of required information.

BIMQ is a requirement and quality management tool developed by AEC3, which is a BIM consulting firm based in Germany and the UK (Liebich, 2010). BIMQ is a kind of online database for creating and managing contractor request information and the quality assurance of BIM models. Because finding the right information for every business process is a complex and laborious undertaking, well-structured and standardized information is becoming more significant in BIM projects. To overcome such challenges, BIMQ provides digitally defined information requirements based on the web and a database. Through this data-driven system, capturing and managing the EIRs become easier and faster, permitting the separated information to be gathered, customized, and reused. Moreover, the corresponding roles and responsibilities of the information requirements can be precisely defined and reused separately as well. One of the advantages of BIMQ is that it supports detailed information requirements, such as level of detail (LOD), level of geometry (LOG), and level of information (LOI), in each business use-case. With the separately defined models, the quality assurance of the BIM model is secured by rule checking. These quality-checking rules can be exported through mvdXML for proper BIM-checkers, such as simpleBIM and the Solibri model-checker. Thus, employers, project managers, or other users can easily understand and control the BIM project with their correct models. Currently, however, BIMQ supports only two software packages—ArchiCAD and Revit Architecture—for the exporting function.

Another information management solution for BIM execution planning is MODLESPACE, developed by Gravicon Oy in Finland (Henttinen, n.d). MODELSPACE is a comprehensive built asset management solution that consists of four modules that cover the entire lifecycle of construction from the initial to operational phases: investment planning, space management, project management, and facility management. These four modules can share and reuse the information management model because MODELSPACE is a web-based tool that can automatically synchronize BIM models with the database. This means the information stream is seamless. All the information related to investment and contracts are under control, making it possible for information model-based decision making for investment process planning. In the project management modules, the project schedule, scope, and cost can be coordinated, and real-time monitoring is possible during the construction project. One of the most beneficial aspects is a quick response for changing information, thereby increasing project productivity. According to the task history record, the documentation is directly connected with the requirements of the agreed-upon BIM guideline. Also, this type of document management serves as a starting point and reference for developing the following business models, which should be better than previous models.

The BIM execution plan generator is part of a solution package called *BIM Supporters* in the Netherlands (Berlo, 2008). Different from the abovementioned software, the purpose of the BIM execution plan generator is to find an optimal collaborative work process at the beginning of any stage of the project. In other words, the BIM execution plan generator helps configure and coordinate the collaborative work environment to achieve the goal of the project rather than directly dealing with the information through the BIM models. In the creation of a BEP in this tool, for example, a project manager inputs the project overview information, such as the goals, participants, modeling guidelines, templates, and information status. After initiation, all project participants should submit an online survey about their preference of working method, including software and data format types. Then, the BIM execution plan generator aggregates the answers and proposes the optimal collaborative working process method, if the survey yields many common responses. When the collected answers show a large difference, however, the BIM execution plan generator detects the need for further discussion to find a better process rather than recommending certain method.

Although the existing solutions provide a variety of management services to implement BIM execution planning, no solution can fully support the development of IDMs and MVDs. They, however, do not focus on the information delivery process.

3.2 Previous Studies on IDM Development Frameworks

The first study for integrating the IDM and MVD started at the Georgia Institute of Technology before IDM was formally specified (Lee et al., 2006, Lee et al., 2007). The basic concept was called process-to-product modeling. Product modeling means a formal and structured representation of product information, and the first step of product modeling is to define a process model. GTPPM is the first software engineering approach based on the process-to-product modeling method for addressing the integrated development of the IDM and MVD. After the GTPPM, the xPPM (eXtended Process-to-Product Modeling) method was developed at Yonsei University in South Korea to fully support IFC and the ISO 29481 IDM standard (Lee et al., 2013). There are three major improvements to the previous IDM development process. First, the ISO 29481 IDM standard recommends the use of business process modeling notation (BPMN), which is very complex to use due to the overwhelming number (over 200) of shapes, as a PM modeling notation. xPPM extracted and proposed the use of essential 22 BPMN shapes by analyzing the use BPMN shapes in previous IDMs. This proposal was formally adopted by the revision of ISO 29481 (ISO, 2016). Second, previously the IDM and MVD development processes were two disconnected processes. xPPM proposed a seamless development process from the IDM to the MVD by eliminating the functional part between them. Third, two XML schemas, erXML and fpXML, were proposed to exchange ER and micro MVD documents. Micro MVDs are subsets of an MVD. As a separate effort, mvdXML, an XML schema for MVDs, was developed by buildingSMART International (Chipman et al., 2016). More discussions on mvdXML are followed in the next section.

A new methodology focusing on the reusability of exchange information for developing the IDM has been proposed (Eastman and Sacks, 2010, Eastman et al., 2010). This new IDM development process is based on the specific object and intent of information exchange. The existing terms of the ER and FP were replaced by an exchange model (EM) and an exchange object (EO). The EM contains several EOs, which together comprise an information unit that must be exchanged between users and tools. Since the concept of EM and EO involves reusable elements, the proposed IDM development framework provides detailed and explicit information that has already been exchanged and validated in the previous use case. In terms of improving the usability of the IDM, an IDM package with a new framework for dividing existing IDMs into smaller units based on the work breakdown structure methodology was proposed (Mondrup et al., 2014). The concept of an IDM package entails an IDM being divided and enumerated by 33 criteria of the OMNICLASS and ISO lifecycle stage. Then, a set of small IDMs provides a modular methodology that contains each best practice of the use cases. The purpose of this study was to activate the existing IDM by modifying these IDM packages for other projects. Although this framework will be helpful in improving the reusability of IDMs, mapping the corresponding MVDs into each IDM package still remains a challenge for future studies.

3.3 Existing Efforts for MVD Development

On the other hand, several studies on the methodology of MVD development have been conducted separately with the IDM. Ultimately, one of the goals of the IDM configurator is to obtain a reliable MVD that can be interpreted by computer and used for solution providers. This section presents previous efforts made to develop MVDs and the current status of existing MVDs.

Weise et al. (2003) proposed the generalized model subset definition schema (GMSD), a methodology for extracting MVD using a subset query method from the IFC database concept. GMSD is not just a language but a schema that consists of two inter-related parts; *object selectio*n and *view definition.* This structured approach makes the partial model view simple and clear. One of the greatest advantages here is that GMSD improves data exchange and sharing through the reduction of unnecessary information. As a generation tool of BIM-based multi-model views, ViewEdit was developed by Katranuschkov et al. (2010). It is easy to use and to specify multiple MVDs. The major purposes of multi-model view generation are to make separately manageable models, avoid additional work for data transformation, and exchange and integrate BIM data with non-BIM data.

Another effort to extract valid subsets is the rule-based subset generation method proposed by Yang and Eastman (2007). This study introduced a formal method for defining a schema subset, called a “base set.” However, a base set is a “set of data types relating to only one base entity” and is incomplete as a subset schema. To automatically extract the smallest MVD (called a "minimal set") that corresponds to a concept (such as “structure”) from IFC, Lee (2009) proposed a concept-based MVD (IFC subset) extraction method. The IFC model view extractor was developed based on the subset generation rules proposed in the aforementioned study. Users can obtain a minimal set of semantic subsets of the “concept,” which is the same as an input keyword into this software.

One of the key roles that MVDs can play, when they become available, is to validate the quality of a BIM model. Quite a few efforts have been conducted to automate model checking and IFC documentation generation. buildingSMART first published a specification of mvdXML in 2011, and mvdXML1.1, the latest version, was released in 2016 (Chipman et al., 2016). The mvdXML is a computer-interpretable format for representing MVDs and associated exchange requirements. The original MVDs can be converted into mvdXML through the IFC documentation generator, an ifcDOC provided by buildingSMART (Chipman, 2013). The objectives of mvdXML include defining the generic structure of MVDs, enabling automated validation of BIM models, generating relevant documentation as a required product of BIM projects, and providing filtering of IFC data for exporting from one BIM application to another. Among these, functionality for automating quality checking is the major concern of mvdXML.

To validate MVDs, a series of studies on the model view checker were conducted (Zhang et al., 2014, Weise et al., 2016). The model view checker identifies and checks whether the exchange requirement includes the correct information based on predefined rule-sets. The implementation platform for the validation process was developed using the open source xBIM toolkit. Detected errors were exported in a BIM collaboration format (BCF). A model view checker developed later also provided 3D visualization.

Two of the commonly known MVDs that are officially approved by buildingSMART are the references view (RV) and design transfer view (DTV) (bSI, 2015b, bSI, 2015a). The RV is defined as a subset of the IFC4 schema that comprises a set of MVDs for reference workflows such as iterative design review and coordination in BIM projects. The RV can represent geometry and properties as read-only: that is, RV users can extract data from RVs, but cannot edit them. On the contrary, as an extension of the IFC4 RV, the IFC4 DTV supports handover workflows and allows editing, such as inserting, deleting, and modifying DTVs. Some use-cases of RV include background reference, coordination planning, clash detection, and visualization. Those of DTV include takeover or import data from a previous design. The scope of DTV is larger than that of RV; in other words, the RV is considered a subset of DTV. In addition, other MVDs, such as coordination view, structural analysis view, and basic FM handover view (East et al., 2013), are still in development. More model views being developed by other organizations can be found on the IFC Solution Factory website (buildingSMART, 2005).

4. CONCLUSION

The public policies such as the UK BIM requirements has facilitated the demand for a method to rapidly and efficiently specify information requirements and BEPs by sharing and reusing exiting information definitions and BEPs as templates. The IDM configurator was proposed to provide such an environment. This study introduced the IDM configurator and reviewed a number of previous efforts to develop methods, tools, and standards, which could be regarded as foundations of the IDM configurator. Existing efforts were classified into three categories. Each review section showed core concepts and technologies that can yield benefits as well as several limitations that must be overcome in the future.

For successful implementation of the IDM configurator, managerial issues beyond the technical issues discussed in this paper should also be considered, such as quality assurance, copyright, and the authority of both existing and new IDM/MVDs. In order to supply and share the qualified information, motivation and compensation policy should also be followed.

5. ACKNOWLEDGEMENTS

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REVIEW OF DIGITAL TECHNOLOGIES FOR PRODUCTIVITY GAINS IN NEW ZEALAND BUILDING INDUSTRY

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ABSTRACT: *New Zealand building industry continues to face pressures for improving productivity and lowering construction costs. With the need to build more houses, quicker, to high quality and on time, there is a need to upscale to use of advanced technologies. Going digital is a solution that can transform the building industry. This paper is an overview of digital technologies (DTs) to analyze their impact on productivity and cost. The findings conceptualize the theoretical roles of DTs for improving productivity and cost efficiency. Thirty-one DTs are identified and as a basis for analysis, the technologies are isolated into three key functions: (1) Ubiquitous Digital Access, (2) Whole Building Whole-of-Life (WBWOL) decision making, and (3) Cost Reduction Engineering. This study is a literature-based theoretical exploration, and a preliminary stage of an on-going doctoral research aimed at signifying digitization as a function of productivity performance in the New Zealand Building Industry. The review identified the need to investigate management practices for incorporating DTs industry wide and how the key functions influence adoption of DTs may also be explored further.*

KEYWORDS: *productivity, cost efficiency, construction life cycle, digital technology.*

1. INTRODUCTION

Megatrends, like the increasing urban population, constantly remodel the construction industry to improve productivity, provide affordable housing, and expand capacity of infrastructures (Buehler & Gerbert, 2017). There is numerous consensus in literature on how the sector's fragmented nature, difficult on site management, poor safety, and project delivery delays impact construction efficiency (Kim *et al.*, 2013). Scenario in New Zealand (NZ) construction industry is much alike. Low economies of scale, regulatory impediments, shortage of skills and innovation embracing practices are industrially inherent (Carson & Abbott, 2012). Moreover, the need to accommodate 87% of the population residing in urban areas, add constraints to building new infrastructures (BRANZ, 2014). In this regard, the significance of improving sector productivity was prioritized by the Productivity Commission (2012) into housing affordability. Enabling new technologies and improved processes will deliver quality, cost-effective buildings needed to meet NZ housing needs (Macgregor, 2017). Digital technologies (DTs) is a viable solution that can transform the sector to improve its overall efficiency. DTs are advanced information and communication technologies (ICTs) that enable capturing, storing, processing, communicating, displaying, integrating and collaborating information (Hamelink, 1997). Starting point of this revolutionary agenda can be traced back to Latham's report (1994) to assist the UK construction industry become internationally competitive. Latham recognized the role of information technology (IT) to provide speedy solutions in reducing cost and project duration. It appears that the link between productivity, cost, and technology is not limited to the industry and underpins economic growth. For instance, in Australia, a 10% efficiency increase in construction industry would in turn increase the economy's gross domestic product (GDP) by over 2.5% (ICCPM, 2014). Similarly in New Zealand, 1% increase in sector productivity would generate an increase in GDP of around $139m annually (PWC, 2016). Bearing these figures in mind, it is vital that the sector is given guidance on how DTs impact the construction efficiency.

Several reports systematically reviewed DTs applications for multiple functional areas, for instance construction safety (W. Zhou et al., 2012; overview of Radio Frequency Identification Technology (RFID) in construction (Valero *et al.*, 2015); and construction progress tracking (Omar & Nehdi, 2016). The current paper extends recent literature review on the theoretical applications of DTs in order to understand relationship between DTs and productivity. For the context of this study, productivity performance dimension is limited to cost efficiency. The overarching objective of this paper is to identify key functions of DTs for encouraging digitization as a function of productivity performance in the New Zealand Building Industry. How digitization impacts both productivity and cost is poorly understood, creating an area for this research paper.

2. RESEARCH METHOD

This study addresses research method adopted from Zhou *et al.* (2012) and Guo *et al.* (2017). Authors selected papers published between 1998 and 2018 using Scopus as the main source of literature. The method consists of three main phases, as shown in figure 1. Phase 1 include article selection by 'TITLE-ABS-KEY'. Search key words include (but not limited to): 'digital technology AND construction lifecycle; 'digital technology AND productivity AND construction industry'; 'digital technology AND cost AND construction industry'; 'industry 4.0 AND construction industry'; 'digital technology AND construction projects'; 'information and communication technology AND construction industry'. Authors selected top ranked, peer reviewed, and English journals only. Sources published under categories of conference, government reports, notes, letters, books, briefing, were excluded at phase 2. Articles that did not focus on DTs applications to construction lifecycle (CLC) activities were discarded in phase 3.

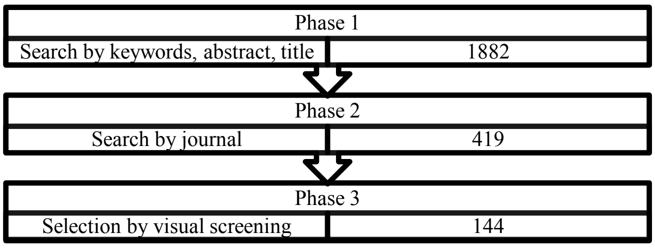

Figure 1: Research framework and outcome from Scopus

3. RESULTS

3.1 Distribution of publications

Findings show that Journal of Automation in Construction, Journal of Computing in Civil Engineering, Journal of Construction Engineering and Management, Electronic Journal of Information Technology in Construction, and Canadian Journal of Civil Engineering account for more than 70% of related publications. Relatively less coverage is observed across the other journals (Figure 1). Contribution is realized from 33 countries, as shown in figure 3. Around 67% research participation is found from researchers in USA, Canada, and UK. This is perceived logical because industrial and government practices enforce a great emphasis on implementing DTs in these countries (Patacas, Dawood, Vukovic, & Kassem, 2015). An increasing number of publications (figure 3), indicating growing DTs applications in construction industry.

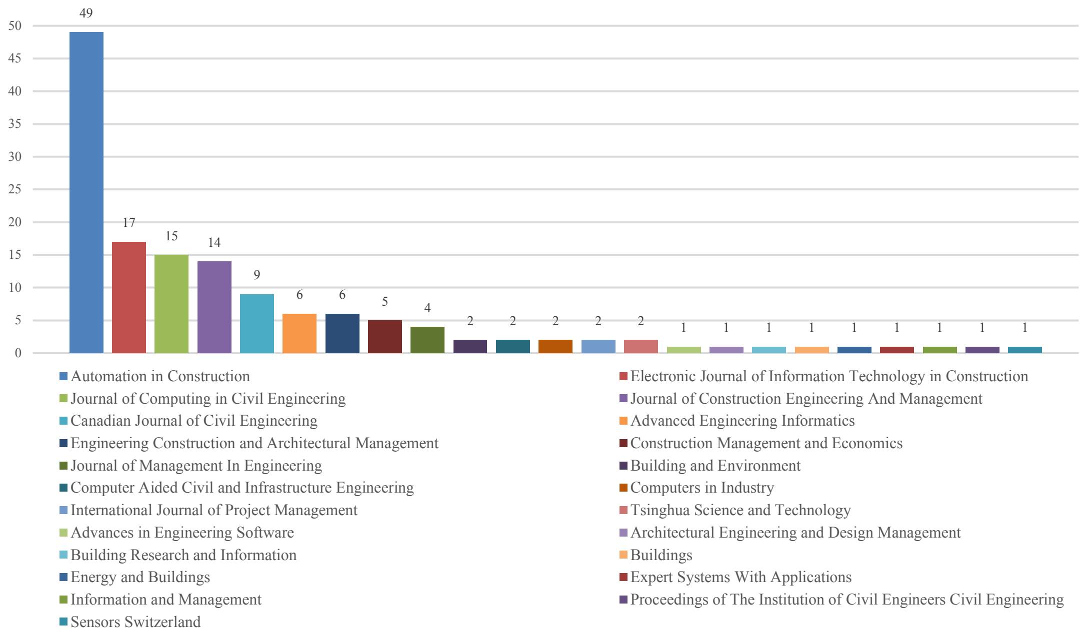

Figure 2: List of selected journals and number of publications

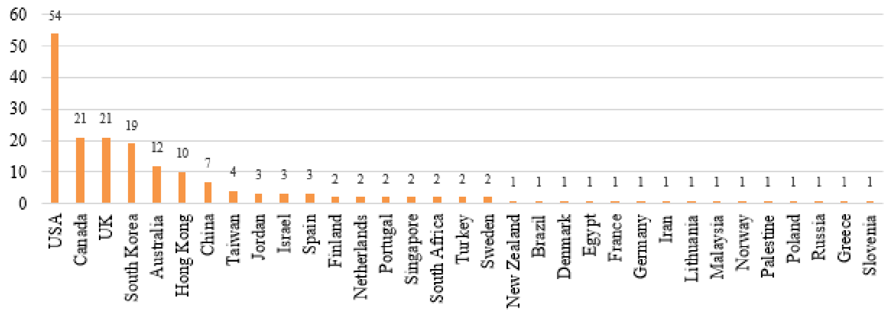

Figure 3: Geographical origin of publications

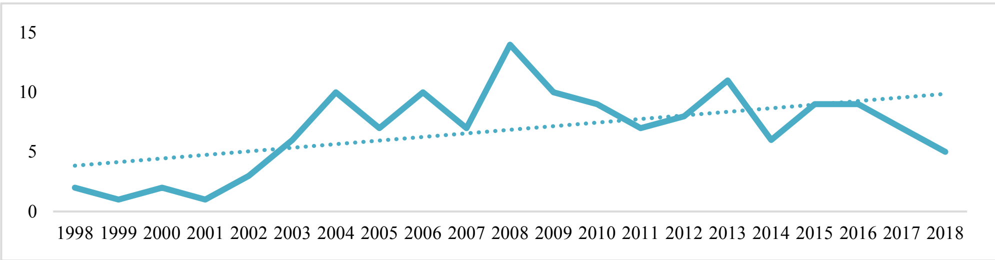

Figure 4: Yearly distribution of publications

3.2 Linking digital technologies to construction life cycle activities

Froese (2010) referred to DTs as paradigm shift in the use of emerging IT, such as computer aided design (CAD), email, building information modelling (BIM), and web based project management (WBPM) applications. From the account of Ibem & Laryea (2014), DTs are stand-alone, web based technologies and tools used for executing construction procurement activities. Whyte & Lobo (2010) identified role of DTs to facilitate social interactions, knowledge sharing, and coordination practices among stakeholders. Ibrahim (2013) addressed DTs to profoundly support construction procurement, management, and delivery of building projects. From these definitions, it is understood DTs removed constraints upon volume, and reliability of data handling and quickened the speed of data transmission geographically. For the purpose of this study, DTs are referred to advance ICT and tools used in amplifying productivity and cost efficiency across CLC.

CLC is embedded in the management of construction projects in order to add value to services, reduce the whole life cost, and improve overall productivity (Lee, Song, Oh, & Gu, 2013). Since New Zealand is the context region of study, authors refer to the CLC framework established by BIM Acceleration Committee (BAC) in New Zealand (2014): pre-design, design, construction, operate, renovate. Findings reveal that out of 144 papers reviewed, most papers address DTs application in construction and design phase, while no application for renovate/refurbishment/retrofit phase. Also in view of the surveyed literature on DTs, table 3 identified some aspects of CLC activities enabled by DTs this study focused on.

Table 1: CLC activities identified from literature

Author	CLC activities
Kumaraswamy et al. (2004)	Construction information management; Collaborative decision making among stakeholders; Quality management process; Design development; Integrated supply chain management
El-Omari & Moselhi (2009)	Data acquisition; Work progress monitoring; Resource management; Database management
Aouad *et al.,* (2010)	Establish client requirements; Early contractor involvement; Construction; Operation; Strategic partnership between client & contractor; Communicate end-user needs
Lin & Su (2013)	Facility maintenance management; Operations; Ability of maintenance staff to access information; Support decisions & improve process throughout project lifecycle; Identify design conflicts; Procurement
Zhou *et al.*, (2013)	Automatic monitoring & visualization of field operations; Information communication for construction safety; Real-time location systems for monitoring site activities; Simulate safety problems of construction processes

Heller & Orthmann (2014)	Life-cycle cost savings; Quality management; Building process efficiency; Construction Operations; Establish value for involved stakeholders
Patacas *et al.* (2015)	Facilities management data handover; Design development; Service life planning; Workforce & process efficiency
Wu et al. (2016)	Automated production process; Design development; Waste management; Life cycle cost calculations
Kuenzel *et al.,* (2016)	Project initiation; Real-time automated information exchange; Construction budget & schedule; Site management

Even with the abundance of publications on DTs used in construction sector, research on the theoretical roles of DTs to directly address productivity gains and cost efficiency is sparse. This paper approached to address this gap through the lens of DTs applications on CLC activities. 31 DTs were identified: 3D Printing, Artificial Neural Network (ANN), Artificial Reality (AR), Autonomous vehicle / robotic system, Barcode technology, BIM, Case based reasoning (CBR), Cloud computing, Context aware mobile computing, Electronic commerce (e-commerce) technologies, including web-based project management, WBPM, e-Marketplace, e-payment platforms, and email, Electronic Data Interchange (EDI), Enterprise Resource Planning (ERP), Extensible Markup Language (XML) technology, Game technology, Geographical Information System (GIS), Global Positioning System (GPS), Infrared, Laser distance and ranging technology (LADAR) / 3D Scanner, Mobile devices (smart phones, tablet, handheld devices, such as the personal digital assistant, PDA), Multimedia technology, Photogrammetry (digital cameras), RFID, Software applications: 3D, 4D, CAD, Ultrasound, Virtual Prototyping, Virtual Reality (VR), Wearable devices, Wireless local area network (WLAN), Wireless Sensor Network (WSN) technologies including Ultra Wide Band (UWB), Bluetooth, ZigBee, Wireless technology.

Thrust of efforts in synergistic application of DTs makes information available on demand and through interconnected automated systems. For instance, RFID equipped with GPS for enhanced location tracking and real-time information flow (Cai, Andoh, Su, & Li, 2014); integrating AR technology in BIM for onsite information system of construction site activities (Wang, Truijens, Hou, Wang, & Zhou, 2014); proposed system by Li *et al.* (2005) integrating GPS and GIS to minimize onsite construction material wastage. This synergy reduces the time and cost of planning, design, and construction (Miettinen & Paavola, 2014). Since this is an exploratory study, no attempt is made to group the DTs into any specific order or category. Findings indicate positive contribution to productivity and cost efficiency, foci of the study. How the key functions of DTs achieve both, is discussed in the next section.

4. DISCUSSION

Findings indicate that a majority of publications focus on applications of DTs in design and construction phase to improve the visualisation (Patacas et al., 2015), ubiquitous access to on-site and off-site information (Ruwanpura *et al.*, 2012), safety control (Zhou *et al.*, 2012), communication (Vlist *et al.*, 2014), and progress monitoring (Zhang & Arditi, 2013). Based on the emerging functions of DTs, authors developed a framework for productivity analysis (figure 5). The framework points towards three key functions of DTs that enable productivity and cost efficiencies in the construction process.

4.1 Ubiquitous digital access

Ubiquitous digital access is the capability afforded by technologies to enable mobile access to information (Shin & Jang, 2009). Construction industry is highly information dependent. Among the digital access is information about materials, equipment handling, and construction workers activity recognition (Akhavian & Behzadan, 2016). A good access to data and its management are critical to project management and depends upon shorter construction cycle time and transparent exchange of project information between all parties. Also transient project locations restrict timely data access. Traditional method of acquiring information is time consuming and error-prone, leading to delays and cost overruns (Tindsley *et al.*, 2008).

DTs provide access to data to manage a number of sensitive issues - of interest to this study are productivity and cost efficiencies. DTs namely, BIM, GIS, GPS, UWB, RFID, AR/VR, LADAR imaging, have significant applicability in real time data acquisition (Irizarry *et al.*, 2013). This enable construction stakeholders working with inadequate access to efficient digital information. This access is beneficial, in particular during design and construction stage, for efficient data handling which in turn improves decision making (Martínez-Rojas *et al.*, 2016), and reduces design deficiencies and clash detection. The latter helps managing the work schedule later in the construction phase (Harty & Whyte, 2010). Ubiquity of digital access improves communication among the stakeholders who can then identify and minimize design discrepancies (Abeid & Arditi, 2003). This communication is further enhanced by visual representation of the construction process, using 3D/4D animations leveraged by VR/AR (Ganah *et al.*, 2005). State, behavior, and context of the workers can be achieved by mobile technologies, such as smartphone devices and wearable technology, with embedded sensors (Awolusi *et al.*, 2018).

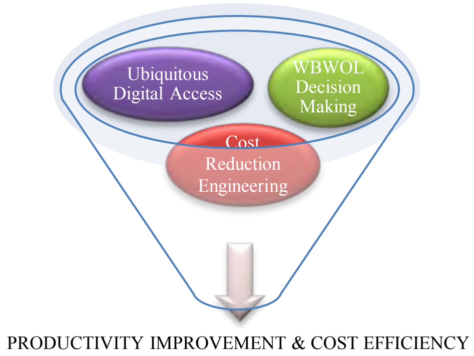

Figure 5: Framework of DTs key functions contributing to productivity and cost efficiency

Internet is yet another ubiquitous source of information that enhances accurate and timely data exchange with real time visibility and remote supervision of the construction process (Husin & Rafi, 2003). For instance, in the prefabricated public housing projects in Hong Kong, real time information from RFID and GPS have been connected with BIM in the developed Internet-of-Things (IOT) enabled platform. This integration enabled stakeholders to gain access to the physical building information, monitor the whole process, and make decisions collaboratively when necessary (Li *et al.*, 2018).

In a survey towards the uptake of mobile computing technology in New Zealand building industry, Liu, Mathrani, & Mbachu (2017) indicated that adoption of mobile applications provided better client relationship management and satisfaction. This in turn has positive correlation with sector's overall productivity and profit (Liu, Mbachu, Mathrani, Jones, & McDonald, 2017). Although the basis of analysis covered a very small survey sample, it provided a starting point for encouraging further uptake of multiple mobile technologies in the sector. Previously, on a similar venture, Venkatraman & Yoong (2009) developed a mobile facsimile application, called ClikiFax, to facilitate image-based messaging to a smart phone or fax machine and collaborate time-critical information among contractors, architects, and owners, at remote construction sites. As evident from literature, ubiquitous technologies enable new functionalities from the early design phase to the very end of an asset's life cycle, in real time, irrespective of location.

4.2 Whole-building whole-of-life (WBWOL) decision making

The WBWL framework was commenced by Building Research Association New Zealand (BRANZ) to establish the environmental impacts of building design and encourage more consistent use of building, based on life cycle assessment (LCA). The framework is significant to the New Zealand building industry because, in particular, it facilitates a stronger connection between supply and demand for construction products. In the academic literature, life cycle considerations focus on benefits of early involvement to overcome technical discrepancies, design deficiencies, and organizational challenges. It needs to start at early design phase to prevent cost and time wastage rather being considered at a later stage. This is logical as it would reduce the possibility of cost and time wasting design changes, if left for later. A number of studies investigated the use of DTs with lifecycle considerations. Quantitative digital tools, such as 3D CAD and BIM are used throughout the lifecycle from design, planning, clash detection, scheduling, estimation, and project management (Ibrahim, 2013). Valero et al. (2015) demonstrates uses of RFID in four main stage of the lifecycle of a facility: planning and design, construction and commission and operation and maintenance. With increasing use of automated data acquisition technologies, such as RFID and GPS, facilitate assessment of as-built phases and integrating LCA-based data into the design process become easier and quicker (Ma *et al.*, 2005). DTs facilitate the management of real-time data, like current production status across building lifecycle. This consequently facilitates improved collaboration and teamwork necessary for lifecycle based decision making toward maximization of productivity.

Visualization capabilities of BIM enable decision making for operation and maintenance phase activities. This is of particular interest to project stakeholders to support decision within a whole lifecycle perspective. For instance, in the UK, government mandated BIM adoption in all public projects sustaining from 2016. The initiative is intended to leverage the UK construction strategy of 2025 to reduce whole life cost of built assets by 33%, overall time by 50% (Chang *et al.*, 2017). In New Zealand a similar government initiative to improve productivity by 20% by 2020 (Fuemana *et al.*, 2013) can be greatly leverage by DTs. This is also a reminder to the BIM enabled projects driven by BAC New Zealand (2014) and financial benefits from the integration, in particular workflow efficiency, reduced material and labor waste, and shorter construction time. Although BIM was not utilized for the whole life cycle, the outcome point towards a common notion that to get maximum benefit from BIM it is important to use it from inception to completion. These findings established that DTs cuts across the entire spectrum of project cycles, improving collaboration, visualization, design development, and boost productivity.

4.3 Cost Reduction Engineering

Another key function of DTs is cost reduction engineering (CRE). The CRE concept depend heavily on cost reduction capabilities of DTs. When the cost of constructed facilities is reduced, the facilities themselves become more affordable, and, therefore, more accessible to a greater proportion of the population (Slaughter, 1998). Rework and design deviations typically add to life cycle cost overruns. Cost of deviation and rework was long pointed by Burati et al., (1992) and Egan (1998) as a high contributor, 12.4% and 30% respectively, to total project cost. Harnessing DTs can minimize such error and save cost of rework by optimizing construction process. Multimedia, VR/AR, and 3D/4D visual imaging technologies help eliminate design error (Dawood & Mallasi, 2006). A major benefit of visual tools is to identify deviations in as-built and as-planned work that account for significant portion of total project cost (Kumaraswamy et al., 2004). In view of this challenge, Omar & Nehdi (2016) developed a visual system in close range photogrammetry that is able to deliver work progress, continuous monitoring and controlling of construction site activities. The visual monitoring not only reduces unnecessary site visits but also makes it easier to provide corrections, and make timely adjustment to the process, mitigating time and cost consequences.

Another aspect of cost control is by managing safety on site. Construction sites contain several supporting facilities that are required to perform construction activities. These facilities may be exposed to hazards and lead to adverse consequences for the whole construction process, in terms of worker productivity, project completion time, quality and budget. A range of DTs, in particular RTLS, PWS, CBR, ANN, and Game Technology, are addressed for enhancing safety education and training, hazard identification and accident prevention (Zhou *et al.*, 2013). The advent of worldwide web and Internet have evolved online business solutions, in particular electronic commerce (e-commerce), to provide cost-effective support for information flow and communication, at any given time (Kong et al., 2004). E-commerce technologies, such as web-based project management, e-Marketplace, electronic payment platforms, and email, facilitate outsourcing work to diverse participants in the construction industry (Love & Irani, 2004). It manifests cost efficiency through decreased transaction costs, inventory levels, staffing requirements, and procurement cycles. Contractors and owners benefit from this technology by reduced administration and communication costs, and construction costs respectively (Zou & Seo, 2006). DTs revitalize the construction process by automating activities. Intelligent systems like BIM, wireless technology and cloud computing (Ibem & Laryea, 2014), RLTS, geospatial technologies, and vision technologies, such as LADAR (C Kim, Son, Kim, & Han, 2008) enable data storage, without the need for a physical device, like computer hard drive. This eliminates the need for IT personnel, thus reducing staffing and overhead costs. Automated activities make site intervention less necessary. This can save valuable labor hours and added cost to construction. Wang et al. (2014) succeeded in achieving automated progress control by integrating AR in BIM. The system reduces manual intervention, and time, adding to cost-effective deliverable for the entire project. Another emerging automation technology, although long used in the manufacturing sector, is 3D printing. It is gaining popularity in the construction industry owing to its potential to provide flexibility in design, reduced manpower, construction time, and waste (Wu *et al.*, 2016). 3D printing allows inclusion of BIM in the construction process to further improve scheduling requirements of the project, reducing construction time on site, production cost, and overall lifecycle cost. Given the scale of Auckland housing shortage and rebuild of Christchurch, automation technologies may leverage meeting housing demands in the country (Buckett, 2013).

5. CONCLUSION

This study is a desktop survey of DTs applications to support productivity and cost efficiency in the construction life cycle. From a review of 144 papers, thirty-one DTs were identified and three emerging functions of DTs are analyzed that contribute to productivity improvements. BIM, RFID, Cloud Computing, GIS, GPS, and Mobile Computing appear to be the emerging leading paradigm among others. The array of international studies concluded that DTs demonstrate great potential to productivity gains and profit margins. This is a significant resource to encourage digitization in the New Zealand building industry. Reflecting on the survey, a number of agenda are drawn for future research. This study was analyzed based on results from an overview so a quantitative analysis may be performed to validate the results. Also how the three key functions analyzed in turn influence adoption of DTs can be further investigated. These key functions are essential for improving productivity and cost efficiency in the construction projects, despite the possible barriers in the uptake of DTs and required skills. Turning these barriers to drivers present a good agenda for future work. In the context of New Zealand, a number of technologies, namely BIM, RLTS, and mobile technologies, have promising potential to enhance workflow efficiency and some studies are already exploring the opportunity. Future efforts should be made to examine the processes required for incorporating new DTs, industry wide. This will leverage achievement of the national agenda of 20% productivity improvement by 2020.

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IMMERSIVE VIRTUAL REALITY TELECONFERENCE SYSTEM WITH DESIGN CHANGE TRACKING AND 3D EDITING

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ABSTRACT: *A design process usually consists of meetings and distributed individual work. Owners, designers, engineers, etc., have meetings and decide what to do until the next meeting for each participant. They make changes in design, estimate cost, make construction plans, etc. and may need to discuss some matters between the meetings. Teleconferences using the Internet are conducted more frequently to reduce traveling time and cost. However, the flat screen-based teleconference usually lacks the feel of participants' presence and mutual understanding, especially when they discuss design change, pointing objects in BIM models. Furthermore, it is difficult to track and understand what has been done to the BIM models by multiple, remote participants. Thus, in this research, the Immersive Virtual Reality (VR) Design Teleconference System (IVDTS) is proposed to improve participants' presence and the stereoscopic effect. Further, a general model was developed to represent the design change process to BIM models. The teleconference system includes a facility to show and track the design change. The proposed system consists of three subsystems: an immersive VR teleconference system, a design tracking system, and a cloud-based 3D editing system. A prototype system was developed and tested for bridge design.*

KEYWORDS: *Virtual reality, Teleconference, Product model, Collaboration, Game engine, Virtual meeting, Building Information Modeling (BIM)*

1. INTRODUCTION

In construction industry, the low productivity is a serious problem. Low productivity in construction industry is globally common (Ghaffarianhoseini et al., 2016). For example, in Japan, improvement of productivity of construction industry is crucial in order to develop social infrastructure and protect communities even in the declining birthrate and aging society (Ministry of Land, Infrastructure, Transport and Tourism, 2017). Building Information Modeling (BIM) is expected to solve the problem by sharing 3D product models through the project.

During the construction project, owners, designers, engineers, etc., have meetings and decide what to do until the next meeting for each participants. A concurrent design process is a cycle of co-designs and distributed designs (Yabuki et al., 2009). Fig. 1 shows the progress of construction project. The construction project consists of iterations of meetings and individual works. They make changes in design, estimate cost, make construction plans etc., and may need to discuss matters between the meetings. Teleconferences using the Internet are conducted more frequently to reduce traveling time and cost.

However, a flat screen-based teleconferencing has the following problems: (1) lack of the feel of participants' presence, (2) lack of mutual understanding, especially when they discuss design changes, pointing objects in BIM models, and (3) lack of editing function in the virtual environment. Furthermore, it is difficult to track and understand what has been done to the BIM models by multiple, remote participants.

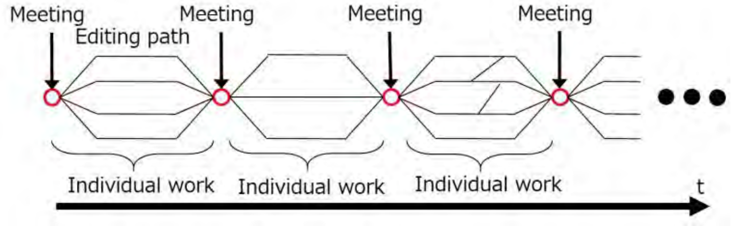

Fig. 1: Iteration of meetings and individual works during the construction project.

In this research, in order to solve the problems of the flat screen-based teleconference and to support comparison of civil infrastructure design, an immersive virtual reality (VR) teleconference system using 3D models with attributes and tracking design change is proposed.

2. LITERATURE REVIEW

2.1 Immersive VR teleconference

Zhang et al. (2013) developed an immersive VR teleconference system. However, the system is not for architecture, engineering and construction (AEC) design. Beck et al. (2014) developed a teleconference system using telepresence. However, operations of 3D models are not implemented by the system. Shi et al. (2016) developed the walkthrough system with remote participants in the shared building. However, the developed system does not operate the model of the building. van den Berg et al. (2017) developed a VR design review system. However, the system is for pre-meeting.

2.2 Design change tracking

Arthaud (2007) developed tracking change system during design process. However, the system is based on flat-screen. Yabuki et al. (2009) proposed a generic methodology for tracking changes during distributed work in the design process and for comparing product model data. However, the proposed methodology is not for VR. Isaac et al. (2012) developed tracking design change system for identifying the impact of design change. However, tracked changes are not visualized in the system.

2.3 Cloud-based 3D model editing

Edwards et al. (2015) developed a teleconference system by end-users and professionals. However, 3D models are not used. Adamu et al. (2015) developed a teleconference system using BIM models. However, immersive VR is not used in the system.

Although there have been these studies of immersive VR teleconference, design change tracking and cloud-based 3D model editing, there still exists gap in a VR teleconference that approaches all of problems mentioned in Section 1. Thus, our proposed system integrated an immersive VR teleconference system, a design change tracking system and a cloud-based 3D model editing system.

3. PROPOSED SYSTEM

3.1 Overview of the proposed system

In this research, the teleconference system called Immersive VR Design Teleconference System (IVDTS) is proposed for discussing infrastructure design in the virtual environment. Fig. 2 shows the overview of the proposed system and Fig. 3 shows the configuration of the IVDTS. The IVDTS consists of the immersive VR teleconference system, the design change tracking system and the cloud-based 3D editing system. Multiple remote participants can have teleconferences synchronously in the shared virtual environment using 3D models with attributes. 3D models changed by engineers during individual works are shared via a shared storage before IVDTS (Fig. 4).

In IVDTS, head mounted displays (HMDs), microphones, headphones, game pads and PCs are used. A user uses a HMD as a video output device to view the stereoscopic virtual environment. Microphones and headphones are used for discussing during the teleconference. Game pads are used for operating the position of users in the virtual environment and the user interface (UI) of the IVDTS. When users wearing HMDs, it is hard to see the real environment during the teleconference. Thus, in order to improve the operability, game pads that have less keys than keyboards are used in the IVDTS.

3.2 Immersive VR teleconference system

The immersive VR teleconference system has the function of sharing the virtual environment with remote participants by avatars that represents them. Fig. 5 shows the immersive VR teleconference system. User A and User B share the virtual environment via their avatars as shown in Fig. 5. The rotation of avatars reflect the position of avatars acquired with sensors of HMDs.

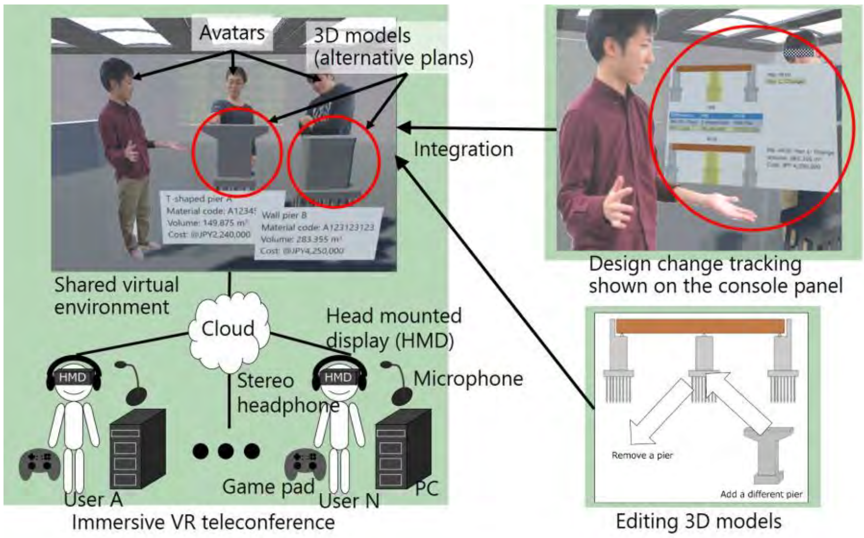

Fig. 2: Conceptual diagram of the proposed system.

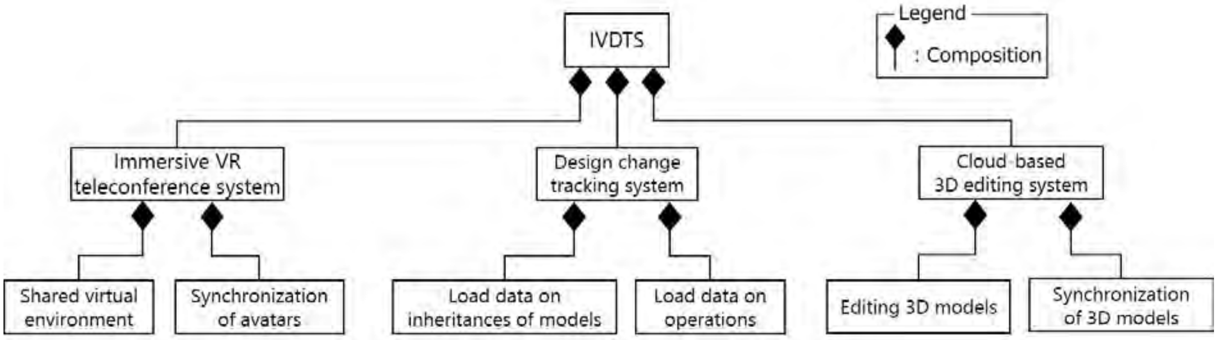

Fig. 3: Configuration of the Immersive VR Design Teleconference System (IVDTS).

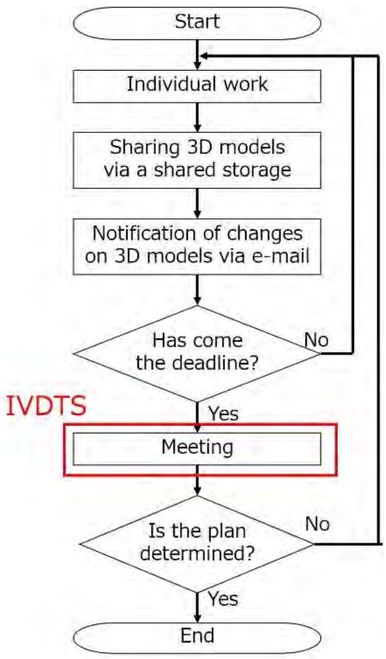

Fig. 4: IVDTS in the flow of the design process.

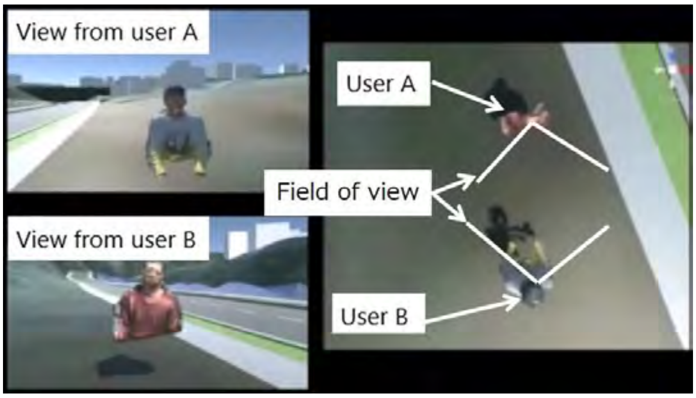

Fig. 5: Teleconference in the virtual environment.

3.3 Design change tracking system

The design change tracking system has the function of tracking operations on geometry and attributes of 3D models. Fig. 6 shows the history of the changes made to 3D models. Design change among multiple participants has these features: (1) iteration of meetings and individual works, (2) identification of 3D models, (3) inheritance of geometry and attributes of 3D models from other 3D models, (4) multiple participants and (5) identification of order of editing.

We defined the general 3D model to illustrate the features as shown in Equation (1):

$$M\ (S_i, M_j, P(List\ of\ M_k), A_n, T_{i\text{-}j}) \tag{1}$$

where

M: a 3D model of civil infrastructure design,
S_i: a session number (i = 1, 2, 3…),
M_j: a model number (j = 1, 2, 3…),
M_k: a parent of M_j (k = 1, 2, 3…),
$P(List\ of\ M_k)$: a list of model numbers of parents of the model,
A_n: a code of engineer who edited the model (n = 1, 2, 3…),
$T_{i\text{-}j}$: time when editing of M is ended.

Fig. 7 shows an example of design change tracking which uses the proposed general 3D model. Engineers make operations to the models that inherit geometry and attributes from other previously edited models during the individual works. In Fig. 7, three engineers design an infrastructure based on M_1 that the participants selected in Meeting 1. The model edited by an engineer is allocated model number M_i in the order of time when editing of the model is ended. In the individual works of Session 1, M_5, M_8, and M_{10} are output and these alternative plans are discussed in the next meeting. The parent-child relationship is defined as Equation (1) and thus, the differences of two alternative plans are clarified by referring the paths between them.

3.4 Cloud-based 3D model editing

The cloud-based 3D editing system has the function of editing geometry and attributes of 3D models in the virtual environment during the teleconference. Fig. 8 shows the definition of operations on the 3D models. An operation on 3D models is divided into two operations because the IVDTS deals with 3D models that have attributes.

An operation made to geometry is divided into four operations: (1) Add, (2) Remove, (3) Change and (4) Move. Adding geometry is an operation of adding an element that has attributes to a 3D model. Removing geometry is an operation of deleting an element from a 3D model. Changing geometry is an operation of modifying a shape of a 3D model's element. Moving geometry is an operation of translating and rotating an element of a 3D model.

An operation made to attribute is divided into four operations: (1) Add, (2) Remove and (3) Change. Adding attribute is an operation of adding an attribute to an element of a 3D model. Removing attributes is an operation of deleting an attribute from an element of a 3D model. Changing attribute is an operation of modifying an attribute of a 3D model's element.

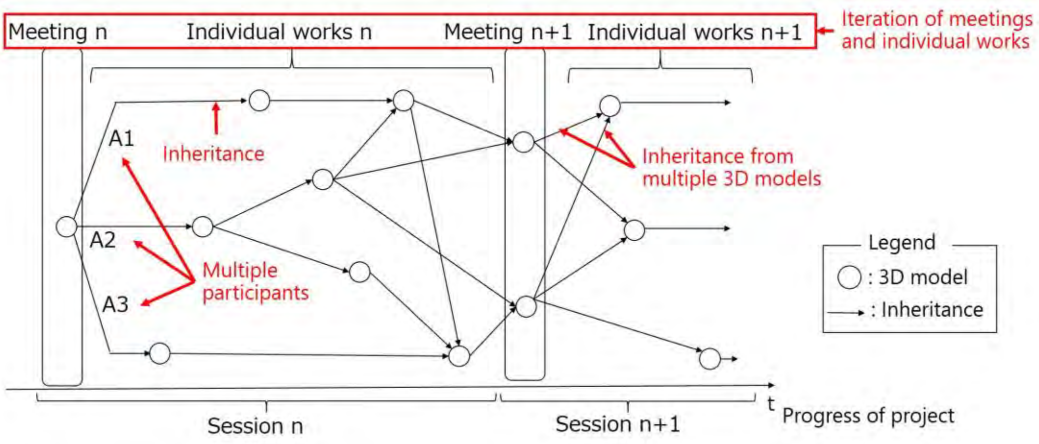

Fig. 6: Diagram of design change.

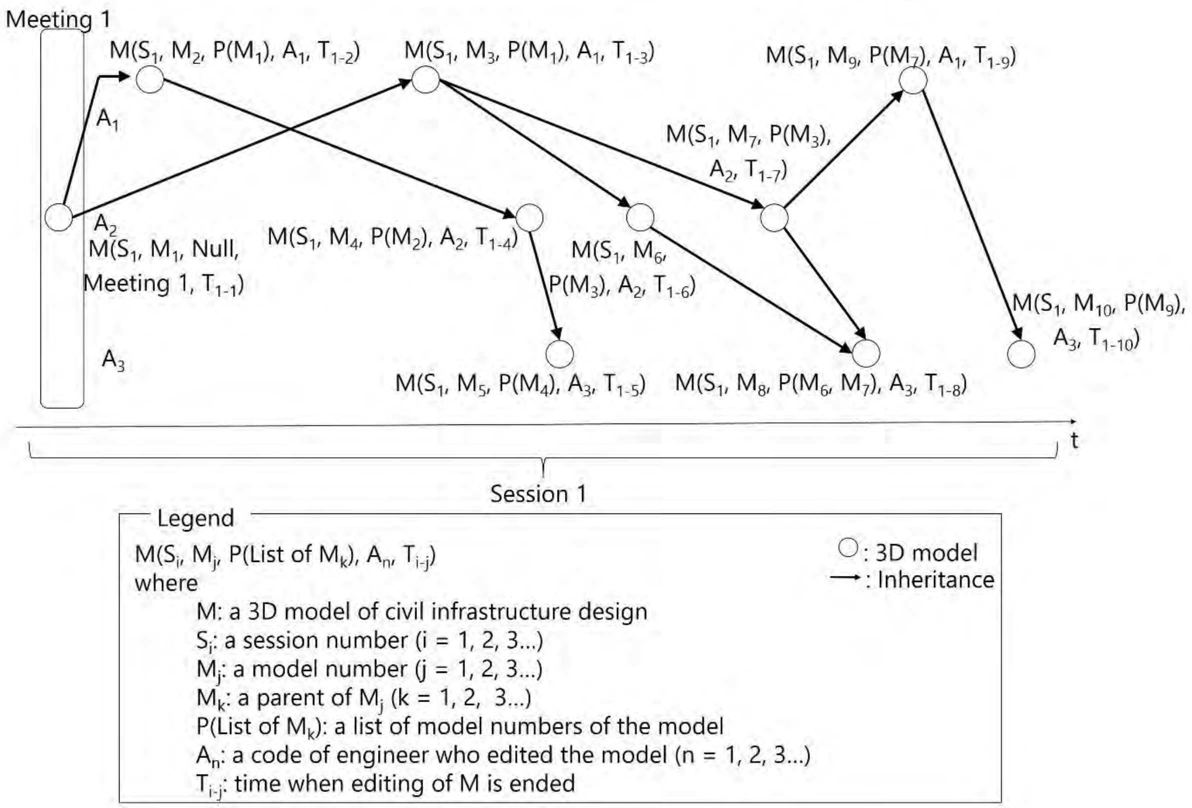

Fig. 7: Example of design change tracking.

4. IMMERSIVE VR DESIGN TELECONFERENCE SYSTEM (IVDTS)

4.1 Overview of the prototype system

We developed the prototype system to validate the proposed method. Fig. 9 shows a user using the developed system. Users use HMDs as video output devices and gamepads as controllers. Table 1 shows the hardware and software used for developing the prototype system. We used a game engine as the development infrastructure. The game engine supports developing VR applications and implementation of communication via the Internet.

Fig. 10 shows the developed prototyped system. In the shared virtual environment, users can discuss the design of civil infrastructure design, check the design change tracked and operate 3D models with the console panel. HMD was used for video output device in the developed system. Therefore, the developed system enabled users to view 3D models stereoscopically.

A 3D model for discussing design was designed in advance with the design application for AEC and converted a BIM model to a 3D model. This research used Autodesk Revit as the design application and Autodesk 3ds Max as the 3D modeling application that converted a BIM model to a 3D model. Moreover, 3D models lack attributes during being converted from BIIM models. Therefore, we developed a new plugin of Revit. The plugin extracted attributes from BIM models and output them on the comma-separated values (CSV). Extracted attributes are linked to elements in the developed system (Fig. 11).

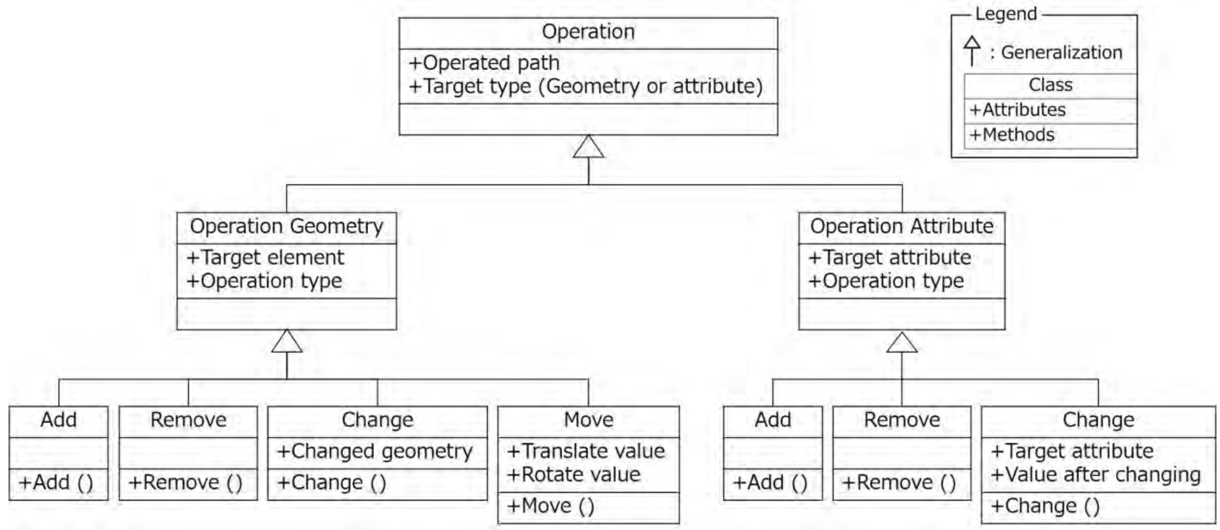

Fig. 8: Definition of operations made to 3D models with attributes.

4.2 Functions of the prototype system

Users could see other users' avatars in the shared virtual environment via the developed system. Avatars were made with structure from motion (SfM) in advance. This function enabled multiple remote users to share the same room through the Internet.

The developed system enabled users to edit the 3D models in the virtual environment with the console panel. Users can edit geometry and attributes of 3D models via the proposed operations.

Users viewed the design change tracking during the teleconference. Fig. 12 shows the panel of the diagram of design change tracking. The developed system automatically read the CSV of 3D models' information that is defined in Section 3.3 and operations' information made to models.

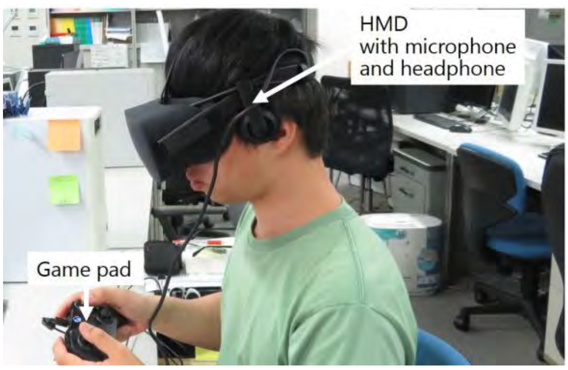

Fig. 9: User who is using the developed prototype system.

Table 1. Hardware and software used for developing the prototype system.

Type	Name	Use
Game engine	Unity 5.6	Development infrastructure
Integrate development environment	Visual Studio 2017	Script programing
Online game engine	Photon Realtime	Networking
Add-in	Photon Voice	Voice chat
HMD	Oculus Rift CV1	Video output device

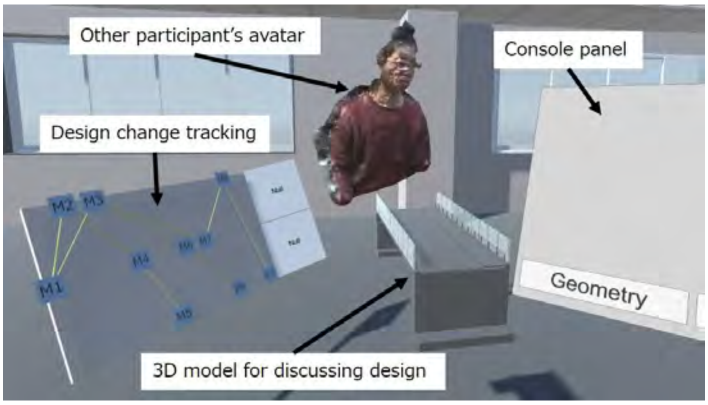

Fig. 10: Developed prototype system (View from a user).

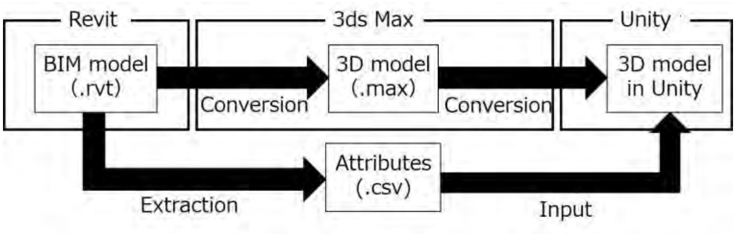

Fig. 11: Conversion of BIM model and extraction of attributes.

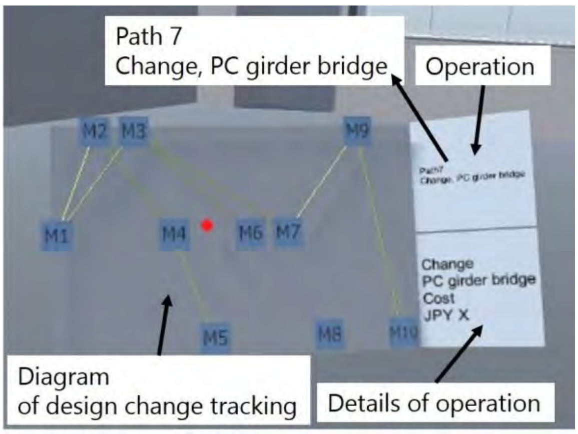

Fig. 12: Diagram of design change tracking and operations made to a 3D model.

5. DISCUSSION

This research proposed the immersive VR teleconference system called IVDTS to solve the problems of the flat screen-based teleconference. To confirm that proposed system solve the problems, we developed the prototype system.

In the flat screen-based teleconference system, users' face or rooms are shown in the flat screen. Presence of users using the conventional system is far from the real meetings in which participants share the same room. In the developed prototype system, participants shared the virtual environment. Therefore, the feel of other participants' presence would be improved. However, the proposed VR teleconference system does not have the function of reflecting users' facial expression and gesture except for position and rotation of their heads. The lack of reflecting expression would be the problem of the proposed system.

The flat screen-based teleconference have the problem of mutual understanding of 3D models. In the developed prototype system, participants saw 3D models stereoscopically with HMDs. Therefore, participants who use the proposed system would mutually understand 3D models' three-dimensional shape during the teleconference.

The flat screen-based teleconference lacks the editing function in the virtual environment. The developed prototype system has the editing functions of 3D models that have geometry and attributes in the virtual environment. These functions would support the teleconference that multidisciplinary participants attend because the proposed system deal with not only geometry but also attributes that have various such as cost, time, physical property, etc. Although the proposed system deals with attributes, parametric modeling is not used. Parametric modeling enables users to operate 3D models according to constraint conditions. Therefore, it is practical to implement parametric modeling. Furthermore, the proposed method does not have the function of converting 3D models changed during the teleconference into IFC files. It would be effective to implement the system of converting 3D models into IFC files that Nandavar et al. (2018) proposed.

Difficulty of tracking and understanding of the design change made to 3D models by multiple remote participants is also a problem of teleconference. The developed prototype system tracked design change by dealing with the history of design change and users could view the tracked design change during the teleconference. Developed design change tracking system shows differences of alternative plans. Therefore, the proposed system would be effective for tracking and understanding of the design change. Although the proposed system has design change tracking system, it does not have the function of registering the data of design change. The registering system that has the function of avoiding confliction of model editing needs to be developed to make a progress of project more effective.

6. COCLUSIONS

This research proposes a VR teleconference system called IVDTS using 3D models and attributes to support comparison of civil infrastructure design. The proposed system consists of the immersive VR teleconference system, the design tracking system, and the cloud-based 3D model editing system to solve the lack of the feel of participants' presence, the lack of mutual understanding pointing objects in BIM models, the lack of editing function in the virtual environment and the difficulty of tracking and understanding of changes made to the BIM models. We implemented the proposed system as a software. Users shared the virtual environment and 3D models with others by using the developed prototype system.

The further studies are needed to reflect users' gestures, develop parametric modeling methodology in the shared virtual environment and output IFC files that reflect changes during the teleconference. Furthermore, we must conduct a case study to evaluate the proposed system quantitatively.

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SMART INSPECTION: DOCUMENTING ISSUES IN 3D WITH AUGMENTED REALITY

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ABSTRACT: *During the construction period in civil engineering, every technical discipline has certain deliverables. Several inspections take place over the time, where construction engineers, architects and owners review the work and document their issues in analogue or digital lists. The locations of these findings are mainly described with text and sometimes complemented by photos. The lists are submitted to the responsible technical crew of the discipline, which reproduces the locations before searching and fixing the claim on-site. Augmented Reality (AR) applications use tracking frameworks to visualize virtual elements at the right position in reality. Spatial Mapping (used by the Microsoft HoloLens) enables markerless tracking of the user's position in wide environments. Using this technology in combination with structured 3D models (extracted from the BIM), issues can be placed intuitively and precisely as virtual markers at their exact position by using the AR system. Photos can be created and attached to the issue object. Tasks can be directly created and assigned to the technical disciplines as responsibilities can be extracted from the BIM. Using this approach, issues can be located precisely in 3D space, submitted directly to the technical discipline and fixed as fast as possible.*

KEYWORDS: *BIM, Augmented Reality, Tracking, HoloLens, Inspection, Issues*

1. MOTIVATION

The Building Information Modeling (BIM) approach is one of the most discussed topics during the last years. The buzzword created a lot of promises regarding productivity and lifecycle improvements in Architecture Engineering and Construction (AEC) industries (Luming and Singh, 2016). Luming determined and analyzed the most important BIM-enhanced practices and named in this connection the clash detection, visualization, quantity takeoff and scheduling (Luming and Singh, 2016). Most use cases enhanced by BIM focus on process improvements in administrative departments. BuildingSMART describe BIM with regard to the widespread approach to an open standard called openBIM as sharing of information between the project, design, procurement, maintenance and operation teams (buildingSMART, 2018). When taking a look at the construction processes on-site performed by multiple disciplines like dry construction, sanitary or electricians the reality looks somewhat different. The as-designed situation is represented by manually modified construction drawings leading to misunderstandings and in the worst case to construction errors, which are costly and time consuming (see Figure 1 left). To extract the individual relevant information and reduce the interpretation effort, information are often transferred to the real environment, e.g. by drawing them directly on the workpiece (see Figure 1 right). The reasonable effect was described by Chandler and Sweller, and is called the split attention effect (Chandler and Sweller, 1992).

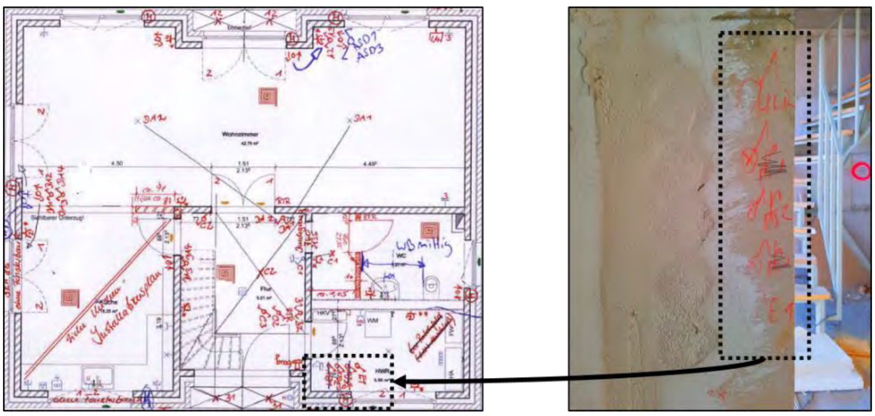


Figure 1: Modified Construction Drawing and the Use On-Site

During the construction process, after specific work packages are completed, inspections take place to compare the as-built (actual) with the as-designed (target) state. The participants involved in the inspections are often not the ones responsible for the remedy of the issues. Hence issues noticed during inspections are discussed for example between customer and main-contractor although also affecting other parties (subcontractors) who are responsible for the work. Important information which deliver more details about the outstanding work get lost during the information flow across the parties. BIM as a backbone can deliver the necessary information regarding geometry, responsibilities and time schedule. Augmented Reality can enable an easy to use access to this information which can be used directly by the inspectors and workers on-site. This paper focuses on combining existing approaches in BIM and Augmented Reality from civil engineering and the outfitting of ships and extending them to enhance inspection processes.

2. DIGITIZATION IN CIVIL ENGINEERING

2.1 Industry Foundation Classes (IFC)

BIM makes use of object-oriented 3D models, i.e. it extends the capability of a traditional 3D-CAD approach by defining and applying intelligent relationships between the elements in the building model. Furthermore each of the building elements also contains lifecycle information (Luming and Singh, 2016). The segregation of different disciplines involved in the planning and construction of buildings each using specific software solutions with usually proprietary data formats leads to challenges in data exchange and consistency. A solution for this problem is provided by openBIM, which aims at offering a universal approach for collaborative design, realization and operation of buildings based on open standards and workflows (buildingSMART, 2018).

The associated open standard Industry Foundation Classes (IFC) constitutes as a highly important and widespread data model for BIM. IFC is based on a strict separation of geometric and semantic descriptions. Therefore it is possible to couple a single semantic object with multiple geometric representations (Borrmann et al., 2018), which follows a hierarchical structure. The semantical objects top-down structure is broken down into project, site, building, building storey and building elements based on a set of IFC classes. IFC classes contain necessary attributes to describe a certain element, e.g. a wall or a window element with attributes like size or manufacturer.

One of the key elements of BIM and the BIM Collaboration Format described below is the use of global unique identifiers (GUID) (Borrmann et al., 2018; Paasiala, Solibri et al., 2016). This ensures each element in the BIM / BCF context being referenceable through a single GUID, which allows connecting different elements in a comfortable way.

2.2 BIM Collaboration Format (BCF)

Inspections and issue elimination are typical processes on a construction site and part of a quality management system. Both are facilitated significantly by the extension of IFC with the BIM Collaboration Format (BCF) as an additional standard, which in comparison to IFC isn't a data model but a zip-file container. Furthermore it doesn‘t include any geometrical model data but references to affected building elements (in the IFC model) as well as associated tags and annotations instead. It thereby allows for a structured description of model related conflicts and issues. In conjunction with BCF an issue is referred to as a t*opic* and for each of these an individual directory is created. The directory holds several files, which reference to each other. Figure 2 shows selected data fields in the IFC file and the BCF container which have a high relevance for this paper.

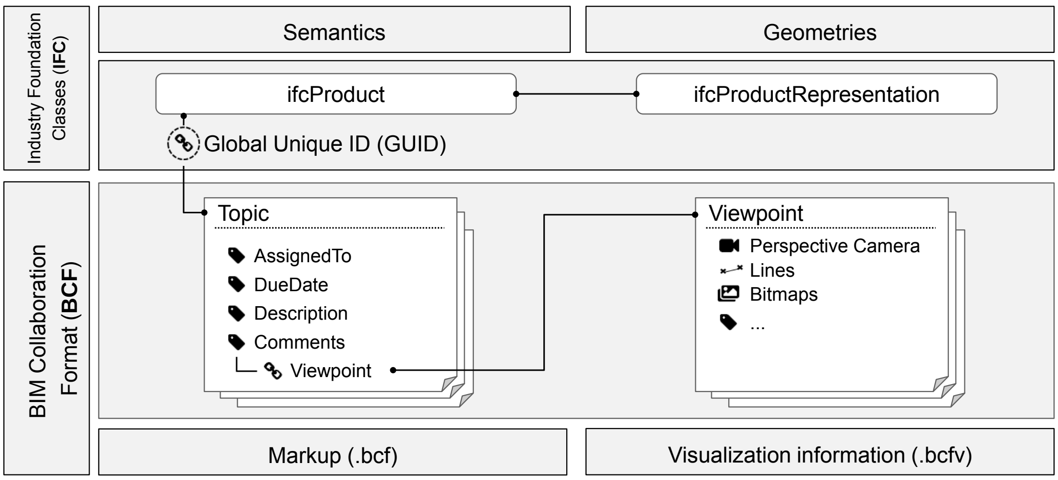


Figure 2: Selected Data Fields in IFC and BCF

This selection is made from the total available data fields presented in the BCF v2.1 technical documentation (Paasiala, Solibri et al., 2016). Markup-files contain a header giving general information like the ifcProject and referencing the corresponding ifcElement via its GUID. A Topic within the markup contains specific information like *AssignedTo*, *DueDate*, *Description* or *Comments*. It also allows for association with external documents like issue reports or acceptance protocols. Comments in turn can reference *Viewpoints* which are characterized by a specific camera pose, lines and bitmaps.

2.3 Augmented Reality for Construction Processes

Since Azuma defined Augmented Reality (AR) as the combination of real and virtual elements which are interactive in realtime and registered in 3D-space in 1997, many industrial sectors evaluated the use of this technology to improve their processes. Especially for one-of-a-kind productions in shipbuilding industries a high potential has been proven by Friedewald et al. The assembly processes for mechanical parts in ships were improved by 16% because the necessary information were present directly at the point of interest (Friedewald et al., 2016). The solution addresses exactly the problem shown in Figure 1 on the right. Instead of drawing the information on the room's surface, measurements and additional information for the work piece are augmented virtually in 3D space.

Researches in AEC industry have shown potentials of Augmented Reality especially for the purposes of progress monitoring, defect detection, model evaluation, model validation and model updating (Rankohi and Waugh, 2013). Rankohi predicts a high potential for collaborative AR systems which enable users to update and synchronize information from a remote location through internet and web-based solutions (Rankohi and Waugh, 2013). Friedewald et al. presented collaborative AR systems connecting on-site workers and distant engineers for remote support purposes in aviation as well as shipbuilding industries (Friedewald et al., 2017a, 2017b). The solutions describe a basic infrastructure to organize the AR instances and connect the collaborating partners. In contrast AEC industries offers with BIM a mature and open data standard environment which enables collaboration in a standardized way. BCF enables managing issues in real-time so that the responsible person can be identified reliably and the issue can be remedied quickly. Although the potential of collaborative AR solutions has been proven, the approaches have to be customized to be compatible with the BIM environment.

Park et al. have presented a framework supporting issue management using BIM and AR. The application focuses on detecting wrong measurements by performing a visual comparison of the as-built (reality) and the as-designed (virtuality) situation (Kwon et al., 2014; Park et al., 2013). The solution uses marker tracking to match virtuality and reality. This requires a high effort for positioning markers in the real environment or otherwise causes tracking errors. Kwon therefore addresses markerless tracking approaches for future developments (Kwon et al., 2014). In general it seems to be difficult to detect small defects with the approach of visual comparison since it is just a qualitative assessment. Especially very small or very large dimensions cannot be visualized in a suitable manner on a small screen of a handheld device. Once more it is unclear how issues are processed by the BIM environment after creation. It cannot be assumed that everyone involved in the construction process uses the exact same solution for creating and visualizing issues, that is why the use of proprietary solutions is questionable. Koch introduced the use of natural markers like exit signs which avoids the high effort for placing markers (Koch et al., 2014). The approach is helpful for a general navigation inside a building but not for precise information overlays since the position of natural markers are known only approximately.

3. INSPECTION PROCESSES AND THEIR CHALLENGES

3.1 Activities during Inspection Processes

Inspections during and after the construction phase aim at approving or declining a delivered construction work. If a deviation between the as-built and the as-designed state of a work occurs, a construction issue is present (Berner et al., 2015). Inspections require the participation of different parties which exchange information concerning present issues. In general three parties are involved in inspection processes: The customer, the main-contractor and several subcontractors (Marsh, 2001). A customer has a contract with a main-contractor. The main-contractor therefore is responsible to fulfill the agreed work packages. However the agreed work is not fulfilled by the main-contractor itself, which is why he instructs subcontractors to fulfill sub packages of the total agreed work and thereby creates a responsibility from their side towards him.

Because of the contractual relationships and the mutual responsibilities, issues noticed during inspections have to be processed across multiple parties involved in the construction process (see Figure 3).

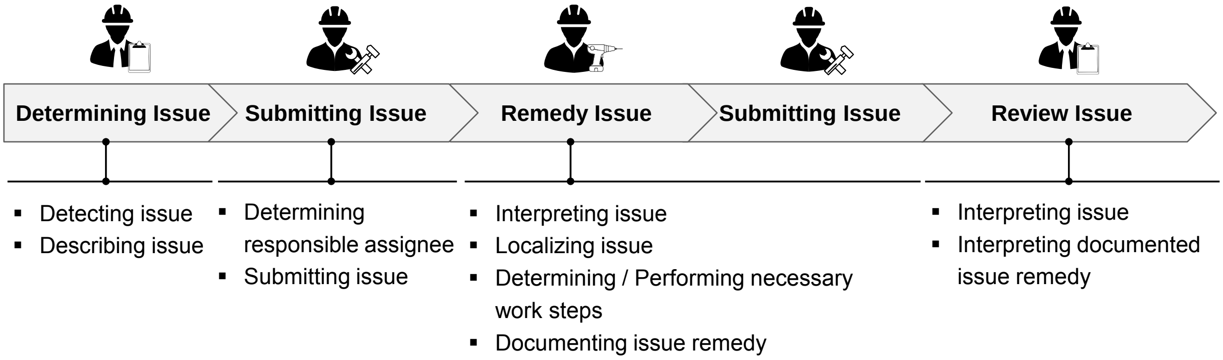


Figure 3: Activities during Inspection Processes

The process can be described based on an example from dry construction: A customer detects a presumably wrong measurement between two drywalls during an inspection with the main contractor. Because the main contractor engages a subcontractor for dry construction he has to pass the issue to him. Because many subcontractors are involved in the construction process not every subcontractor can participate in the inspection, which is why the issue has to be described with words and documented with pictures as precisely as possible. The main contractor determines the responsible person of the subcontractor and submits the issue to him. Later the workers of the subcontractor read the issue, have to interpret the exact problem and localize it in the construction environment. They determine necessary work steps, perform them and then document the remedy of the issue with a status complemented by pictures. The remedy has to be submitted back to the main contractor, who then informs the customer about the successful remedy.

3.2 Factors of Information Exchange

When passing an issue from one person to another an information exchange takes place. This exchange process is the field of action in this paper. To get a more detailed understanding about the process and to compare different solutions in the following, four descriptive factors are defined (see Figure 4).

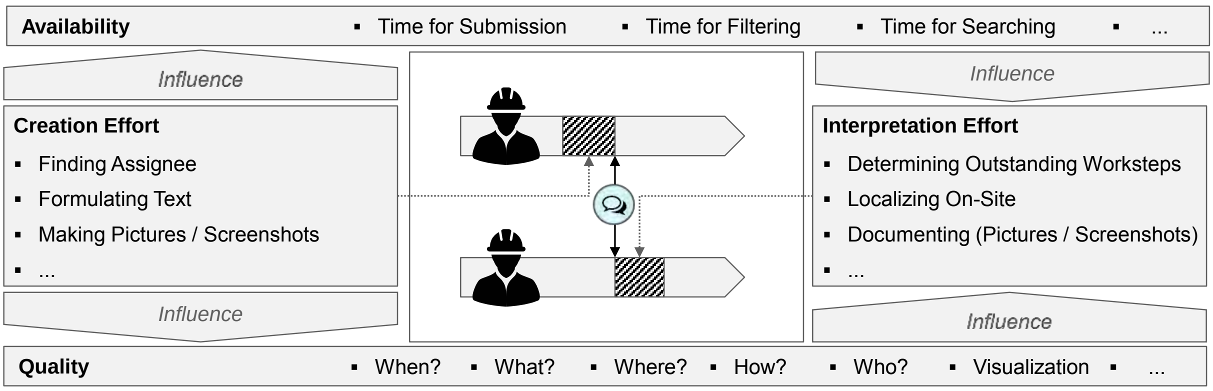


Figure 4: Factors of Information Exchange

1. Quality: The quality of an information is the precision by which it describes the message to be transferred from the sender to the receiver. Halata therefore analyzed the flow of information in shipbuilding processes and mentions four questions an information has to answer (Halata, 2018): When?, What?, Where? and How? Since Halata concentrates on already personalized worklists, a high quality issue description in the context of this paper furthermore needs to answer the question about who is responsible for the remedy of the issue.

- **When** does the issue need to be remedied?
- **What** element / which work step is affected by the issue?
- **Where** exactly does the issue occur?
- **How** does the issue have to be remedied and which boundary conditions have to be taken into account?
- **Who** is responsible for the remedy?

2. Creation Effort: However, the information needs to be created, which requires a certain effort. Text has to be expressed, pictures must be taken. The effort for creating the information directly influences the quality of the information. If the issue is described in more detail, the information represents the content of the issue more precisely. On the other hand the quality does not directly correlate with the size of the information content. Large-scaled descriptions might blur the real issue leading to a bad quality. In this regard the effort for creating the information is the second factor.

3. Interpretation Effort: Depending on the quality, a certain effort is necessary to interpret the information. Imprecise formulation of the answers to the questions mentioned above leads to difficulties when understanding the actual issue and determining outstanding work steps. A missing information (for example where exactly the issue occurs) leads to additional effort (the responsible worker has to search the exact point on-site). Furthermore studies have shown that the effort for interpreting information (concerning the four questions named above) is much higher when the individual answers are displayed separately from each other (Chandler and Sweller, 1992). The third factor of information exchange is the interpretation effort.

4. Availability: The last factor of the exchange is the availability of the exchanged information. A fast remedy of an issue can only be achieved if the information is transmitted to the responsible person as fast as possible. This means the information needs to be technically available for the recipient as soon as possible after creation. The information is easy to find and not hidden in between other irrelevant information (short time for searching / filtering).

3.3 Challenges

Previously the relevant parts of the BIM environment were presented. Existing AR solutions were discussed and a deeper look at the processes on-site was taken. In summary the following challenges are present:

- **BIM Integration**: BIM gives us a mature and open backend to route data from one party to another. There is a high amount of BIM tools for creating, viewing and editing BIM data. When developing a new tool in the BIM context, this environment has to be taken into account to be suitable in the long term.
- **AR Tracking**: One of the key deficits of current solutions is the used tracking technology. Markers have to be placed with high effort or are unprecise. A solution should primarily strive for a low initialization effort.
- **As-Built vs. As-Designed**: An Inspection aims at comparing the as-built situation with the as-designed situation. This means a rough visual comparison but as well a detailed look at certain measurements.
- **Collaboration**: Issue management involves many different parties. A solution therefore needs to support collaboration concerning the technical exchange as well as the visualization for a certain user.

The solution described hereafter supports the issue management process by explicitly addressing these issues.

4. SMART INSPECTION

4.1 Approach

To support the inspection process, the ***Smart Inspection*** application was developed. It is a solution using the AR approach to support inspectors as well as workers concerning the management of issues in construction processes. Figure 5 shows the basic structure of the approach.

Figure 5: Smart Inspection Approach

On one side, the application gathers all information concerning the as-designed status of the construction elements from the BIM, more precisely from the IFC part of the BIM. Information can be the target geometries, target measurements, the structure but as well information like the manufacturer for a certain element. All of this becomes part of the application in the form of virtuality. On the other side, the application captures the reality which represents the as-built status. Information which have to be included are actual geometries, actual measurements, the present defects which later on issues refer to and the user itself.

Combining both sides within one Augmented Reality application leads to several functionalities supporting the inspection process. The approach provides a fast and precise issue creation, an easy to use setup process for the AR tracking, tools for comparing as-designed but as well as-built measurements, support of IFC models and data and the support of different AR hardware. In the following the implementation of this approach is presented by the example of a tablet application but later on as well by an implementation on the Microsoft HoloLens.

4.2 User Interface

The user interface (see Figure 6) is split up into four areas: Geometrical visualization and camera view in the middle, textual information area at the bottom and two sidebars for interactions on the left and right. It is the main user interface of *Smart Inspection* and is used by the inspector when creating an issue but as well by the worker when working on issues.

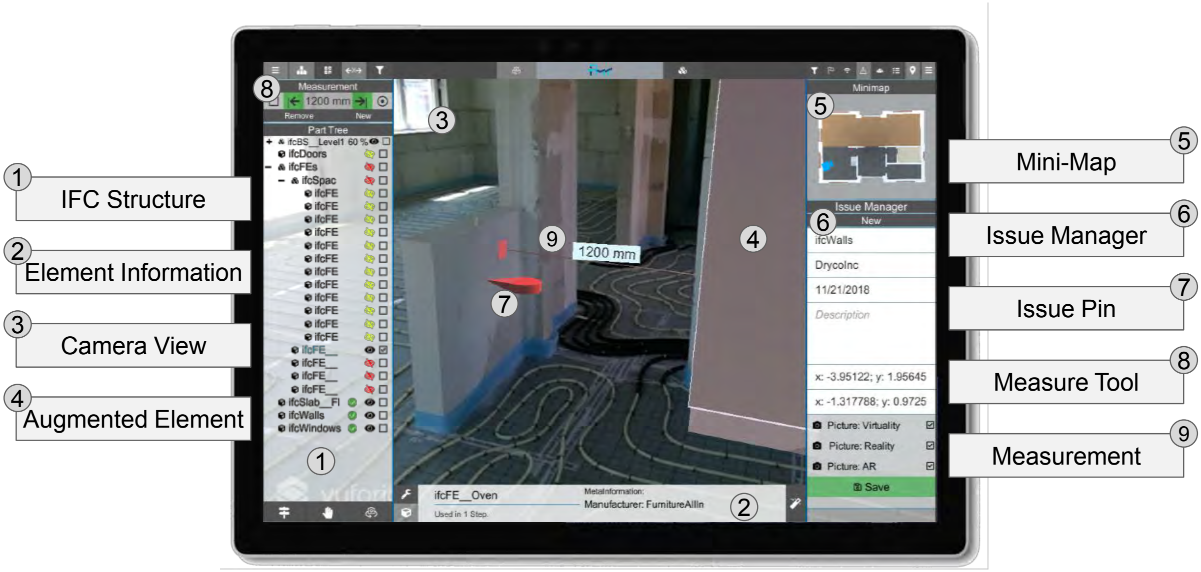


Figure 6: Smart Inspection User Interface

The left sidebar shows the structure of the loaded IFC model ①. Elements can be selected and are highlighted in the visualization areas. Information like the manufacturer of an element are shown in the textual information area ② and the 3D model is displayed as an overlay of the device camera view (③/④). A mini map shows the position of the user within the model from a bird's eye perspective to give the opportunity to orientate more easily ⑤. The issue manager ⑥ in the right sidebar is the central element for creating and reviewing issues. It is designed as a form which can be filled manually but partly automatically as well. After initializing a new issue, the user can hit a spot on the screen (2D). The system calculates which (virtual) element was hit and where exactly (3D). The hit spot is indicated with an Issue Pin ⑦. Here a simple screen to world point transformation based on the IFC model is applied (unity, 2018). The selected element enriches the issue form with its GUID and assigns the issue to its manufacturer. The due date of an issue and its description can be typed manually with the onscreen keyboard or (depending on the used hardware) generated with a speech to text module based on (Microsoft, 2018). Since the Viewpoint can be extracted from the AR tracking data, several bitmaps (pictures / screenshots) can be generated in the background: The pure camera view showing the real environment, the picture of the augmented environment (camera + AR), a screenshot of exclusively the virtuality from the exact same perspective, a screenshot from different preconfigured perspectives (for example in each direction of the coordinate system), a screenshot only of the element that has been hit and furthermore. The process for creating those bitmaps runs in the background of the application. When working with a Microsoft HoloLens instead of a tablet PC the 2D interface becomes a 3D interface floating in the users view (see Figure 8: ①). User inputs are performed with speech and gestures.

4.3 AR Tracking and Initialization

As mentioned in section 3.3 tracking is one of the key challenges for AR applications. *Smart Inspection* uses a markerless tracking which directly uses the IFC model to detect the device's pose. The **Model based tracking** system tries to detect a known virtual 3D model in the camera view (Figure 7 bottom). Therefore edges are extracted from the camera feed and compared with multiple perspectives on the virtual object. The best fitting perspective is the result of the tracking procedure. To limit the possible perspectives and therefore enhance the process, the method needs an initialization pose. Normally this pose is preconfigured which makes the system inflexible and not suitable for the use case. With *Smart Inspection* the user can select the initial pose with the use of an additional CAD view (A) by navigating through the 3D space with common multi touch gestures. When switching to AR mode the last perspective in CAD is taken as the initialization pose (B1) and the AR experience can start (C).

Tests with *Smart Inspection* on a building site showed, that this approach works fine for distinctive areas with a lot of corners and edges but fails for ambiguous ones like clean white walls. Therefore a second, **marker based tracking** approach was implemented in the tracking framework, For a successful tracking, the system requires a printed marker at a known position in the real environment (Figure 7: top). The marker is detected by the camera and the tracking system calculates the relative position to augment virtual elements in the right perspective. To bring the marker into the reality usually high measuring efforts are necessary. With the so called dynamic-marker-positioning of *Smart Inspection* the user places a virtual marker in the CAD view on a surface in the virtual working area. With an edge detection running on the 3D meshes, the marker automatically aligns on virtual surfaces' edges (B2). Because flushness is a condition which is easy to reproduce in a real environment without any measuring mechanism, the user can easily place the real marker flushing with the real edge. The marker tracking and the AR experience can start now (C).

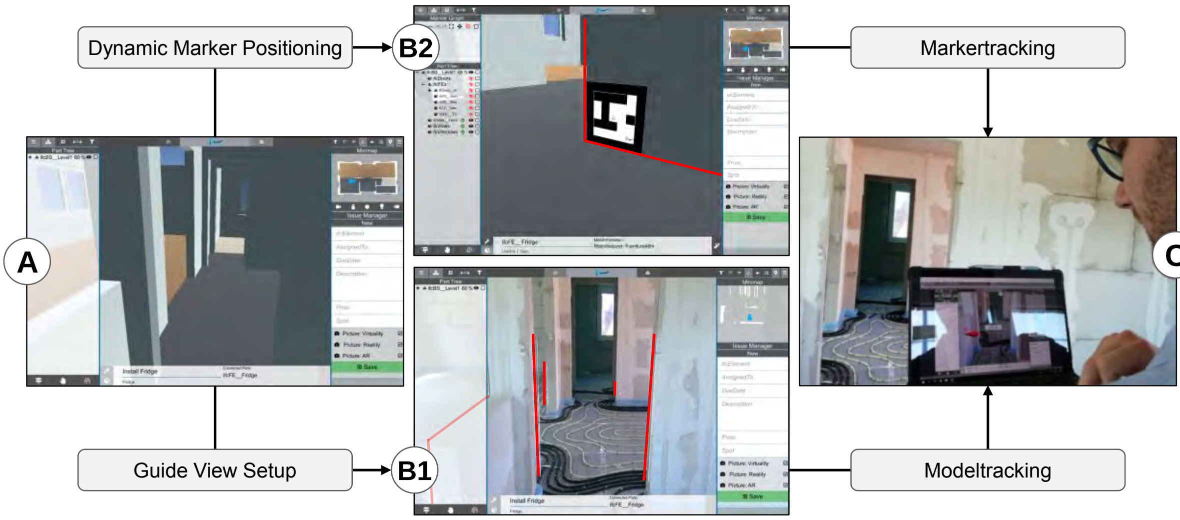


Figure 7: Tracking Technologies

Both tracking technologies base on the established tracking library Vuforia (Vuforia, 2018). Both are complemented by the so called *extended tracking* mechanism. This ensures that the tracking remains stable for a while even if marker or model are no longer captured by the camera. Nonetheless stability and quality of the tracking decrease when moving too far away. When using the Microsoft HoloLens the internal incremental tracking mechanism which uses depth information of the environment (see also Figure 8 left) can be used to track the relative change of the device's position and orientation. This mechanism complements the tracking and leads to much more stable results even if the device is moved far away from the marker / initialization pose.

4.4 Measurement Tools

Since a visual comparison of as-designed and as-built situation is not suitable to detect very small or very large deviations, extended measuring mechanisms are implemented in *Smart Inspection*. Capturing measurements from the as-designed model is straightforward: With the measurement tool (Figure 6: ⑧) the user can fulfill point to point and point to plane measurements by selecting two points. The system calculates the distance based on the IFC model (virtuality-virtuality) and the resulting measure ⑨ is shown in the geometrical visualization area. Measuring between two points in reality (as-built) or even between one point in reality and one in virtuality is much more difficult. The tablet solution implements a Bluetooth protocol for wireless laser distance meters. A measure between two virtual points therefore can be complemented with the response of the laser measuring between the corresponding two points in reality. When using the Microsoft HoloLens the depth information (spatial map) of the environment can improve this task. The two points for a measure can be placed directly on the spatial map (see Figure 8). This enables the user to perform reality-reality but as well reality-virtuality measurements to check the as-built status against future elements.

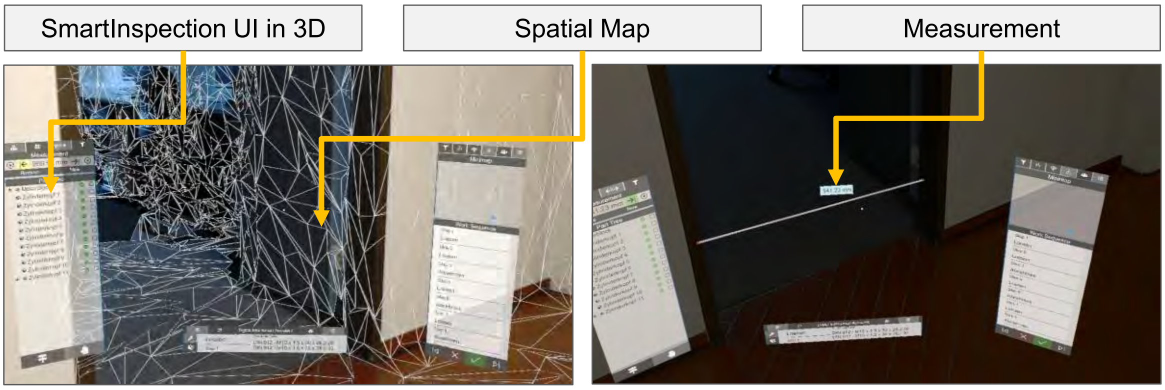


Figure 8: Measuring with the Microsoft HoloLens

4.5 Export and Import

The creation process is designed to match the BCF data standard described in section 2.2 (see Figure 2): The responsible person, a due date and the description are saved into a topic connected to the selected ifcElement. The topic then is enriched by comments representing the as-built and as-designed measurements which are saved with a reproducible syntax. The actual perspective of the user (more specifically of the AR device) is saved in a viewpoint. The exact 3D spot (coming from the hit point) is saved into a line element as a part of the viewpoint definition by specifying the same starting and endpoint. The viewpoint is then extended by the automatically generated pictures and screenshots. The issue answers precisely the questions When, What, Where, How and Who. Because of the strict use of the BCF data standard, issues created with the *Smart Inspection* application might be reviewed with conventional BIM viewers as well.

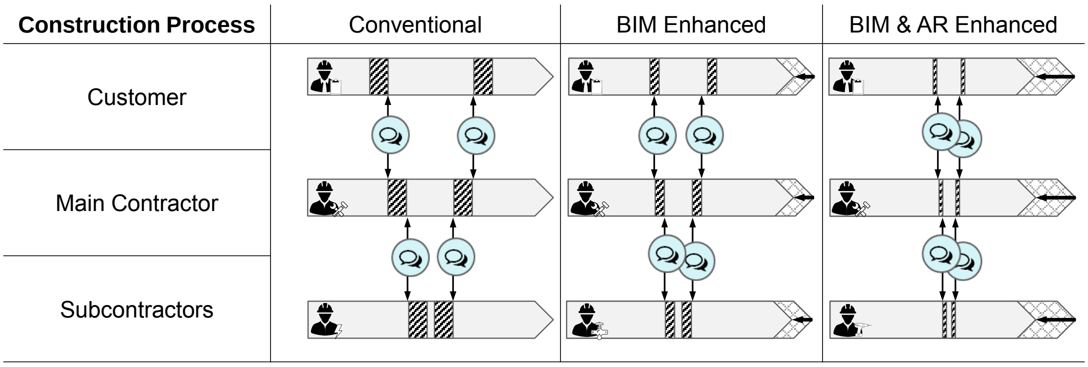
When opening a BCF container with *Smart Inspection*, it parses the issues and maps them to the 3D space. The application provides a FlyTo mode (CAD mode only) (Friedewald et al., 2016) and an arrow navigation (AR mode only) to find issues fast in 3D space. If orientated properly the application can be switched into the AR mode to get the information overlay and find the exact location of the issue in AR. With a Freeze function, the AR view can be frozen and the tablet then be put aside to get the work done and simultaneously have the AR view as a reminder. After completion or if questions occur, the issue can be complemented with comments or pictures / screenshots which are generated in the same way like for creating the issue.

5. BENEFIT OF SMART INSPECTION

For comparing *Smart Inspection* with a conventional (paper based) and a BIM enhanced process for managing issues the four factors of information exchange (described in section 3.2) were assessed qualitatively (see Figure 9). The assessment rates the fulfillment from - - (very bad) to + + (very good).

In **conventional**, paper based processes, the as-designed situation is represented by 2D drawings and textual specifications. If the as-built situation seems to differ, photos are taken and the issue is documented in written form or just kept in mind before transmitting it to the corresponding person. The information are often complemented with additional red ink annotations in the drawings and pictures of the site. The responsible subcontractor is looked up later in the process documentation. Because of the manual processes, the effort for documenting the issue properly is very high. The quality of the information is low because the central questions are often hidden in lengthy descriptions and multiple information carriers (speech, text, picture, drawings) are used. When interpreting the information, the transfer thinking from 2D to 3D has to be performed once more which is why the effort is very high.

With the use of **BIM Issue Management**, the availability of information is increased massively. All issues are present in the BCF container and can be exchanged in real-time. The creation effort is fully digitized, but filling out digital forms and taking screenshots / photos still leads to medium effort. Although the quality of the information is good because all necessary questions are addressed, information are still presented at distant areas and not directly where needed. When interpreting the information, the level of abstraction is lower, because of 3D representations, but the information still have to be transferred from a 100% correct digital environment to the present as-built situation in reality.



Factors of Information Exchange	Conventional	BIM Enhanced	BIM & AR Enhanced
Creation Effort	- -	o	+ +
Availability	- -	+ +	+ +
Quality	- -	o	+ +
Interpretation Effort	- -	-	+ +

Information Exchange · Creation / Interpretation Effort · Reduction of Process Time

Figure 9: Potential of BIM & AR Enhanced Inspections

The *Smart Inspection* extension of the existing BIM Issue Management with **AR enhanced** input and output devices solves the remaining deficits. Screenshots and pictures are taken automatically and simultaneously. Furthermore issues are localized precisely on a more detailed level than the BIM element structure since the user can point directly at the corresponding spot and the AR device can evaluate the coordinates in the BIM environment. Information are of high quality because all information are presented bundled and directly at the point of interest. Furthermore the level of abstraction when interpreting the information is much lower because the user does not have to switch between visualization device and reality. The reduction of effort for creation and interpretation but as well the higher quality lead to a reduction of downtimes for handling information. A higher information quality additionally can avoid inquiries and on-site meetings which as well leads to a reduction of the overall process time.

6. CONCLUSION AND FUTURE WORK

Smart Inspection is an Augmented Reality application which enables inspectors to create issues with a high depth of information quickly and easily. With just one click on the screen an issue is created, photos and screenshots are generated, meta information are extracted from the corresponding BIM and the issue is saved in a BCF compatible format. The continuous flow of information without media disruptions leads to a more efficient construction process and time savings. For the AR experience, *Smart Inspection* implements a marker and a model based tracking technique which both are enhanced with an easy to use initialization process for setting up the system on-site in seconds. The concept has been implemented on different hardware (Microsoft Surface / Microsoft HoloLens). During an early analysis in a construction environment the potential of *Smart Inspection* has been proven. The qualitative assessment is based on rating the introduced four factors of information exchange: *Creation Effort, Quality, Availability and Interpretation Effort*. Although the challenges resulting from common solutions have been mainly solved, the AR tracking system needs improvements before an extensive use of *Smart Inspection*. The approach of model based tracking in combination with the initialization process is user friendly and easy to use but the reliability, stability and quality of the tracking is not suitable. Patience is needed to detect the initialization pose and to start the AR experience. The spatial map of Microsoft HoloLens is only suitable for rough measurements since the accuracy is >10mm. Finally the BCF format is supported entirely but not tested in combination with a server based workflow. Future work will focus on those challenges and aims at a quantitative evaluation of the system.

7. ACKNOWLEDGEMENT

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I-TRACKER

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ABSTRACT: *This paper introduces a next-generation augmented reality-based modeling for Construction Engineering Management (CEM) projects using mobile devices to empower situational learning in the field of civil engineering through visualizing Building Information Model right into the physical context of each construction activity or task. This paper discusses an approach on how BIM can be extended to the job-site via the AR. i-Tracker retrieves design information from existing parametric-engineering-design- object database (architectural, structural, mechanical objects) and create a fully animated scene using Augmented Reality. We calculate the position and orientation of the device with respects to the area it is in and create a virtual world around the user. This paper also discusses efficient methods for Indoor 3D feature tracking to address the demanding tracking needs of Augmented Reality (AR). Indoor real-time positioning and tracking systems have been gaining increasing interest due to the significant progress of mobile devices, portable devices and the necessity of a solution for Augmented Reality services. This paper also discusses the challenges of building a mobile-based application using large-scale Building information models which possess a greater number of objects. We present on how to import and render these objects on the mobile or a head-mounted display device for smoother transitions in the application. We discuss in brief the steps to pipeline the Building information models into the unity platform which is eventually used in developing the application. We provide in this paper with the evaluation results of the i-tracker project and briefly discuss the challenges faced in feature tracking such as luminance, the processing speed of the system, ambiguity in the features tracked, etc.*

KEYWORDS: *Indoor Tracking, Augmented Reality, 2D feature Tracking*

1. INTRODUCTION

This paper aims to explore an innovative approach that integrates advanced computing and information technologies to enhance situational awareness experiences at the job site. This research thus empowers project stakeholders, personnel in-situ, to incorporate advantages of new technology to immerse users to visually experience the location the design in-situ at scale and in context during walkthroughs.

Although visualization of project designs through virtual models such as Building Information Modeling (BIM) has improved the quality of understanding of the maps (Woo, 2006), much in-situ personnel still fail to relate and use abstract knowledge to anticipate problems at the job site.

This paper presents the initial results of a study aimed to design and implement an interactive augmented reality (AR) learning tool to assist personnel in-situ to develop a comprehensive situational awareness that leads to the understanding of designs and its associated text-based information such as the specification of products. The tool presented in this paper is a component of our *i-Tracker* concept. *i-Tracker* is a learning environment that is composed of sensors, and mobile computing and wireless technologies to enable users to simultaneously view: (1) location tracking, using an indoor-position system for location awareness and navigation management; (2) spatially located design components, using computer generated 3D objects as Augmented Reality (AR); and (3) static modeling of surrounding objects, using scanned surfaces and reference data as annotated point clouds. The outcome of this ongoing project will be the design and implementation of a learning tool that uses augmented reality (AR) visualization and real-time object tracking to enable students to develop a comprehensive understanding of the CEM projects through real-time interaction with a remote site. *i-Tracker* aim is to enhance engineering design cognition using computer-generated information representation, ultimately improving design interpretation skills by transferring critical contextual issues (e.g., location of materials, functionality of temporary structures, installation sequence of design components) from a physical context into the AR environment. It is expected that our approach will significantly enhance the users' (construction personal in-situ, construction engineering learners) systematic understanding and coordination among engineering systems, designs, construction resources (e.g., materials, parts, and equipment), processes (e.g., erecting a steel structure), and the organizational aspects of a project (e.g., the management of multiple trades in a construction activity). This coordination requires the integration of spatial and temporal information, which is imperative in many engineering contexts, especially CEM, as the processing of complex spatial-temporal configurations routinely impacts efficient reasoning and problem-solving in the management of construction-related activities. Spatial information defines how construction resources are related to one another in a contextual space, and temporal information specifies the order, sequences, and hierarchies of the resources in a process. Individuals' abilities to relate the spatial and temporal information and representations (engineering designs) is their spatial-temporal cognitive ability (P. Antonenko & I. Mutis, 2017; P. D. Antonenko & I. Mutis, 2017; Ivan Mutis, 2014, 2015; Ivan Mutis, 2017).

2. LITERATURE REVIEW

2.1. Augmented Reality

Augment Reality (AR) is a computer technology that differs from virtual reality (VR) which combines virtual objects and real-world images that are inputted through a camera in real-time, where virtual objects not only come into view as part of the user's environment but also interact with them (Azuma, 1997). As interest in Augmented Reality has grown over the past several years, so has the demand for visual tracking methods that do not rely on artificial markers or fiducials.

Due to the recent advances in technology, many new AR implementing techniques have come into existence. The typical AR executing procedure using mobile computing devices is as follows. First, images of objects are detected by the camera and the relative positioning and location of the device is estimated by mapping the image data to the point cloud data. Next, virtual objects are registered with the physical location using estimated information. Finally, virtual objects are combined with real-world images.

2.2 Augmented Reality in the field of Architecture and Construction Engineering

Recent advances in computer interface design and hardware power have fostered a certain number of noted recent AR research prototypes or test platforms in the arena of construction (Aggarwal, 1999).

2.3 Building Information Modeling

During the past decade, BIM concepts have been actively explored for expanding the usage into any construction environment. It is encouraging that this expansion is moving away from merely 3D modelling, towards more engineering analyses and various construction business functions. In 2008, McGraw-Hill Construction (Construction, 2008) surveyed about 300 practitioners who involve BIM in their daily work. One of the significant findings is that BIM has been used in a wide variety of ways with diverse functions, however, surprisingly, only 18% use BIM for daily construction monitoring work of the management crew. Nothing has been done or even conceived to use BIM for construction site use that can guide the hands-on physical tasks of workers. Designing in BIM is one thing, and effectively building according to as planned is another thing. During construction, BIM information should drive the physical deliverables of the construction.

2.4 Expanding BIM to Immersive Technologies

BIM visualizations are on the completely virtual position on the reality-virtuality continuum. Very few endeavors have been made in the past to explore BIM using immersive technologies like augmented reality and virtual reality. Existing approaches are aimed at building immersive environments. For example, Wang and Xiangyu (Wang, 2014) had integrated building information models and AR technology to control onsite construction process for liquefied natural gas industry. Irizarry and Javier (Irizarry, 2013) had also stated a mobile-based augmented reality approach to accessing building information through a situation awareness approach.

3. METHODOLOGY

The goal of this AR system is to integrate virtual objects of 3D Building information models (Woo, 2006) with a real-world environment at construction sites on a mobile computing device or a light-weight wearable solution that allows real-time augmentation via a head-mounted display (HMD) without obstructing the user motion. In this contribution, we empower the user to gain situational awareness while providing indoor positioning and structural view of the object and the construction project progress.

The system is mainly divided into 3 Phases as discussed below (See Fig 2).

Phase1: Application Development and Deployment
Phase2: Post Deployment
Phase3: Augmenting the virtual Objects

3.1 Phase 1, Application Development and Deployment

This is the phase where the input is given to our system. In our case, the input is a building information model. The application is developed using a game-based engine development platform (e.g., Unity3D). The workflow to pipeline building information model from Revit to Unity is as follows.

The BIM model is exported from proprietary based file (e.g., rvt) to an interoperable standard. In this case, the BIM model was exported to FBX format. This FBX file is then imported into our project's assets folder inside unity. The building information model is later referred to as a Game-Object inside unity. Building Information Model plays a significant role in our system. This BIM model is the source of data. Our system retrieves the BIM which is an object notation of 3D construction models and visualizes the 3D model at construction site aligning those objects to their physical existence, thus creating the user a visual glance of an entirely built construction site. Each game object in the application is associated with an invisible layer surrounding it which is called a collider. These colliders help in detecting the collision. Every time a game object tries to encounter other game objects the colliders of both the game objects intersect and informs the object regarding the collision. The same way these colliders also helps in detecting touch input. When a user tries to touch a game object on the mobile device, the collision happens with the collider of that game object. BIM game-objects in the application is associated with colliders to implement physical features to the virtual objects. These virtual colliders are attached with event listener functions and are provided with a specific task to perform whenever they collide with other colliders like mouse pointer of finger touch collider. In our system, each object of the building information model displays its name and changes color when touched or clicked.

The application is thus developed and is ready to be deployed. The deployment of the application was developed on Android Software Development kit to compile and build Android Package Kit(apk). This APK is then installed as an application on the Tango Android Device (Google Project Tango, 2015).

3.2 Phase 2, Post Deployment

This Phase consists of the design and implementing the indoor positioning approach for localizing the augmented objects to the physical world via Visual based localization Techniques such as Motion Tracking which allows a device to analyze its motion as it moves through an area. We initially scan the physical area where our system is augmented, and the features tracked in the site are stored as a file which is later retrieved by the system to align 3D objects to the physical area.

Our system uses a mobile computing device as the main viewpoint. As the user moves his or her viewpoint, the computer-generated objects must remain aligned with the 3D locations and orientations of real objects. In markerless AR application, alignment is dependent on tracking (or measuring) the real-world viewing pose accurately as opposed to marker-based AR systems which use targets. The viewing pose is considered as a six-degree of freedom (6DOF) measurement: three degrees of freedom for position and three for orientation. The tracked viewing pose defines the projection of 3D graphics into the real-world image, so tracking accuracy determines the accuracy of alignment.

The camera in the mobile device captures the scene frame by frame, since the elements in the frame act as landmarks. This vision-base system mainly relies on the camera. The mobile device is also equipped with sensors such as an accelerometer, gyroscope which are used to combining with the visual features. The system projects an Augmented Reality (AR) virtual 3D media into the user's view as a superimposed layer of the real world in real time. Ideally, it appears to the user as if the virtual 3D objects (text, models, or images) exist in the real environment. One of the critical requirements for accomplishing this illusion is a motion tracking system that measures the position accurately and the orientation of the observer's location in space. Without accurate motion tracking and registration, the virtual objects will not appear in the correct location at the correct time, diminishing the level of immersion regarding the co-existence with the real objects. The computing device we used consists of a powerful gyroscope that provides orientation data based on rotatory motions across all the three X, Y and Z axis. It also comprises of 3-axis accelerometer which helps as to know the acceleration in all directions. Hence, we can monitor change in all the 6 degrees of freedom. We also use an l6 MP fish-eye camera to help us identify the position and orientation of the device. As we are handling spherical images from the fisheye lens, care must be taken to compensate the spherical distortions using local planar rectification. Also, the camera rotation is measured using a 3 Degree of Freedom inertial sensor at a 100Hz rate. The rotation data is used to compensate for fast head rotations and to predict image feature positions. With the combination of these three sensors, we devised a novel way to identify depth which finally helps us in the identification of a change in the position of the device to the environment. Figure 1 Depicts the various steps involved in our system.

For motion tracking, we incorporate a highly efficient 3D tracking approach based on Koch (Koch, 2005). The approach uses a markerless Image-based 3D Tracking for virtual reality, which technique is divided into three components: (1) Tracking initialization, (2) 2D feature tracking, and (3) 3D pose estimation. The approach also aided by an accelerometer and a gyroscope. The system runs two separate threads (possibly on a 2-processor unit) that separate the 2D feature tracking from the 3D Structure from Motion (SFM) pose and structure computation. The estimated 3D pose along with visual augmentation is superimposed onto the user view.

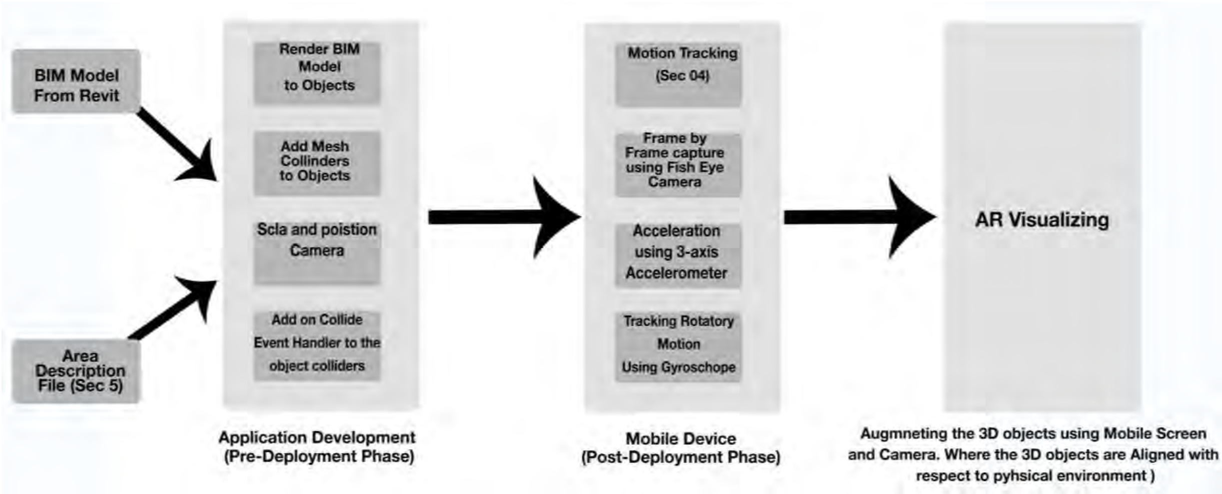

Figure 1: Overview of the System

3.2.1 Motion Tracking

The system needs to know when we move. This can be achieved by Motion Tracking which is the method of recording the movement of an object and then applying the tracked data for the movement of another object. The device should be able to analyze, understand, and orient to the physical world which is made possible by the data collecting hardware like cameras, gyroscopes, and accelerometers, etc. Therefore, understanding the environment to render augmented experiences by detecting planes is crucial. The 3D tracking system facilitated by the 3DoF inertial sensor discussed in section 3.2 is divided into tracking initialization, 2D feature tracking, and robust 3D pose estimation.

3.2.2 Tracking Initialization

This is the initial step in our systems. In this initial step, a set of most noticeable 2D intensity corners are detected in the first image of the sequence. These 2D features are then tracked throughout the image sequence by local feature matching with the KLT operator. To further facilitate 2D matching, the 3D camera rotation velocity is measured by the inertial rotation sensor and the rotation is compensated in the images.

Feature-based vision systems have better performing results when salient features are registered and tracked from frame to frame. The challenge is not tracking selected features but their association with the physical points in the world (Shi, 2000). We consider and identify the most noticeable 2D intensity corners as our window. With small inter-frame displacements, a window can be tracked by optimizing some matching criterion with respect to translation (Lucas, 1981), (Anandan, 1989) and linear image deformation (Förstner, 1987), possibly with adaptive window size (Okutomi, 1992). Feature windows are selected on the measure of texturedness, such as a high standard deviation in the spatial intensity profile (Aggarwal, 1999), the presence of zero crossings of the Laplacian of the image intensity (Marr, 1979), and corners. In 2D feature tracking method, the patterns of image intensities change in a complex way. However, away from occluding boundaries and near-surface markings, these changes can often be described as image motion.

3.2.3 2D features to 3D structure projection:

From the given 2D features from the previous step, an SFM approach (Hartley, 2003) can be applied to estimate the metric camera pose and 3D feature positions simultaneously.

The tracking from fish- eye cameras leads to an especially robust tracking for two reasons:

1. The field of view covers a vast scene area whereas moving objects include only a small part of the scene, which tends to be static. The second reason is subject to substantial and jerky rotations of a camera when mounted to a human head. The rotation sensor partially compensates this rotation, but still, the head may rotate the camera quickly out of view. This will not happen quickly with a fisheye camera with a hemispherical view.

2. It can be shown that a full field of view stabilizes the pose estimation (Davison, 2004). For perspective cameras with a small field of view, the motion towards the optical axis is always ill-defined because the camera moves towards the focus of contraction (FOC). Only the motion perpendicular to the FOC can be estimated reliably. In a spherical image, image position is always perpendicular to the FOC; hence the estimation of the camera motion is always reliable.

3.3 Phase 3, Augmenting 3D objects

Our System has two functional modes. One is Area learning, and the other is augmentation (see Figure 2). Area learning is where the application renders the user's physical location frame by frame. Once this location is rendered the users' path or motion along with the tracked feature details are stored in a file called ADF. Augmentation is the other phase. If the system recognizes that an ADF file is available already, then it imports this file and matches the stored 2D features with the ones inputted from a fisheye camera and thus localizes the virtual objects accordingly.

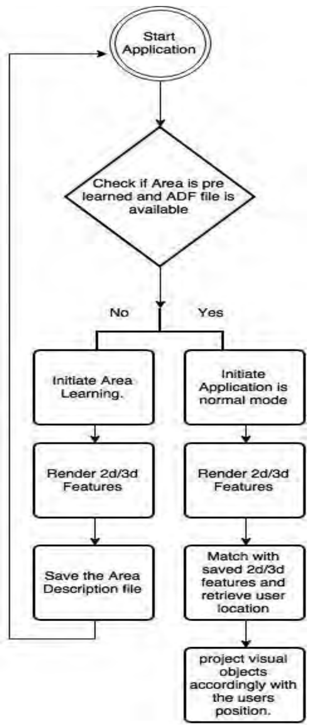

Figure 2 Flowchart of the system.

3.3.1 Generating Area Description File

In the previous step, we have stated that the 3D feature positions are determined with a rotation relative to an initial camera position and up to an unknown overall scale which would be inserted into the system from external data (Koch, 2005). This data in our system is referred to as Area Description File or ADF.

ADF contains metadata of 2D features tracked in the location. This ADF file is generated as follows:

1) The application is set to learning state. During learning state, the application starts with the camera position coordinates as (0,0,0).
2) The users walk through the area in the real world while holding the device tight. Meanwhile, the system tracks the movement of the user with respect to the real world.
3) As stated in step 3.2.1 for motion tracking the system relies on the good 2D features that it sees in the path of user moment.
4) These features will be combined with the relative camera position coordinates as metadata which is then stored as the ADF file.
5) As a single camera cannot calculate the 3D scale (cameras only measure rotation), we need the help of another sensor to measure the missing camera scale IMU. By the help of a gyro and an acceleration sensor, we can compute scale and fuse both camera and IMU measurements such that the time stamps of camera and IMU are time-synchronized (millisecond precise) and correctly match IMU and camera measurements.

Hence at any given 2D feature, the camera position coordinates with respect to the initial position of the camera are known.

3.3.2 Localizing in the previously learned area:

In the previous step, the application is set to learning mode where it only checks for the 2D features to track in its way and stores them in the file rather positioning itself. However, the application in this step is set to actual running state. The metadata created in the previous step is used as the reference points for the device to position itself in the area that it learned previously. As soon as the application is loaded it imports the user specified Area Description File. Later it detects the 2D features in the physical area and searches for similar features in the loaded ADF file. Once the features are detected the application retrieves the camera position coordinates and adjusts itself accordingly.

4. VALIDATION AND EXPERIMENTATION

All experiments mentioned in the paper are conducted on an Android-based device called Project Tango(Google Project Tango, 2015), a technology platform which enables mobile devices to detect their position and navigate the physical world like a human walking around an indoor and outdoor environment.

The first device featuring Google Tango was an Android platform tablet, which was released in June 2014. Since then, several applications have been developed using its motion tracking and depth sensing technologies similar to our system. We used Unity to develop our system. The 3D building information model is built using Revit and then imported to unity Environment where the 3D mesh is rendered, and respective mesh colliders are added to the objects of the BIM.

On top of the motion tracking and Depth Sensing evaluation metrics of Project Tango discussed as in Raffle's paper (Roberto, 2016) we would discuss some additional metrics which are keenly related to the augmentation of Building information model at construction sites. Metrics are as follows:

4.1 Viewpoint changes and ambiguity

In section 3.2.3 we have discussed how our system detects 2D features and build a 3D structure using structure from motion. The major factor that influences the 2D feature detection could be ambiguity. Ambiguity could also be referred to as the duplication of features in the same area.

As a use case consider using the system in a three-store building where every floor of the building has a same architectural view with regards to ventilation, coloring, and alignment of different components. In this case, 2D features detected in every floor of the building is same and then area learning features detected in section 3.3 could be error prone while using the system in such environment. Figure 3 depicts a similar kind of situation faced while running the application.

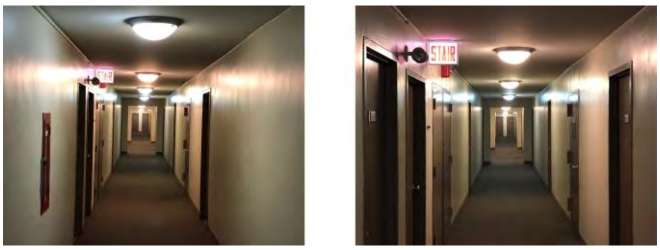

Figure 3: Images captured on two different floors whose view look alike and thus causes ambiguity for an area learning

One solution for this problem could be adding latitude, longitude and altitude attributes to the area description file and retrieves the appropriate features based on the 2D features detected along with the latitude, longitude, and altitude observed at a position.

Viewpoint changes are one of the significant factors that influence the image matching techniques like scale-invariant feature transform (SIFT), Speeded up robust features (SURF), Binary Robust Independent Elementary Features (BRIEF). In our use case, as the system will be used in the construction sites, a drastic change could be counted for viewpoints. A controlled experiment is designed to evaluate the performance of SIFT matching for the image-based positioning system. Multiple images from the same position are shot during the multiple stages of construction and at different Time periods.

4.2 Spatial Mapping

Building a representative 3D model (Surface Reconstruction) of the site comes in handy as it helps in creating 2D and 3D Floor Plans in Construction. A high-resolution mesh based is generated on a point cloud which renders in mapping the environment. Data can be collected by walking through the construction site with Tango device. With the wide-angle fisheye camera combined with motion tracking capabilities of Tango stack, it creates a dataset of the environment which is then uploaded in the cloud. Additionally, different mapping runs for each given site in every frame will detect hundreds of visual features which can be computed to find the 3D location of corresponding points in the scene. These collected datasets are then processed, aligned and compressed using middle-out into a cloud map. This mapping is based on purely visual feature tracking(Google Project Tango, 2015).

Every capture and recapture of a site is incorporated to the map which helps in improving overall modeling. Finally, after localizing, we can move through the environment looking for visual features and matching those against the stored cloud map. This provides continuous adjustment and alignment between device position and all AR content which has been placed in that space creating experiences that allow in-site personnel to have a shared experience across multiple devices. Thereby adding digital content to the real world and enhancing user satisfaction.

4.3 Illumination Estimation

For image-based positioning and navigation systems alike, which depend on visual information and image matching techniques for localization, one limitation is that illumination changes, which is especially common for outdoor environment, may affect a navigation solution. The reason behind is that most existing local descriptors including the SIFT are based on luminance information rather than color information. It also noted that in an indoor vision-based positioning scenario, lighting condition could be easily controlled and kept inconsistency.

Furthermore, let’s assume the system is only useable outdoor during daytime and sun is the only major light source in an outdoor scene. The only light source needing estimation from the sun will suffice as it provides primary lighting. Additionally, the sky which is providing secondary lighting can be estimated as ambient light. Also, in this case, the system should be constrained to only running under conditions with no precipitation, as it will alter the reflectance properties of the surfaces in the scene (Jensen, 2006).

4.4 Working on Large 3D models

One challenging aspect of i-Tracker is to import large-scale building information models and to build an augmented scene. We build our system on top of Unity 3D software. Each BIM file contains many building components called as objects. It has been observed from the experiments conducted that streaming large BIM models with more than 5 thousand objects makes the system temporarily unresponsive. In contrast, with small BIM model, motion tracking along with the camera position in the system is precise to the user’s physical speed and coordinates. The speed of the camera movement gradually decreases upon increasing the BIM model size, creating temporary unresponsiveness feel to the application.

Figure 4 shows the experiment being rendered with 100 and 500 objects respectively. The system rendered with 100 objects is Fast accurate and aligns 3D objects to the physical world accordingly to the user’s moment. However, while trying to augment with 500 objects, the system seems hanged or lagged. Moreover, the 3D objects attain a delay of few seconds to align themselves with respect to the physical world while the user keeps moving.

We can overcome this problem by limiting the no of objects to the ones that are visible to the user at any given point in time. All the objects that are not directly seen from user location at any given point are hidden or disabled and are reactivated only when the user reaches a particular point from where those objects are visible. This way we can restrict the system to process only a few objects per scene.

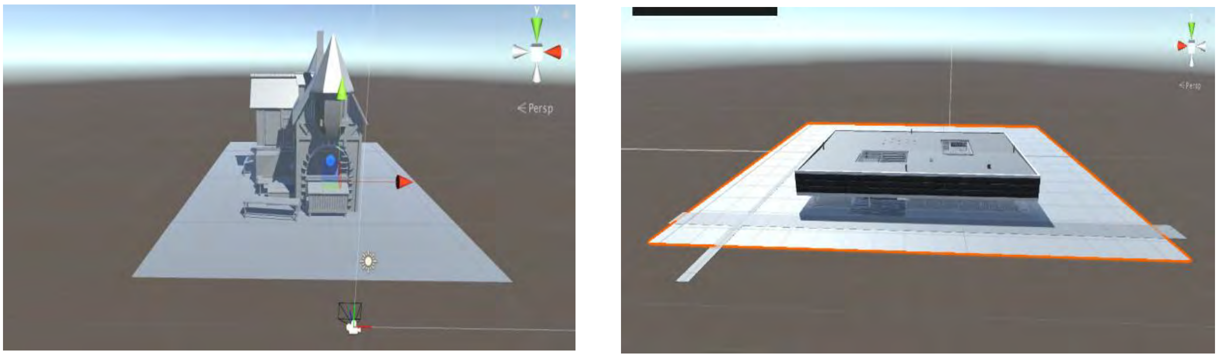

Figure 4: BIM with 100 objects (left) and BIM with 500 objects (right)

5. CONCLUSION

The presented approach shows the methodology for leveraging Augmented reality in the field of Construction and Architecture engineering to empower situational learning. This paper introduces an efficient method to Augment Building information models and create a virtual site visit experience for the students in the classroom and to extend Building Information model to construction sites through a mobile-based augmented reality application. The presented approach shows that a robust markerless 3D tracking from a fisheye camera system for real-time motion tracking in Augmented Reality applications. This paper also discusses concepts on Area Learning, indoor features tracking and indoor position system for integrating virtual object with the real-world environment. The system presented is in an early stage, and further fine-tuning is needed.

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KNOWLEDGE MANAGEMENT WITH 3D MODELLING SIMULATION FOR A SEAWALL CONSTRUCTION PROJECT IN THAILAND

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ABSTRACT: *Construction personnel can broaden their knowledge through education and job site experience, however most organizations cannot obtain informal/uncodified knowledge from these experts. Normally, implicit learning and tacit knowledge is not transferred, documented, and reused for solving constructability problems and creating standard work processes. To retain and articulate the information regarding best practices and learning lessons within a particular construction project, knowledge management (KM) is an efficient tool which can be adopted. This tool can be utilized not only for improving construction processes, but also for educating junior engineers. This paper looks at the adoption of knowledge management in a seawall construction project, applying a 3D modelling simulation, on the eastern coast of Thailand. Using this approach, users can visualize and understand the construction practices and knowledge of expert engineers. The 3D simulation developed on the project was demonstrated to undergraduate civil engineering students in order to measure their level of knowledge improvement of seawall construction. The results indicated that the 3D construction simulation can effectively enhance the knowledge of junior engineers and assist them in identifying problems prior to performing actual works.*

KEYWORDS: *Knowledge Management, 3D Models, Simulation, Seawall Construction*

1. INTRODUCTION

Knowledge management (KM) has been defined as the systematic process of creating, sharing, and utilizing knowledge within an organization, thus enabling an organization to exploit its intangible assets in order to achieve its goals and continuous improvement (Robinson et al., 2005 and Fernandez and Sabherwal, 2010). In the last two decades, the construction industry has become increasingly aware of the importance of adopting knowledge management (KM). Implementation of a knowledge management system can facilitate innovation, decrease project time, improve quality, enhance competitive advantages, and also lead an organization to success in their business (Love et al., 2003). In order to detach organization knowledge, there are two distinct kinds of knowledge, namely tacit and explicit knowledge. The first is individual knowledge that is stored in a human's head and is difficult to externally share or communicate. The latter is codified knowledge which is stored in a format type, such as manuals, procedures, or information systems. This kind can be easily transfered to other people (Nonaka and Takeuchi, 1995), but most of organization knowledge is tacit knowledge (Ly et.al, 2005). Due to its unique, complicated, and dynamic nature, the construction sector also depends on a human's heuristic (Tupenaite et al, 2008 and Dave and Koskela, 2009). A construction project requires experienced and skilled personnel who are competent in solving problems and executing complex tasks.Many previous studies have highlighted the desperate need for the implementation of knowledge management in the industry.. (Ly et.al, 2005, Rezgui et.al, 2010, Forcada et al., 2013, and Wibowo and Waluyo, 2015). Over the years, many tools and techniques have been discussed associated with using knowledge management and information and communication technology (ICT) to facilitate and collaborate the implementation of knowledge management application (Dave and Koskela, 2009).

This paper presents a particular case study of the adoption of knowledge management, applying the 3D modelling simulation, for a seawall construction project on the eastern coast of Thailand. Due to the difficulties of the construction project location, special skills and experienced personnel were required to perform tasks, such as project planning and controlling construction processes. Individual learning and tacit knowledge of experts was captured, stored, and transferred to novice engineering students. Using the 3D simulation approach, inexperienced staff can visualize and easily understand the construction knowledge of professional engineers. To evaluate the improvement in the knowledge of junior staff regarding seawall construction, the 3D construction simulation that had been developed was demonstrated to undergraduate civil engineering students, whohad to perform a pre-test and posttest to measure their level of knowledge

2. CASE STUDY

2.1 Study area

This seawall construction project, located in an area of a public hospital on the coastline of Chonburi Province, Thailand, was used as a case study for this research. The area had encountered erosion problems in the past and the existing seawall had been damaged not only by waves, but also by rainfall erosion, as shown in Fig. 1. Now, a new seawall construction project has been invested in by government and the new seawall will eventually be used as a recreation area for patients, patients' caregivers, and hospital officers. The components of this project consist of three parts which are on the left side and right side of seawall, and a multi-purpose building with port, as presented in Fig. 2. One of the leading construction companies in Thailand was awarded this 90 million baht contract.

Fig. 1: Existing damaged seawall at the case study

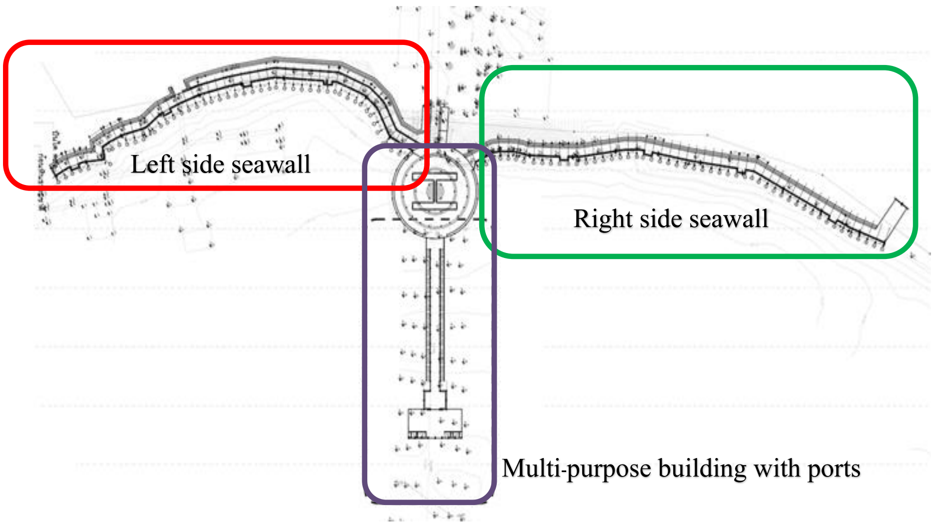

Fig. 2: Components of the construction project (Plan view)

2.2 Building Structure

In order to protect this area against coastal erosion, the type of building structure used has to be able to withstand the full force of waves and storm surge. An additional function of this seawall is to also provide soil slope protection because the cliff height is over 6 meters. Project designers selected the vertical seawall type to prevent water level going above the seawall's designed height. A typical cross-section of the reinforced concrete structure seawall is shown in Fig. 3, however the rigid vertical structure may lead to the reflection and scouring which will probably cause the subsequent failure of the wall. Piling was, therefore, applied to solve this problem.

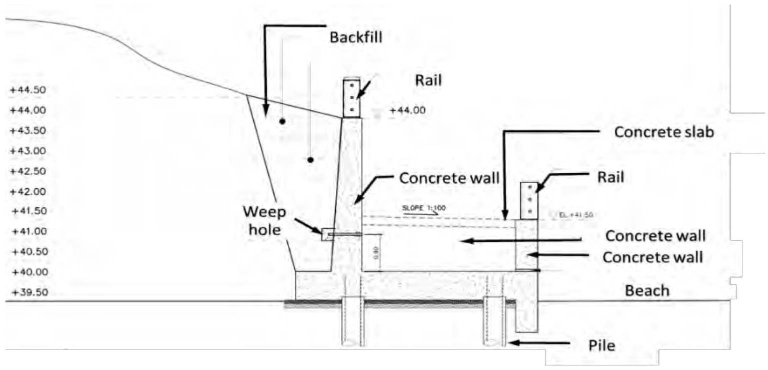

Fig. 3: Typical cross-section of seawall

3. METHODOLOGY

According to the processes of knowledge management, there are four main activities, namely discovering, capturing, sharing, and applying knowledge (Fernandez and Sabherwal, 2010). In this research, the seawall construction project on a coastline with a high, steep sloped cliff was selected as a case study for knowledge discovering. Construction practices and tacit knowledge were captured from the experts by using face-to face in-depth interviews, which were seen as the best way to retrieve data and information about how they managed this project. Three experienced engineers from the contractor company, who all had more than ten years' experience in maritime construction, were interviewed. These interviews were guided by a semi-structured questionnaire which was sent to them by e-mail prior for collecting more detailed data and information. The information about project management consists of site access and transportation routes, demolition and land clearing operation, stock yards determination, temporary works, wave protection, equipment selection, construction method and techniques for structural components such as piling, foundation, beam, slab, and wall, backfill and finishing work, and safety is inquired. After interviewing, implicit knowledge which is data and information about construction method such as equipment, processes, and special techniques was arranged, codified, and converted to explicit knowledge by using writing report and 3D simulated modelling software (SketchUp). Furthermore, narration of construction process and techniques was combined with 3D simulation for enhancing the audience understanding. The experts, then, reviewed this developed construction simulation, in order to correct and modify it until it was completed. In this process, meetings and brainstorming were conducted. In order to prove the achievement of knowledge management, the captured knowledge of seawall construction was demonstrated to 70 undergraduate civil engineering students who would be junior engineers in the future. Appling pre-test and posttest, which consisted of questions about equipment, process, and techniques about seawall construction were done. Testing data was analyzed by paired sample t-test (Ferguson, 1981 and Gravetter, 2009) at .05 level of significance to find out the improvement of the observations' knowledge.

4. RESULTS

4.1 3D Simulation of seawall construction

This section presents how the 3D simulation of the seawall construction was developed, using data and information collected and verified from the experienced engineers. There were eight main construction activities, which consisted of demolition and site clearing, access road preparation, site survey and piling location determination, piling, foundation construction, concrete slab construction, concrete wall construction, backfill and finishing. However, there were further sub activities within some of these eight main categories, for example, in the concrete wall construction process, there were three sub activities, namely reinforcement and formworks installation, concrete pouring, and formworks dismantling. Fig. 4 to Fig. 6 shows examples of 3D construction simulation for site clearing, piling, reinforcement and formwork installation. The equipment for the site clearing process in Fig. 4 (left) was a crawler hoe with 0.97 m^3 bucket size which performed with six wheeled trucks and a crawler hoe with breaker was applied to demolish the existing wall. In the confined area, heavy machines were replaced by hand held pneumatic hammers and workers had to carriy out these tasks. Due to difficulty of site access and high, steep sloped area, big pile driving equipment couldn't be transported along this coastline, thus the engineers prefered to select a tripod system for dry process bored piles as shown in Fig.4 (right). Techniques for piling construction, such as pile casing installation and dismantling, soil type consideration, concrete pouring were gathered. To construct piles and slabs, engineers had to consider tide tables for tidal prediction and planning tasks such as concrete pouring. When there are low tides, small sand bags and water pumps were used to protect structural components from raising water. The height of the concrete wall was more than 4 meters, stretching along the coastal path, therefore engineers decided to construct only half of its height initially. Once the first half of the structure has been complete, the second part of the wall will be constructed as presented in Fig. 6. Information regarding equipment, processes, techniques, and special considerations was arranged and narrated in the simulation. The overall completed construction project was depicted in Fig. 7.

Fig. 4: 3D simulation of site clearing and piling

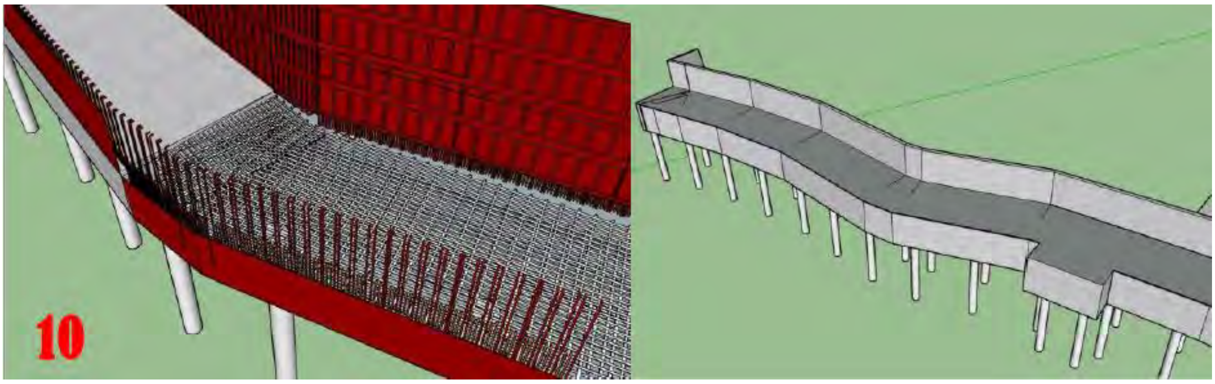

Fig. 5: Simulation of reinforcement installation and concrete slab pouring

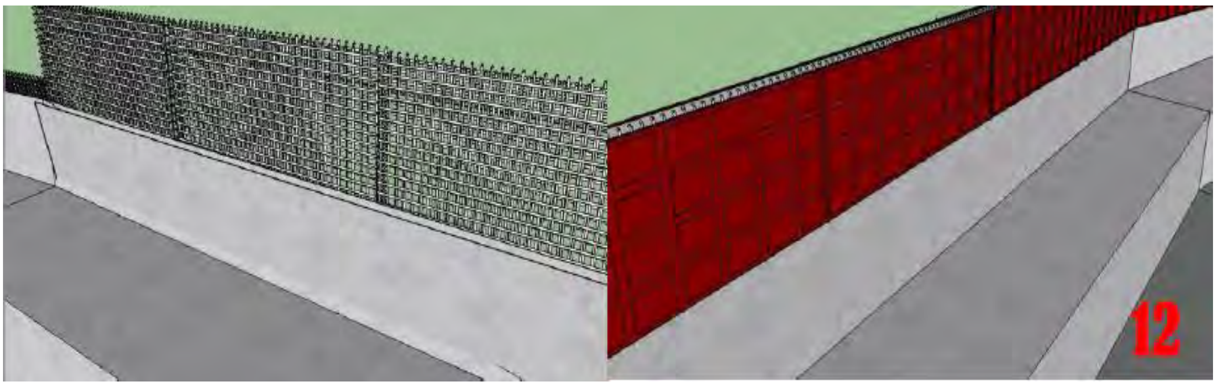

Fig. 6: reinforcement and formworks installation for concrete wall

4.2 Knowledge improvement of the observations

To evaluate knowledge improvement, fifteen questions, consisting of five multiple choices questions and ten right or wrong questions, were created and used to test undergraduate engineering students. The contents of the test questions included the definition of a seawall, suitable equipment for shoreline construction, methods for wave protection, type of bored pile for seawalls, overall construction processes, equipment installation approaches in maritime areas, techniques for protecting bore pile hole stability, demolition consideration, distance between bore pile position, machinery for site clearing, solutions for bore pile construction when discovering bedrock layers, effects of the tide table, concrete pouring techniques for wall construction. In this study, paired sample t-test hypotheses were determined as follows, the null hypothesis (H0) assumed that the mean difference is equal to zero and the upper-tailed alternative hypothesis (H1) assumed that the mean difference is greater than zero. The testing evaluation of 70 undergraduate civil engineering students is presented in Table 1. All of them were fourth year students who were going to graduate and work as engineers in the following two months. The mean score of the pre-test was 9.385 with a standard deviation of 1.80 and the mean score for the posttest was 10.786 with a standard deviation of 1.64. The test statistic t^* is 5.957, and the *P*-value is 9.72E-8. This result highlights that there was asignificantly different effect between pre-test and posttest knowledge on seawall construction at the 0.05 level of significance because the test statistic t^* (value)was greater than the critical value (1.667).

Fig. 7: 3D models of completed construction project

Table 1: The pre-test and posttest results

Evaluation	N	Mean	StDev	T	P
Pre-test	70	9.385	1.80	5.957	9.72E-8
Posttest	70	10.786	1.64		

5. CONCLUSION

In the construction industry, the implementation of knowledge management is still required to improve and sustain organizations. Tacit knowledge of experienced engineers must be discovered, stored, shared, and utilized for assisting junior engineers and developing innovation. Presently, information and communication technology is applied to fulfill knowledge management. Therefore, this research aims to adopt the usefulness of ICT for enhancing the level of knowledge management for the seawall construction on the eastern coast of Thailand. Knowledge was captured from the experts who had conducted the marine work in the leading construction company and then created a 3D modelling simulation using SketchUp. This obtained knowledge was transferred to 70 undergraduate civil engineering students via 3D construction simulation with narration. They were also tested before and after taking this class to evaluate their improvement. The results showed that there were significant differences between pre-test and posttest of these observations at the 0.05 level of significant and the mean scores of posttest was higher than pre-test. Thus, this knowledge of 3D seawall construction simulation can enhance the expertise of junior engineers who do not have the experience in that kind of construction.

6. ACKNOWLEDGEMENT

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AN OVERVIEW OF GENERATING VR MODELS FOR DISASTER ZONE RECONSTRUCTION USING DRONE FOOTAGE

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ABSTRACT: *Post-disaster building safety assessment typically involves visual observation of structural and non-structural damages to the building which often requires the observer to enter the building. Doing this will expose the observer to several risks especially if a structural failure occurs. Therefore, the inspectors must be aware of hazards at the disaster site. This paper aims to explore the use of photogrammetry model for reconstruction of damaged infrastructure within a disaster site, so it can be used for a real-life scenario in a virtual reality safety training. Previous studies focus more on large-scale or terrain visualization. However, there has been little known about photogrammetry's capability in visualizing a realistic interior that can be used to develop a VR training tool. This paper explains the process of developing photogrammetry-based model from data acquisition of UAV footage to model integration in the virtual environment.*

KEYWORDS: *Virtual Reality, disaster, training, photogrammetry*

1. INTRODUCTION

The practice of building damage evaluation, especially for early post-disaster damage evaluation, usually involves an observer to visually inspect the exterior of a building from the ground level. The rapid building inspection allows the inspector to quickly determine the damages based on established criteria shared by many countries (Anagnostopoulos and Moretti, 2008). This inspection plays a crucial role for the next phase, i.e. disaster recovery. It is one of the major focuses for any recovery team because hazards could threaten the rescue workers (Fardhosseini and Esmaeili, 2015).

Several approaches were conducted to do the inspection safely. Recent studies delved into the use of 3D scanning to help with the inspection. This would enable the recovery team to assess the damages to the environment and those to the surrounding facilities. In addition to help with the inspection, the product of 3D scanning can be used to recreate an interactive virtual reality environment as a tool to train the inspection worker. Using the training tool, training scenario can be developed to raise the inspector's awareness of safety issues at the disaster site.

This paper explored the idea of developing VR training scenarios for the recovery team by using detailed assets extracted from the post-disaster scenes recorded by drone footage. The researchers aim to establish the technical groundwork for future research. This paper will explain the conversion process, from acquiring images to incorporating the model into a VR environment. In addition, the paper also establishes a way to evaluate the viability of virtual reality as a medium for damage assessment.

2. LITERATURE REVIEW

2.1. Use of Photogrammetry in Disaster Mitigation and Response

Photogrammetry is the science of map-making by means of measurements on photographs. In the nineteenth century, this technique was used to conduct measurement from photographs. There are two approaches in photogrammetry measurement: terrestrial photogrammetry and aerial photogrammetry (Church and Quinn, 1948). As the name implies, terrestrial photogrammetry is a measurement of distance of points in photographs taken from ground level. Likewise, the aerial photogrammetry measures distances based on photographs taken from the air.

Photogrammetry were used to determine real-life measurement based on photographs. However, as of recently, it has been used as a method in 3D scanning. Photogrammetry technique is implemented in modern software application to create a point-cloud model, a representation of 3D model comprised of digital points instead of polygon. It has seen several uses including architecture visualization, historic preservation, and disaster mitigation and recovery.

One study utilized terrestrial photogrammetry for structural evaluation of a damaged building. The study involved the usage of custom-made equipment that was comprised of GPS, HMD, electronic compass, camera, and HMD to generate an augmented-reality overlay of a building. The results served as proof of concept of photogrammetry technology. However, the technology must be worn by an operator and the experiment was only conducted on the exterior of the building. (Dai et al., 2011)

Another method of photogrammetry is through aerial photography. In this method, the images are taken from an aerial vehicle such as plane or balloon by pointing a camera towards the ground. Recent technology advances have made it possible to use unmanned aerial vehicle (UAV) for data acquisition. This platform can be equipped with several measurement system such as small-sized video camera, LiDAR system, or infrared camera.

In general, UAV photogrammetry would require the operator to plan a flight path for the image capture process. From there onward, the UAV will either automatically follow the path or be controlled remotely by an operator. The image data acquisition can follow a computed 'waypoints' or based on a scheduled interval. (Remondino et al., 2011)

UAV photogrammetry, aside from being able to capture both small or large-scale objects, is easy to operate and provide a low-cost solution. Since they can be remotely controlled, UAVs can be used to navigate high-risk areas such as flood plains, volcano, or earthquake zone. Furthermore, UAVs are good aerial photogrammetry platform because data transmission can be done almost instantly. (Nishino et al., 2011)

Even though UAVs have limited maximum reach, it is still adequate for operator to monitor and capture an area from a safe distance. Thus, it is a preferred method in generating photogrammetry-based disaster map (A B Cahyono & R A Zayd, 2018).

Sophisticated software and better algorithm has made it possible for accelerated model generation, which enables incorporation of multiple types of technology into the data acquisition process. In a study conducted at a Bosnia-Herzegovina region, a terrain model was developed from a combination of aerial photo and laser scan mounted on a UAV. The combination resulted in faster workflow, allowing the researchers to capture a large area within a relatively short amount of time (Cescutti et al., 2018).

The advantage of UAV photogrammetry was also addressed in the study of a post-earthquake scenario in Italy. In the case study, a UAV was used to generate a photogrammetric model of an area previously hit by an earthquake. The technique provided high-resolution images to be used to generate several outputs including orthophotos and 3D models. The outputs can serve as a starting point for a reconstruction plan. (Dominici et al., 2017)

Based on the literature review it is apparent that photogrammetry offers a solution for post-disaster 3D reconstruction. However, most of them focus on large-scale aerial photogrammetry. As of currently, there is not enough precedence of using photogrammetry to model heavily damaged interior of a building. When conducting a visual assessment, a building must be thoroughly inspected by the inspector. Any visual damage, especially on the critical structural components, must be well documented (Associates et al., 1991). A building can appear not damaged from the outside while the interior could contain several hazards whether from the building itself or from other items that are still inside the building when a disaster occurred.

There are several potential use cases where interior photogrammetry can bring advantages:

- Visual assessment of post-disaster building safety.
- Rapid asset generation for disaster training.

Current software packages available on the market offer automated photogrammetry workflow. One of them is Agisoft PhotoScan. Agisoft outlined several best practices for image acquisition. In general, the images must be clear and overlap with each other. The suggested amount of overlap is 60% of side overlap and 80% of forward overlap. Good lighting also helps in achieving better results, especially when the object contains a lot of details. (Agisoft LLC, 2016).

2.2. Implementation of Virtual Reality

Virtual Reality Technology could enhance the understanding of subjects through representation. Even though it is a form of display, it brings additional benefit through immersion of the user in the virtual environment. This immersion brings familiarity to the user due to its interactivity.

The term virtual reality itself has shifted from generally any computer simulated 3D environment into a 3D environment that can be experienced using a specific headset. The shift is mainly caused by technology advancement and VR’s depiction in popular cultures.

In virtual reality, an operator interacts with the environment and manipulate virtual objects in several ways from motion controller, eye tracking, or positional tracking. Studies found that the virtual reality could enhance observation memory retention, especially when the operator is subjected to representation of objects in real life.

There has been attempts to bring real-world location into virtual environment. One research recreated a Los Angeles neighborhood in virtual environment. The model was developed manually by the research team. (Jepson et al., 1996). Even though there was minimal interaction within the virtual environment, it served as a foundation for future studies regarding urban visualization in virtual environment.

In learning process, virtual reality was found to be able to help with physical skills training. It has been implemented in several disciplines including military, flight simulation, engineering, automotive, and manufacturing (Vaughan et al., 2016).

Given the benefit of immersion and enhanced representation, virtual reality has been implemented for disaster preparedness training. Participants of the training also benefited from the controlled scenarios because parameters in the scenario can be modified to be suitable for demographic of the participants. (Farra et al., 2015)

3. METHODOLOGY

The general outline of the tool development covered in this study is comprised of two steps: creating asset and programming the interaction in a middleware. This paper emphasizes more on the asset creation, especially in the interior aspect of the building.

This study is generally limited to the development of the model as an asset for the virtual reality environment. To develop the asset, the researchers obtained the image data through online search for efficiency. A high-resolution footage was acquired from an online video sharing service and used as the primary case study for this research. From the footage, five hundred images were extracted to build the point cloud model. The point cloud model became the base model for the 3D polygonal model. developed and optimized for the virtual reality tool to be used for this study.

In addition to the environment asset development, researchers considered function that can facilitate evaluation of virtual reality as a medium to damage assessment. However, at this point of the research, the viability of virtual reality as the tool is yet to be tested.

4. RESULTS

4.1. 3D Scanning Process

The researchers selected a disaster site in the Philippines to develop the model. The site was hit by Typhoon Haiyan, also known as Super Typhoon Yolanda, in 2013. A footage of the disaster site was acquired from an online video sharing website with the permission of its creator. The footage shows a walkthrough of a collapsed building including the interior. In addition, there was a moment where the UAV captured the whole damaged city as demonstrated in the figure below.

Fig. 1: Original UAV footage of the selected disaster site, showing the interior of a building captured by the drone (Whyld, 2014)

With the footage, the researchers were able to generate a 3D model using Agisoft Photoscan. The software automated the determination of the camera positions and the generation of a resulting detailed 3D model. The software optimizes the automated model generation workflow so the output model can be used in other real-time visualization tools. In general, the workflow consists of:

1. Photographs alignment

This process is done to determine the camera position of each photograph in the 3D space. As demonstrated in the figure below, the process identified images that have overlapping details and placed them in a 3D coordinate system. Afterwards, the algorithm estimated each point's distance from the camera. This step is necessary for the software to build a sparse point cloud model. A default setting was used for the alignment. In our case, the images were sufficiently overlapping with each other and helped in improving the accuracy of camera position computation. Once this process was completed, the software marked the camera position and orientation, signified by blue boxes as shown in (Fig. 2). The blue boxes also indicated how the camera moved when the drone captured the disaster area.

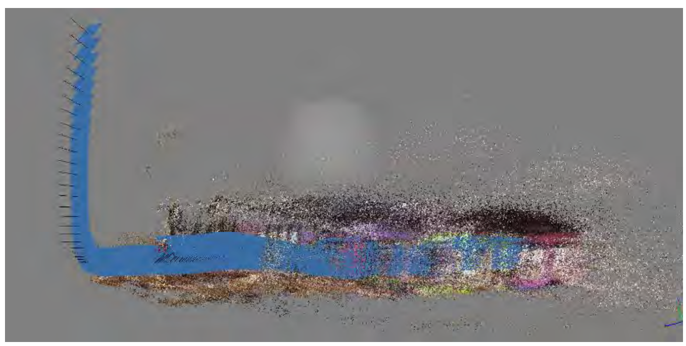

Fig. 2*:* Sparse point cloud model and camera positions. Camera position and orientation are denoted by the blue box.

2. Point cloud generation

There are two steps in this process: sparse cloud (Fig. 2) and dense cloud (Fig. 3). Either step could produce a 3D model, although the dense point cloud would generate a more detailed model.

Fig. 3: Dense point cloud model. This model is used to generate 3D mesh.

3. 3D mesh and texture generation

This step follows the algorithm of generating mesh based on the point-cloud data. For mesh, a high face count option was selected to build a highly detailed model. Once the mesh had been built, texture was applied based on the acquired images, as demonstrated in Fig. 4.

Fig. 4: Textured mesh in PhotoScan (left) and a screen capture of UAV footage (right).

4. Mesh Optimization

The process generated a model that was comprised of 1,317,226 faces. Since this would create a performance issue in mainstream hardware when running in virtual reality, the mesh had to be decimated into 50,000 faces. Despite the greatly reduced detail, the model still retains most of its original representation (Fig. 5).

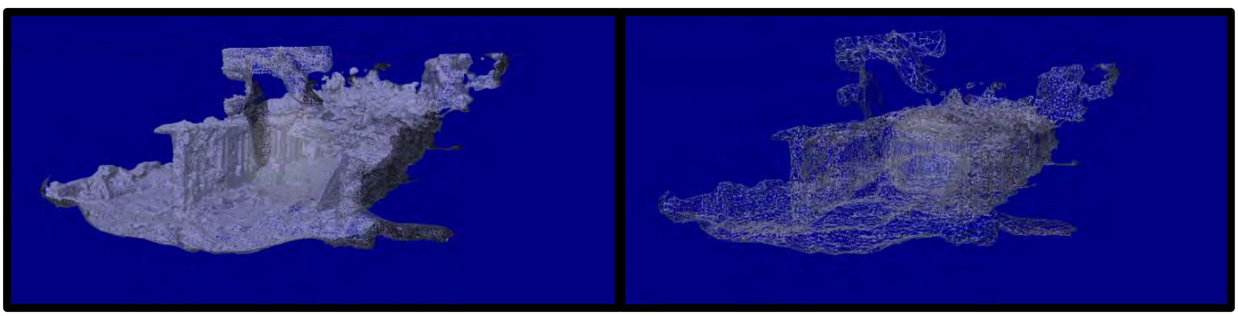

Fig. 5: Comparison between high-polygon model (left) and optimized model (right)

The decimation was done mainly due to the performance requirement in the virtual reality display, which must provide the user with a high level of comfort. The performance, represented in frame per second unit, must achieve 60 frames per second. In non-VR scenario, when a slowdown occurs, the image quality or resolution is typically reduced. This practice is not recommended in a VR scenario because it could induce discomfort and motion sickness to the operator (Kim et al., 2018).

4.2. Developing an Early Prototype for Building Safety Inspector Training Tool

User interaction with the intended training tool was achieved by using modified VR templates from Unreal Engine 4. Unreal Engine provides ready-to-use templates for virtual reality devices such as HTC Vice, Oculus Rift, and Windows Mixed Reality. Using this approach, the research could quickly assess the model in VR and optimized the model if any performance issue was identified.

The virtual reality template offered by Unreal Engine already supports several virtual reality headsets that are now available. Most of these headsets have the capability of both motion and positional tracking, which means movements in real life can be translated directly into the virtual space. In addition to physically move, the virtual reality template provides alternative solution to locomotion. Users can teleport using a motion-tracked controller such as the Vive or Oculus controller. This function is very useful when the user's physical space is limited. It also corrects users position relative to the shape of the terrain.

In this research the modification to the blueprint was done to the teleport mechanism. In the modified function, users would slowly fly/zoom in to the destination instead of teleporting. This approach was taken to minimize user's disorientation after teleporting.

The resulting model looks adequate in Unreal Engine 4 and can be used for a further study after some adjustment. More details need to be added especially on the roof area. In the original footage, the roof was not captured very well. Some adjustments were also done on the material by modifying the material's specularity and roughness in Unreal Engine 4. Originally, the material looked very reflective across all surfaces.

Fig. 6: Model in Unreal Engine 4.

Measuring the model's efficiency in representing a disaster scenario can be done to validate future researches using virtual reality. One approach is to use a gaze-based heatmap to evaluate which part of the model illicits more focus from a user as demonstrated in Fig. 7. Heatmap, also generally known as saliency maps are often used for tracking a user's attention. By implementing the heatmap, viewer's attention on specific parts of the 3D model can be visualized and analyzed. The visualization of the attention can be used for several purposes, particularly the usability aspect of the tool (Pfeiffer and Memili, 2016):

- To improve the detail of the areas that drew most attention from the user.
- To focus the development of disaster scenario within the area that received most attention.
- To evaluate the efficiency of the user interface used for the training tool.

It should be noted that most VR devices don't have eyetracking capability. The virtual camera's line of sight, which is synonmous with the user's line of sight, was used for the tracking instead of the user's eye. The heatmap function in this tool was achieved by altering texture value based on how long the user's line of sight intersects with the object in front of him/her. The color of the texture would gradually change from blue to yellow, and finally red. This process would loop until the texture reach its maximum value (red). In Unreal Engine 4, this inplementation was achieved through the engine's built in Render Target texture.

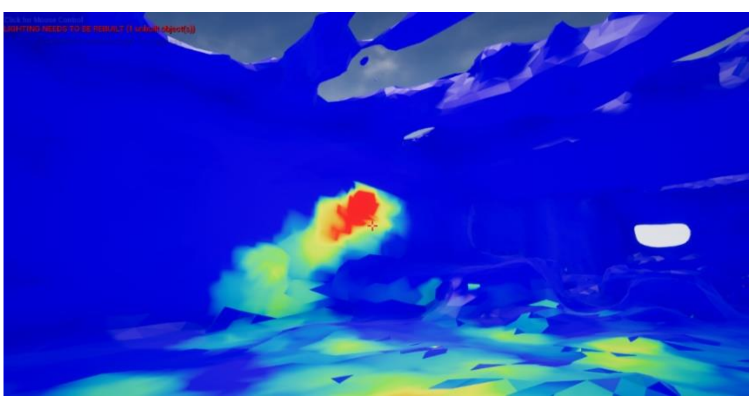

Fig. 7: Gaze-based heatmap implementation on the model in Unreal Engine 4.

The process of developing the heatmap texture appears to be efficient when the photogrammetry object was used. The photogrammetry object only uses a single texture map for the entire model. This allows for the researchers to create just a single heatmap texture for the model as opposed to multiple texture when the model was developed manually. The heatmap texture was set to 512x512 pixels as demonstrated in Fig. 8.

Fig. 8: A gaze heatmap Render Target texture in Unreal Engine 4. The white spots represent the area that was observed by the user. This would be translated into colored heatmap in the 3D environment.

This heatmap function can be used to determine whether a user could identify an existing hazard through visual observation. It is expected that when a user sees a hazard the user would focus his/her attention more on the particular hazard. As a result, the heatmap around the area of the hazard would be represented by the red color.

In addition to evaluation of the VR itself, the heatmap function can be used to evaluate the users themselves whether they were successful or not in identifying the hazard. This can be useful for training workers in post-disaster environment, so they can be aware of hazards that are present at their workplace.

4.3. Benefits and Challenges of Using Photogrammetry for Virtual Reality

The paper highlighted on how photogrammetry could help in rapidly generating a 3D model for disaster site reconstruction. This would offer greater benefits compared to traditional 3D modeling approach where the model is handcrafted:

1. Faster model creation and less effort since the recreation is done mostly by the software's algorithm. Handcrafting the model, especially since it is a disaster site, would require much time and effort.
2. Easier scripting due to the model was generated as one object, so references in the programming can be made to just one model.

However, the researchers encountered several challenges when attempting to bring the model into virtual reality:

1. The model had poor collision box. This could severely impact the experience as the user would clip through the floor because the collision box was not properly defined. To mitigate this, researcher created custom collision box within Unreal Engine 4. Handcrafted model could've easily overcome this difficulty because the modeler could easily adjust collision boxes when developing the model.
2. Due to Unreal Engine 4's limitation, the texture would display several artifacts due to the lower texture resolution. Handcrafted model could have more flexibility in terms of texture resolution because each object is modeled individually, unlike the photogrammetry object where the scene is modeled as one model.

This research was done using an adequate model. After several attempts, the researchers found that in order to recreate an adequate model there are several conditions that must be considered:

1. The amount of photograph should be able to cover most, if not all of the subject's surface. This would determine the completeness of the final product.

2. The photographs should have overlapping parts. By having several overlapping points, the software's algorithm would be able to accurately recreate the shape of the object as a 3D model.
3. Lighting in the image is important so the details can be reproduced by the software's algorithm.
4. Image resolution would allow for the produced 3D model to have better definition.

5. CONCLUSION

The photogrammetry approach was primarily used to generate 3D model terrain maps. However, this research explored the potential of using it as a more affordable and faster alternative interior scan method. The process might require laborious effort, especially in the image acquisition process. However, this can be mitigated by using camera footage instead of taking photos. In addition to work efficiency, using footage allows for flexibility in determining the number of images to be used for a better-quality model generation.

There are several arguments that support the importance of interior photogrammetry:

1. Visual observation of building requires the observer to enter the building. This might put the observer under risk due to potential unsafe condition inside a damaged building.
2. UAV can reach places that are not normally physically accessible by an observer. Thus, using the UAV to generate an interior photogrammetry model could help as a foundation for more detailed observation.
3. The model can be used as a real-life scenario for disaster safety training tool.

By incorporating the model into virtual reality, visual assessment can be done. Future research could study its efficiency in a safety training module by using people's memory retention when exposed to a virtual reality scenario using the model created during this study. The gaze-based heatmap system implemented in this study can be used as a mean to analyze trainee's attention on the model.

This study's subject is limited to a footage acquired from the internet which caused artifacts on the model due to video compression. Directly capturing footage from a UAV-mounted camera could have produced better model. There was also no assessment on the scale of the model compared to the real-world measurement. Therefore, future research could address the accuracy of UAV-mounted camera for model creation.

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USING THE RATE OF COLOR EVOLUTION OF A POINT CLOUD TO MONITOR THE PERFORMANCE OF CONSTRUCTION TRADES

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ABSTRACT: *Some of the conflicts between project planning and execution are attributed to the labor-intensive and inaccurate data collection mechanisms, which in many cases fail to identify delayed activities causing uncertainties during execution and ultimately preventing the onetime delivery of projects. To address this, many studies have looked into the generation of as-built models from the built environment using laser scanning, and its integration with BIM. Particular attention has been given to the development of as-built laser-scan data to generate a set of data points, or point cloud, to monitor the progress of construction projects. A point cloud represents, through a 3D coordinate system, the existence of a given object. With the proper equipment, they can be used to register the color property of a surface. The color of the points on a point cloud dataset has not been given a lot of attention, yet the rate of color evolution through time can be linked to the performance (through evaluating progress) of a given construction trade. This paper provides a conceptual framework that considers the color change of the point cloud over the construction of a project to assist construction managers to monitor their projects in real-time effectively.*

KEYWORDS: *Building Information Modeling (BIM); Construction progress; Delays; Image processing; Performance of construction trades; Point cloud; Project monitoring; RGB.*

1. INTRODUCTION

The purpose of construction progress monitoring is to assist project managers in identifying discrepancies between planned and as-built conditions, which might lead to schedule delays and cost overrun. Construction sites are characterized by the different construction trades working, on many cases concurrently, at different times. The crew assigned to accomplish a given task for a single discipline (i.e., carpenter, rebar installation. Masonry, plastering, painting) is associated to a trade, which may be a contractor or subcontractor. Although the different trades might not have a contractual relationship, their tasks are typically highly interrelated and affect each other at different levels; these interrelationships and influences are hard to include in the project schedules or traced during the progress of the project. In addition, due to the complexity and volume of work on site, it is generally challenging to determine the performance of individual trades, and track their impact on other tasks or trades. The current way in which construction activities (i.e., construction trades) are usually monitored, relies on manual onsite visual and verbal data collection. Processing the data collected is labor intensive, cost sensitive and can be prone to error (Yang et al., 2016). Delivering on-time support and incentives to potentially delaying trades, or rewarding best-performing ones, requires a dynamic and accurate progress prediction mechanism that can be used to support project teams during progress meetings, such as the ones conducted using the last planner system (Ballard, 2000) or Scrum principles (Sutherland, 2014; Streule et al., 2016).

The demand for accurate and efficient construction monitoring methodologies has increased the interest of researchers to focus on applications of Point Cloud Data (PCD) processing. In recent decades, the use of PCD has been widely studied for construction performance and monitoring (Braun et al., 2015; Tuttas et al., 2017). These studies are mostly focused on the development of methodologies to compare the as-built 3D PCD model with the planned 4D BIM model (Turkan et al., 2012). Attention has been given to imaging systems where PCD can be acquired with accurate point color information (Quintana et al., 2018). However, very less attention has been given to the color attribute of PCD in construction progress monitoring studies. An element in a construction site passes through phases of color change related to the project advancement. Construction trade performance refers to the proper functioning of various specialized disciplines involved in the construction process. Performance is primarily defined depending on the productivity, timeliness, and quality and safety aspects of construction (Lee et al., 2017). This is because, delays of a trade significantly affect subsequent tasks due to interdependency (Wambeke et al., 2014). Moreover, the cost is also highly affected by schedule overruns. Daily output is the quantity installed per labor hour (Lee et al., 2017).

1.1 Current advances in construction trade performance monitoring methods

The current construction monitoring practices are dominated by traditional (i.e., paper-based) approaches which are mainly related to inaccurate and delayed progress reports, and large file size which makes it difficult to store, read and analyze them. Moreover, inaccuracies and report delays result in misunderstanding and confusion (Behnam et al., 2016). Researchers have investigated the use of imaging technologies to overcome limitations of traditional monitoring systems. Laser scanning generates higher quality point clouds when compared to photogrammetry and videogrammetry technologies. However, photogrammetry and videogrammetry methods have better affordability and portability advantages (T. Omar & Nehdi, 2016). Omar et al. (2018) proposed a photogrammetry-based method to monitor construction progress. They captured images from different directions to ensure overlap. Moreover, images are captured after daily duty time to avoid obstructions caused by workers and equipment. Collected images were processed to develop a 3D point cloud model. Delays were determined by computing the difference between the geometric dimensions of the as-built and the as-planned 3D models; this made the system highly dependent on the mismatch between the dimensions of modeled and planned structures. This method keeps its accuracy limited to activities, which cause a change of volume on an element. In general, they were able to produce a progress report in less than one hour. However, the report does not provide details on the trades causing the delay. Another approach, proposed by Kropp et al. (2018), recognizes the state of construction from an as-built video data. The recorded video was transformed into a sequence of images which were registered on a 4D BIM model. Edge lines were extracted from the images to form the 3D as-built model. The comparison between the 4D BIM and the developed 3D models were used to identify delays. Their approach assumes fully visible objects with pre-defined lighting conditions. However, in real conditions partial visibility of the object and different lighting conditions created challenges. In addition, errors can potentially propagate in each of several interlinked registration and recognition processes. In their study, they indicated that the activities performed ahead of schedule may not be captured and registered accurately, creating a shortcoming of this method.

The previous work took advantage of image processing. However, data attributes on image files are not entirely exploited. Kim et al. (2013) developed a method of construction progress monitoring from 4D CAD simulation using color-based image processing. RGB site images were converted into an HSV (hue, saturation, value) image space to reduce the effect of luminance. In the meantime, the RGB image was processed into a binary image to obtain a clear difference between the construction items and uninterested equipment. Processed images were further filtered to get an as- built schedule. Merging an as-built schedule with a 3D CAD model, they have formed an automatic 4D CAD updating method. When comparing the developed automatic as-planned schedule with the actual execution, a 92% accuracy was achieved in progress identification. Unnecessary images interrupting the camera during image capturing was found to be a cause of error. Since productivity can be measured as the ratio of the amount of work installed to the time required for a given crew in a normal 8-hr workday (also known as the daily output), a reduction in the daily output would indicate a project delay. The decision-making process requires refined data to appreciate or support trades according to their onsite daily output (i.e., job performance). Although onsite construction activities can be automated (García de Soto et al., 2018), which will help with the improvements of productivity in the construction industry, it is challenging to automate labor productivity measurement (Navon, 2008). However, multiple construction crew management and monitoring approaches have been proposed to achieve the data refinement level required for an accurate decision-making process. Kaya et al. (2014) applied data mining techniques to understand the pattern and interlink between experience, crew size, and age with the construction productivity. Navon and Goldschmidt (2003) developed an automated data collection model to monitor labor inputs on a construction site depending on the movement and time spent on a specific spot where the path data is acquired using GPS and Radio frequency identification (RFID) methods. In this paper, we propose a new automated construction trade performance monitoring system which compares the rate of color evolution between computational values resulted from planned expectations and actual point cloud information. We prepare database composed of initial and final color status of elements to predict the rate of evolution on our as-planned color-based productivity determination stage. We transform Red Green, and Blue (RGB) space values of PCD color attributes into a luminary independent CIELab format. Moreover, we introduce a system of computing rate of color change between two construction stages from CIELab space to identify the performance of responsible construction trade.

Despite the data organization challenges, traditional project monitoring and forecasting techniques such as Earned Value Method (EVM) suffer clear separation between decisive factors (schedule, work, and scope) which results in performance measurement confusions (Vandevoorde & Vanhoucke, 2006). Chang and Yu (2018) recently proposed a three-variance approach to account the work variance in addition to the traditional cost and modified schedule variance. The incorporation of the new work variance in the method helps to separately measure the work performance and time performance status of project’s execution, and it can resolve index and variance interpretation confusions of the traditional EVM with particular importance for overdue projects. In this paper, we will quantify the amount of work with the color parameters and adopt the work variance approach to our progress monitoring method.

1.2 Color space selection for monitoring

The main challenge when using color as a primary property in construction monitoring is the selection of color space. This is because color is not an intrinsic property of a material as its characterization is derived from the properties of the light source, reflection characteristics of a material and the sensation capacity of the observer (Broadbent, 2017). Imaging technologies, which involve camera technologies, perceive the RGB color characteristics of an object. The numerical specification of a sample color can be found by filtering and computing the RGB values from the reflectance values at a series of wavelengths through the visible spectrum (Gilchrist & Nobbs 2017). However, this numerical color specification represents a particular lighting and camera condition. It is not feasible to maintain a specific lighting condition to precisely quantify the color difference between multiple stages of an element in a construction site. On the RGB color space, the three color components are sensitive to changes in illumination (Chen & Wang, 2017). Therefore, it is necessary to separate the luminance and chrominance information from the measured RGB values.

The Hue, Saturation, and Value (HSV) color space is the commonly used color space for image processing. The hue value on HSV color space is taken as the main wavelength obtained, while saturation is the degree of concentration of the color compared to white component and Value indicates the brightness. The effect of illumination is relatively smaller on the hue scale. Therefore hue is considered as the most relevant factor in image processing systems (Zou & Kim, 2007). The hue-based color difference could also be difficult to determine for colors such as achromatic or monochromatic, where both color properties could be highly perceived in construction materials like concrete. Achromatic colors (black, gray and white), have zero hue value, whereas monochromatic colors are known to have the same value of hue (Son et al., 2012). The other robust color difference method to overcome application challenges on the construction site is CIELab (Chen & Wang, 2017). CIELab color space models the color space on *L*, *a* and *b* color coordinates, where *L* (lightness component) is perpendicular to *a* and *b* arises. Characterizing lightness on the *L* axis. The chrominance components are represented by *a* and *b* values, where *a* is for redness – greenness quality and *b* is for yellowness – blueness quality (Gilchrist & Nobbs, 2017). Therefore, color stages of construction progress can be quantified by computing a space distance on an *a*-*b* plane. In this paper, data obtained on RGB space values are transformed into CIE Lab space for accurate color difference computations.

1.3 Point cloud Processing

Characterizing the color specifications of PCD acquired from a construction site requires accurate and efficient surface segmentation. However, the complex environment in the construction site frequently causes outliers, occlusions, the uneven density of points and disturbances in a point cloud (Xu et al., 2018). Therefore it is necessary to filter the measured point cloud data to reduce noise and obtain relatively accurate data suitable for further color based processing. Researchers have proposed various robust methods of point cloud filtering. Han et al., (2017) have presented an overview of recently introduced filtering approaches. On their paper, they have selected and compared seven different and widely cited filtering methods including voxel grid (VG), Normal based Bilateral Filtering (NBF), Moving Least Square (MLS), Robust Mean Least Square (RMLS), Weighted Locally Optimal projection (WLOP), Edge Aware Reassemble (EAR) and L0 minimization (L0).

The performance comparison between the methods was made depending on the efficiency (running time required) and the quality (error matrix). As a result, the L0 minimization method was found to be the most time taking while Voxel grid method was the most efficient regarding running time. However, Voxel grid resulted in relatively lower quality data while L0 provides the relatively certain filtering effect. The time-saving performance of NBF for a number of point cloud less than 200,000 was also revealed in their comparison. NBF was found to be slower than MLS, RMLS, and WLOP for point cloud data of larger than 500,000. MLS was computationally slower than VG and NBF (for point cloud data less than 200,000). However, it was also confirmed to have better accuracy than both VG and NBF methods. Although MLS provides moderate accuracy within reasonable running time, identifying sharp corners pauses a challenge. EAR (Huang, 2013) and RMLS (Fleishman et al., 2005) explicitly addressed edge recognition limitations of MLS. However, according to Han et al., (2017), relative to MLS, the EAR was six to eleven times slower. Moreover, MLS performed on average as twice as fast as RMLS does. In this study, collected PCD is proposed to be filtered using MLS method to take advantage of average time efficiency that it offers and the relatively better accuracy when compared with VG and NBF.

2. METHODOLOGY

The proposed method (i.e., conceptual framework) consists of three elements (Figure 1): 1) as-planned color based productivity determination, where the as-planned information is organized and processed to determine productivity, 2) real-time PCD processing, where the as-built information is structured to define productivity in terms of colors collected from site, and 3) trade performance identification, where trade performance is computed by comparing the rate of color evolution with the expected daily output (as-planned vs. as-built productivity).

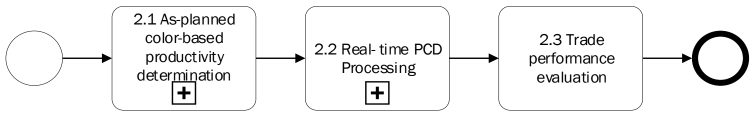


Figure 1: Proposed methodology

2.1 As-planned color-based productivity determination

In general, the level of detail of the BIM is not sufficient to track construction progress to the details of element-wise trade outputs (Han & Golparvar-Fard, 2015). The purpose of this study is not to improve the level of details of the BIM by breaking down tasks to sub-tasks or detailing activities, but to enrich the model with more information (in this case, color information), which can help the monitoring process used to evaluate tasks to the level of crew or trade. This can be achieved by linking the project schedule (start/finish of activities) with the color changes that the material(s) for the different activities will go through. Each color within the phase evolution is the result of the crew/trade work. The primary purpose of the first part of our methodology is linking each color observed of materials/elements to the expected time of occurrence based on the project schedule. Therefore, the first step is to enhance the general BIM model with additional task-specific color information (Figure 2). To achieve this, a database of material color information is established. The database is populated with processed material color data, which could be obtained from material suppliers and manufacturers. It is assumed that the color information made available at this time is for RGB, so conversion to the CIELab space is considered. It is expected that with time manufacturers will provide the CIELab information directly, so small modifications to the proposed process to avoid that extra step will be necessary. The color information of unique (i.e., first-time use) materials (e.g., materials to be produced on site), or for those for which the manufacturers do not have color information, is locally developed and is registered into the database for future use. The objective of incorporating color information in the existing BIM is to link the geometry and the schedule with color attributes and to define expected daily outputs, represented regarding the expected color evolution. This process is done for *m* number of materials.

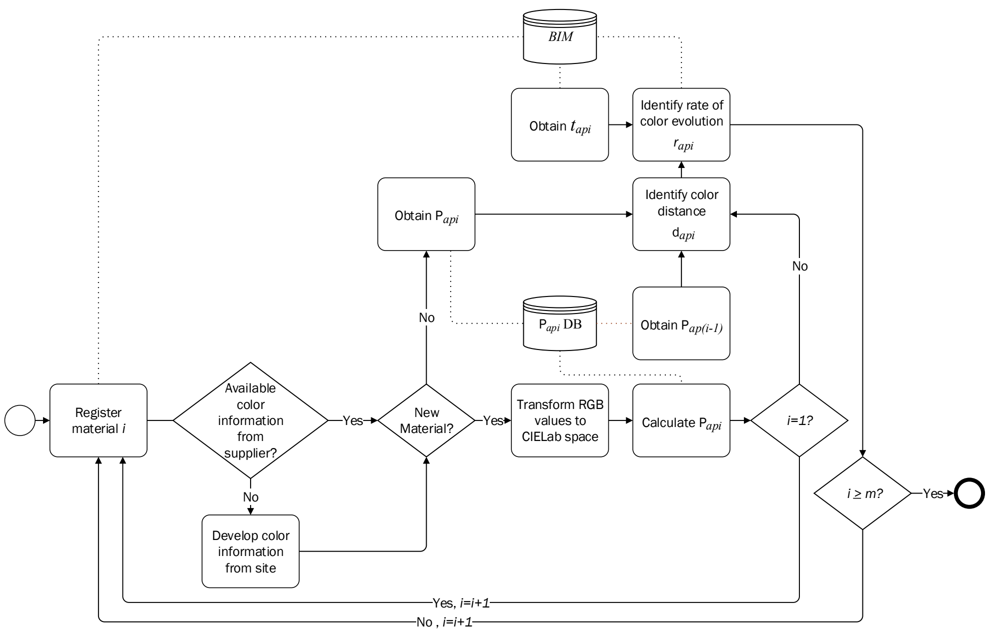


Figure 2: As-planned color- based productivity determination.

The space conversion is achieved using color space transforming equations presented by Gilchrist and Nobbs (2017). In this paper, the 10° standard observer position is assumed for all color space conversion computations.

The L component is ignored to avoid the effect of illumination and create a light source independent material property. A 2D coordinate points of the converted data is further analyzed to find the representative central point in the 2D color space. The centroid of the concentration of points, P_{api} (where subscripts *ap* is for as – planned and index i is for the material related to trade designation) on the a-b plane is computed using equation 1 (where P_i is P_{api} for as-planned cases) and used to define the color of a given building element pertaining to a given task (scheduled activity). Depending on the distribution and density of points in the a-b space, (a_{ci}, b_{ci}) is the coordinate of the color centroid representation points on a-b plane of material i; where n is the number of points on the space, and (a_j, b_j) are the j^{th} coordinate on the a-b plane.

$$P_i = (a_{ci} \ \ , b_{ci}) = \frac{1}{n}\left(\sum_{j=1}^{n} a_j \, , \sum_{j=1}^{n} b_j\right) \qquad \text{equation 1}$$

The determination of the central points of all expected color values is followed by determining the color distance (d_i) (equation 2). d_i between the centroids of consecutive tasks for as-planned (*ap*) conditions is denoted as d_{api}.

$$P_{i-1} - P_i = \quad d_i = \left((a_{c(i-1)} - a_{ci})^2 + (b_{c(i-1)} - b_{ci})^2\right)^{\frac{1}{2}} \qquad \text{equation 2}$$

The as-planned distance (d_{api}) between consecutive colors of task accomplishments represents the amount of work the crew/trade must accomplish during the planned schedule. Therefore, the expected rate of work (productivity) can be equated with the expected color evolution (r_{api}), which is computed using equation 3 as a ratio of d_{api} and the time (t_{api}) required to complete the amount of work between the two color phases.

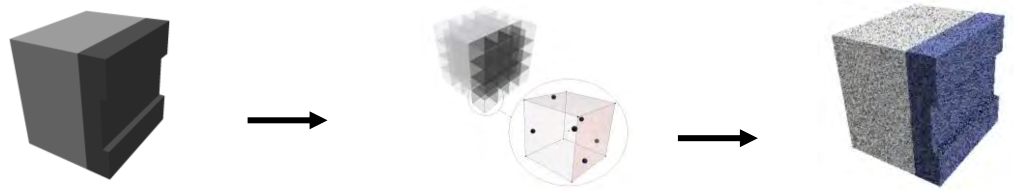
$$r_{api} = \frac{d_{api}}{t_{api}} \qquad \text{equation 3}$$

Although the level of detail of the BIM is not adequate to accommodate every activity which will result in color change, the value of t_{api} can be obtained from construction schedule, and usually derived from standard crew daily output databases (i.e., RSMeans database). Finally, the expected productivity value calculated regarding color distance is added to the new BIM field.

2.2 Real-time PCD processing

Once construction activities have started, PCD is collected using color image scanning technology. To make the proposed method valuable for low-quality scans, the data acquired is filtered using the MLS method before it is analyzed further for point color property. The MLS method first tries to fit a model into a randomly selected set of points. The residuals are calculated from the difference between positions of a point on the fitting model and the measured points. The best fitting model is selected after the least square method of iteration (Fleishman et al., 2005). However, on this paper, once the surface fit is identified, measured points which are situated within the upper and lower boundaries (square root of mean squared residuals) of the model are taken instead of the approximated points for further processing. The reason for considering the original points within the boundaries is to avoid over-approximation of the color attribute attached with the geometric points; which could be caused by generating color data for approximated geometric points.

A 3D BIM model of the element is fragmented into rectangular cells using an octree-based partitioning system. Filtered points are clustered into the cells depending on their Euclidian distance from the representative point in a cell; where the representative point can be defined by vertexes which are approximated from the 3D BIM model. Neighboring cells which are positioned on the designated position on the BIM for the same element material are merged, and points in the cells are clustered together (darker cells). Once the points are registered into their respective clusters, the attached color attributes are processed (Figure 3).



(a) (b) (c)

Figure 3: 3D BIM model (a), volume of element fragmented into space cells (b), point cloud fitted and clustered (c).

The number of registered points in an element must be higher than the minimum required point cloud density (n_{min}) on the surface to proceed to color processing. The value of n_{min} is approximated to be sixteen points per square meter area, where the assumption is made considering a meter cube element is fragmented into sixty-four octree cells; and each of the sixteen cells on one face of the cell assembly contains a single point.

The measured RGB values are converted to CIELab space. The centroid of as-built (*ab*) CIELab points on the a-b plane, P_{abi} (P is for point, subscripts *ab*- is for as-built, and i is for the material related to a given task/trade), excluding the L parameter, is calculated using equation 4 (replacing P_i with P_{abi}). To ensure that enough points on the a-b plane are accounted for, an error radius (e_i) with a magnitude of a standard deviation around the determined P_{abi} has been considered. This will ensure that about 68% of the points are considered (assuming a normal distribution). During progress monitoring, if P_{api} lays within the acceptable error radius enclosed around P_{abi}, the colors of the construction stage are considered to be matched. This implies that the expected stage color is satisfied with the actual site condition. However, if the color points are not matched as expected, the as-planned color centroid database will be updated with the newly obtained color center for future use. Following a similar procedure as the as-planned color distance is calculated, as- built color distance (d_{abi}) between the two central points related to two consecutively scheduled tasks is also computed using equation 2 by replacing d_i with d_{abi}. However, to take the acceptable error radius on the actual color distance calculation, upper and lower bounds are formed (equation 4). Furthermore, the actual rate of color evolution (r_{abi}) is computed by taking the ratio of d_{abi} with the actual time (t_{abi}) required to complete an activity resulted in a single color change (equation 4).

$$r_{abi} = \frac{d_{abi}}{t_{abi}} \pm \frac{e_i}{t_{adi}}, \quad where, e_i = \left(\frac{1}{n}\sum_{i=1}^{n}\left((a_{i-}a_{mean})^2 + (b_i + b_{mean})^2\right)\right)^{\frac{1}{2}} \qquad \text{equation 4}$$

The real-time processing of the PCD is split into two parts: 1) the rate of color evolution, and 2) the detailed filter of the PCD segmentation. Due to space constraints, only the part for the rate of color evolution is shown (Figure 4). This process is done for s number of segments. The filtering of the PCD segmentation (not shown) is done for n number of points.

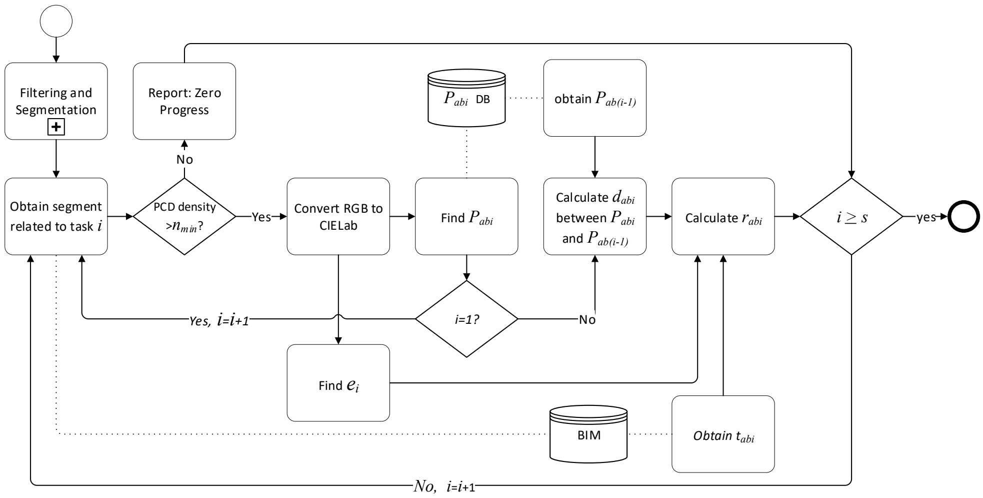


Figure 4: PCD color processing using the rate of color evolution

2.3 Trade performance evaluation

The planned color evolution rate calculated on the as-planned color-based productivity determination stage is compared to the as-built color evolution result obtained during the real-time PCD processing phase. Results are numerically compared to come up with the status of an activity (equation 5). If r_{api} is between the upper and lower bounds of r_{abi}, the activity is on time. However, if the lower bound value of r_{abi} is less than r_{api}, then this implies that the project is delayed. Furthermore, if the upper bound of r_{abi} is less than r_{api} this means the activity is ahead of time.

$$if, \quad r_{api} \leq r_{abi-min} \rightarrow delayed \qquad \text{equation 5(a)}$$

$$else, r_{abi-min} \leq r_{api} \leq r_{abi-max} \rightarrow ok \qquad \text{equation 5(b)}$$

$$else, r_{api} \geq r_{abi-max} \rightarrow ahead\ \ of\ \ time \qquad \text{equation 5(c)}$$

The as-planned and as-built color distances measured between the start and the end of a specific activity is approximated to be the same unless the scope of the activity is changed during construction. Therefore, the amount of work can be generalized to be represented by the color distance. The earned value method (EVM) of construction performance monitoring can be applied by replacing the effect of cost with the color distance. Accordingly, Earned Value (EV) is the amount of color distance completed to date, while the Planned Value (PV) is the scheduled amount of color distance to be done to date. Work Variance (WV) is the difference between EV and PV. The Work Performance Index (WPI) is defined as the ratio of EV and PV. WV and WPI indicate less (more) work than planned if their values are less than (greater than) zero and one, respectively.

3. Example

To illustrate the proof of concept of the proposed framework, a simple example is presented. It consists of the construction of a concrete column and the required sub-tasks, in particular, the installation of rebar (task 1.1), formwork (task 1.2) and casting concrete (task 1.3) (Figure 5). The planning and design of the concrete column are not considered. It was assumed that all the material and equipment needed is on-site before construction begins. It is also assumed that the BIM model is linked to a resource-loaded schedule (i.e., including crew assignment details). The crew assignment and daily output are obtained from RSMeans (Plotner, 2018) and used to determine the duration. The color property (p_{api}) of the materials for all sub-tasks is acquired from the manufacturer or developed on site.

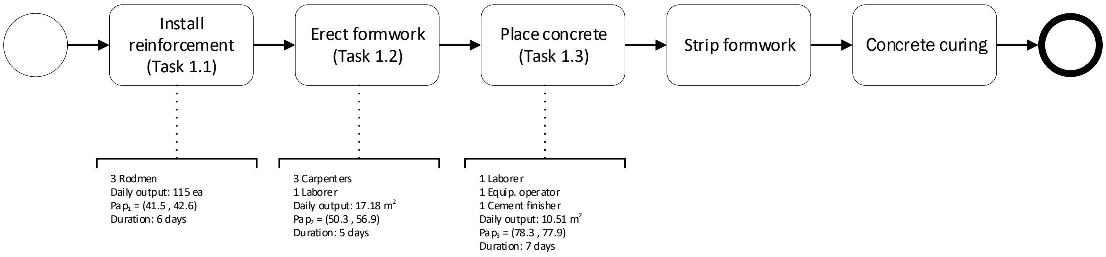
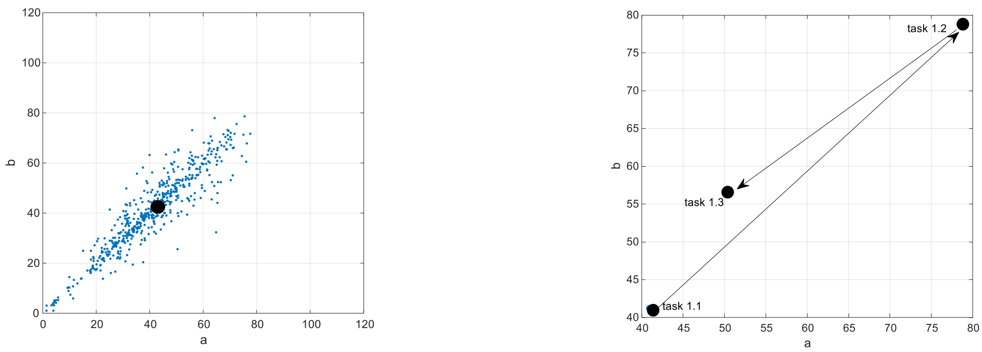


Figure 5: As- planned tasks for the construction of a concrete column with relevant information (including color)

3.1 As-planned color based productivity prediction

Depending on the sequence of tasks on as-planned schedule, material RGB color data is collected. The data is converted to CIELab space, following the conversion, color centroid (Figure 6-a) is calculated, and the database is established. The graph plot (Figure 6-b) shows the plot of as planned color centroids determined for tasks 1.1, 1.2 and 1.3 on the a-b plane. In a similar manner, all of the materials in every stage of the schedule are analyzed, and the centroid values are stored in the database. Once the color point centroids are identified for the three consecutive tasks of the schedule, the shortest distance between points is computed and made ready for the rate of color evolution calculation.



(a) (b)

Figure 6: Centroid of the point distribution of material color for task 1.1 (a) and centroids of tasks 1.1, 1.2 and 1.3 (b)

The rate of color evolution is calculated using the estimated task completion time obtained from the BIM model (where daily crew output is loaded). The predicted productivity (i.e., the rate of color evolution), is incorporated into the BIM as a new field.

3.2 Real-time PCD processing

Colored point cloud data is collected on a routine basis to monitor the site construction activity and track the planned productivity ratio. The first set of points are generated to initiate the process of completion of task 1.1. The PCD collected from construction site could result in better accuracy with optimal computation time when filtered according to the proposed methodology. In addition to that, the element segmentation proposed is also required to identify the color characteristics of objects from the PCD. The number of points registered in the segmented object did not satisfy the required minimum criteria; the process will be flagged, and the process will continue for the next segment. This illustrative example assumes that the entire point cloud is filtered and segmented; in addition to that, it is assumed that the PCD density on the segmented element satisfies the minimum point density requirement.

Through every routine, the collected filtered and segmented PCD is further processed for its color characteristics. The initial step is to convert the PCD attribute, RGB color values into CIELab color space. After conversion, the acceptable error radius and the centroid of color points are calculated. Depending on the time taken to complete tasks related to the color changes, the as-built rate of color evolution calculated. Human intervention is required to acquire data for elements which progresses under a covered environment (inaccessible to color PCD acquisition system), in this case, task 1.3. However, the method will remain uninterrupted for missing data of the specific task; it will continue functioning depending on the performance and status of succeeding and preceding activities.

3.3 Trade performance evaluation

The results from the comparison between the as-built and as-planned data for tasks 1.1, 1.2, and 1.3 are depicted in Figure 7. It shows the color distance (d_i) between sequential tasks for the planned and actual conditions versus time. The rate of color evolution (i.e., the slopes of each line) implies the productivity of the crew involved in a specific task. Since task 1.1 is the first task, the color change is made with respect to a reference color (e.g., perfect white). Points on line A represent the completion of task 1.1 (going from no color to the color for task 1.1). Similarly, points on lines B and C indicate the completion of tasks 1.2 and 1.3, as indicated by the color change from task 1.1 to task 1.2, and from task 1.2 to task 1.3, respectively. Of course, consideration should be given to the construction progress, so that it is adequately represented when calculating the color evolution (e.g., by considering the percentage of the number of color points with the initial or final color of the task at a given time of inspection).

With this information, different performance metrics can be used. For example, the actual color rate between task 1.1 and task 1.2 was lower than planned (8.50 vs. 9.91), indicating that task 1.1 was delayed (by one day). Also, the Work Variance (WV) for this case is -8.50 (negative indicating delay) with a WPI of 0.86 (i.e., performing only at 86% of the planned performance).

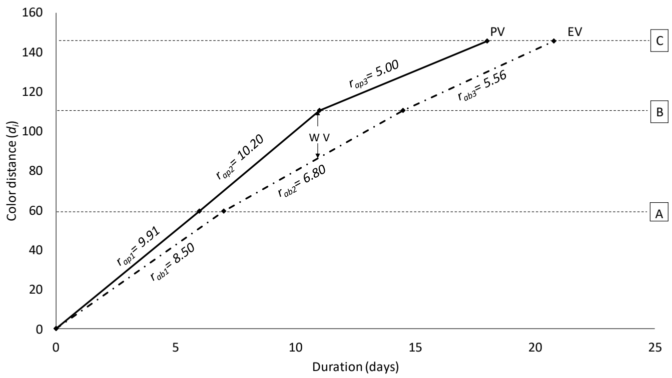


Figure 7: Planned (solid line) and actual (dotted line) productivity plot based on color distances

The project manager can use the rate of color evolution to assess the performance of the different trades by tracking the progress of different construction activities. This is particularly useful to provide on-time support and incentives for delaying trades, or rewarding best-performing ones in a dynamic and real-time basis, ensuring a proactive approach to the management of construction project without relying on traditional and progress updates.

4. CONCLUSIONS AND OUTLOOK

Construction monitoring practices are dominated by traditional approaches which are subjected to inaccurate and delayed progress reports. To address this, attention has been given to the development of as-built laser-scan data to generate a set of data points, or point cloud, to monitor the progress of construction projects. However, the color attribute of the PCD in construction progress monitoring studies has not been fully exploited. This paper proposed a conceptual framework that uses the color attribute of the PCD, usually ignored in construction progress monitoring activities. As-planned color property of construction materials is generated and transformed to an appropriate color space to remove the effect of light source and illumination. A specialized database is proposed to be established which can ease the enrichment process of the BIM with a color-based productivity field. The progress is monitored by acquiring a PCD on a timely basis. The method of PCD data filtering and element segmentation from the acquired PCD data without altering the color attributes proposed. For each segmented element, color data is treated to reduce the effect of illumination and to represent the status of the work. Finally, the color-based as-built productivity ratio is computed. The performance of the construction activity can be represented using the comparison between the as-planned and the as-built color-based productivity ratios, and the result is used to generalize the performance of the construction progress and to support the decision. This paper systematically linked schedule, work, and trade using the color property of the material which can help trace the trade activity and provide support or incentives mainly when the level of details of the schedule is low.

The proposed method has been tested on a fictitious and simple case. Ongoing work includes testing it on actual construction sites with actual activities and color information from related materials. Particular attention is given to changes in construction procedures and scope might alter the material color data registration and processing phase.

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DESIGN A BIM BASED VITURAL ENVIRONMENT INTERFACE FOR OCCUPANCY INFORMATION COLLECTION

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ABSTRACT: *Architecture visualization has gained more attention these decades. The form has changed from building geometry to building information and building performance optimization. Although computer-generated renderings improve the visual experience, imagining spatial is still a problem, let alone building information. As virtual reality becomes affordable, it is a considerable tool for architecture visualization, especially for the users who do not have architecture background, or occupants who do not involve in the design stages. Therefore, occupant information can be collected in an innovated method and thus sustainable design can be optimized. This paper presents the design of a virtual interface which allows occupants to communicate with architects in a common environment. This BIM based virtual reality prototype integrates Building Information Modelling and game. The interface has several components including metaphors, mental models, navigation, interaction, and appearance for uses understanding and interacting with the system in a better way. As users have different perceptions, the interface and information visualization are designed simply to avoid misperceptions and cognitive overload, and consequently users' interaction with environment got missing. Digital City Infrastructure and Technology Innovation (D-CiTi) Lab is used to test the prototype. Several scenarios and tasks are designed for users to participate*

KEYWORDS: BIM, virtual reality, architecture visualization, occupant

1. INTRODUCTION

Building energy performance gap is defined as the mismatch between the predicted energy performance of buildings and actual measured performance (de Wilde, 2014). There are various causes resulting in performance gap. De Wilde (2014) divided the root causes into three stages: design stage, construction stage including hand-over, and operation stage. Menezes et al. (2012) classified the causes on predicting and actual sides. Generally speaking, the performance gaps are caused by the inaccurate prediction in design stage, the lack of information integrity in construction process and the unexpected energy use in operation stage.

Apart from information loss, occupant behavior plays an important role. For example, from the survey of O'Brien et al. (2017), occupant behavior was regarded as the leading source of discrepancy between building performance simulation tool predictions and measurements and about 56% participators presented that occupants used more energy in reality than what are assumed in building performance simulation tools. Martinaitis et al. (2015) conducted five different studies and also concluded the similar result. Furthermore, Schakib-Ekbatan and Çakici (2015) found that occupants' behavior was always been overlooked within the chain of design, construction, operation and maintenance. This is one of the factors leading to the inaccurate prediction and the lack of information integrity. Moreover, the sustainable intentions of the designers are difficultly expressed to the users who operate the devices in inappropriate ways. This further extend the performance gap.

Occupant behavior has the characters of complexity and dynamic. The study involves multiple disciplines, such as sociology, psychology, economics, engineering and design, and need an integrated consideration (Delzendeh et al., 2017). In consequence, occupant behavior is overlooked due to the high cost of collecting occupancy information, On the other hand, occupants' behaviors highly erratic and unpredictable. Designers prefer relying on rules of thumb or official guidance. Moreover, end-users participate the design process rarely and involving users' experience in the design is in the initial stage. Actually, users' experience significantly influences the energy consumption and environment as about 30% to 40% of the greenhouse gas are produced in the operation phase (2007).

Therefore, in order to protect the information integrity and thus narrow the performance gap, it needs a non-linearly, complex, iterative and integrated manner which support a more efficient construction process. On the other side, it need more communication between the customers, designers and constructors, also between the engineers of various disciplines involved. Therefore, building information modelling (BIM) is suitable to solve the problem, which provide a single data source to integrate all the information and make it visualized. People can get all the informant required in a designed construction process. They can also communicate with other participators for the real-time message delivery.

Apart from information integration, occupancy information collection and analysis are also challenging. Because occupant behavior is highly erratic and unpredictable, Pre-Occupant evaluation is used which observes occupant behavior and analyzes it before the building is built, test exactly the building performance. In order to achieve this, information visualization (such as spatial information, building information and energy information) is required for occupants understanding designs and being involved into every stage.

This report presents an advanced prototype applying building information modelling and virtual reality to build a virtual environment with the concepts of user centered design and design with intent. The concepts will guide the design the framework. BIM and VR provide the underlying technology that enables the building representation to be communicated to a virtual environment. Occupants behave differently with different assumptions indicated in models by designers. The object-oriented modelling of BIM provides comprehensive model data including objects and their properties, which can be easily used in VR. Parametric modelling provides an easy way to change the models both in BIM and VR when alternates are required. The application of VR involves occupants from initial phases and facilitates communications between building designers and occupants. The virtual interface help uses understanding and interacting with the system in a better way. As users have different perceptions, the interface and information visualization are designed simply to avoid misperceptions and cognitive overload. This prototype aims to collect occupancy information and thus to optimize sustainable design.

2. RESEARCH BACKGROUND

2.1 Occupant Behavior Data Sources

In order to build an occupant behavior model based on reality rather than unfounded assumptions, collecting data by observing how the occupants behave is necessary. There are various types of sensors and a selection of mixed sensors are often applied when collecting Occupant behavior information. The collected occupant data can be transmitted through a building automation system (BAS), a wireless sensor network, or the internet (Dodier et al, 2006).Based on the previous studies, the occupant monitoring approaches are divided into three main categories, that is in-situ studies (observational studies), laboratory studies and survey and interview studies.

2.1.1 In-situ studies (observational studies)

The in-site approach installing existing or additional occupant sensors in the nature environment of the occupants to observing and collect their behavior. The current sensing contents of occupant behavior includes occupant presence, people counting, movement tracking, human-building interactions, such as turning lights on/off, using plug-in appliances, adjusting thermostats and window blinds, energy consumption and environment impacts of miscellaneous loads. The interactions between the occupants and some components is unprecedented (O'Brien et al, 2013), and may exhibit seasonal variations, such as windows (Rijal et al, 2008). Usually, it need a long period, typically extend over at least numerous months, to monitor in-suit occupant behavior for a relatively accurate data.

For human behavior, there are two main focus areas, one is occupant presence and movement and the other one is occupant interaction with ambient environment. Based on these two areas, the selection and placement of sensors are different, and the sensing approach are also divided into two groups, that is occupancy and equipment use monitoring and adaptive behavior monitoring (Yan et al, 2015). When monitoring occupant presence, people counting, movement tracking, approach of occupancy and equipment use monitoring is applied. The approach of adaptive behavior monitoring is often used when monitoring human-building interactions, energy consumption and environment impacts of miscellaneous loads. In this situation, the ambient environment, such as temperature, air quality and daylight, has a significant influence on occupant behavior. Therefore, both the environment data and the occupant data are collected.

<u>Occupancy and equipment use monitoring</u>

The purpose to develop the occupancy detection is improving the accuracy. Main approaches in the past decades include motion detectors (e.g., passive infrared and ultrasonic), carbon dioxide sensors, video cameras with computer vision, wearable sensors, security-based systems, and diaries (Richardson et al, 2008) (Lam et al, 2009), where motion detectors are the dominant form of occupancy sensors (Lam et al, 2009).

Passive infrared (PIR) sensor and coupling motion detectors (such as carbon dioxide sensors) are commonly used to detect the movement of the occupants or count occupants. However, both PIR sensors and coupling motion detectors are unable to detect nearly motionless activities and activities in small scale space.

Beside PIR sensors and coupling motion detectors, cameras and wearable sensors are used by researchers to identify occupancy, count the number of occupants and detect the motion vectors of human body. In order to mine high-level features from raw data, expertise from different disciplines such as artificial intelligence and computer vision are required (Trivedi et al, 2000).

Adaptive occupant behavior monitoring

Major adaptive occupant behaviors include light-switching, window blind-adjusting, window-opening, thermostat-adjusting, clothing level-choice and adjustment, fan use, and door use. It is time-consuming, expensive cost to install numerous cameras for comprehensive monitoring these adaptive occupant behaviors (Yan et al, 2015). Besides, the results are prone to inaccuracy. Manual observation methods are also inappropriate because they cannot capture enough sample size to develop statistical models. Therefore, it often uses sensors or meters to record states of devices, such as window blind, thermostat and fan. Data logs recorded by sensors or meters are used to reflected adaptive occupant behaviors. For instance, thermostat adjustments are influenced by thermal comfort including air temperature, solar radiation, wind, relative humidity, clothing level and metabolic rate. Integrated sensors or setpoint logs are commonly used to measure the adjustments (Gunay et al, 2014). The resulting data logged by the modern digital thermostats is often available remotely via the Internet – especially for web-enabled thermostats.

2.1.2 Laboratory studies

Different from the in-suit studies, laboratory-based studies put the human into a controlled environment with a specific scientific aim, such as identifying thermal (Zhang & Barrett, 2012) or visual comfort (Konstantoglou & Tsangrassoulis, 2016), or social and physiological impacts on occupant behavior (age, culture, gender, etc.) (Schweiker & Wagner, 2016). The data collected from the laboratory studies is more specific and controllable compared with that form in-suit studies.

However, there are several disadvantages of laboratory studies. First, it need adequate number of the human participating the studies to ensure the accuracy of the studies. Even when the adequate number is achieved, it may be unclear whether behavioral models can be developed from laboratory settings. Without longevity and natural working or living environment, occupants may behave infrequently, this make the laboratory studies perform impractically (Reinhart & Voss, 2003). Moreover, it is difficult and expensive to reproducing a realistic environment, for example, social constraints and dynamics, stressors cannot be simulated in laboratory studies. Occupant behavior may also be affected by unfamiliar environment and available adaptive behaviors (List & Levitt, 2005). Besides, individuals may alter their behavior under observation.

2.1.3 Survey and interview studies

Survey and interview studies are another ways to collect data regarding perception and social aspects of occupant behavior based on a self-reporting mechanism (Zhou & Yang, 2016). These studies provide a large sample size in a cost-effective way. Therefore, it is suitable in a cross-country situation to gain insights on behavioral patterns, drivers, causes, and perceived effects of behavior and to find connections between human, social, and local comfort parameters.

Before beginning the survey and interview studies, some challenges are considerable. Like in laboratory studies, participants may knowingly or unknowingly misrepresent their behavior. Participants may not recall their behaviors and the severity of discomfort. Participants may respond the way they think they are expected to (Gunay et al, 2014). Therefore, frequent computer-based surveys are used to remind occupants' comfort and behavior in recent history (Haldi & Robinson, 2008). Furthermore, the influences of the surveys on the occupant behavior are also needed to research.

2.1.4 Improvements on occupant behavior data collection

There are gaps in occupant behavior data collection due to the lack of standardization and the amount of equipment and time required. The appropriate sample size for measurement and the adequacy number of occupants are still argued. Moreover, the accuracy of the collected data for the most suitable explanatory variables is required to improve. After building an occupant behavior model, it is better to compare the results with the real ones for ensuring the practicality and accuracy of the model and developing the method of data collection and model built.

Moreover, with advanced artificial intelligence technologies, more intelligent systems will be developed, such as capable of self-adaptation to change the environment and to recover from failure. For example, sensors are required to update which are costly and requires heavy maintenance efforts now. Therefore, the abilities of wireless transmitting of data, intelligent and self-powered, view-invariant human motion capture, smart processing, and minimum communication demands are needed for high required and wide application. (Yan et al, 2017).

Apart from the technology advance, the balance between the privacy and ethical factors of the individuals and the requirement of their knowledge should further studied.

2.2 Virtual Reality (VR)

2.2.1 Definition and characteristic of virtual reality

It is hard to find a standard definition of "virtual reality". For the aspect of emphasizing on visual sense, it can be defined as a technology that conveys the virtual information produced by the computer to man's senses through some media. For the aspect of emphasizing on participation and experience, it was defined as a "computer-generated environment that, to the person experiencing it, closely resembles reality" by Collins Dictionary (Dictionary, 2014). For the aspect of emphasizing on synthetic and fabrication, it was defined as "the component of communication which takes place in a computer-generated synthetic space and embeds humans as an integral part of the system…" (Regenbrecht & Donath, 1997).

Therefore, the characteristics of VR was concluded by Sherman and Judkins's (Sherman & Judkins, 1992) as five 'i's that is intensive, interactive, immersive, illustrative and intuitive. This highlighted the point of experience and synthetic. While based on Takuya Onoue (Takuya Onoue, 2010), the characteristics of VR included a real-time spatiality of three dimensions, interaction and the self-projection. Both of them mentioned that VR has an ability to copy or simulation of the reality. Therefore, it is suitable for the Pre- Occupant evaluation task with the product being cost and checkered.

2.2.2 Virtual reality interface

The VR interface is a platform where the users can "communicate" with the designer. Therefore, it is necessary to design an interface that the users understand well. User interface have several components including metaphors, mental models, navigation, interaction, and appearance (Marcus, 2002). Head motion can be used as an interface in HMD teleoperation systems (Martins & Ventura, 2009).

Appearance in a virtual environment is associative with the realistic visualization. With the improvement of the technologies, the expectation of how real the virtual reality could be increases. It is obvious that abstract representations that cannot provide an immersive environment are inappropriate (Daniel & Meitner, 2001). However, unlike in some specific disciplines, such as health sciences, reality needs to be extremely accurate and highly multi-sensory, complete accuracy may not be necessary in VR application of AEC industry (Lange, 2002). Complete accuracy costs time and computing and it has requirement for the hardware of the users. Therefore, the requirement of the realness in the virtual reality depend on the context of application (Zube et al, 1987) and to what extent the realness could be accepted need further research.

Metaphors are the essential concepts in user interface which replace the underlying code and terminology of operating systems, applications, and data to acceptable words, images, sounds, and even touches (Marcus, 1998). In virtual reality, physical input devices are different from traditional devices such a s mouse and keyboard. Metaphors are still needed to provide dynamic, interactive symbolic and iconic artifacts, so the user can manage their interaction and communication with the virtual environment. For example, in a virtual building, the symbol of tapeline tells the users that they can measure the dimensions of the building.

Navigational capabilities include moving forward, backward, turning left or right, jumping and teleporting. In a small-scale environment, moving as that in reality, like walking or running, may make the user feel comfortable, but in a large-scale environment, teleporting may be needed to have a better view of the whole space. Interactive and intelligent navigation needs to combine the free walk-through and the guided tour. The guided tour suggests the users to move in a predetermined path and thus optimizes their behavior. For example, in virtual construction, when the user close to the edge of a platform without a railing, a note will appear to warn them it is unsafe. Besides, due to the HMD occupies the entire visual field of the user, a gamepad is used as an egocentric navigation interface to control the movement of the avatar in the virtual environment. (Fabroyir & Teng, 2018)

3. METHOLOGY

The main concept of the methodology is based on users to design the virtual environment. It tries to attract users in all the construction stages and dig out occupant behaviors and underlying patterns in a serious of areas. Besides, it influences occupant behaviors towards expected patterns.

3.1 User Centred Design (UCD)

User centred design (UCD) is a framework of processes (not restricted to interfaces or technologies) in which the needs, wants, and limitations of end-users of a product, service or process are given extensive attention at each stage of the design process. For instants, Bullinger et al. (2010) suggested an approach introducing user centered design (UCD) in the architectural planning process for overcoming the communication problems. The aim of their study is to change the traditional design process and involving of the utilization phase of the building to improve planning reliability and efficiency. A large-scale 3D VE based building prototype was built for the non-professional users to understand the building design by applying immersive media technology tools. The users were involved from the beginning of the basic assessment phase stage to the integrated planning process stage and defined the building requirements including geometric volume layout, form variants and detailed planning. Their updating requirements were recorded and fed back to the planers and design experts to optimize the design. The design was represented by the virtual prototype of the building. “Centre of Virtual Engineering” placed on the extended grounds of the Fraunhofer Institute Centre in Stuttgart-Vaihingen, Germany was regarded as an ideal precedent to apply UCD approach as it had high impact on the architectural aspect.

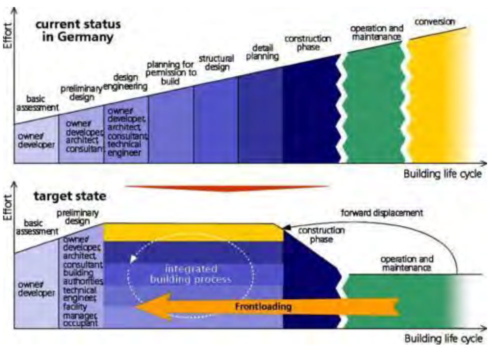

Fig. 1: Building life cycles with/without user participant

3.2 Design with Intent (DwI)

Generally speaking, the Design with Intent (DwI) developed by Lockton (2009) intends to influence the occupant behaviors toward a certain pattern. Regarded as a “suggesting tool”, DwI provides an environment for users to interact with through a series of design strategies and sequent influence human behaviors. For example, designers expect occupants to use some devices which are over-complex in energy-efficient ways. DwI help educate occupants understanding these devices. DwI has two modes: inspiration mode and prescription mode based on designers’ preference. In inspiration mode designers can group the design patterns based on their intension, and in prescription mode designers formulate a range of target behaviors and assign them to suitable design patterns for users achieving them. For example, if designers expect users to prefer PV powered appliances, they can produce notes in the interface which told users how much energy and cost being saved when these PV powered appliances are used.

3.3 Design in BIM Based Virtual Reality

The first step of designing the experiment is to identify the intension of the experiment, such as the evaluation purpose. Because it is still unpractical to evaluate a comprehensive condition covering all the operation situations. Some specific scenarios are designed, such as saving electricity consumption and HVAC consumption. Next, the target occupant behaviors and corresponding design patterns are settled. Designers can observe occupant activities and collect information through experiments. Different design patterns can be used with the same intension to select the appropriate design strategies.

Because the experiment is designed in a virtual environment, there are several additional points need to be considered. Firstly, designers should collect enough information in reality to provide the immersive experience for users and ensure users act as they in reality. For example, when observing the behavior of using light switch, different solar intensities should be simulated. Secondly, virtual experiments are repeatable and representative of the real variability and data collected in VR are highly correlated to data potentially collectable in real world. Therefore, the results can be validated and compared. Besides, the selection of hardware and design of interface should be considered to meet the requirements form users with different perceptions and cognitions. Last, the visibility of virtual objects depends on users' personal and cultural backgrounds. Therefore, simplicity in information visualization has to be achieved in order to avoid misperceptions and cognitive overload, and consequently users' interaction with environment missing.

4. CASE STUDY

To implement the prototype, it began with the model of Digital City Infrastructure and Technology Innovation (D-CiTi) Lab in the University of Nottingham Ningbo China (UNNC). The purpose of the study was to collect the occupant behavior information of lighting use. Meanwhile, it aimed to test the feasibility of the virtual environment interface. The target users were divided into two groups, one were the staffs and students working in the D-CiTi Lab, and the other one were visitors who did not work there. The experiment required the users to enter the lab and go to the target places. After 20 minutes, they were required to leave the lab and the building. The daylight was designed to be an overcast day. Oculus Rift was used to provide an immersive experience. During the experiment, the users were supposed to turn on/off the lights along theirs paths toward their workplace according to their visual perceptions. In this way, the designer could observe user's behavior and record it manually. Furthermore, based on the task completed, the designer could test if the interface and the information visualization is simple enough for the users to understand and interact with the system in an expected way.

4.1 D-CiTi Lab Model Built

The D-CiTi Lab model was first built in Autodesk Revit which was built based on the D-CiTi Lab drawings. The materials are assigned to relative components. This ensured the maximum consistency of the model and the real construction. It used 3ds Max as the intermediary to transfer BIM data to VR. Importing the Revit model to 3ds Max with the function of Link Revit, it gained the model as shown in Fig. 2. Under the shaded mode, the textures and colors of the model materials changed. Besides, they lacked reality. To figure out this, we would replace the textures of the surface materials with the 3ds Max standard material type through Material Editor, so they could be recognized by Unity. In addition, using appropriate bitmaps made the model more realistic. Partial exporting the amended model with FBX format (which facilitated change), it imported these files into Unity to gain the model as shown in Fig. 2. This model would be displayed in the VR hardware, so it further improved the model and did lightmap for a stronger immersive experience. Through importing Oculus or HTC Vive script, the D-CiTi Lab model could be "visited" in VR hardware.

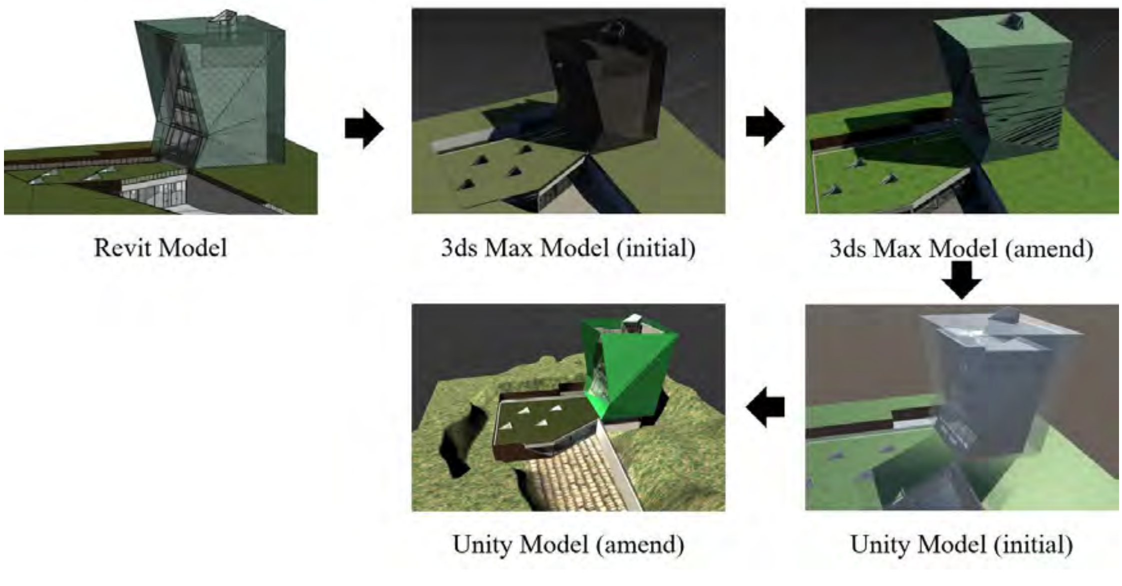

Fig. 2: Process of building D-CiTi Lab model

4.2 D-CiTi Lab Model Setting

Two methods were used to prepare activities in the virtual environment. The first one was using Unity plugin named Playmaker. It worked by defining triggering conditions and variables, as well as connecting the factors. The benefit of this method was it did not need programing and operated easily. However, it could only be used in limited conditions. Another method was using script in Unity to establish scenes. Contrary to Playmaker, although this method need the ability of programing, it had a wider application.

4.3 Experience in Virtual D-CiTi Lab

The appearance, mainly referring to the geometry and the materials, of the virtual D-CiTi Lab were as close as possible to those of the real building. This provided the realistic visualization. However, the Level of Detail (LOD) was lower than what was applied in construction. This made the experiment affordable for ordinary PC.

Enquiries about the users' gender, age and occupation were set for further evaluation of occupant behavior patterns. The enquiries are presented in Fig. 3.

Fig. 3: Enquiry about the users' information (gender, age and occupation)

Users could walk freely in the virtual environment through the Xbox of Oculus Rift. When alternative solutions existed, they also had different selections. For example, when they approached the end of the lobby and attempted to go upstairs, a transfer question appeared. The users were transferred to the place they selected where the options of First Floor and Second Floor were corresponding to the function of elevator.

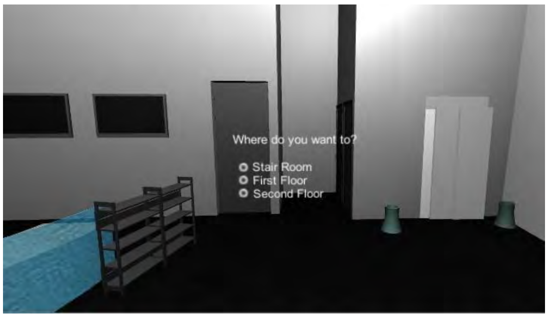

Fig. 4: Alternative solutions about going upstairs

The main interaction between the users and the virtual environment was the control of the light switch, so users could turn on/off the lights according to the sunlight intensity and their behavior patterns. There were light switches on the wall as shown in Fig. 5. The users could touch the switches using Xbox and saw the task options. More than one options could be selected according to the users' visual perception and behavior pattern as shown in Fig. 6. When the users were satisfied with the lighting environment, they could touch the symbol of close to exit the option interface.

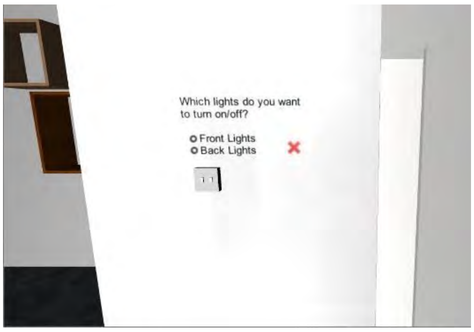

Fig. 5: Lighting control

Fig. 6: Lighting effect

4.4 Results

User information were collected by observed and recorded during the experiment. There were also surveys from the uses to get their feedback.

It found people working in the lab could complete the tasks better than the visitors. The staff and the students were more familiar with the paths towards the lab and the location of the switchboards, while the visitors spent time on searching the rooms. It also fond gender had limited effort on the task completeness but age had influence. The elder people had more difficult to finish it. It spent more time to explain the usage of the controller (Xbox) to the elders and they might face several problems. For example, they stayed in corner and were motionless, or they lost their direction and walked in the same room for a long time.

About 75% of the users (45% of visitors and 30% of staffs and students) turned on the lights. Some staffs and the students thought it was more convenient to move under a relatively dark environment than to go to the switchboard and turn on the lights. Among the users who turned on the lights, nearly 20% of them did not turn off the lights. There were two reasons to explain this behavior. Most of them forgot that the lights were on. The others need the help of the artificial lighting to find the way towards the entrance, but the switchboards were far away from the entrance.

For the feedback from the users, the virtual environment and the task were supposed to be easy to understand. The locations of the furniture and switchboards were almost the same as those in real. The operation of turning on/off the lights was regarded to be easy in the virtual environment. Besides, the navigation system was useful. However, about 80% of the users reported they suffered dizziness if they wore the VR glass for a long time. Moreover, they thought the virtual environment was a bit darker than the real environment. The time between entering and leaving was different from that in real, which might lead to an incorrect result.

1. According to the results and the feedback of the experiment, there were some improvement suggested:
2. For the virtual environment, increasing the LOD of the model to make the environment more real;
3. Rendering the model better to achieve a real light environment;
4. Redesigning the design time;
5. Adding more visual tasks;
6. Adding a map in the virtual environment;
7. For the real building, add more navigation devices, such as room plate, indicators;
8. Adding switchboards neat all the entrance.

5. ANALYSIS

The proposed prototype is regarded as combining the features of laboratory study and survey study. The environment and scenarios can be controlled by designers. Meantime, it can be used by users worldwide regardless their countries, ages and occupations based on network technology. Therefore, compared to laboratory study, it has the advantage of low cost for site deployment, adequate number of participators. Compared to survey study, it provides a visualized environment, which reminds the users about their real feelings and reduces the behavior misrepresent caused be the gap between actual occupant behavior and the one they think they expect to do. However, some problems are still existing, such as infrequent behavior, glorified behavior, lack of social constraints.

In the aspect of filling the performance gap. The greatest contribution of this prototype is to transform the evaluation approach from Post-OE to Pre-OE. This provides a chance for every new building having a specific human characteristic which increases the prediction accuracy. Together with in-suit study, it has more potential functions. Besides, with the low threshold for users to participate the design process, the communication between occupants and designers rise. On one hand, occupants' opinions are becoming easy to "hear" by designers which optimizes the design. On the other hand, designers' concepts are more easily accepted by occupants.

6. CONCLUSION

This report firstly introduces the current requirement of energy design optimization and occupant behavior evaluation. It expresses the building performance gap and its causes, especially in the aspect of occupant behavior. Common methods of the occupant behavior data collection and the use of virtual reality are followed described. Based on the above information, it proposed a BIM based virtual reality prototype with the concept of UCD and DwI. A case study was presented. It also explained the interface of the virtual environment which helped the users complete the tasks. The results of the experiment were reported. At last, it concluded the benefits of using the proposed prototype, as well as its shortcomings.

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TOWARDS AUTOMATED GENERATION OF PARAMETRIC BIM FOR STEEL STRUCTURES BASED ON LASER SCANNING DATA

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ABSTRACT: *As-built building information models (BIMs) are increasingly needed for construction project handover and facility management. To create as-built BIM, laser scanning technology has gained popularity in the recent decades due to its high accuracy and high measurement speed. However, most existing methods for creating as-built BIM from laser scanning data involve plenty of manual work, thus become labor intensive and time consuming. To address the problems, this study presents a semi-automated scan-to-BIM approach that can obtain required parameters to model a steel structure with complex connections from terrestrial laser scanning data. An algorithm based on principal component analysis (PCA) and cross-section fitting techniques is developed to retrieve the position and direction of each structural component. Normal-based region growing and random sample consensus (RANSAC) are adopted to model the connections between structural components. The proposed approach was validated on a bridge-like steel cover structure with 125 structural components. The results showed that the proposed approach could efficiently generate parametric BIM of the steel structure.*

KEYWORDS: Building information modeling (BIM), Terrestrial laser scanning, Point cloud data, Geometric modeling, Circular component

1. INTRODUCTION

Building information models (BIMs), generally refer to semantically rich digital facility models, have been widely used in different stages of a facility's life cycle. Usually, building information models are created based on design information before construction phase, known as as-designed BIMs. However, a facility may not be constructed exactly as it is specified in the design phase. Changes may occur due to the subsequent design revisions during the construction phase so that such as-designed BIMs may not be sufficient or accurate to reflect the real condition of an existing facility. As-built BIMs, as the 3D digital representation of existing structures, are getting more popularity in the AEC industry. As-built BIMs allow owners to visualize and analyze proposed retrofit and renovation solutions and ensure that these solutions meet the owner's requirements and provide optimal effects (Woo et al., 2010).

According to Agapaki and Brilakis (2017), structural elements are the most frequent object type, which account for 33% of all industrial objects. Steel structure element is one of the major types of structural elements. A steel structure may consist of steel beams, steel columns, steel trusses, steel plates and other components made of steel. The joints, bolts or rivets are usually used to connect components or parts. Because of the light weight and simple construction, steel structures are widely used in large-scale factories, stadiums, and super high-level areas. To model those large-scale structures, laser scanning has been adopted due to its ability to rapidly and accurately collect 3D spatial data.

This study proposes a semi-automated approach to generate parametric BIM from laser scanning data for a steel bridge-like structure. The proposed method first manually separates different components from the steel structure and classifies each component into different categories, namely strut, connection plate, top chord, and bottom chord. Then, to extract geometry information from each category, an algorithm based on principal component analysis (PCA) and cross-section fitting technique is developed to retrieve the position and direction of each structural component. Normal-based region growing and random sample consensus (RANSAC) are adopted to model the ends of each strut and irregular connection plates between structural components. Finally, the parametric BIM of the whole structure is generated automatically using Revit and Dynamo. This paper is organized as follows. Section 2 provides research background on the creation of as-built BIM model and data collection from 3D laser scanning. The developed approach to extracting geometry information from laser scanning data and generating parametric BIMs is described in Section 3. Section 4 uses illustrative examples to validate the proposed method and discusses the experimental results. Finally, Section 5 provides a summary and conclusion of this study.

2. RESEARCH BACKGROUND

2.1 Creation of As-built BIM Model

The creation of as-built BIMs involves measuring the appearance and geometry of a facility, as well as processing measured data to generate logical objects which can be documented, visualized and modified. Generally, the process can be divided into three parts: (1) Spatial data acquisition of an existing facility on site through surveying technologies, such as measuring tapes, total-station, photogrammetry and laser scanning. Among these surveying methods, manual methods based on measuring tapes or total-station are time-consuming and impossible to be performed on large-scale projects. Photogrammetry has advantages in economy and accessibility but suffers from low accuracy (Golparvar-Fard et al., 2011). To rapidly and accurately measure the 3D shape of the environment, laser scanning is gaining acceptance and usage in the AEC/FM industry for creating as-built BIMs. (2) Data processing. For data acquisition using laser scanning, the resulting spatial data are sets of point clouds. Many studies have been done to extract information for as-built 3D modeling from point clouds. For example, Jung et al. (2014) proposed a method to produce 3D geometrical drawing of indoor structures and manually create as-built BIM. Lee (2000) presented an algorithm using the improved moving least-squares technique to reconstruct pipe surface. Huber et al. (2011) studied an approach to recognize and model building interiors including openings and occlusions. However, all those techniques are applied to simple-featured components such as columns, walls, pipe surfaces, floors and ceilings. Research efforts are lacking for the modelling of complex structural components. (3) Generating the as-built BIM model. Tang et al. (2010) pointed out that no single software can accomplish all aspects of geometric modeling in the current practice. Generating as-built BIM is largely a manual process performed by using different software packages which can cause information loss due to limitations of data exchange standards or errors. A skillful worker may spend several months to finish a project with respect to the complexity of the facility and modeling requirements (Hoffman, 2005). Even the state-of-the-art software such as Edgewise and FARO's PointSense Plant add-in are still semi-automated tools with limitations to modeling specified types of components such as walls and pipe (Agapaki and Brilakis, 2018). To conclude, no solution exists for automated creation of as-built BIM for complex steel structures.

2.2 3D Terrestrial Laser Scanning

Terrestrial laser scanning uses ground-based static laser scanner to measure 3D environment. The scanner is placed on a fixed position and the scanner head or mirror keeps rotating vertically and horizontally, emitting laser beams and measuring distance simultaneously. There are two range measurement principles, time of flight (TOF) and amplitude-modulated continuous-wave (AMCW). TOF scanner measures distance by emitting and receiving light pulse and recording round trip time, and the distance is derived from the velocity of light pulse and the round-trip time. It is usually used in long-range scanning up to several kilometers, with a lower accuracy. On the other hand, AMCW scanner emits amplitude modulated continuous wave and measures the distance by recording the phase difference between the emitted and reflected waves. This kind of scanner usually has a higher accuracy than TOF scanner and is suitable for measuring short-ranged or medium-ranged environment with maximum ranges from 50 to 450 meters (Toth and Petrie, 2018).

3. METHODOLOGY

This section illustrates the developed technique for parametric BIM generation based on point cloud data. Fig. 1 shows the overview of the proposed method including four steps: 1) data segmentation, 2) geometry information extraction, 3) determination of model parameters, and 4) parametric BIM model generation. In data segmentation, different components of a steel structure are separated and classified into different categories using a 3D point cloud processing software, CloudCompare. Then, an algorithm is developed in MATLAB for geometry information extraction and determining parameters for model generation. Each object category has a different workflow and the developed algorithms are used to obtain parameters for model generation, as illustrated in Section 3.1. Finally, parametric BIM of the whole structure is created in Revit and Dynamo as described in Section 3.2.

3.1 Geometry information extraction

The bridge-like steel structure consists of four types of structural components: strut, connection plate, top chord, and bottom chord. This paper particularly focuses on struts and connection plates of steel structures. Fig. 2 shows the algorithms applied to extract geometry information for strut and connection plate. The details are illustrated in the following subsections.

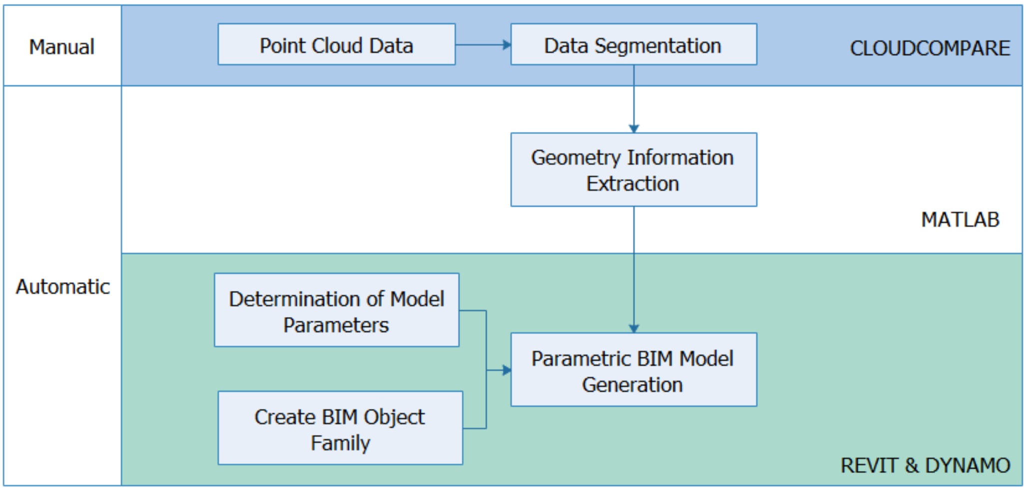

Fig. 1: Overview of proposed method

3.1.1 Strut

A strut is usually a circular structural component which consists of body, lower end and upper end as shown in Fig. 3. The body of a strut has a circular hollow section with a specified diameter, and each end of a strut is cut by two inclined planes to form a sharp edge and provide smooth connection with thick connection plate. Besides, the two planes at the end are always asymmetrical so that they need to be extracted separately. Generally, to model a strut, two pieces of information need to be extracted including (1) the centerline direction and position of each strut, (2) the position and direction of planes at the end part.

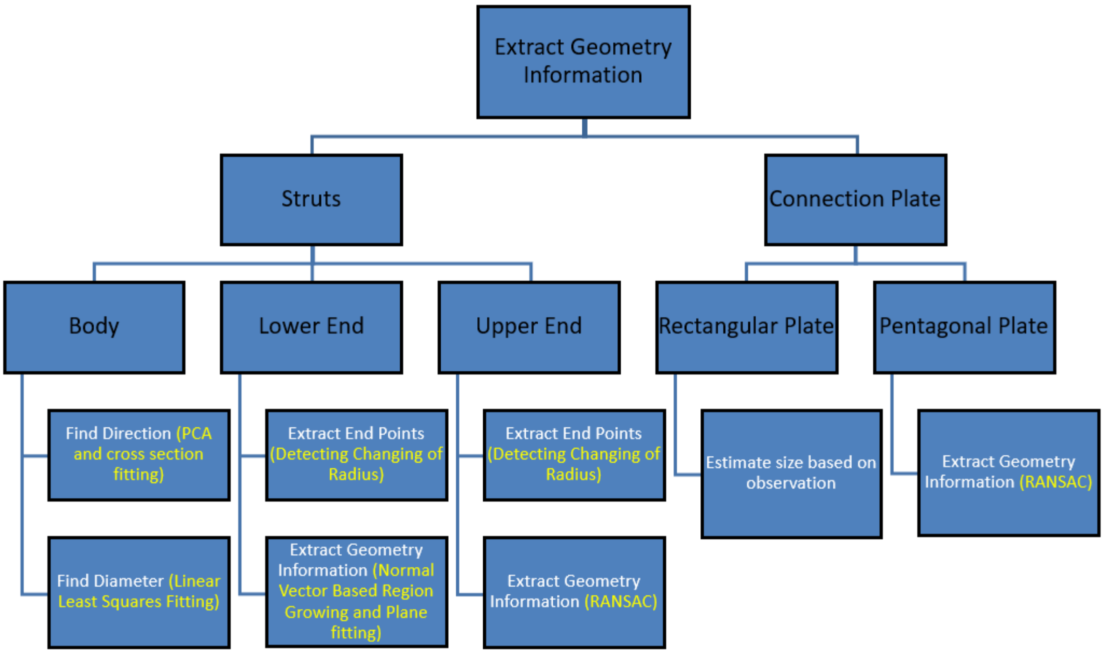

Fig. 2: Geometry information extraction for strut and connection plate

3.1.1.1 Centerline direction and position of each strut

To find the direction and position of the centerline, an algorithm based on PCA and cross section fitting is applied to the body of each strut obtained from data segmentation. This algorithm first finds the principal direction of a dataset by applying PCA (Jolliffe, 2011). The principal direction of a dataset is the direction of the greatest variability in a dataset. For a dataset forming a cylinder structure, the obtained principal direction is very close to the centerline direction when the dataset has uniform density and high completeness. However, the 3D laser scanning data always have missing parts because of occlusions. Besides, large-scale projects usually conduct multiple scans at different positions and the point clouds are a combination of data from multiple scans, resulting in varying densities. The above-mentioned reasons make the obtained principal direction different from the centerline direction, as shown in Fig. 4(a).

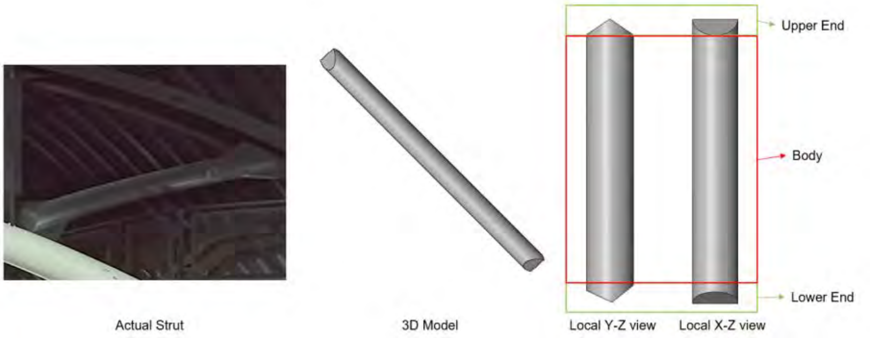

Fig.3 Illustration of strut

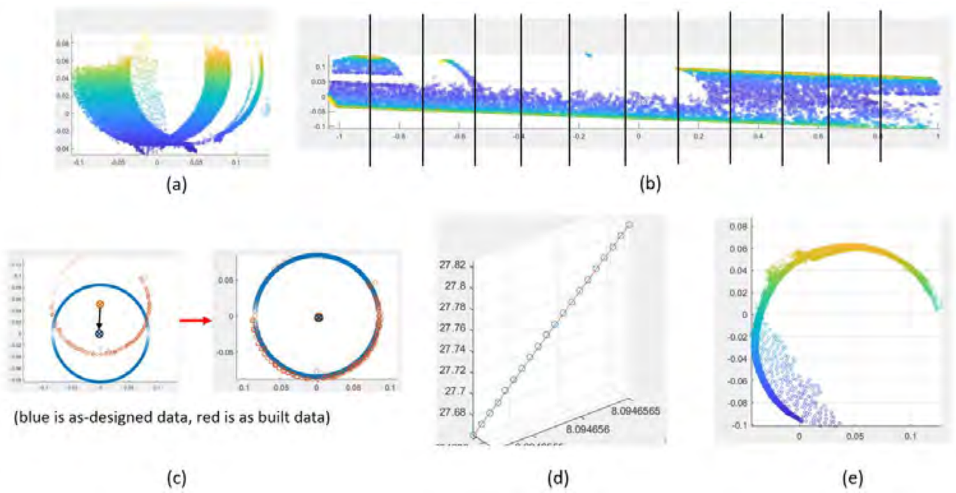

Fig.4 Extraction of centerline. (a) Cross section view after applying PCA (b) Extraction of cross sections (c) Cross section fitting and judgement (d) 3D line fitting. (e) Cross section view after enhancing PCA result

To address this problem, an iteration algorithm using cross section fitting is developed to enhance the PCA results. First, a local coordinate system is constructed by taking the three principal directions from PCA as the X, Y, and Z axes, respectively. The X axis is also the initial estimated centerline of the strut. Fig. 4(b) shows the X-Y view of the point cloud data in the constructed coordinate system. Second, several cross sections of the point cloud data are extracted along the X axis (cross section locations are shown as vertical lines in Fig. 4(b)). For each cross section, the point cloud data at the cross section are matched with the as-designed cross section by minimizing the root mean square distances (RMSD) between them (Wang et al., 2017), as shown in Fig. 4(c). Based on the matching result, the center point of each cross section is obtained. Third, a new centerline of the strut is obtained as the fitting line of all the previously obtained center points of cross sections, as shown in Fig. 4(d). Fourth, the previous three steps are conducted iteratively and terminates until the angle difference between the two consecutive centerlines is small than a threshold value. Eventually, the final centerline estimation is obtained, and Fig. 4(e) shows the Y-Z view of the point cloud data based on the final centerline estimation.

3.1.1.2 Position and direction of planes at the end part

(1) Locating ends of body

To detect planes at the end part, two ends of strut body need to be located, as shown in Fig. 5(a). The whole strut is divided into two parts from the middle so that the upper part has positive Z values and the lower part has negative Z values. For the two parts, the extraction of end of body is conducted separately. In general, the algorithm finds the end of body by detecting the change of cross sections based on the bisection method. Taking the upper part as example, Z_1 is the end of the whole strut, which belongs to the end part; Z_2 is at the middle of the strut, which belongs to the body, as shown in Fig. 5(b). Therefore, the end of body must be located between Z_1 and Z_2. Hence, the middle position between Z_1 and Z_2 is extracted (denoted as Z_{mid}) and checked. The cross section of point cloud data at Z_{mid} is extracted and fitted to a circle using least squares fitting. The fitted circle is compared to the as-designed cross section of the body part to decide whether Z_{mid} belongs to the body or the end part. If Z_{mid} belongs to the end part, Z_{mid} is set as the new Z_1; on the other hand, if Z_{mid} belongs to the body, Z_{mid} is set as the new Z_2. Using the new set of Z_1 and Z_2 values, the above-mentioned steps are repeated. The number of iterations(N) is decided based on equation (1):

$$\mathrm{N} = \mathrm{round}\left(log_2 \frac{Z_1 - Z_2}{k}\right), \tag{1}$$

where the k is the distance between Z_{mid} and Z_2 in the last iteration.

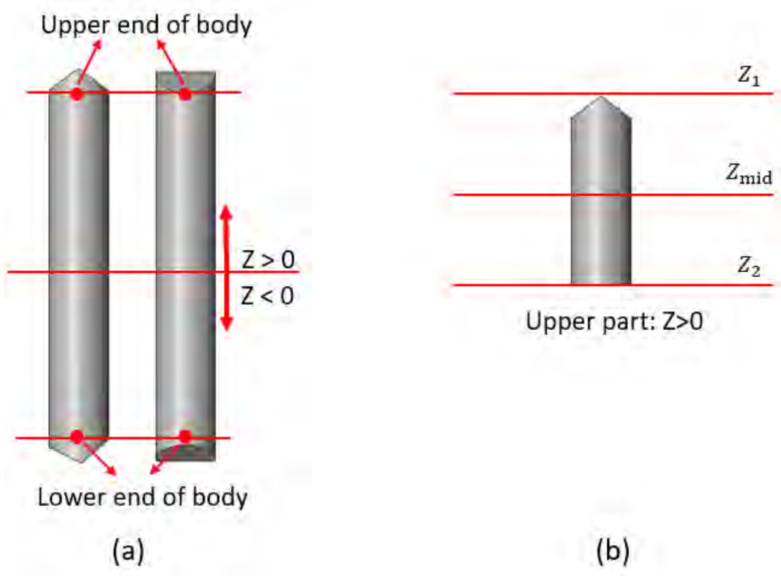

Fig.5 Locating ends of the body part. (a) Ends of the body part. (b) Extraction of Z_{mid} as the middle point between Z_1 and Z_2.

(2) Extraction of lower end planes

After locating the ends of the body part, two end parts are extracted. Usually, the laser scanner is placed at the bottom level for scanning. Therefore, the density of point cloud data from top to bottom varies significantly. The upper parts are sparse and sometimes not dense enough for algorithms that require a lot of points. Thus, two different methods are used for the upper end and bottom end, respectively.

For the lower end, a normal-vector based region growing algorithm is applied. This algorithm segments smoothly connected areas in point cloud data by estimating and comparing local surfaces normal (Rabbani et al., 2006). The normal of each point is estimated by fitting a plane to its neighbor points and K nearest neighbors (KNN) is adopted to select neighbor points considering the nonuniform density of point cloud data. To group points belonging to smooth surfaces, region growing is performed by setting a smoothness threshold (θ_{th}) which is defined as the angle difference between the normal of current seed and its neighboring seed. The segmentation result using region growing is shown in Fig. 6(a), where point clouds are segmented into several clusters. To find the two target planes from all the clusters, a plane fitting algorithm developed by Hoppe et al. (1992) is performed. Each cluster is fitted to a plane and the average orthogonal distance of points to the fitted plane (D) is calculated. Clusters with lower D values are selected (Fig. 6(b)) because clusters for target planes have lower D values than clusters for curved surfaces.

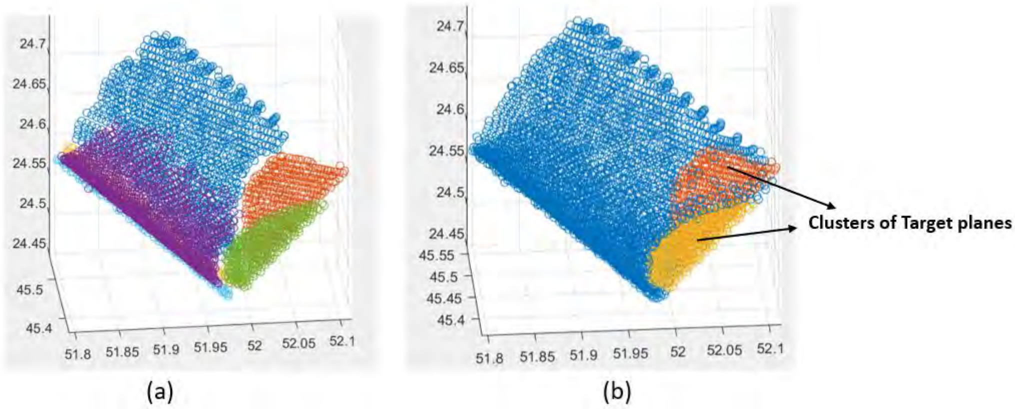

Fig.6 Extraction of lower end planes. (a) Smooth surfaces segmentation. (b) Target plane detection

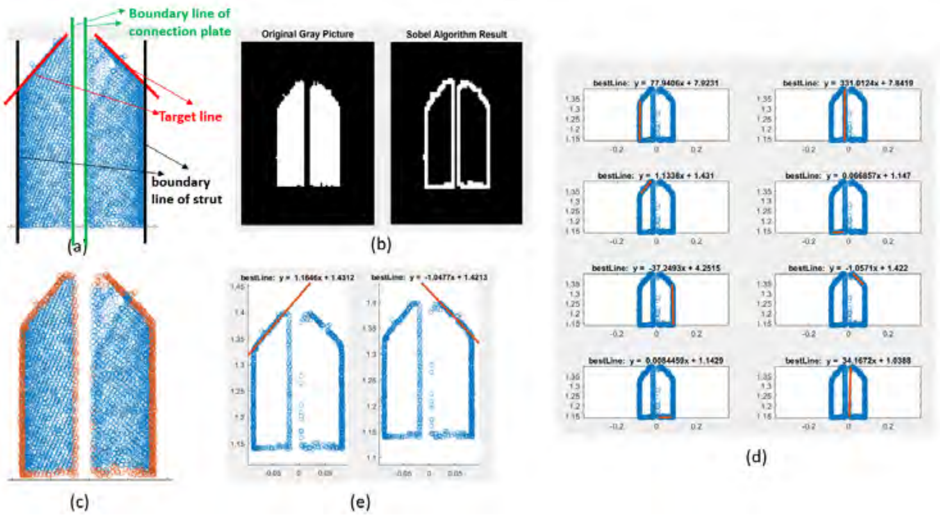

Fig.7 Extraction of upper end planes. (a) Local Y-Z view of upper end. (b) Edge detection using Sobel algorithm. (c) Detected border points. (d) RANSAC results. (e) Filtered target lines

(3) Extraction of upper end planes

Unlike lower end, the upper end always has sparse points, which are not sufficient to perform surface segmentation using region growing. However, after processing the lower end, the local coordinate can be determined so that the upper end part could be projected to the local Y-Z view, as shown in Fig. 7(a). In this way, extracting two end planes turns to extracting two edge lines. The point cloud data projected to 2D view are converted a binary image as shown in Fig. 7(b). An edge detection algorithm, namely Sobel algorithm (Sharifi et al., 2002), is adopted to find the border pixels in the image as shown in Fig. 7(b). Next, the border points are extracted by converting border pixels back to its corresponding points (Fig. 7(c)). Furthermore, the RANSAC algorithm developed by (Fischler and Bolles, 1981) is adopted to detect all lines in the border points (Fig. 7(d)). Among all the detected lines, the target lines are distinguished (Fig. 7(e)) because they are inclined and connected with the vertical strut boundary lines.

3.1.2 Connection plate

Connection plate is convex polygonal steel plate with specified thickness used to connect structural components. As shown in Fig. 8, two types of connection plates are discussed here, rectangular plate for vertical strut and pentagonal plate for diagonal strut. Based on end positions of each strut obtained in the previous steps, the end part with connection plate could be split out and projected to local X-Z view. By observing point cloud data, the width of rectangular plate is too narrow, and sometimes the edge points are missing or contain too much noise as shown in Fig. 8 which make the boundary line of rectangular plate too vague to detect. Therefore, the geometry information of rectangular plate is determined by estimation. As for pentagonal plate without specified specifications, two lines started from the edge of the strut and extended to other structural component are the key to determine the shape of pentagonal plate. To extract these two lines, similar to the process of extracting upper end plane of the strut, RANSAC is performed to detect all lines in a point cloud, including target lines. Comparing two target lines with other lines, the start points of target lines are near to the strut. Therefore, by setting constrain of the position of the start points of all lines, two target lines could be filtered out.

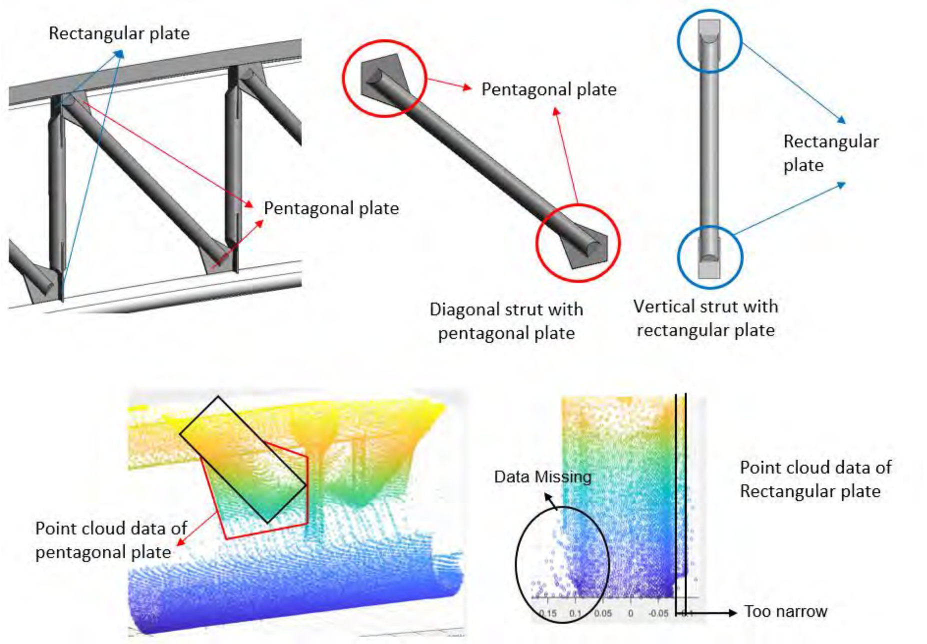

Fig. 8 Illustration of connection plate

3.2 Parametric BIM model generation

Parametric model is a model that could be defined by using a finite number of parameters, including dimensions used to create model features, formulas used to describe swept features, imported data to describe reference surfaces, etc. The model could modify parameters and be updated accordingly to reflect the modification. Different parameters are used to determine different structural components. A strut is created by extruding a circle to form a column and subtracting two triangular prisms at each end. Nine parameters are determined to model the shape of strut as described in Fig. 9(a). Besides, the direction and position of a strut are controlled by reference surface and reference vector which form another nine parameters. As for connection plate, the model is generated by extruding polygon with parameters including positions of vertexes and the thickness. However, in the geometry information extraction process, not all boundaries of connection plate can be extracted. According to Fig. 9(b), only two vertexes (point A and point E) and the direction of line AB and line DE are obtained for pentagonal plate. To form a complete connection plate, other vertexes need to be retrieved by finding the intersection points between lines and surface. An open source graphical programming tool, Dynamo, is used to achieve this goal. Point B is the intersection between line AB and the neighboring connection plate; Point C is the intersection of two connection plates and the bottom chord or top chord. Point D is the intersection between line DE and the bottom chord or top chord.

After extracting geometry information of each structural component from point cloud data, parameters determined in previous step are calculated and exported to Excel spreadsheet. Besides, self-defined family models are created in Revit based on the parameters. A face-based family is created for strut so that each strut could be placed on any work plane freely. For connection plate, an adaptive family is adopted to form components that use predefined adaptive points to control its shape. Finally, Dynamo is used to generate family instances in Revit by automatically assigning parameters stored in Excel to the corresponding family types.

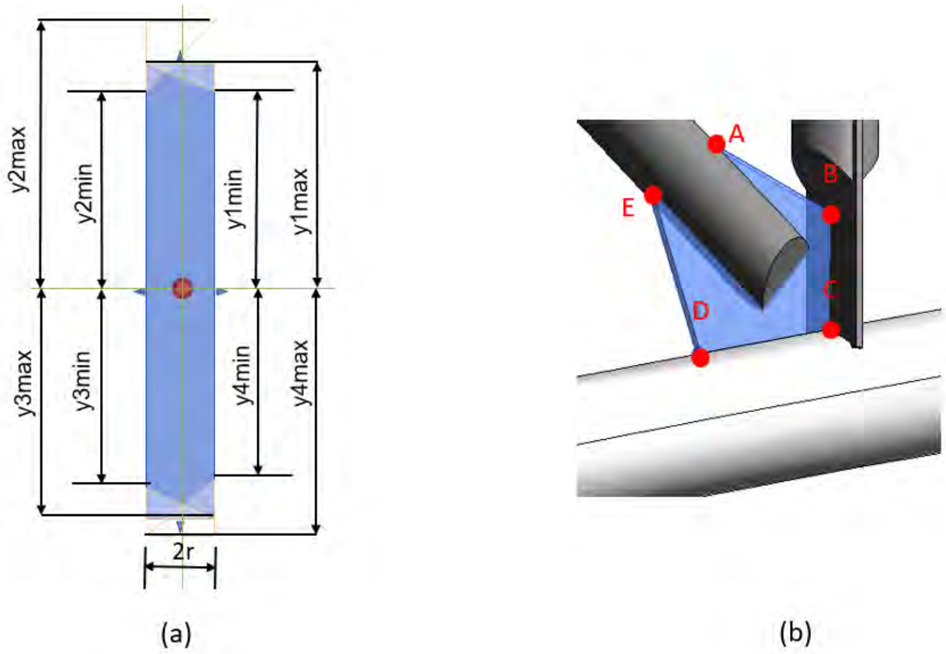

Fig.9 Self-defined parameters for (a) strut and (b) connection plate

4. Illustrative example

4.1 Point cloud data

To validate the proposed method for automatic generation of as-built BIM models based on laser scanning data, a point cloud of a bridge-like steel structure was collected using FARO Focus 3D X300 laser scanner with specifications specified in (FARO, 2013). The whole scene of a construction site was scanned including the bridge-like structure which is highlighted in Fig. 10. Because of the complexity and large scale of the scanned structure, multiple scans were conducted with over 15 scan locations to reduce occlusions and FARO's 3D documentation software FARO SCENE was used for scan registration. The resolution is approximately 3.5 mm point spacing at 10 m distance and data collection took about 20 minutes in total. The final output is a single PTS file containing the X, Y, Z coordinates and R, G, B value of each point. The steel structure consists of 41 struts with connection plates at the end, a curved bottom chord and a curved top chord. Two chords are modeled manually and are not discussed in this paper.

4.2 Conduction of proposed method

The proposed method was applied to the point cloud data. First, the output file was imported into CloudCompare to perform data segmentation and data format conversion. The body part of 41 struts were manually segmented. The format of output files was converted to TXT file so that those files could be imported into MATLAB. In MATLAB, the developed algorithm is conducted to extract geometry information of each strut. Centerline direction and position of each strut was determined based on PCA. When locating ends of the body, k is chosen as 0.5 mm so that the difference between the theoretical ends position and the iteration result could be smaller than 0.5 mm and the iteration number won't be too large. In the lower ends plane extraction process, D value is determined to be 0.0009 mm based on experiment to effectively distinguish target plane from all clusters. Since all connection plates have a similar relative position to the ends of the body, after obtaining positions of ends of the body, a rough view range of the connection plate at each end could be determined so that the connection plate part could be separated out from the whole structure. When the occlusion occurs, the information of corresponding strut and connection plate will be incomplete, so they will be deleted. After finishing information extraction, an EXCEL file contains all information could be generated and stored in a specified position. Then, by clicking run bottom in Dynamo, geometry information could be read, and a BIM model could be generated automatically in Revit.

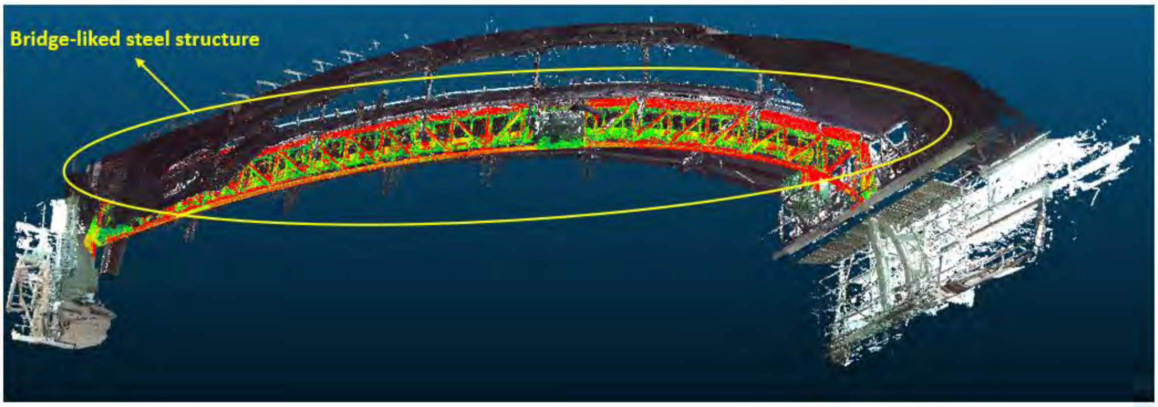

Fig.10 Point cloud data from construction site

4.3 Results and discussion

The proposed technique was applied to the point cloud data of the steel structure. The Geometry information extraction process for struts and connection plates and automatic BIM modeling took about 140 minutes and 2 minutes, respectively. With conventional modelling approach using software like FARO's PointSense Plant add-in or Edgewise, several days are needed with skillful workers to complete such a complex and large-scale model from point cloud data. As a result, the proposed method can significantly reduce the modeling time and effort. 39 out of 41 struts and 78 out of 82 connection plates are modeled successfully. Two failure cases are mainly due to data missing resulting from occlusions as shown in Fig. 11.

5. CONCLUSIONS

This study provides an efficient approach to extracting geometry information for irregular-shaped steel structure components from laser scanning data and automatically constructing as-built BIMs based on the extracted information. Geometry information including the direction and position of strut body, planes at ends of strut, and boundary lines of connection plate is extracted from point cloud data. This information is converted to predefined parameters that could describe and control a model and Revit families are built base on these parameters. Finally, a programming tool for Revit, Dynamo, is used to automate the BIM model generation. The proposed technique was validated on a large scaled bridge-like steel structure. During geometry information extraction, 39 out of 41 components were extract successfully and failures were all due to occlusions. All successfully extracted information could be used to automatically generate BIM model. Moreover, this method can be modified and adopted to other steel structural components with similar features. Limitations of this study is that the curved top chord and bottom chord are modelled manually. Algorithms and modeling method for this part need to be further developed.

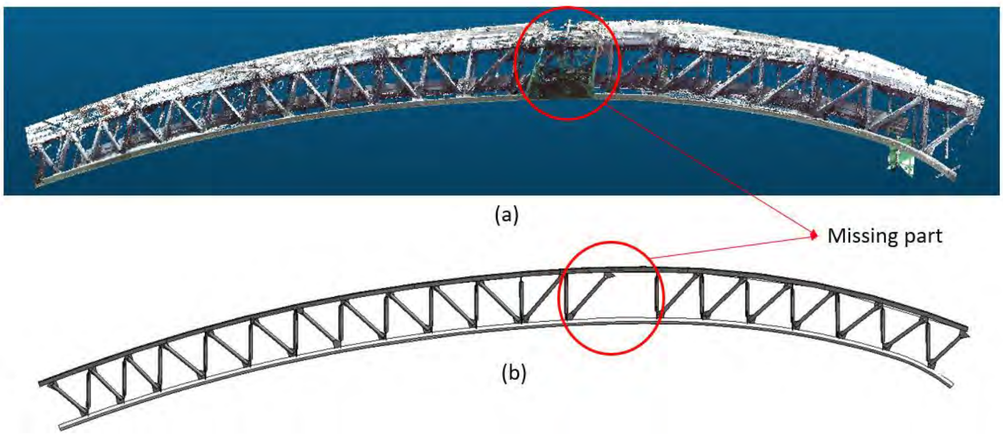

Fig.11 Bridge-like steel structure. (a) Point cloud data. (b) Automatic generated model

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A DIDACTICAL APPROACH FOR THE TRAINING WITH VIRTUAL REALITY

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ABSTRACT: *Virtual Reality has been proven a beneficial alternative to common trainings in selected use cases. Multiple studies demonstrated its positive benefits as it may reduce training costs and may be executed anywhere in the world. Specifically in mechanical and civil engineering, seasonal workers may be trained easily – e.g. for the construction of modular systems.*

Besides the applied technology, the didactical approach is crucial to the results of the training. As the content becomes more complex, the workers cannot remember all working steps at once. Consequently, the approach has to adapt itself to the current abilities of the worker – e.g. by providing more levels of difficulty. However, the more levels of difficulty a training contains, the more expensive the setup becomes. Therefore, the question is how to set up a VR training in order to maximize the benefits without increasing the effort to create it.

This paper uses the characteristics of VR to optimize trainings for construction tasks in mechanical and civil engineering. Thereby, special attention is paid to derive multiple levels of difficulty automatically with only one sample solution. Using this approach, VR trainings can be created and executed with little effort and a high didactical value. Proving its point, this paper also describes its implementation into a software prototype and plots the results of the tests being carried out.

KEYWORDS: *Virtual Reality, Didactical Approach, Training, Maintenance, Construction Tasks, Modular Systems*

1. MOTIVATION

Engineering companies and construction sites all over the world rely on seasonal workers. Obviously, this staff does not have the same experience and knowledge as long-term employees – which results in typical challenges. For example, untrained workers will need more time to complete a task. At the same time, they will distract experienced workers by asking questions. Also, untrained workers are more likely to make mistakes. If not discovered, this may result in a delayed completion and a lower quality of the entire structure up to stability problems. Finally, an untrained worker is more likely to hurt himself as he is not yet aware of the threats of a construction site. In order to maintain a high quality of the product, a punctual completion and a safe working environment, construction companies have to enforce counter measures. The common choice of means is to prepare a mock-up for training purposes or to have an experienced worker supervise the unexperienced (on-the-job-training). Both alternatives are expensive and time consuming for the company.

Virtual Reality (VR) offers the potential to reduce these problems by preponing part of the learning process. Multiple studies have already successfully demonstrated its positive benefits in specific use cases (Dick et al., 2017; Haase et al., 2009; Ordaz et al., 2015; Vaughan et al., 2016). Schroeder et al. also provide an IT architecture to set up a training with manageable effort (Schroeder et al., 2017). These VR trainings are usually limited to a single training case. An adaption of the scenery or the working task usually requires programming skills. Also, none of the concepts compares the effort to set up a training with its outcome or considers the individual learning speed of the trainee.

Besides the didactical approach, none of the concepts sufficiently considers the choice of technology for a training – such as desktop applications, augmented reality etc. As this choice largely influences the outcome of a training, it becomes indispensable when defining an industrial training environment. However, using a non-suitable approach for evaluating the effects of the chosen technology would distort the outcome. Therefore, this paper focuses on testing only the developed approach, leaving the choice of technology to future elaborations.

The question arising from these considerations is: "*How should a didactical approach be set up in order to maximize the benefits of a VR training without increasing the effort to create it?*" The objective of this paper is to answer this question and present a verification of the developed approach.

2. VIRTUAL REALITY FOR CONSTRUCTION TASKS

Burdea et al. define VR as a "*high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels. […]*" (Burdea et al., 2003). Such a system contains a computer, the VR scene data, an input device, an output device and a VR software (Runde, 2007). It is characterized by the features immersion, interaction and the human imagination (Burdea et al., 2003). It may be used for several industrial use cases – e.g. medicine, engineering or training (Dick et al., 2017; Haase et al., 2009; Ordaz et al., 2015; Vaughan et al., 2016).

This paper seeks to maximize the benefits of a VR trainings for a low-qualified workforce in the construction industry. Referring to the definition of a qualification, that implies to teach a defined set of knowledge, abilities and skills that is required to properly execute a professional task (Erpenbeck and Sauter, 2015). Thereby, abilities cannot be changed in the given time and the skills are too simple to justify the expenses of a VR training (e.g. the proper use of a hammer). Consequently, this paper focuses only on the transfer of knowledge.

As knowledge consists of the information and its cross-linking (North, 2011), the information to be taught consists of the answers to the following questions: *When?*, *What?*, *Where?* and *How?* (Halata, 2018). *When?* refers to the correct order of working steps. *What?* refers to the correct part to be installed. *Where?* refers to the final installation position and *How?* refers to the tool to use. Again, the tool is not relevant in this context, as teaching the proper use of a hammer does not justify the expenses of a VR training.

As stated before, multiple studies have used VR to educate personal in the manufacturing and construction sector. Among these are use cases to train the decision making process or to implement a safety management in the construction industry (Goulding et al., 2014; Guo et al., 2013; Hilfert et al., 2016; Sacks et al., 2013). However, only few studies refer to the training of a low-qualified workforce in order to prepare them for the actual construction tasks. Haase et al. use VR to train technical specialists. In order to do so, they propose to implement four different modes in the VR training setup (Haase et al., 2009):

- the discovery mode to explore the virtual scene and functionalities without a specific task
- the presentation mode to give the user a first impression of the task
- the guided mode to apply and train the task
- the free mode to train a complex task without instructions of a trainer or the program

While Haase et al. do not consider the time to set up such a training, Schroeder et al. implement the three generic steps "creation", "execution" and "evaluation". The goal of this architecture is to allow a setup of a new VR training without programming skills (Schroeder et al., 2017).

Anyhow, using the analyzed concepts and applications to teach a low-qualified workforce construction steps, results in at least one of the following problems:

- The guided mode does not consider the individual learning speed of the worker.
- The effort to create a new VR training is proportional to its ability to adapt to the workers' needs.
- Developing a new VR training scene usually requires programming skills.

3. DIDACTICAL APPROACH FOR VR TRAININGS

3.1 Requirements

The didactical approach is not supposed to be used only in a laboratory environment, but also in use cases in the engineering and construction industry. Therefore, the approach has to provide a clear, quantified benefit towards a VR training without this didactical approach. In this context, the benefits are measured in terms of a reduced time of training, a reduced processing time, a reduced amount of mistakes during the first execution in real life and a better motivation of the workers. These shall be the target values for the experiment described in chapter 4. In addition, the approach has to cope with the following requirements:

- The effort to create a new training scenario does not depend on its ability to adapt to the workers' needs.
- The worker may freely choose the best fitting learning speed according to his knowledge.
- The controls are intuitive and easy to learn. Both workers and trainers may use it without a long introduction to the software.
- The software has to record any action taken by the worker that is relevant for evaluation. This way, an

automatic evaluation of the workers knowledge can be implemented.
- The software provides an examination mode that allows the user to test whether he or she has learned the content of the training.

3.2 Learning Sequence

To derive the potentials for a learning approach, this paper divides the process of memorizing a construction task into a set of generic learning sequences. By doing so, the didactical approach may focus on each step individually to improve the outcome of a training.

The very first step in such a learning sequence is to *receive the information* of the task. This may be in form of an oral or written instruction, a picture, a drawing or simply the desire to solve a problem. Once the task is clear, the worker must *identify the component* and *identify its final position*. Even though the trainee has already received the information, he or she still has to transfer this knowledge to the real world. These two steps may be interchangeable. The last and most important step is to *execute the work step* in order to learn and memorize it. A control mechanism may be implemented afterwards by asking questions about the training situation (Haase et al., 2009). The proposed learning sequence is displayed in Figure 1.

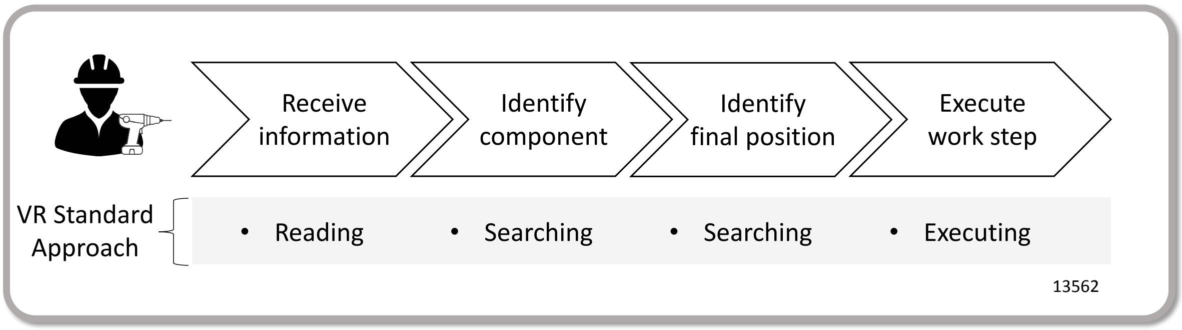

Figure 1: Standard learning sequence for VR

3.3 Didactical Approach

Considering the characteristics of VR and the requirements mentioned in chapter 3.1, this approach is based on three pillars – an immediate control mechanism, adaptive levels of difficulty and a high level of activity. Each pillar is described in detail in the following.

According to Haase et al., an appropriate *control mechanism* is valuable for the user in order to self-evaluate the performance (Haase et al., 2009), so that the worker can improve himself and finally cope with the training task. This may be implemented in two ways:

a) The software may conduct a control mechanism when reaching a milestone which may be the end of the training, the end of a construction group or simply a certain number of steps defined by the trainer.
b) The software may conduct a control mechanism immediately after each working step.

Option a) is argued to be the more sustainable approach. On the other hand, this approach needs more time for the trainee to become effective. Option b) is argued to be much faster as it does not allow the trainee to proceed when making a mistake. Anyhow, as the trainee counts on being corrected immediately, the knowledge conceived is considered to be less sustainable. As the worker is expected to execute the task plenty of times after the training and therefore internalizing it, this paper weighs the reduced training time to be more important than the sustainability of the learned knowledge. Hence, this approach proceeds with option b).

This paper's approach is to enlarge the four training modes of Haase et al. by integrating the individual learning speed. Therefore, it proposes to use five *levels of difficulty*. Generally, the user starts with a simple approach in which he or she is provided with all necessary information. With an increasing level of difficulty, the user receives support for less steps of the sequence until he or she has to recite all information. While Level 1 and 5 have special purposes, level 2-4 are the actual training levels.

- *Level 1*: This level works as a showcase. Nonetheless, it can be useful for simple tasks that do not require a full training approach. In this level, the user may animate one step at a time by clicking a button. He or she may therefore use the 3D feature of VR to understand complex structures better.

- *Level 2*: This is the first and easiest training level. The user receives all information necessary – the part to be moved, its final position and its orientation. Therefore, the correct part blinks until moved by the user and a silhouette of the part indicates its final position. The user is interacting with the system in real-time and in 3D by moving the objects with the controllers.
- *Level 3*: This level matches level 2 except that the software does not indicate what part to take. The user may receive a hint by touching an object. In case of the correct part, it is highlighted. The user cannot move an incorrect part. The user still has to interact with the system in real-time and in 3D by moving the objects with the controllers.
- *Level 4*: During this level, the software provides no information. Still, the user may not move an incorrect part and by touching the objects with the controller he or she may find the correct part. The user still has to interact with the system in real-time by moving the objects with the controllers.
- *Level 5*: This level represents the final examination and is therefore not part of the actual training. The worker may either use this level to test himself or the company may ask the worker to prove his ability to fulfil the task. The user may move an incorrect part and proceed with an incorrect order.

While the 5 levels represent only three of the four proposed modes, the free mode can be used, if no level is activated. Thereby, all 4 modes of Haase et al. are represented. In case the worker has to learn a sequence of many construction steps, the entire training may be split and each part may be repeated several times using the levels of difficulty named above. The five levels of difficulty, their connection to the learning sequence as well as the use of the control mechanism are visualized in Figure 2. The active training is continuously present.

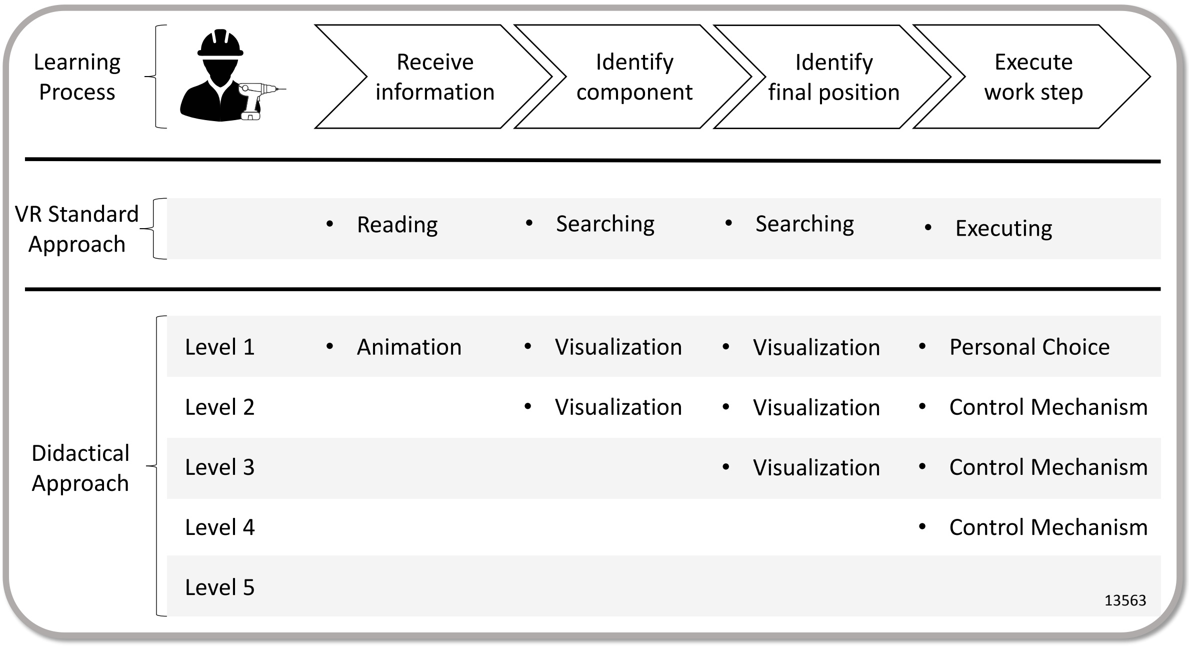

Figure 2: Didactical VR approach vs. Standard VR approach

It is still valid, that an *active training* is more effective than only receiving information (Dale, 1969; Freeman et al., 2014). Taking into account the features of VR, this approach asks the user to interact with the Virtual Reality as much as possible. Therefore, the user has to manipulate the objects with the controllers whenever possible. The alternative – having the user observe a scenery changing on his command – is argued to be faster but less effective.

4. EVALUATION

4.1 Prototype

A software prototype shall prove the feasibility of the developed approach using the platform Unity. The software is set up for VR glasses, specifically for the HTC Vive. The user may autonomously start and terminate the training mode and select one of the training levels. To use one setting for multiple training situations, the user may then select his preferred sample solution – which generates the chosen level of difficulty. When not choosing a training level, the user is in the free mode. While in training, the user may receive additional, textual information via the work-board that is attached to the left controller. This may include instructions and hints to further clarify the task.

Figure 3 shows the prototype including the work-board used for an artificial training scenario in first-person perspective. Thereby, the user may choose between a common controller (left picture) and a preset tool – e.g. a wrench (right picture).

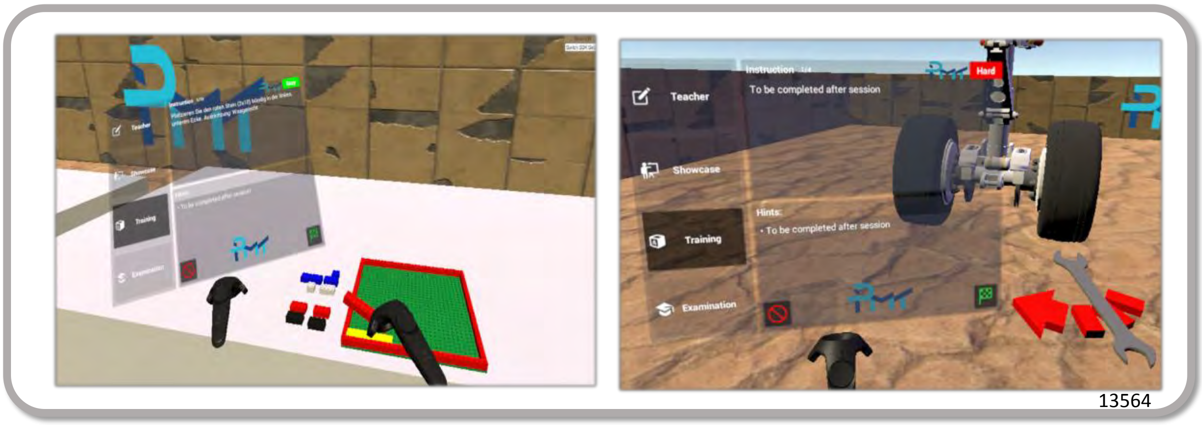

Figure 3: VR training prototype at the IPMT including the work-board and the tool-change

To help the user to successfully execute the training, the following tools have been added:

- *Automatic Visualization*: Depending on the chosen level of difficulty, the part and its final position can be highlighted (see Figure 3 – left picture). This tool derives its information from the sample solution, which is prepared by the trainer in VR.
- *Automatic Control Mechanism*: As stated in the previous chapter, the software is supposed to check whether the user executed the working step correctly. In order to simplify its usage, the program continuously checks whether the part is at the place indicated by the sample solution. Once this is the case, the next working step is automatically activated and the user may immediately proceed. There is no need to manually initiate a control function and activate the next step.
- *Magnetic Effect*: When placing objects in a defined radius to the correct final place, the software will automatically pull the moved object into its final position. This way, the user does not have to focus on precision (which is not part of the training content).
- *Text Instructions*: As the user is supposed to learn by himself, he may still need additional hints. Therefore, the trainer has the opportunity to define text elements for each working step that are presented to the user when requested. The user may look at the work board if he fails to remember the next step. This function is optional.
- *Rotation Control*: When placing a symmetric object, its rotation is not relevant. Therefore, the trainer may define that the software does not check the final orientation of an object in order to consider a training step passed.
- *Final Position Control*: For mounting tasks, the final position of an object is crucial. Nonetheless, once an object is disassembled, the final position does not matter any longer – the worker may put the part wherever he or she desires. Therefore, the trainer has the opportunity to define whether the final position shall be checked by the software.
- *Tool Selection*: If desired, the trainer may define tools (e.g. a hammer or a screwdriver) to be used. The worker may choose between the preset tools, which appear in his hands instead of the common controller (see Figure 3 –the right controller has been replaced by a wrench)

4.2 Creation of a new VR Training

In order to evaluate the software prototype against the requirements from section 3.1, the effort to create a new VR training needs to be quantified. Once the initial situation is set up in the VR environment, the trainer has to provide a sample solution. As stated by Schroeder et al., this is done by executing the training one time in VR. The software records any action taken in a suitable way. Any textual instructions can later be added into the files if needed.

In order to quantify the effort, three participants of the experiment have taken the position of a trainer and carried out a training in the teacher mode. The goal was to determine whether a trainer with only little experience with

VR could create a training. As it is not the task of the trainer, the participants did not have to prepare the CAD data or set up a proper training scene. The participants only had to execute ten simple steps to assemble a pipe system. Each of the participants had one attempt to adapt themselves to the program. The second attempt was recorded.

The participants needed 1:01 min, 1:07 min and 1:54 min with an average of 1:21 min. This includes only the execution by the trainer. It does not include setting up a proper scene in VR, preparing the CAD data according to VR requirements or preparing the textual instructions for the work-board, as these steps are similar in other approaches. In order to determine the overall time of setting up an entire training, the duration of these tasks would have to be included. In conclusion, all trainers were able to create a new VR training containing all steps and all levels. Even though these numbers are not statistically significant, the experiment shows that a training may be taught to the program within minutes by a trainer with little experience in VR.

4.3 Training with the Didactical Approach

The objective of the experiment is to determine whether the use of the developed approach has a positive effect on at least one of the target values. Thereby, none of the ten *participants* were familiar with the construction tasks. One participant was involved in the early stages of developing the software prototype. The age of the participants was between 23 and 31 years (average 26 years).

In order to quantify the benefits of the developed approach, it has to be compared with existing VR training approaches. As none of the analyzed concepts of chapter 2 fulfill the requirements, this paper defines the *opposing approach* as the one with the least required effort to set it up. The outcomes for such an approach are expected to be lower than the ones of the analyzed concept. Anyhow, more effort to set up a VR training would prevent industry from using the training regularly in different scenarios. Therefore, the following characteristics are assumed for the opposing concept:

- The worker receives any information from a written list with instructions.
- All objects that are part of the training situation are present and can be manipulated.
- The worker receives no feedback on his training actions in VR.

The *testing procedure* is set up as follows: Before starting with their first scenario, an instructor provides an introduction to the specific functionalities of VR and the software. Once comfortable, each participant deals with his first scenario. Directly after, the participant has to rebuild the setup in real life without any help. Later, the participant deals with his second scenario. All actions are recorded in order to determine the target values afterwards. In order to avoid any learning effects to affect the results, half of the group starts with scenario 1 and the other half starts with scenario 2. Using the didactical approach in scenario 1, the participant undergoes the three training levels building the system three times in total in VR. Correspondingly, the participant using the opposing approach, builds the systems three times in scenario 2. Both scenarios are carried out without any restrictions of time. In order to avoid tiredness to affect the test results, at least one working day is in between the two scenarios. Within these limits, the participants are supposed to memorize the sequence in a way according to their individual preferences. It is expected that the chosen learning patterns – e.g. try-and-error, internal repetition etc. – effects the outcome of the experiment. Anyhow, due to the small number of participants, not enough individuals chose the same pattern. Thus, the experiment could not determine any statistical effects.

The *testing scenarios* must represent the difficulties of a construction task – which is to know the correct part (what?), the correct sequence (when?) and the correct final position (where?). The correct tool is not considered in these testing scenarios as it is clear to workers that screws are loosened with a screwdriver. At the same time, the scenarios have to be equal in terms of the step quantity, the part quantity, the complexity and the resulting difficulty to remember the training. Any advantage from previously acquired knowledge must be strictly avoided to prevent secondary effects. Even though an existing construction task would be preferable in terms of plausibility and practicability, the remaining requirements are more important in this context. Following this, Lego is chosen as a proper testing scenario. It is easy to handle which allows the test to focus on cognitive skills. It offers a great variety of parts and multiple ways to combine them which allows to set up proper scenarios. Also, it does not cost as much as real industrial products and is easy to rebuild. Therefore, this testing scenario can represent any training situation characterized by the learning sequence in section 3.2 – e.g. modular construction systems. Figure 4 displays the chosen setups for the scenarios including the required order of work steps.

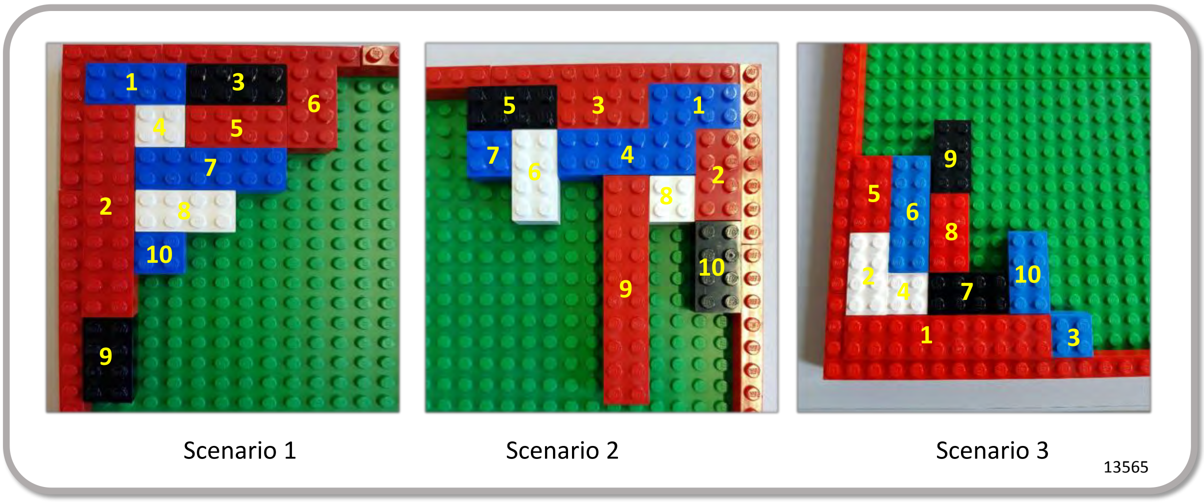

Figure 4: Testing scenarios including the correct order of the work steps

The following *target values* are measured for each participant:

- the training time
- the processing time of the first etarxecution
- the mistakes during the first construction of the setup in real life (part, order and orientation)
- the motivation

The paper analyzes the *results* of the experiment for each target value. The population is assumed to be normally distributed. The analysis is based on a paired t-test. The null hypothesis is: The use of the didactical approach has no influence on the target value. The chosen significance level is α=0.05. The sample size is n=10. The critical value for the t-statistic is t*=1.83 for one-tailed tests and t*=2.26 for two-tailed tests.

Training time: On average, the participants needed 256 s to pass through the training with the didactical approach contrary to 710 s with the opposing approach. This indicates a reduction of the training time by 64%. Therefore, the analysis proceeds with a one-tailed t-test. The t-statistic is t=8.68. The p-value is p=0.000006. The null hypothesis can therefore be rejected. The use of the didactical approach has an influence on the duration of the training time in this experiment with α=0.05. The results of the experiment are displayed in Figure 5.

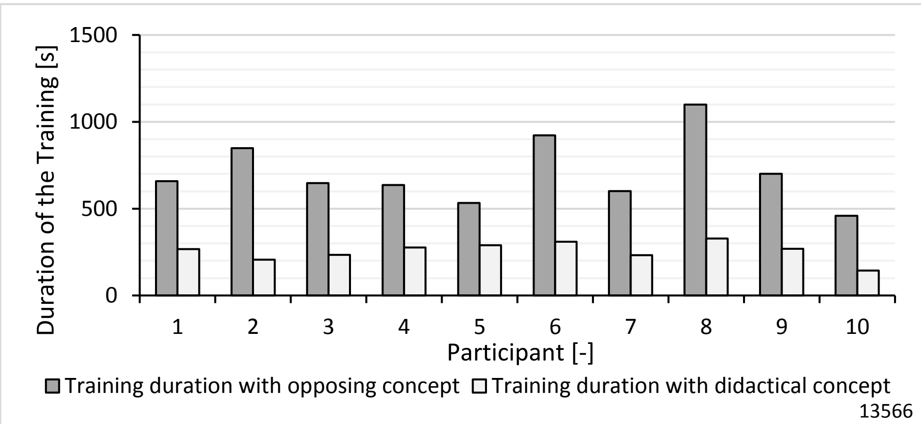

Figure 5: Duration of the training

Mistakes: On average, the participants made 2.7 mistakes without the opposing approach and 1.9 mistakes with the didactical approach. Due to extreme outliers in both directions, this analysis proceeds with a two-tailed t-test. The t-statistic is t=0.49 and p=0.31. The null hypothesis can therefore be accepted. The use of the didactical approach has no statistical influence on the mistakes made in reality. Figure 6 displays these results. Anyhow, subjective observations give the impression that the training became too simple for some participants with the didactical approach and as a result the participants did not focus on the task. These participants participated in a third scenario with unlimited training time and set up cycles. Even though they only needed 58% and 31% of their training time with the opposing approach, they were able to reproduce the task without any mistakes.

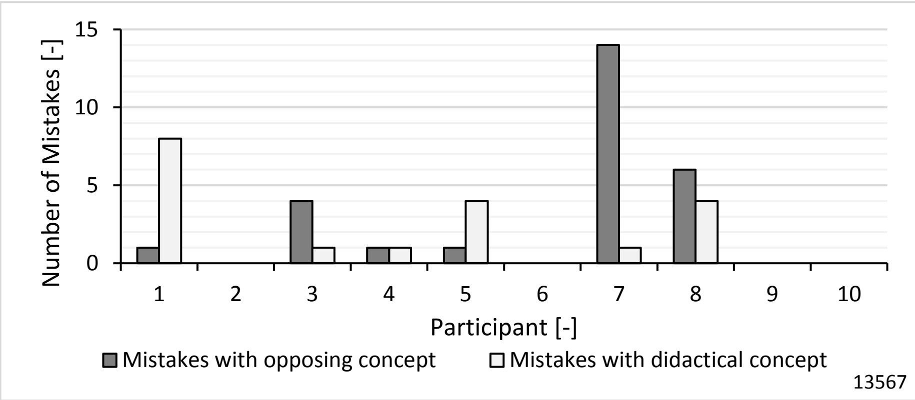

Figure 6: Mistakes made by the participants

Processing time: On average, the participants needed 43 s to build the scenarios in reality after a training with the didactical approach contrary to 73 s with the opposing approach. Still, due to one outlier, this analysis proceeds with a two-tailed t-test. The t-statistic is t= 1.72 and p=0.06. The null hypothesis is therefore accepted. The use of the didactical approach does not have a statistical influence on the processing time. Figure 7 displays the results.

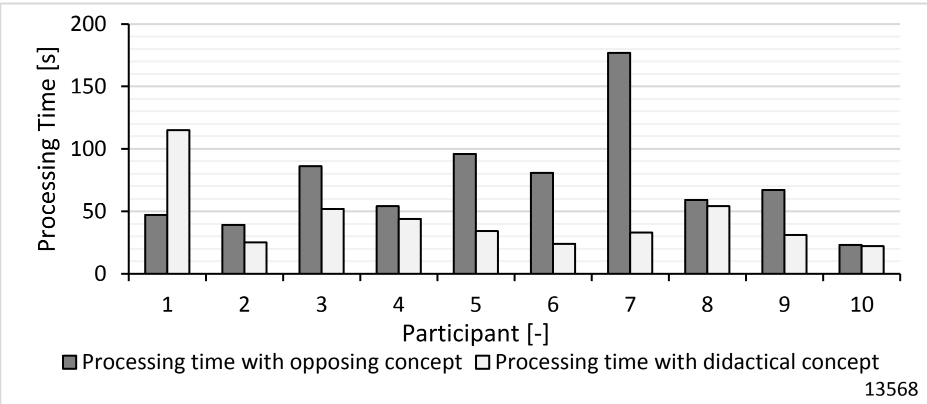

Figure 7: Processing time of the first execution in reality

Motivation: Each participant was asked to evaluate the didactical and the opposing approach with up to 15 points (15 points being the best). On average, the ten participants gave 12.4 out of 15 points for the didactical approach contrary to 5.2 out of 15 for the opposing approach. As none of the participants evaluated the opposing approach better, the analysis proceeds with a one-tailed t-test. The t-statistic is t=6.9 and the p-value is p=0.000032. The null hypothesis is therefore rejected. The use of the didactical approach has a statistical effect on the evaluation of the participants. Figure 8 displays the results.

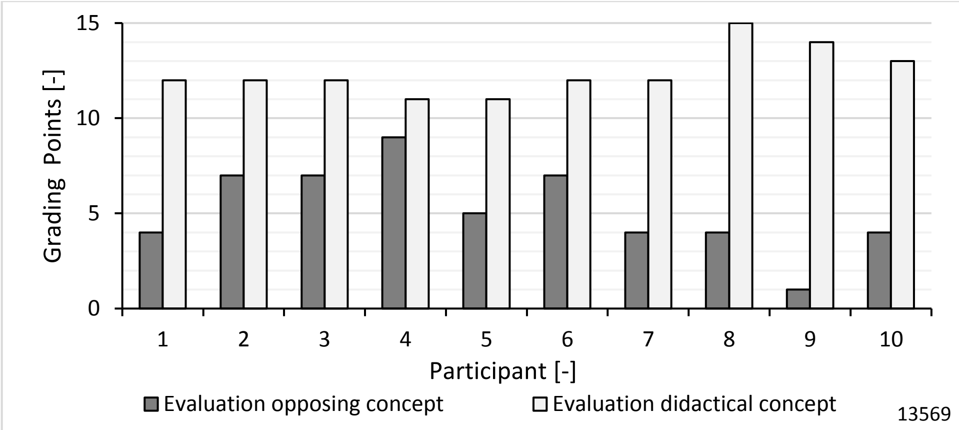

Figure 8: Motivation of the participants to use the didactical approach

5. CONCLUSION

The goal of this paper was to develop a didactical approach for VR trainings and to determine its benefits. Thereby, the approach fulfilled all requirements. The approach allows the user to create new trainings with multiple levels of difficulty with the same effort as for only one level of difficulty. Also, the user may freely choose which level he would like to train with. The evaluation of the test participants indicates that the controls are intuitive. Finally, the approach provides an examination mode and records any action by the user for a later evaluation.

The effort to create a new training was measured with an example of the AEC industry (architecture, engineering and construction). Compared to the positive effect it is rather low – ranging between 1:01 min and 1:54 min excluding the setup of the initial situation. Hence, the additional effort to create such a training with the didactical approach compared to the opposing approach pays itself off with the first trainee.

Furthermore, the tests describe the effect of the developed approach on the user considering the four target values. The test results show that the main potential of the approach lies in the reduced training time and the higher motivation of the users. While the training time dropped by 64% compared to the training time with the opposing approach, the motivation rose from an average of 5.2 points out of 15 to an average of 12.4 points out of 15. While these target values showed an improvement with a significance level of 5%, the results for processing time and the mistakes during the first execution remained within the expected range. No statistically relevant difference was detected. However, subjective observations give the impression, that the aids of the didactical approach simplify the training too much for some users – consequently they do not pay enough attention. In order to avoid this effect, the user may repeat the training as often as he likes. With only two participants going through this third scenario, the numbers are too small to indicate any potential. Still, both participants finished the training with an average of 45% of the training time of the opposing approach and did no mistakes in the construction in the real world. Consequently, a final examination of the user is recommended to ensure the training outcome. This may either take place in reality or using level 5 of the prototype.

As the approach is still in its early stages and the tests were carried out with only few participants, the results of this paper may only be seen as a pre-test giving an early indication of the potential. Further tests including more participants, different scenarios and technologies are required to determine the final potential with statistical significance. Among these will be tests including different levels of complexity and duration. Also, the authors will identify further business cases in which a use of the didactical approach is beneficial.

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A REVIEW OF THE APPLICATIONS OF COMPUTER VISION TO CONSTRUCTION HEALTH AND SAFETY

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ABSTRACT: *Computer vision is an emerging term that acquires, processes and analyses image or video data to help computers have a high-level visual understanding of the world. In recent years, it has been introduced into the construction industry for improvements of occupational health and safety (OHS). Although a number of published works described several classical uses of computer vision for OHS, very few studies exist that have summarised its potential benefits from a holistic view and its far-reaching implications for OHS are still unknown. To overcome this gap, the purpose of this paper is to explore the state of the art as well as the state of practice of computer vision related technologies for OHS by discussing its three levels of development and application, i.e. recognition and tracking, assessment, and prediction. The paper then discusses its theoretical challenges and links to safety research traditions (i.e. safety management system, safety culture, high-reliability organizations, and accident investigations and models), and addresses recommendations for future research at the end.*

KEYWORDS: *Computer vision; Construction health and safety; Automation.*

1. INTRODUCTION

In the construction industry, workers' unsafe behaviours and acts contributed to nearly 80% of accidents (Li et al. 2015). Previous studies indicate that safety performance can be significantly improved through identifying, monitoring, analysing and modifying unsafe behaviours on construction sites (Duff et al. 1994; Komaki et al. 1978; Yu et al. 2017). Behaviour-based safety (BBS) research has been an emerging and promising trend in safety research. A number of behaviour based techniques (e.g. feedback, goal setting, and worker involvement) were developed (Godbey 2006; Guo et al. 2018; Han and Lee 2013) to assist this process. In the workplace, to mitigate foreseeable health and safety risks, design solutions and construction procedures and methods are often reviewed and evaluated before actual construction implementation (Zou et al. 2017; Zou et al. 2017). Site observations and inspections are commonly used to assist the identification and analysis of risks involved in the ongoing works and existing site conditions (Hinze and Godfrey 2003). A risk document that lists all identified hazards with likelihood and severity information is then compiled by safety personnel to help manage hazards during the dynamic construction process. However, the current engineering practice largely relies on manual observation, recording and analysis of unsafe behaviours, which is time-consuming and labour-intensive. Hazard information may not be delivered and communicated timely and accurately. In addition, manual observation and inspection are also difficult to cover the whole site and monitor all workers (Yu et al. 2017). As large-scale and complex construction projects are more and more common, the manual way for on-site health and safety monitoring needs more skilled manpower investment and becomes challenging in daily practice today. There is a growing need to develop automated technologies to overcome these limitations.

Computer vision is an interdisciplinary area that deals with how computers can provide enriched information to support and achieve a high-level understanding by digital images or videos. In recent years, it has attracted a growing research interest in the construction industry due to its potential for automated and continuous monitoring for many construction fields, e.g. occupational safety (Seo et al. 2015), productivity (Ibrahim et al. 2009), and quality (Akinci et al. 2006). Computer vision can process and analyse the obtained images or videos in a timely manner and provide a rich set of information (e.g. site conditions, locations and behaviours of project entities) about a construction scene to provide the accurate and comprehensive understanding of construction activities (Seo et al. 2015). There have been a number of existing studies on applying computer vision techniques for occupational health and safety (OHS). For example, Yu et al. (2017) tested the feasibility and accuracy of using computer vision for recognising three types of unsafe construction behaviours. Han and Lee (2013) proposed a new computer vision-based framework for unsafe action detection and behaviour monitoring. Similarly, Fang et al. (2018) developed a set of computer vision algorithms to detect workers not wearing harnesses. Although the published works described the use of computer vision for OHS in particular scenarios and tasks, very few studies exist that have summarised its potential benefits from a holistic view and links the latest literature with safety research traditions, and its far-reaching implications for OHS are still unknown.

To overcome this gap, this paper reviews the state of the art as well as the state of practice of computer vision technologies for OHS to: 1) understand the current status of applying computer vision to construction health and safety, 2) link current computer vision applications to safety research traditions (i.e., safety climate and safety culture, behaviour-based safety, and resilience engineering) in the construction industry, and 3) discuss the challenges of applying computer vision to construction health and safety, and (4) recommend future research directions on computer vision for construction health and safety.

The paper firstly reviews the literature of computer vision applications to construction according to a three-level of the development framework, i.e. recognition and tracking, assessment, and prediction. It then discusses the theoretical links between current computer vision applications and traditional research of OHS, which is followed by a discussion of theoretical challenges and future research directions.

2. METHODS

This paper used a method of literature review adopted by Guo et al. (2017). The method consists of three main steps: (1) literature search, (2) literature selection, and (3) literature coding. Three academic databases, Science Direct, Taylor & Francis, and the ASCE Library, were selected for the survey due to the comprehensive coverage of relevant peer-refereed academic papers. 456 papers were identified by the preliminary search. Search terms and results are presented in Table 1.

Table 1: Preliminary search terms and results

Datebase	Search terms	Results
ASCE Library	"Computer vision" OR "object recognition" OR "object tracking" OR "action recognition"	116
Science Direct	("Computer vision" OR "object recognition" OR "object tracking" OR "action recognition") AND (“Construction” AND “Safety”)	182
Taylor & Francis	[[All: "computer vision"] OR [All: "object recognition"] OR [All: "object tracking"] OR [All: "action recognition"]] AND [All: “construction”] AND [All: “safety”]	158

In the literature selection phase, all book reviews, editorials, and conference papers were excluded and only journal articles were selected. To limit the scope, this paper reviewed existing literature in computer vision that focused on health and safety through recognizing, tracking, and monitoring project-related objects and conditions. Literature that uses computer vision technologies for structural assessment and defect detection was not included in this study. This resulted in 67 papers for further analysis. All remaining papers were coded according to (1) publication year, (2) journal title, (3) country or region, (4) function (i.e., object recognition, object tracking, action recognition, object assessment, behaviour assessment, condition assessment, behaviour prediction, and incident prediction), and (5) development level (i.e., recognition, assessment, and prediction).

3. RESULTS OF LITERATURE CODING

Results of literature coding are presented in terms of the journal title, publication year, and country or region. As Table 2 shows, Automation in Construction, Journal of Computing in Civil Engineering, and Advanced Engineering Informatics cover around 87% of the identified journal articles.

Table 2: Journal title and number of reviewed papers

Journal title	Number of papers
Automation in Construction	27
Journal of Computing in Civil Engineering	14
Advanced Engineering Informatics	17
Journal of Construction Engineering and Management	5
Computer-Aided Civil and Infrastructure Engineering	3
Journal of Management in Engineering	1

Figure 1 shows the annual distribution of the identified papers from 1997 to 2018. In general, there has been an increasing trend during the period. As shown in Figure 2, the first authors of reviewed 67 papers are from 7 countries/regions: USA (36%), China (19%), Canada (18%), UK (7%), Korea (12%), Germany (5%), and Australia (3%).

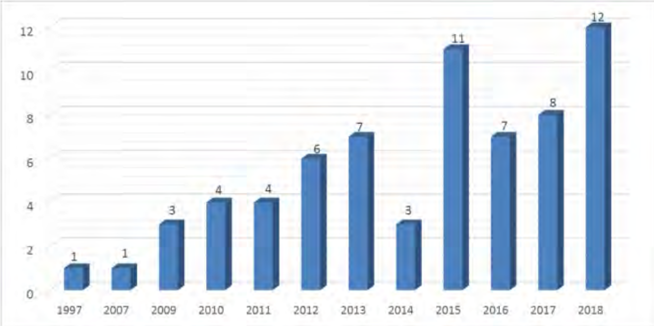

Figure 1: Annual distribution of publications from 1997 to 2018

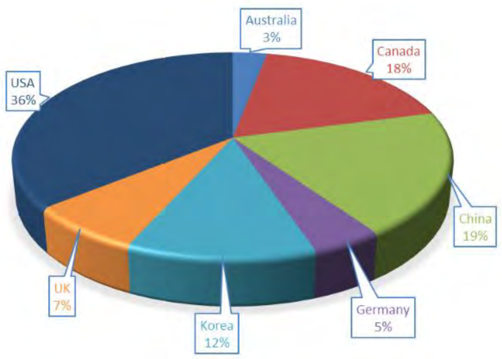

Figure 2: Geographical distribution of publications

4. DEVELOPMENT FRAMEWORK

From a health and safety perspective, there are three levels of computer vision development and applications: L1 recognition and tracking, L2 assessment, and L3 prediction, as shown in Table 3.

Table 3 Development framework of computer vision

Development Level		Function	Key research questions
L1: Recognition and tracking	L1.1	Object recognition	What is the object?
	L1.2	Object tracking	Where is the object?
	L1.3	Action recognition	What is the object doing?
L2: Assessment	L2.1	Object assessment	Is the object a hazard?
	L2.2	Behaviour assessment	Is the action unsafe?
	L2.3	Condition assessment	Is the working condition (scenario) safe or unsafe?
L3: Prediction	L3.1	Behaviour prediction	How will the object behave?
	L3.2	Incident prediction	Will the next incident occur?
	L3.3	Early warnings	What are the leading indicators of the next incident?

4.1 Recognition and tracking

Construction sites involve various project-related objects (e.g., workers, equipment, tools, and resources) and a wide range of activities (e.g., earthmoving). To enable computer systems to understand the complex scenes of construction and perform safety assessment, a pre-condition is to detect, recognize, and track objects and activities of interest. In general, object recognition aims to recognize the objects of interest on site from images and video frames using object detection algorithms (e.g., Histogram of Oriented Gradients (Dalal and Triggs 2005), Haar-like features (Lienhart and Maydt 2002), joint boosting (Torralba et al. 2004), and the region-based fully convolutional network (R-FCN) (Dai et al. 2016)).

Object recognition is usually an initial step for object tracking. Once the object has been identified, tracking algorithms can be applied to track the movement of the object. Commonly used tracking algorithms include mean-shift tracking (Comaniciu and Meer 2002), Bayesian contour tracking (Teizer and Vela 2009), and active contour tracking (Freedman and Zhang 2004).

With the aid of object recognition and tracking, a rich set of information of the object can be provided, including identity *(ID_i)*, spatial and temporal location and path (L_i, path P_i), and speed (V_i). Object recognition serves as a preliminary step for object tracking and action recognition (Seo et al. 2015). The information also forms a fundamental basis for health and safety assessment.

Over the last decade, researchers have made significant efforts to recognize different project-related objects using computer vision. As shown in Table 4, research focus has been placed on recognizing and tracking workforce and site equipment. More recently, a number of particular efforts were made to apply object recognition to construction health and safety. For example, Kolar et al. (2018) developed a safety guardrail detection model based on convolutional neural network (CNN). Fang et al. (2018) used a Faster-R-CNN method to detect the presence of a worker and a deep CNN model to determine if workers are wearing a safety harness when working at heights. In addition, Fang et al. (2018) used a Faster-R-CNN method to detect construction workers' non-hardhat-use. It should be noted that such safety assessment based on object recognition is simple and straightforward in that it utilizes common sense knowledge and does not require reasoning and inference.

Table 4 Objects that can be recognized and tracked

Objects that can be recognized and tracked	References
Concrete columns	(Zhu et al. 2010)
Dump Trucks	(Rezazadeh Azar and McCabe 2011)
Excavators and dump trucks	(Golparvar-Fard et al. 2012)
Hydraulic excavators	(Azar and McCabe 2012)
Tower crane	(Yang et al. 2012)
Workers	(Park and Brilakis 2012; Zhu et al. 2016)
Excavator, loader, dozer, roller and backhoe	(Tajeen and Zhu 2014)
Dump truck, excavator, loader, concrete mixer truck, and road roller	(Kim et al. 2017)
Trade recognition	(Fang et al. 2018)
Concrete mixer truck	(Kim and Kim 2018)
Safety harness	(Fang et al. 2018)
Safety guardrail	(Kolar et al. 2018)
Hardhat	(Fang et al. 2018)

Action recognition is an active research topic in the computer vision community (Vrigkas et al. 2015). The goal of action recognition is to correctly classify input data (e.g., video sequences or still images) into underlying action category. It provides useful data (i.e., action (A_i)) for productivity analysis, progress monitoring, and safety assessment. Vrigkas et al. (2015) classified activities into six levels with respect to their complexity: (1) gestures, (2) atomic actions, (3) human-object or human-to-human interactions, (4) group actions, (5) behaviours, and (6) events. Table 5 lists the actions that were recognized in past literature in terms of complexity defined by Vrigkas et al. (2015).

Table 5 Actions that can be recognized

Actions	Level	References
Operating or idle of hydraulic excavator	atomic actions	(Zou and Kim 2007)
Climbing, leaning, dumping of workers	atomic actions	(Yu et al. 2017)
Ladder climbing of workers	atomic actions	(Ding et al. 2018), (Han and Lee 2013), (Han et al. 2012)
Breaking, measuring & cutting, idling, picking up, putting down, walking, holding of workers	atomic actions	(Khosrowpour et al. 2014)
Worker posture (e.g., standing', 'bending', 'sitting', or 'crawling', effective, contributory, and ineffective human pose)	gestures	(Ray and Teizer 2012), (Bai et al. 2011)
Ergonomic posture	gestures	(Yan et al. 2017)

In some cases, action information can directly be used for safety analysis. For example, Yan et al. (2017) developed an ergonomic posture recognition technique based on 2D ordinary camera for construction hazard prevention through view-invariant features in 2D skeleton motion. Yu et al. (2017) tested the real-time image-skeleton-based method to recognize actions (e.g., climb, dump, and lean) and identify unsafe behaviours based on the value ranges of key parameters. In addition, action recognition has been applied to recognize unsafe ladder climbing behaviours (Ding et al. 2018; Han and Lee 2013; Han et al. 2012).

4.2 Assessment

As aforementioned, in simple scenarios, it is possible to determine if an action is safe or not based on the information extracted from action recognition only using common sense knowledge. When a safety risk scenario is more complex and dynamic, it becomes difficult, and even impossible, to assess safety conditions in a reliable and comprehensive manner. The basic information extracted from object recognition and tracking and action recognition needs to be further assessed based on rule-based or ontology-based knowledge models. For example, Chi and Caldas (2011) demonstrated how the data acquired from object recognition and tracking can be utilized for automatic safety assessment. They designed safety rules to detect three types of safety violation (i.e., speed limit, dangerous access, and close proximity violations). Similarly, Kim et al. (2015) developed an on-site safety assessment system which incorporates two modules: vision processing module (VPM) and safety assessment module (SAM). VPM collects the spatial information of workers and equipment from computer vision, while SAM assesses the safety levels using IF-THEN rules and fuzzy inference. Ray and Teizer (2012) applied to a linear discriminant analysis method to classify worker posture and then used predefined rules to determine if the posture is ergonomic or not.

4.3 Prediction

To fully reap the benefits of computer vision, it is desirable that computer vision can be applied to predict behaviour and incident. Computer vision-based prediction aims to infer ongoing activities from videos that only contain the beginning part of the activities and enable early recognition of unfinished ones (Ryoo 2011). Activity prediction is particularly useful for proactive safety management. From a proactive safety management perspective, computer vision-based systems are required to identify an intended action of workers and equipment before they fully execute the action so that they can provide early warnings of unsafe actions and incident. Although no studies were found that utilized computer vision for prediction in the construction industry, there have been attempts made in the computer vision community to predict human activities (Lan et al. 2014; Pentland and Liu 1999; Ryoo 2011).

5. LINKS TO SAFETY RESEARCH TRADITIONS

Le Coze (2013) distinguished four historical traditions of safety research: safety management system, safety culture, high-reliability organizations, and accident investigations and models. This section aims to examine and clarify the roles of computer vision in accident prediction and construction safety management by linking it with these research traditions. Table 6 presents a brief description of each safety research tradition and links with computer vision applications.

Table 6 Links between computer vision and safety research traditions

Safety research traditions	Description	Links with computer vision
Safety management system (SMS)	An SMS is a system consisting of a set of safety policies and practices with the aim of influencing employee behaviour and creating a safe and healthy workplace.	Computer vision can be applied to a number of safety practices, such as • Audit, • Inspection, • Risk evaluation, and • Review
Safety culture	"the attitudes, beliefs and perceptions shared by natural groups as defining norms and values, which determine how they act and react in relation to risks and risk control systems" (Hale 2000).	• Behaviour-based safety (BBS) program • Beliefs, norms and values *vs.* Technologies
High-reliability organizations	The main features of HROs include managing complexity through: (1) continuous training, (2) use of redundancy, and (3) numerous sources of direct information. With these features HROs have an ability to become aware of unexpected events and an ability to learn and recover from failures.	• Situational awareness • Proactive safety management
Accident investigations and models	Accident causation models, accident investigation framework	No obvious links

Past applications to construction health and safety have proved that computer vision can be integrated into safety management systems by enhancing a number of safety practices such as audit, inspection, risk evaluation, and review. In specific, computer vision at the recognition and tracking level can be applied to detect and track objects and recognize actions of these objects. The information extracted from the applications can be used as inputs of safety assessment and therefore facilitates safety inspection, audit, and risk evaluation. It can improve digitalization and automation in these site management processes and therefore enhance the efficiency of the whole SMS. Traditionally, there has been tension between safety and production (Guo et al. 2015; Guo et al. 2016). Considering that computer vision is time-saving, it has potential to relieve the tension.

The linkage between computer vision and safety culture is close, due to the fact that safety behaviour has long been an important research topic underlying the research tradition and that computer vision has often been used to identify unsafe actions. One of the common limitations of BBS program is that manual observation and analysis of safety behaviour is time-consuming and the scope of observation is often limited. The main goal of action recognition is to automate these processes. From a cognitive behaviour science perspective, worker behaviours are shaped by their attitudes, beliefs, norms and values. It remains an open question as to how computer vision affects workers' mental processes and finally behaviour on site. Another interesting issue is the relationship between information technology (e.g., computer vision) and safety culture. Previous studies have suggested that technologies can penetrate organizational culture (Hill 1988). Although safety culture has its roots in organizational culture, it is not clear that how computer vision technologies impact safety culture in construction projects.

The concept of high-reliability organizations (HRO) places emphasis on developing the organizational capability to manage complexity and uncertainty. It recognizes that socio-technical systems are highly complex and dynamic. Case studies in HRO research are mainly focused on safety-critical industries like nuclear plants, chemical process industry, and civil aviation. HRO claims that major accidents can be prevented through a combination of organizational design, management, and human behaviour. HRO share many properties with resilience engineering (RE) which was proposed by Hollnagel (2007). Both concepts emphasize the importance of resilient organizations and individuals in accident prevention. Computer vision, as well as many other information technologies (e.g., real-time location tracking), can be applied to collect and communicate site safety information (hazards, unsafe behaviour, and unsafe conditions) in a timely manner. This provides the project team with more capability to deal with dynamic site environments.

Most of the classic accident causation models (e.g., Swiss cheese model (Reason et al. 2006)) focus on modelling the roles of organizational technical, and human factors in an accident. Considering that computer vision is not designed to be a part of the production system, it exerts a minor effect on system complexity and coupling.

6. CHALLENGES AND FUTURE RESEARCH

Most of the previous efforts were made to apply computer vision to health and safety monitoring. In essence, health and safety monitoring covers two key functions: safety behaviour recognition and hazard recognition. Site safety assessment is largely based on these two functions. Therefore, this section aims to discuss theoretical challenges to apply computer vision to these two specific functions.

6.1 Safety behaviour recognition

In the evolution of safety theories over the past decades, understanding and managing safety behaviour has constantly been an important and popular research topic. A number of studies were dedicated to applying computer vision to recognize different unsafe or unhealthy behaviours, e.g. not wearing safety harness and hardhat (Fang et al. 2018; Fang et al. 2018), abnormal ladder climbing (Han and Lee 2013), and unhealthy posture (Ray and Teizer 2012). Despite the fact that these studies have laid an important foundation for developing a comprehensive safety behaviour recognition system, there is still a long way to go before it can be effectively implemented in practice. The six-level of human activity decomposition framework proposed by Vrigkas et al. (2015) is useful to articulate the theoretical challenges. It is clear that past efforts were limited to recognize simple gestures and atomic actions, and, to the best knowledge of the authors, there is no research on recognizing safety behaviour and scenarios (or event). Note that in traditional BBS programs, it is of less interest to record only simple gestures and atomic actions like not wearing hardhat, although they are equally important. These programs often aim to observe and record more complex human-to-object and human-to-human interactions, unsafe behaviours and scenarios. For example, one of the unsafe behaviours in a checklist developed for a BBS program (Guo et al. 2018) is: "The signalman gives a warning signal when the load is lifted or moved and no one is standing under suspended load". To recognize this unsafe behaviour, computer vision must not only recognize involved objects (i.e., workers, crane, and load) in terms of identity, location, movement direction, but also, more importantly, understand the interactions between these objects. It is a common view in the social science that group interactions are more complex than individual behaviour (Lehmann-Willenbrock et al. 2017). Scientific knowledge is still limited that defines the link between group dynamics in the social science and safety performance in the safety science. Without the knowledge, it is difficult to define what a good team is from a safety perspective. Computer vision, combined with machine learning, is powerful to capture and identify low-level of behaviour cues and acts of team members. However, group dynamics is more than these low-level data. High-level and abstract attributes (e.g., leadership, cohesion, safety participation, social support, safety motivation, safety awareness, and safety attitude) also play important roles in determining performance at the team level (e.g. safety). Thus, the challenge is to translate low-level data into models that describe social, organizational, and psychological processes using more abstract constructs.

Literature review suggests that there are a number of important technical challenges in object and action recognition. Details can be found in Seo et al. (2015), Teizer (2015), and Gong et al. (2011). It is equally important to think about some theoretical questions carefully. These questions include:

(1) What are the criteria (or knowledge models) that determine if an action/behaviour/event is safe or not?

(2) How to categorize safety behaviour?

(3) What is the relationship between the criteria and safety behaviour category?

It is clear that the benefits are limited when only classifying actions based on predefined categories (labelled as ‘safe” or “unsafe”) using machine learning. This is because there are too many varieties of conditions characterizing real construction site scenes, and it is difficult and inefficient to identify invariants that characterize a certain action and its dynamics. For example, as indicated by Gong et al. (2011), different action categories can have similar gestures and one action category can have a variety of gestures. In some case, whether an action is safe or not depends on the status of other objects. To fully reap the benefits of computer vision for safety behaviour management, a holistic approach is needed to develop knowledge models which have clear answers to the questions above.

6.2 Hazard recognition

Hazard management has been a core practice in site safety planning and management. Computer vision based automatic hazard recognition is an attractive and promising application that future research can explore. Key challenges involved include, (1) recognizing and tracking all project-related objects simultaneously, (2) recognizing different levels of activities of all project-related objects simultaneously, and (3) understanding site scenes. These challenges are both technical and theoretical-oriented. Previous studies have well discussed the first two challenges (Gong et al. 2011; Seo et al. 2015) and therefore this subsection focuses on the last one. Assume that all objects and their activities can be recognized simultaneously. This does not necessarily mean that computer vision based systems understand the ‘meaning” of the whole site scene. Without a comprehensive understanding of the ‘meaning’, computer vision based hazard recognition would be ineffective and unreliable, as it is only able to identify limited hazards based on a superficial understanding of objects and actions (e.g., identity, location, and speed of objects). Comprehensive hazard recognition requires a higher level of scene understanding.

Past efforts made attempt to match the basic detection and localization data collected using cameras with assessment models to achieve a higher level of scene understanding. This higher level of scene understanding allows to identify more complex hazardous scenarios such as struck-by events (Kim et al. 2015). It should be recognized that it is far more difficult to monitor and understand the whole site scene than focus on limited objects. In addition to the challenges in multiple objects recognition, hazard recognition that is based on scene understanding requires to develop and maintain a coherent representation of 4D construction projects (3D + Time) and safety domain knowledge. An important assumption can be made that the nature of hazard is closely associated with the topological and temporal relationships between building elements, materials, temporary equipment and tools, operations, and workspace. By developing such a spatial and temporal model, we can place a hazard into the model, re-define it using geometric, spatial, and temporal features, and identify specific patterns that can distinguish a hazard from others. To address this challenge, knowledge engineering tools such as ontology can be utilized to enable semantic representation and reasoning. Once basic data (e.g., signal, perceptual features, and physical objects and actions) are mapped into appropriate ontologies, the semantic meaning of real construction site scene would be obtained. Therefore, more powerful reasoning can be performed based on the rich semantics to recognize hazards.

7. CONCLUSIONS

This paper reviewed computer vision research focusing on object recognition and tracking, action recognition, health and safety assessment, and productivity analysis in the construction industry. The focus is placed on understanding the current status of computer vision applications to construction health and safety, investigating the link between these applications and safety research traditions, and discussing the theoretical challenges. A three-level of development framework was designed to classify the complexity and difficulty of existing computer vision applications. Results indicated that the majority of past efforts were focused on Level 1: recognition and tracking. Very limited studies made attempt to assess health and safety conditions based on the information extracted from Level 1. To the best of the authors' knowledge, no studies were found that utilized computer vision for predicting safety behaviour and incident in the construction industry.

Such a distribution is understandable, considering that there are a number of technical issues (e.g., viewpoints, occlusion, light, etc.) that pose significant challenges at Level 1. In general, significant progress has been made to recognize and track project-related objects over the past decades. Limited health and safety monitoring can be made based on basic detection and localization. Nevertheless, the progress has laid a fundamental basis for more powerful health and safety assessment at Level 2. Future research efforts can be made to link computer vision with workers' behaviour simulation models (e.g. agent-based safety behaviour model). Data collected by computer vision can be integrated into the models as input for simulation and validation. Such a combination could be a promising research direction towards predictive analysis of site safety.

An investigation of theoretical implications of computer vision for health and safety reveals that it has strong links to safety research traditions like safety management system, safety culture, and high-reliability organizations. It is clear that computer vision has potential to facilitate several safety management practices and programs and therefore enhance site safety management efficiency. When computer vision is used with other real-time technologies, it is able to improve both workers' and managers' ability to manage the dynamic and hazardous construction process. When future efforts succeed to reap the benefits of computer vision at Level 3 prediction, it can be a useful tool to promote proactive safety management, which aims to identify early warnings of incidents.

This paper also discussed the theoretical challenges involved in computer vision based health and safety monitoring. It is important to recognize that current computer vision applications to health and safety monitoring are still limited and primitive. Theoretical challenges deserve the same level of attention as technical ones. In specific, past efforts to recognize unsafe behaviour seem to be fragmented, with less consideration for a holistic framework that is targeted all possible unsafe behaviours. In addition to the scope issue, behaviour complexity and assessment criteria are key issues to be addressed by future studies. To perform comprehensive health and safety monitoring, a high level of scene understanding is required. Future efforts can be made to obtain a semantic meaning of construction site scene and explore how rich semantics can improve automatic hazard identification and health and safety monitoring.

Note that theoretical challenges involved in health and safety domain are closely related technical challenges in computer vision community. This encourages more collaboration between researchers in these two domains.

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SYSTEM DEVELOPMENT OF AN ON-SITE BIM VIEWER BASED ON THE INTEGRATION OF MARKERLESS AR AND BLE INDOOR POSITIONING

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ABSTRACT: *This study proposes an on-site Building Information Modeling (BIM) presenting system, which integrates technologies of Augmented Reality (AR) and indoor positioning to display all attribute information of models and on-site scenes. In cases where the BIM components are shown as 3D models and words indicate the attributes, AR devices display an overlapping scene of the on-site components and give instant feedback to the user. Bluetooth Low Energy (BLE) beacons are used to build a positioning environment inside the building, which can provide a real-time position of the user inside the building and load corresponding graphics of BIM models. Markerless-based tracking technology based on computer vision is adopted to analyze the feature points of the environment and construction components. The feature points can be used to calculate the position and angles of the system cameras in the BIM model scene corresponding to the user's perspective on site so that the system's camera angle is consistent with the user's perspective. The BIM model scene can then be aligned and superimposed on the image of the construction site to integrate the virtual with the reality.*

KEYWORDS: *Augmented Reality, Indoor positioning, Image Recognition, BIM*

1. BACKGROUND & MOTIVATION

Building Information Modeling (BIM) is used to integrate a three-dimensional (3D) visual model of construction projects and digital data of various fields with properties into a file or a database with a specific format. This integration allows project designers, project managers, construction units, owners, and clients to view the design through a three-dimensional visual model and obtain relevant digital data of the project in a three-dimensional visual model. Commercial BIM software products can integrate 3D models with architectural, structural, electromechanical, air-conditioning, firefighting, and other various field data and store them in a single common BIM project. A feature of these commercial BIM software products is that they primarily support the CAD system of BIM design for a studio work environment. Currently, BIM has been applied successfully during the planning and design phases of projects. However, when one wants to use BIM to support tasks during the construction and maintenance phases, one must bring the BIM to the site to use it.

When implementing conventional BIM models in construction sites, relevant BIM software, such as Revit, 3ds Max from Autodesk, and Tekla Structures, is indispensable. However, the software and operating mode is preferable for use on desktops or high-end laptops. Thus, to bring the concept of BIM into construction sites for on-site operations, BIM viewers such as touch pads or high-end laptops are required, thus raising two issues: (1) Users need to perform manual operations, such as rotating, panning, cross-sectioning and hiding components, to the BIM via a viewer to find the needed BIM models and model attributes. Based on the current operation mode, many manual operations are necessary because BIM software cannot automatically display the model attributes that the users need. (2) The graphics of BIM model in a viewer are different from the on-site scenes, making it is impossible to synchronize the information from both sides because current BIM software cannot view or select the model based on the viewer's perspective and position.

Augmented Reality (AR) is a technology which utilizes computer visualization to superimpose virtual objects on real world images for user interaction (Shin & Dunston, 2008). Its mode of operation is to calculate the position and angle of a video device through real-time positioning or image processing and then superimpose a virtual model and information on the image of the real world. Some studies (Behzadan & Kamat, 2011; Bae, et al., 2012; Park, et al., 2013; Wang, et al., 2014; Zollmann, et al., 2014; Chi, et al., 2015; Behzadan, et al., 2015; Kim, et al., 2016; Zhou, et al., 2017) have attempted to apply AR technology in the field of construction engineering by integrating with Global Positioning System (GPS). The aim is to locate the user and the direction the user is facing to display the corresponding information of the 3D models. However, while GPS is usually used to achieve accurate positioning outdoors, it tends to lose signal or experience inaccurate positioning when used indoors or somewhere with heavy insulation. Additionally, as AR is mainly used for gaming or educational training, it can also face problems of inaccurate positioning or screen shaking when used for engineering purposes. Manual calibration is therefore necessary when matching the BIM models with the construction site.

Indoor Positioning Systems (IPS) were developed because users cannot use GPS to locate themselves when indoors; therefore, many shopping malls, public transportation stations and museums with complex moving routes and many rooms use IPS to achieve route navigation, space viewing and information promotion (Yang, et al., 2015). To solve the complicated component-searching operations of BIM on construction sites, this study introduces IPS to locate the user in the space and pick up the corresponding model of the room from the BIM cloud data center, thus reducing the complexity of the operations. Among the currently popular IPS technologies, such as Bluetooth Low Energy (BLE), Wi-Fi, and Zigbee, BLE is being developed the fastest. BLE is a personal space network technology, designed and sold by the Bluetooth Technology Alliance. Compared with traditional Bluetooth communication protocol, BLE technology consumes less power, costs less, and is compatible with devices such as mobile phones and computers. Due to the ease of deployment, low cost, and energy efficient, the BLE was chosen as the IPS technology in this study.

To integrate virtual models with on-site components and simultaneously display them with BIM materials, this study applies AR on camera-equipped cell phones, pads or head-mounted displays to integrate the virtual with the reality. The broad interpretation of AR is a technique that can combine virtual objects or information with real-world graphics, images, or videos, and indirectly interact with users. Users can see the virtual objects superimposed on the real-world screen through video devices; the virtual model positioning method is further divided into two modes: marker-based tracking and markerless-based tracking.

Marker-based tracking uses special markers to display the virtual model before building the relationship between the marker and the model. However, when presenting a construction site, the deviation of the marker’s size could create a mismatch between the model and the site (Pentenrieder, et al., 2006); therefore, users still need to adjust the model to ensure the graphics are presented accurately.

Markerless AR, also known as natural feature recognition, does not use any special markers, but instead tracks images or objects at the construction site to integrate virtual objects with reality via the links to any objects or patterns. The advantage of this method is that, before using an AR system, there is no need to configure the marker for recognition. Using the door or window of the construction site or a component with a high degree of complexity to perform feature analysis in a computer vision can achieve the same feature-matching effect as markers without any manual adjustments, and overlapping of the graphic is performed automatically, which increases the fluency of the operation. The technology foundation of markerless-based tracking is image recognition. The most commonly used image-recognition tool is OpenCV (Open Source Computer Vision Library), which is widely used in image processing and can read stored images, videos, matrix operations, statistics, image processing, object tracking, face recognition, Fourier transform, texture analysis, and dynamic video image processing. OpenCV is also widely used in AR, human-computer interaction, object recognition, and image segmentation fields. Using OpenCV to identify the floor maps, warning signs, doors and windows of the site, and components with obvious features, even in combination with 3D scanning technology, can enable the feature point of the on-site model to be analyzed, thus facilitating the integration of the BIM models and the display of the materials.

2. OBJECTIVE

Based on the above background, this study addresses the inconvenience of existing BIM systems used on construction sites and constructs a BIM on-site information management system based on indoor positioning and AR technology. The integration of markerless AR technology makes it possible for lightweight devices such as mobile devices and head-mounted displays to view, modify, and manage the data at the construction site. The objective of this study is to develop an on-site presenting mode of BIM information by integrating markerless AR and indoor positioning technologies. Such integration enables the BIM information to be superimposed directly upon a real-time video of the building interior. By overlapping the architectural elements via an AR device, a 3D model, established using the BIM components, is displayed, which presents the property parameters of the elements directly on site, and thus provides immediate feedback to the user.

This study focuses on image analysis methods and examines which kinds of on-site objects among objects of different sizes and shapes can be recognized easily in an indoor space using the image recognition function. This study also attempts to apply this system to the entire life cycle of the construction. The tasks proposed by this system are as follows:

1. Indoor space positioning: When the engineer moves in the building, the system will receive a signal from the Bluetooth positioning device to determine the location in the space and obtain corresponding model information from the database. This method reduces the steps involved in searching for models for the user.

2. The BIM model matches with the on-site scene: The image recognition method is used to calculate the feature points of the on-site objects such as warning signs, floor plans, and door and window components. When the manager's mobile device or head-mounted display scans the on-site object, the corresponding BIM model is presented, and the model is aligned with the on-site scene. The user can click on the virtual objects in the screen for editing or timely discussion.

3. BIM data display and modification: When the site is under construction or has been partly completed, relevant personnel can compare the position and quantity of virtual objects with the actual objects. The system can be used to see identify any deviations between the current on-site conditions and the design. In addition to the component attribute parameters, the presented content includes different subsidiary files corresponding to different component types or user requirements. The information obtained through the instant visualization of the system can be used as a reference for decision-making when the on-site personnel is going to install the physical hardware.

3. SYSTEM FRAMEWORK

3.1 Pre-setting process of the proposed system

This study requires the following settings to be made before performing the actual operation at the construction site. At the first stage, the project model of the system is drafted in Autodesk Revit and imported to Unity to build the scene. However, when the users use the system at the construction site, the hardware of their mobile device might not support the image output of a large-scale 3D model. Therefore, when building Unity scenes, the imported Revit model is manually split into many Unity scene archives based on the type of the room or the size required by the user, and it will switch to corresponding scenes when the user's location moves to the room.

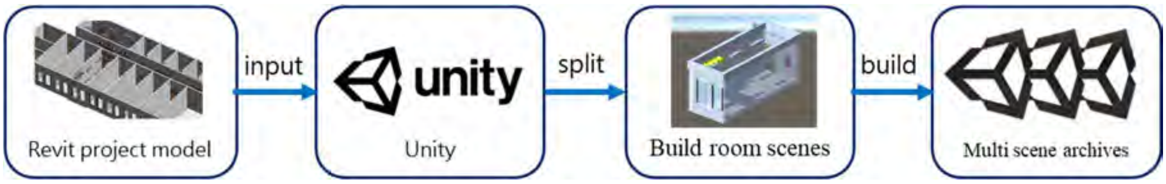

Fig. 1 : The process for partitioning Revit BIM model.

At the second stage, the model data in the system is exported using the Revit project model. For providing BIM information as a Cloud service, the system maintains BIM information in a cloud database using Hbase, instead of using Revit as the BIM server. The system exports model information such as walls, beams, columns, equipment components, and building components to Excel or .mdb files. These data have to be organized first according to the data configuration logic of the cloud database, Hbase, used by the laboratory before being archived in the database. When the user works on the objects in the system, the data can be read and used for the future study of this laboratory. Fig. 2 shows the workflow of the second stage.

Fig. 2 : The process of exporting and storing Revit Model information.

At the third stage, the system archives the objects and materials needed at the construction site, which work as evidence for the system to carry out the image recognition. Standard objects at construction sites include doors, windows, and firefighting equipment. When selecting objects to recognize, the objects with high contrast and clear boundaries are chosen first. After the selection, the object's texture image will be stored in the Unity database, and the recognition image will be placed in the Unity scene in the position corresponding to the scene. The system will determine the model angle of the display of the on-site object according to the image position. Fig. 3 shows the workflow of the third stage.

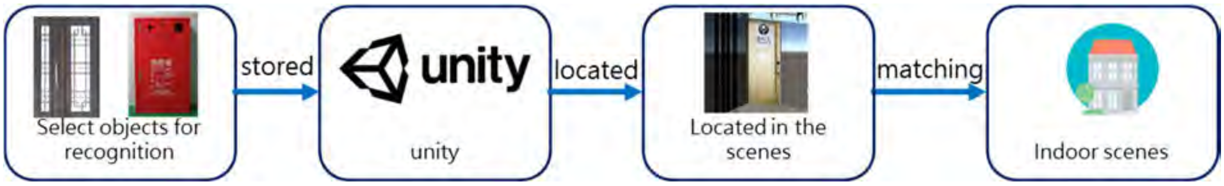

Fig. 3 : The process of selecting and deploying object image for recognition.

At the fourth stage, the system can read the corresponding Unity scenes according to the user's indoor location. To achieve the indoor positioning network, the BLE transmission beacons need to be set up at the site. At least one Beacon should be installed at the center of each room. Since the optimal distance for receiving BLE signal is 8m in our test, more Beacons are required to be installed in room with dimensions that is larger than 8m. Once the setup is complete, the material of the room set with the beacons will be input into the database. After the user enters the site and acquires the UUID(Universally Unique Identifier) of the beacon using the mobile device, the location of the user can be obtained by searching the database. Fig. 4 shows the workflow of the fourth stage.

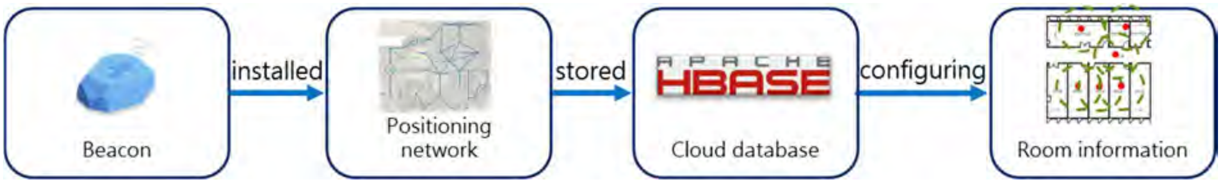

Fig. 4 : The process of deploying the beacon network on-site for indoor positioning.

3.2 System Operating Process

The system operating process proposed in this study comprises three parts: position indoor materials, present AR graphics, and read BIM model properties.

After the system completes all pre-operations and on-site operations, the user can wear the mobile device equipped with the system and enter the construction site. The device will receive UUIDs and signal strength values from the multiple beacons on site. When the system receives the UUIDs, it ranks the UUIDs according to the strength of the signal, and the closest beacon UUID can be obtained. The system can then access the Hbase database, which stores the BLE data through the function provided by Apache Thrift, and the corresponding room name and beacon information are returned to the system. The system switch Unity scenes based on the room name and beacon information.

After entering the corresponding Unity scenes, the system uses OpenCV to catch the camera's vision of the devices and pick up the feature points on the screen. The system then compares the feature points of the device camera with the feature points of the pre-collected recognition images. When the recognition image appears on the screen, the system will get the needed parameters, such as the perspective angle of the image, the position angle of 3D scenes, and the camera settings, to calculate the position of the camera that is responsible for displaying the models. The displays of Unity and the device camera are integrated and sent to the user.

After displaying the system graphics, the user can click on the BIM components in the graphics to prompt the system to export the Revit component ID to the Hbase database. With this ID, the parameters, properties, and category of the component can be found, and these data can be retrieved by the user for further checks and modifications. Fig. 5 shows the system operation process proposed in this study.

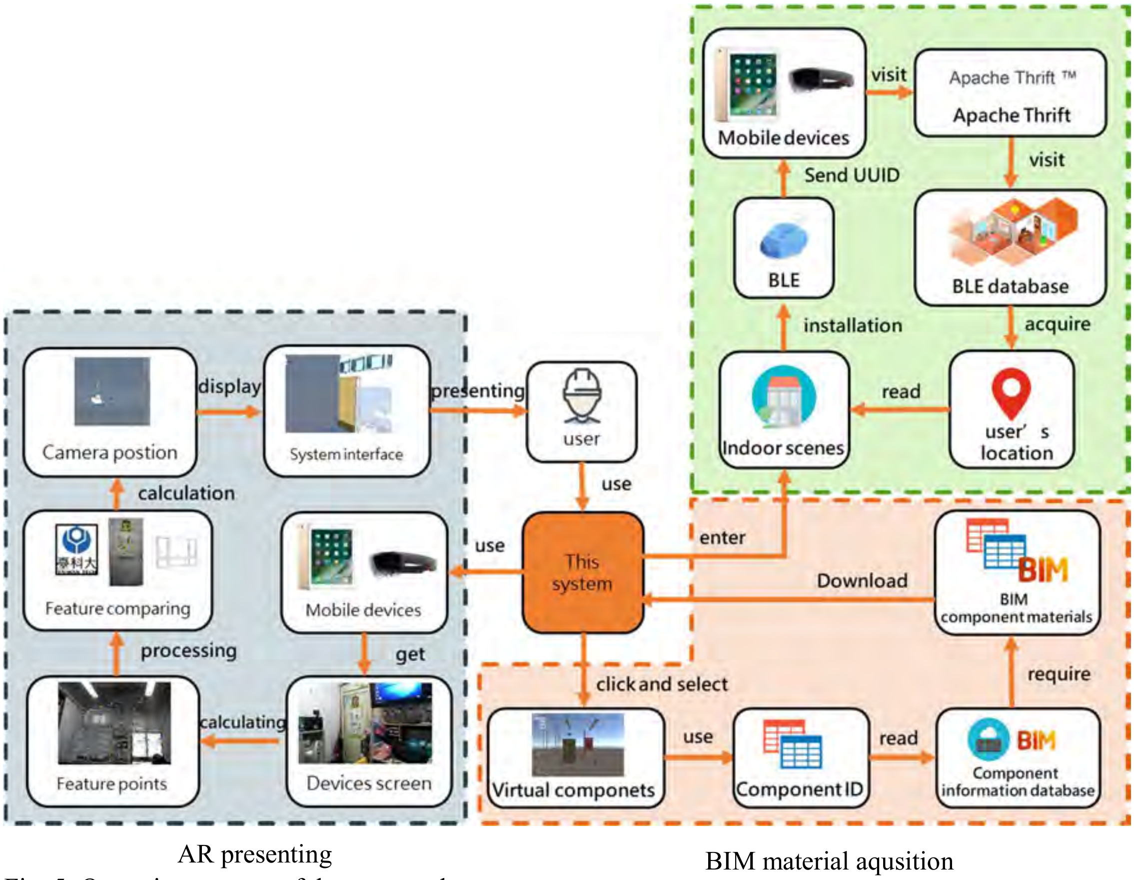

Fig. 5: Operating process of the proposed system.

4. SYSTEM APPLICATION SCENARIOS

This chapter analyzes simulated applications of the system at the construction site during the stages of construction, operation, and maintenance. The simulations comprise four situations: (1) building 3D models and displaying their attribute information, (2) comparing the position and quantity of the components, (3) reviewing and uploading maintenance records, and (4) showing the hidden objects. These are presented on the system screen.

4.1 Presentation mode for 3D model of BIM component and its attribute information

When the workers enter the construction site to check the BIM models, they need to turn on the system in a room equipped with an interactive BIM. The system receives the Bluetooth signal from the on-site beacons and switches to the corresponding room scenes where the user is located. Fig. 6 shows the workflow of this process. Users only need to check hold their device in air, and the system will display the BIM models through image recognition. Users can also check the component BIM information by clicking on the BIM components in the system screen, as shown in Fig. 7.

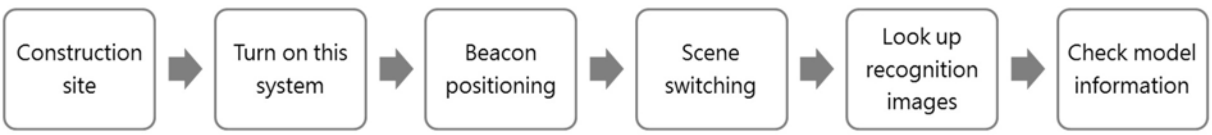

Fig. 6: Application process for presenting 3D model of BIM component and its attribute information.

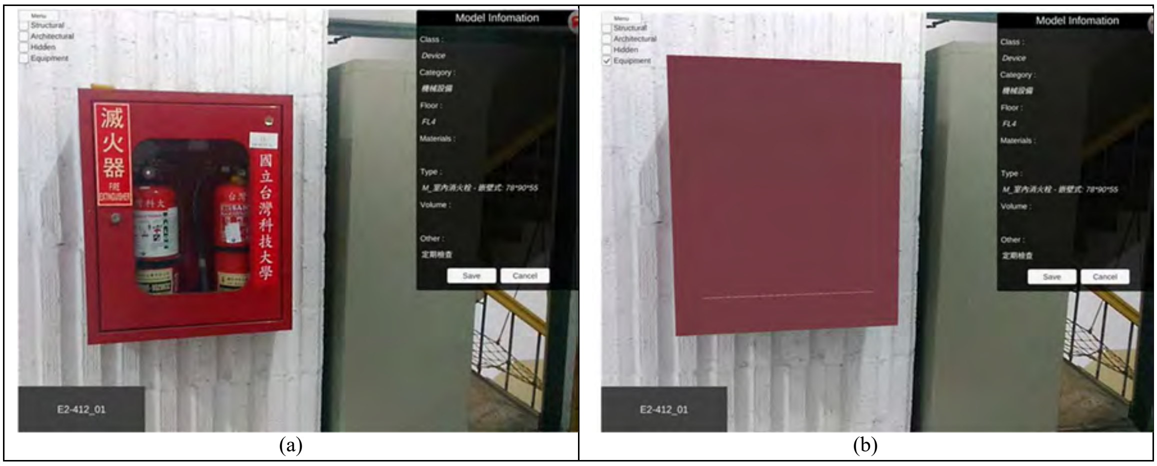

Fig. 7: Presentation mode for presenting 3D model of BIM component and its attribute information.

4.2 Matching mode for the position and quantity of components

When determining components that need recycling at the construction site, users can check the positions of the components to be recycled and compare the quantities before confirming their recycling. Users can also check the attribute information such as the size, position, and materials of the components by clicking on the components shown on the screen. Fig. 8 shows the workflow of this process.

Fig. 8: Application process for the matching mode on the position and quantity of components.

To check the quantity, position, and attribute information of the lighting, users can turn on the devices for searching and hold their device in the air to connect with the beacons. After the system turns on, the device's camera will aim at the components to be checked. At this moment, users can use AR to compare whether the quantity of components on the site matches the quantity in the system, and the attribute information of the lighting can also be checked by clicking on the components. Fig. 9 shows the comparison work of the components.

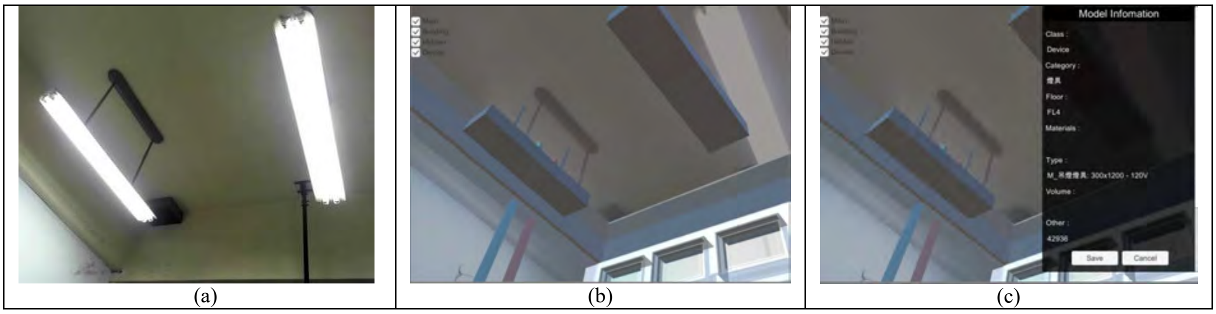

Fig. 9: Matching mode for the position and quantity of components.

4.3 Checking and uploading maintenance records

During operation, some devices will need periodical repairs and maintenance. The repair workers can use this system to inspect the maintenance work, record details of the repair worker, and record the time taken to complete the repair. The recorded information can be provided to managers for future management work. Fig. 10 shows the workflow process.

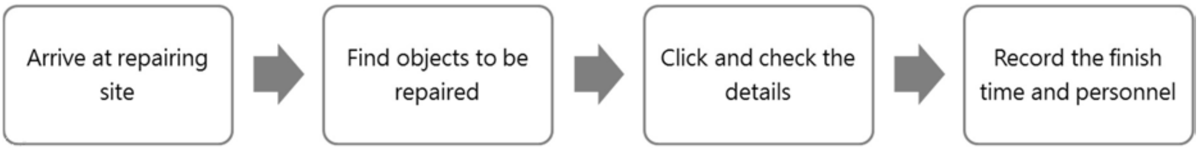

Fig. 10: Application process for checking and uploading maintenance records.

Take the periodical maintenance of a fire equipment storage box as an example. After the repair workers arrive, they check the position of the objects requiring maintenance and view their mission information by clicking on the objects, as shown in Fig. 11. When the repair work is finished, the workers input their names and the time they finished their work in the remarks column of the system, which the system can upload to the database for the managers to check.

Fig. 11: Presentation mode for checking and uploading maintenance records.

4.4 Presentation mode for hidden components

During project operation, pipes sometimes need renovating or repairing; however, when performing repair work on the structural bodies, there is a risk of causing damage to the reinforced steel bars, pipes, or electricity circuit. Using the AR function of this system, the hidden components in the buildings can be displayed on the construction site, thus enabling the workers to confirm the positions of the pipes, which is beneficial to the construction plan. Fig. 12 shows the workflow for repairs to hidden components. Fig. 13 shows that the system enables the engineers to mark the position of the hidden components such as pipes on the wall, which can prevent future damage to the pipes when repairing the wall.

Fig. 12: Application process for presenting hidden objects.

Fig. 13: Presentation mode for hidden components.

4. CONCLUSIONS

This study proposed a system integrating indoor positioning, markerless-based AR and BIM, to achieve a BIM AR presentation without requiring markers to be located on site. In this system, AR integrates virtual models with information of the on-site environment, which it presents to users on the same screen. This system can reduce the steps required for manual operations and lessen the complexity of the human-computer interaction. This system can also overcome the problems with the current BIM software used on construction sites, which requires a large number of manual operations to check the models and view relevant information. Current systems are also unable to synchronize the BIM model in the software screen with actual scenes of the construction site. Indoor positioning can export the models needed by loading corresponding BIM scenes based on the user's location. Combined with indoor positioning, the system can recognize the location of the user through BLE beacons, and the information of BIM components in the room can also be retrieved. The system uses image recognition to present the BIM components and their parameters. By using textures of standard construction components, such as a fire equipment storage boxes, doors and windows, the number of recognition images can be reduced. Compared with the traditional marker-based tracking AR presenting mode, this method can reduce the human resources required to install the markers as well as any deviations of the installation, thus reducing the difficulties of the system operation.

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SMART WORK PACKAGES FOR CONSTRAINT MANAGEMENT IN MODULAR INTEGRATED CONSTRUCTION

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ABSTRACT: *Constraint management is the process of satisfying all bottlenecks to facilitate tasks assigned to crews being successfully executed. However, managing constraints is inherently challenging in Modular Integrated Construction (MiC), due to the fragmentation of processes and information during the project delivery. Enlightened by the broadly accepted work packaging method and the smart construction object (SCO) model, this study first defines smart work packaging (SWP) for constraint management in MiC to leverage the recent advances in smartness, e.g., sociability, adaptivity, and autonomy. Three scenarios, i.e., constraints modeling, constraints optimization, and constraints monitoring, are employed to illustrate the SWP functions with the information hub of Building Information Modeling (BIM). In addition, to elaborate on the implementation of SWP for practitioners, this study develops a layered abstract model as a prototype representation. By catalyzing current construction practices of the work packing method, SWP open new avenues for smart and sound constraint management which are pressing needed by MiC projects.*

KEYWORDS: *Smart Work Packaging (SWP), Modular Integrated Construction (MiC), Constraint management, Building Information Modeling (BIM)*

1. INTRODUCTION

Modular Integrated Construction (MiC) under the principles of industrialization is a modern and innovative approach in Hong Kong that the prefabricated material, components, modules, and units are manufactured efficiently at different locations in Mainland China and then converge at the site for installation, which could alleviate the labor shortage and swiftly provide housings to mitigate the unbalanced housing supply and demand in Hong Kong (Li et al., 2018a). However, the unsustainable rising costs of MiC projects have an adverse impact on Hong Kong's economic growth and competitiveness. For example, current housing construction in Hong Kong typically cost 2-4 times higher than in other cities (Turner and Townsend, 2017). The dominant driver for the rising costs is the pathological schedule delay which was caused by uncertainties and constraints. Reliable schedules are vital for achieving an industrialized construction environment across design, manufacturing, logistics, and on-site assembly to reduce schedule delay and cost overrun (Wang et al., 2016a).

Constraint management is the process of identification, optimization, and monitoring of bottlenecks (e.g., unavailable drawings and specifications, shortage of workforce and materials, limited workspace, uncompleted preceding works, lack of work permits, quality, and safety issues.) to facilitate work package-level tasks assigned to crews being successfully executed (Blackmon et al., 2011). Constraint management systems have proven to be more effective when compared to the reorder-point (ROP) systems and material requirements planning (MRP) systems in the aspects of capacity management, inventory management and process improvement in the manufacturing industry. It is also argued that constraints management can outperform the Just-in-time (JIT) system due to the more targeted nature of improvement efforts in constraints (Boyd and Gupta, 2004). To improve the reliability of MiC schedules, managing constraints in MiC processes per se is to prepare (e.g., detailed and dynamic planning with lean solutions) more and act (e.g., decision-making and collaborative working) fast using available information and knowledge. As such, the primary objective of constraint management is to continually improve the reliability of workflow by ensuring that accurate information is always available at the right time in the right format to the right person. Recently, there has been a wealth of studies focusing on providing precise, timely, and well-formatted information for decision-makers and collaborative workers with smart tools in tasks execution in construction projects (Zhong et al., 2017; Li et al., 2017a). Examples of the smart tools are the Internet of Things (IoT)-enabled Building Information Modeling (BIM) platform and smart construction objects (SCOs) by equipping with radio frequency identification (RFID), augmented reality (AR), and other sensing and tracking technologies (Li et al., 2018a; Li et al., 2018b; Niu et al., 2016). However, there is so far no widely accepted general and sound approach for constraint management in the construction or MiC industry (Blackmon et al. 2011; Wang et al. 2016a).

All the challenges and opportunities have given rise to the smart work packaging (SWP). As such, much effort has been made on using cutting-edge information technologies to make work packages smart (Ibrahim et al., 2009; Abuwarda and Hegazy, 2016). For example, Isaac et al. (2017) developed algorithms for BIM which can be integrated with design structure matrix (DSM) and domain mapping matrix (DMM) to automatically identify relations between prefabricated components and the following sequence in which the prefabricated components should be assembled. In MiC, these are a group of tasks (also the lowest level of work breakdown structure) based on the building systems of product breakdown structure (PBS) involving various resources and approaches that are made smart by equipping task execution processes with capabilities of visualizing, tracking, sensing, processing, computing, networking, and reacting. The resulting characteristics of autonomy, adaptivity, and sociability facilitate the crews better tasks execution. For example, the MiC machinery (i.e., vehicle, crane tower) can be augmented with autonomy to transport or hoist the prefabricated products independently and without direct intervention from surroundings (Chi et al. 2012); the MiC planning approaches can be enhanced with adaptivity to be capable of reacting flexibly and resiliently, such as dynamically re-planning when constraints are not removed (Abuwarda and Hegazy, 2016); the work packages can be strengthened with sociability to interact in a peer-to-peer manner with other work packages or resources in work packages to work collectively on improving constraints (Taghaddos et al., 2012).

This study aims to define SWP based on the established theories of work packaging and smart construction object (SCO) (Isaac et al. 2017; Niu et al. 2016). Work packaging is the approach to break down the MiC processes into manageable pieces to facilitate execution of activities or tasks. However, it is limited in offering practical constraint management solutions such as automatic identification and analysis of constraints and their interrelationships (Hamdi, 2013; Isaac et al. 2017), real-time sensing and tracking constraints status (Liu et al. 2015), and dynamic and optimal constraints improvement planning (Abuwarda and Hegazy, 2016). SCOs are the smart resources with characteristics of awareness, communicativeness, and autonomy, which improve the capacity of resources-related constraints modeling, optimization, and monitoring. However, SCOs are defined on single construction objects, without encapsulating the construction project operations like work packaging. Thus SWP as the integration and extension of work packaging and SCO is to develop smart tasks execution procedure to improve constraint management for achieving mass production in MiC. The smarter constraint management thus involves sophisticated autonomy, adaptivity and sociability based on the intensive interaction among people, technologies, environment, and resources, if this process fails, severe schedule delay/cost overrun result.

2. DEFINITION OF SWP

In this study, SWP is defined as an approach to decompose the MiC workflows (e.g., technical process) by production breakdown structure (PBS) of building systems that are made smart with augmented capacities of visualizing, tracking, sensing, processing, networking, and reasoning so that they can be executed autonomously, adapt to changes in their physical context, and interact with surroundings to enable more resilient process.

The core characteristics, namely, adaptivity, sociability, and autonomy, of SWP are shown in Fig.1. Physical or functional information, such as shape, dimension, products type, the layout of the work section, work procedure, and positions of aids and resources, are not included in Fig. 1 because such information is also required in traditional work packaging method.

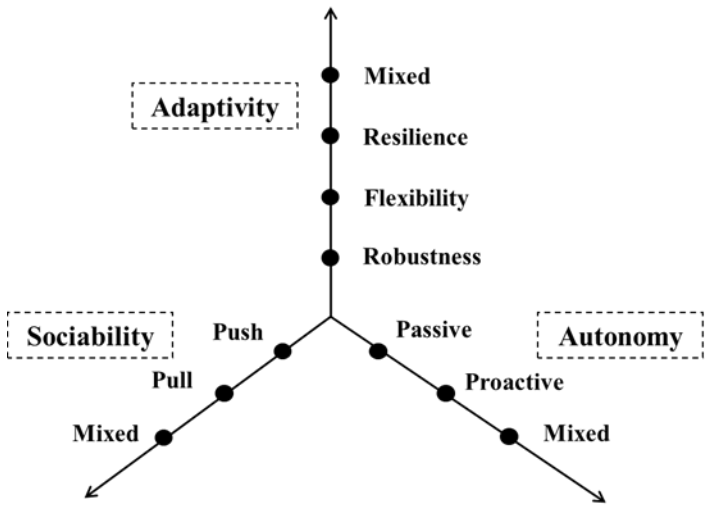

Fig.1. Three core characteristics of the SWP

2.1 Adaptivity

Adaptivity, the most distinct feature of SWP compared with traditional MiC work packaging method, denotes SWP's ability to have a positive response to change, and learn from their own experiences, environment, and interactions with others. This characteristic is based on the concepts of smart workflows proposed by Wieland et al. (2008), which has three adaptivity dimensions, that is, robustness, flexibility, and resilience (Husdal, 2010). The robustness is the simplest the SWP can process. With the robustness, the SWP can quickly regain stability by accepting goal-directed initiatives when encountering constraints. These mainly are primitive tasks (refer to elemental motion with few-steps or short-durations) such as reaching, grasping, picking up, moving, eye travel. Flexibility enables SWP to react to the foreseen changes in a pre-planned manner. It is beneficial for guarding tasks execution against threshold-breaking or exceeding a preset tolerance range and the SWP in this context primarily involving composite tasks such as measure, connect, navigate, select, align, record, and report. Resilience is a high-level adaptivity that facilitates SWP to survive unforeseen changes (severe and enduring impacts) in a dynamic replanning manner. SWP in this context includes operation-specific tasks such as assembly, examining workflow, buffer layout, equipment path planning, and monitoring. For example, SWP with resilience can offer assembly guidance when the as-planned assembly position or operating path is in order and, when a contingency occurs, perform the optimum working path by cross-validating the real-time process with as-planned workflow. Currently, SWP adaptivity can be achieved by advanced optimization approaches when making full use of the information collected from the sensing and tracking technologies.

2.2 Sociability

Sociability ensures that SWP can communicate with the surroundings (e.g., other smart work packages (SWPs), human/machine/products in SWPs). The communication can happen at a pull, push or mixed modes. The pull mode occurs upon demand, i.e., the deliverables/information is delivered when they are requested. In the push mode, SWP actively tracks and updates the information and issues alerts at regular intervals or when an emergency occurs. The mixed mode combines the pull and push to request and deliver information in a peer-to-peer manner. Apart from the three interaction modes of SWP, there are four relationships between SWPs, namely, composition, interface realization, inheritance, and dependency, which can enhance the sociability of SWP in handling the modular products/processes in MiC. Composition in the relationship mostly exists between one SWP and its relevant SWPs which is decomposed by the former. Interface realization refers to a group of SWPs which support or rely on the behavior that is defined in an SWP (work as an interface); Inheritance exists between a parent SWP and its succeeding SWPs. Both the parent and the succeeding SWPs share some common properties while the succeeding SWPs may have their own unique features; Dependency is the most popular relationship where the downstream SWPs is dependent on the upstream SWPs. To achieve the sociability of SWP, there are many communication and networking technologies to enhance the awareness of SWP such as ultrawideband (UWB), ZigBee, Bluetooth, Wi-Fi, near-field communication (NFC), active/passive RFID, electromagnetic, laser, ultrasound, infrared (IR) proximity, conventional radio frequency (RF) timing, wireless local area network (WLAN), received signal strength (RSS), and assisted GPS (A-GPS) (Niu et al. 2016; Zhang and Hammad, 2014).

2.3 Autonomy

Autonomy in this study is inspired by smart construction object (Niu et al., 2016) which refers to the capability of the intelligent resources (e.g., machinery/tools/devices) in SWP to complete control over their own actions and internal state without outside commands/intervention or act through a method of decision making pre-programmed into them. The former mostly demonstrates the proactive autonomy, while the latter mainly indicates the passive autonomy. The proactive autonomy aims to act in advance of a future situation, rather than just reacting. For example, the autonomous crane tower can conduct the hoist plan in an SWP of the product based on the real-time situation it senses, monitors, or predicts, and executes this plan in advance, without including humans in the loop. The SWP with passive autonomy, by contrast, can perform the instant reaction, particularly in an emergency that the response of personnel may lag. For example, the machinery can handle some primitive tasks (e.g., issue an alert) to assist the crews in making decisions and taking actions. Equipping SWP with autonomy is highly dependent on various applications with robust logical reasoning and learning algorithms.

The three core characteristics of SWP, namely, adaptivity, sociability, and autonomy commonly perform in collaboration. Each type of the adaptivity, sociability, and autonomy is not fixed to a bijection. Instead, different types of core characteristics may merge together to carry out, resting on the requirements of different situations. In more complicated scenarios, it is also possible that the collaboration of more than one type of characteristics, such as the mixed mode, is plotted as in Fig. 1. However, the characteristics more advanced than this three for SWP will be initiated in the future.

3. EXAMPLE SCENARIOS AND FUNCTIONS FOR SWPS-ENABLED CONSTRAINT MANAGEMENT

In the following example, an SWP enabling constraint management is illustrated.

An SWP within prefabricated products related functional and physical information, generated from BIM platform based on the building systems and PBS of MiC, is assigned to a site buffer operator for managing related constraints so that efficient on-site assembly process and Just-in-time prefabricated products delivery can be achieved. When the first batch of prefabricated products arrived, the SWP starts to assist site buffer operator in executing constraint management. Firstly, the SWP can identify the critical constraints and interrelationships by networking with other SWP in working status to check out the constraints such as availability of workforce and work face in the assembly position point, the quality of arrived prefabricated products, the availability of space and workforce in site buffer,and their interrelationships such as composition, interface realization, inheritance, and dependency. Secondly, When the most critical one (e.g., space constraint in the buffer, the buffer could only stockpile limited prefabricated products) and its interrelated constraints have been identified, the SWP can assign task with optimal solutions to the buffer operator for improving the constraints: the autonomous crane tower near the buffer will pick up the task to transport the prefabricated products from trailer to the buffer in an optimal path (e.g., safety, short duration). The efficient layout considering both optimal buffer utilization and hoisting sequencing (e.g., first-in-first-assembly) by adopting advanced optimization algorithms is the crucial part of this task. Thirdly, the monitoring both space constraint and the interrelated constraints (e.g., the quantity of prefabricated products transport-in-progress, qualified prefabricated products arrival on-site and assembly-in-progress) in SWP can facilitate the constraints status tracking, updating and predicting. Each SWP can work as a loop for the continual improvement of constraints.

To realize scenarios as the one given, the mentioned three functions including constraints modeling, constraints optimization, and constraints monitoring must be well combined with the core characteristics of SWP for constraint management in MiC.

3.1 Constraints Modeling

Constraint modeling is a critical function to allow a thorough understanding of interconnections among tasks or activities. There are two steps within this function. The first step is the constraints identification. The traditional process for constraints identification is static and normally executed once. The SWP can enhance this step in a passive autonomy manner (See Fig.2) by pre-programming the templated constraints classification with an open-data integration approach for constraints instantiation. Although MiC projects are unique, they share some similar types of constraints at the operational level (Li et al., 2018a), and it is possible to develop a database for organizing the potentially significant amount of constraints (See Table 2). Once the template is applied to the SWP, it instantiates a set of pre-defined constraints and their relationships for critical constraints identification.

Table 2 Templated Constraints Classification

Classification & Definition	**Subcategories**
Physical category：Availability of labor, prefabricated products, machinery/device/tool and other resources related to any physical properties of MIC process	Workforce; prefabricated material/component/module/unit; machinery; equipment; devices; tools; Pre-requisite work; storage space; workspace; safety & occupational health; temporary structures; site facilities/supplies; and environmental conditions
Informational Category: Availability of drawings, instructions, permits, workflows, and plans that are used for performing work	Scope definition; design Information requirements; administrative information/permit; quality & inspection; and transportation

planning

The second step is the constraints relationship mapping. In real MiC projects, constraints are usually not independent and may have dynamic interrelationships. As such, a thorough understanding of these relationships is necessary. Figure 3 shows an example of causal loop interrelationships among constraints in the SWP that is related to the assembly process. Figure 3 (a) shows the system boundary of the SWP, including three modules. It concentrates on mapping the interrelationships of the constraints that can affect the schedule performance of activities/tasks in the on-site assembly process of MiC. More specifically, the on-site assembly module (see Figure 3 (b)) includes the primary variables, such as prefabricated products to be installed, installed prefabricated products, and inspected prefabricated products, which serve as the foundation of the system dynamic model. Based on the on-site assembly model, the constraints causal loop mapping module (see Figure 3 (c)) can facilitate the identification of the interrelationships among physical and informational constraints that can affect assembly efficiency. For example, in the physical constraints loop, the workspace availability can be affected by the uncompleted temporary structures (e.g., scaffolding). Inadequate storage space can limit the availability of the prefabricated product for assembly, and unidentified safety/hazard issues can also restrict the workforce availability because more labor will need to be well trained for hazards identification. Assembly rate is a pull-driven index to request the constraints satisfaction before the reliable assembly execution. The actual and planned percentage of completion on the basis of assembly rate can be compared to evaluate the schedule performance.

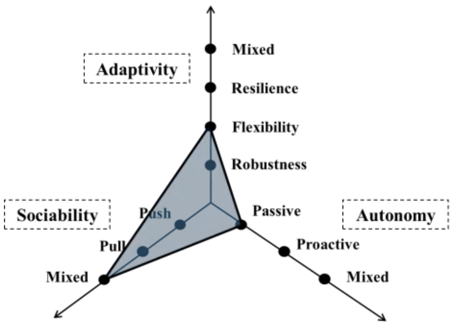

Fig.2. SWP characteristics diagram for constraints modeling

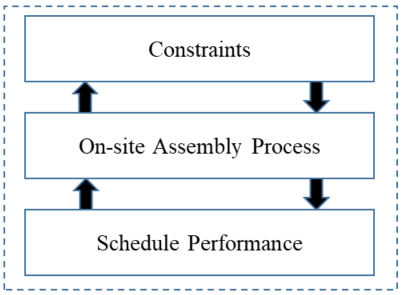

Fig.3. (a) The relationship between the three modules

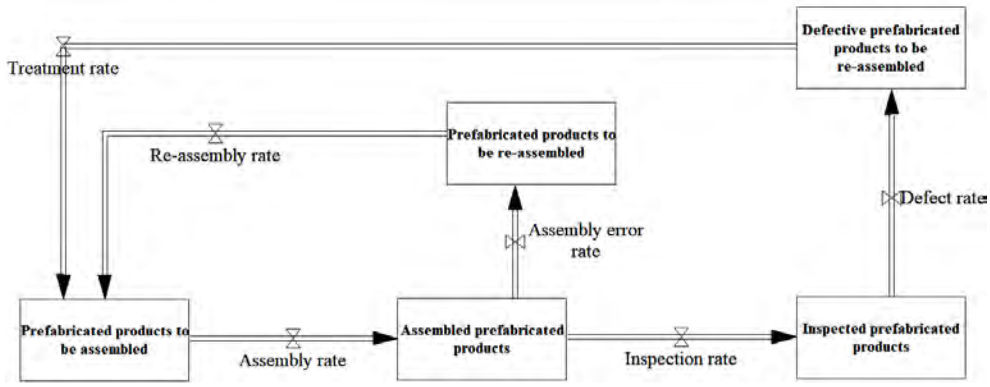

Fig.3. (b) On-site assembly process module

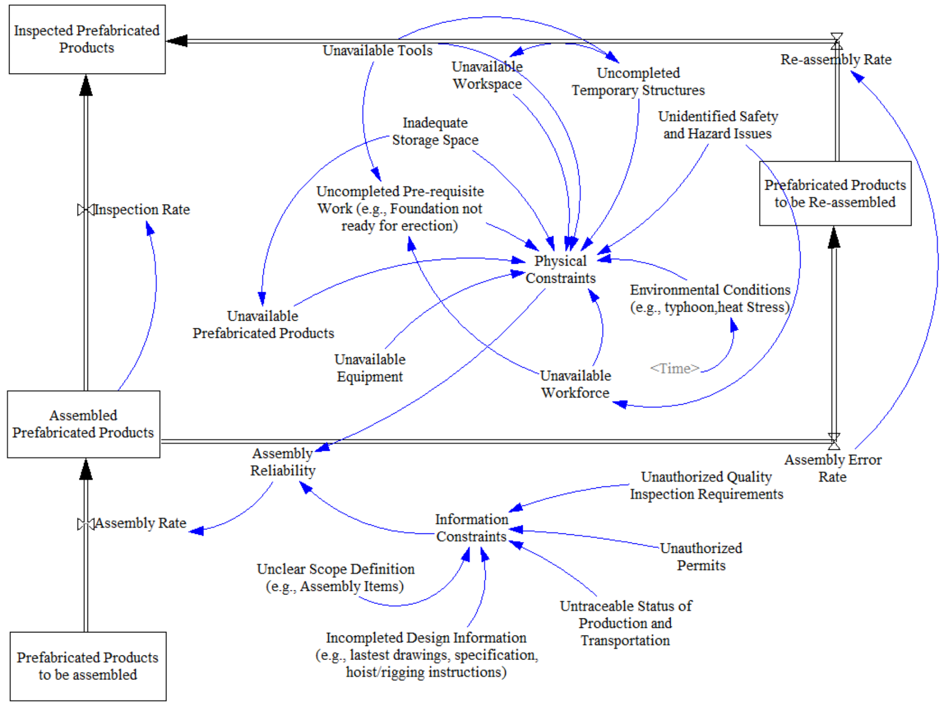

Fig.3. (c) Constraints causal loop relationship mapping module

3.2 Constraints Optimization

Constraints optimization is the succeeding function of constraints modeling. It focuses on securing all critical constraints and ensures that they are dynamically, timely and efficiently improved in constraints improvement planning. There are two push-driven processes enabled by SWP in constraints optimization. The first process is to pre-planning with alternative network paths and alternative constraints improvement methods. For example, the resource leveling optimization problem (e.g., winner determination problem) can be solved under the structure of auction protocol within the greed algorithm, linear programming, and competitive equilibrium. In this constraints improvement planning problem, SWPs can submit their requirements (in terms of the bid) for different resources or combinations of resources. The bidding prices of SWPs are determined by individual welfare (i.e., utility function) of resources. The option with the maximized welfare of the project will be selected.

In addition, as MiC projects can constantly change in various stages, such as design, manufacturing, logistics to on-site assembly, it is highly likely that continuous adjustments and fine-tuning are needed. As such, the second process is to establish the dynamic re-planning approach to incorporate the changes to improve the resilience of the planning. For example, the planner in SWP can conduct agile re-planning on the basis of historical data such as the average queue times for each available work face. If no prior data is available, a default value of 0 is adopted. The SWP issues tasks to each work face in inverse relation to the average queue time. For this specific re-planning problem, an algorithm can be developed (See Fig.4). It has five steps, which are:

- Step 1: to calculate the proportion of an SWP (in a number of tasks) that should be assigned to each work face, based on average batch queue times.
- Step 2: to calculate the number of constraints that each work face should process, by multiplying the number of constraints by the proportion each work face should be assigned.
- Steps 3 and 4: to create a randomized list of work faces based on the number of constraints each work face
- should be assigned from Step 2.
- Step 5: to create the final constraints-to-work face assignment list.

Input:

Smart Work Package W

List of Work faces S

List of Average Queue Times SQ

1.Calculate PS_s the proportion of the Smart Work Package each work face s should process.

for Site $s \in S$

$PS_s = (1/SQ_s)/\sum_{i \in S}(1/SQ_i)$

2.Calculate Num_s the number of constraints each work face s should process.

for Site $s \in S$

$Num_s = PS_s * size\ (W)$

3.Create AS a queue of assignable work faces.

for Site $s \in S$

for Int $i = 1\ to\ Num_s$

$AS.push\_back$ (s)

4. Randomize the list of assignable work faces

$AS.randomise()$

5. Create A_j , the constraint to work face assignment list.

for Constraint $j \in W$

$A_j = AS.pop\_front$ ()

Fig.4. DynaMiC re-planning algorithm

Thus, the capacity of SWPs enabling the constraints optimization can be summarized in Fig.5.

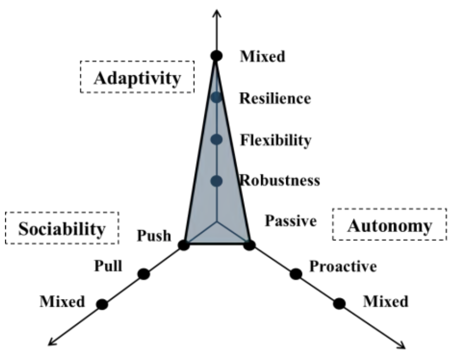

Fig.5. SWP characteristics diagram for constraints optimization

3.3 Constraints Monitoring

In MiC projects, the latest constraints information is essential for the superintendent to check the progress and issue constraint-free SWPs. As such, real-time constraints monitoring is needed. There are three processes within the function of constraints monitoring. The first process is constraints traceability which focuses on tracking each individual constraint. For tracking purposes, a mixed type of autonomy is preferred (Fig.6). For example, the availability of prefabricated products can be tracked by both active and passive RFID (or IoT systems) and visualized in the BIM as the interface of SWP (Li et al., 2017b). The second process is constraints status updating which concentrates on computing the maturity of a task. The maturity index can be used to support short-term decision-making in a mixed type of sociability. For example, an SWP can enable site expeditor with the ability to update the status of the truck and ensure that logistics associated SWPs have the task maturity to achieve JIT delivery (See Fig.7). Meanwhile, the smart objects (e.g., prefabricated products mounted with GPS) in the logistics SWP can push information of the real-time status at regular intervals or via ad-hoc networking to the expeditor interface of SWP for monitoring by providing the visible status within BIM (Niu et al., 2017). The final process within this function is constraints checking and prediction. The constraints checking aims to compare as-planned constraints improvement plan and real-time constraints status. Historical variation can be used to train and predict the next variation in a robustness manner.

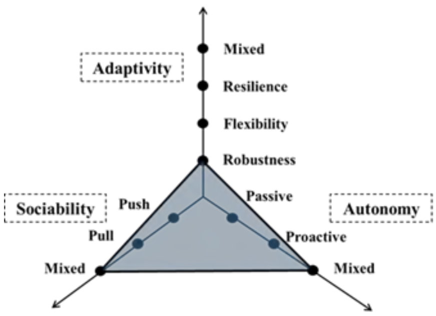

Fig.6. SWP characteristics diagram for constraints monitoring

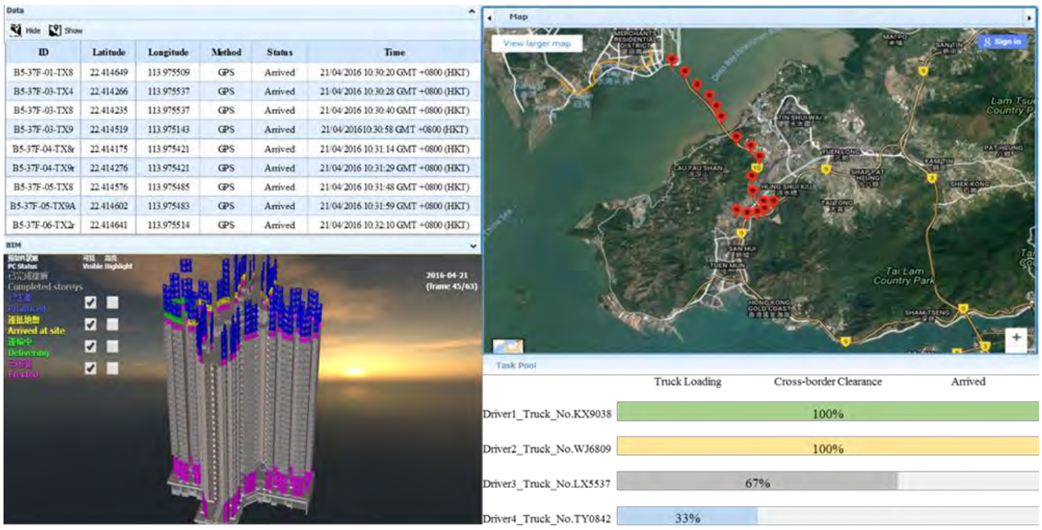

Fig.7. The example interface of expeditor SWP for constraints status updating

4. Evaluation

The evaluation process has also been conducted in the on-site assembly process by using the following indicators. These indicators have been proved to perform better when the approach "SWP for constraint management" is introduced into the MiC process. Due to the limited space here, the evaluation part will be elaborated in the future study.

Stage	Evaluation Indicators	
On-site Assembly	1. Time to update SPOs log when received on site 2. Level of risk when assessing prefabricated products quality 3. Reduction in use of paper sheets to process handover 4. Time to locate prefabricated products on the buffer for the issue to crews 5. Number of prefabricated products not been prepared for pickup 6. Time delays in delivery to workers who are waiting for installation 7. The productivity of knowing what has arrived on-site 8. Average time spent locating a prefabricated product with RFID 9. Worker crews' travel time/distance 10. Time to locate supporting equipment 11. Time to collect work-in-progress information by tracking the SCOs status	12. Est. time saved progressing construction status of a key SCO 13. Percentage of total SWPs progress that can be tracked at a detailed level 14. Reduction in use of drawings to process installation 15. Cost for misplaced prefabricated products 16. Number of misplaced prefabricated products 17. Time to identify misplaced prefabricated products 18. Time to rectify misplaced prefabricated products 19. Reduction in use of paper sheets to process installation 20. Total Man-Hrs saved 21. Expected labor savings 22. Time saved per working shift (hrs) 23. Est. time saved identifying SCOs in the field and locating in smart BIM platform

5. CONCLUSION

Modular Integrated Construction has been plagued with the fragmented processes, which may generate numerous constraints in the critical chain of MiC. If the constraints cannot be timely improved, the reliability of workflow may be reduced and schedule delay, cost overrun will occur. Thus, it is calling for a paradigm shift from the traditional constraint management practice.

The primary contributions of this study to the body of knowledge are twofold. Firstly, Informed by the theories of work packaging and smart construction objects, SWP is defined as MiC workflows decomposed in accordance with production breakdown structure (PBS) of building systems that are made smart by augmenting with the capacities of visualizing, tracking, sensing, processing, networking, reasoning so that they can be executed autonomously, adapt to changes in their physical context, and interact with surroundings to enable more resilient process. An SWP must have three core characteristics, namely, sociability, adaptivity, and autonomy. Each type of the characteristics is not fixed to a bijection. Instead, different types of core characteristics may merge together to carry out, resting on the requirements of different situations.

In addition, equipped with three characteristics, SWP is capable of networking, communicating, computing, and taking action without commands. They can be used to establish a continuous improvement loop for constraint management with three functions including constraints modeling, constraints optimization, and constraints monitoring. SWP can also be combined with the IoT-enabled gateway to act as a loosely coupled, decentralized, multi-agent system to make the constraints status be connected at any time and anywhere.

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2D AND 3D VISION-BASED VISUALIZATION PLATFORM FOR CIVIL INFRASTRUCTURE INSPECTION AND ASSESSMENT

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ABSTRACT: *2D and 3D vision data such as high-resolution imagery and laser scans are increasingly being collected using static and Unmanned Aerial Vehicle (UAV)-based scanners for civil infrastructure. As a departure from traditional data sources such as paper-based inspection reports and 2D drawings/sketches, this type of data (i) can be collected quickly and effectively, (ii) offers much richer details that are of higher resolution, (iii) allows 4D perception of as-is conditions, and (iv) complete documentation of as-is conditions for record keeping and retrieval. Significantly, the visualization needs have also evolved from the time when the information primarily consisted of that extracted from paper-based 2D artefacts. Using concepts such as BIM, Computer Vision and Computer Graphics, this paper proposes and demonstrates a 2D and 3D vision-based visualization platform for civil infrastructure, enabling inspection and assessment applications such as virtual measurement of defects, 4D visualization of defect propagation, and contextual geo-tagging of defects/problem areas, that primarily feed off as-is condition representations. Specifically, the authors use case study scans and images from two real bridges during the development of this platform. Further, this research can potentially advance efforts to integrate 2D and 3D vision data into regular civil infrastructure management practice.*

KEYWORDS: *Laser scanning, Virtual reality, UAV, Civil infrastructure, Visualization, Point cloud, BIM, Computer vision.*

1. INTRODUCTION

Visualization environments help visualize information that is documented for civil infrastructure. By capturing 2D and 3D vision data such as high-resolution imagery and laser scans, and integrating them together with prior project information, such as an as-designed BIM, a facility maintenance record and a construction schedule, a visualization platform can facilitate the communication of projection information among project participants and provide insights for decision making. Applications of a visualization platform consists of: (i) project progress monitoring (Golparvar-Fard, Peña-Mora, *et al.*, 2009; Han and Golparvar-Fard, 2015; Kropp, Koch and König, 2018), (ii) building inspection (E. Anil *et al.*, 2013; Kasireddy and Akinci, 2015; Chaiyasarn *et al.*, 2016), (iii) measurement (E. B. Anil *et al.*, 2013; Wang, Cheng and Sohn, 2016), and (iv) documentation and content authoring (Bae, Golparvar-Fard and White, 2015).

Existing visualization platforms can be generally divided into two categories: model-based platforms and point cloud-based platforms. Model-based visualization platforms such as Revit (Autodesk Inc., 2017) and Civil 3D (Autodesk Inc., 2018) employ 3D models like IFC-BIM and OBJ as their fundamental data representation and allow users to gradually register as-captured data as attachments of a central model. Given a high level of abstraction and a built-in support for semantic information, a 3D model is usually much more compact compared to a raw 3D imaging representation. For example, to represent the geometry of a simple wall, a BIM only needs to record the coordinates of the eight corners of a cuboid, while a wall in a point cloud usually contains thousands of points. The compactness in storage also leads to a high efficiency in data processing such as changing viewpoints and parameterized editing in a visualization platform. However, 3D models are usually created manually which are laborious and time-consuming. A model-based platform solely depends on the availability of at least an as-designed or an as-built model.

In comparison, point cloud-based visualization platforms, such as ReCap (Autodesk Inc., 2015), D4AR (Golparvar-Fard, Pena-Mora, *et al.*, 2009), and Navvis (Möller *et al.*, 2012), use a simple 3D primitive, points, as its data representation. A point cloud can be easily captured from a laser scanner or generated from a collection of images. Although storing and processing point clouds require much more resources, a point cloud-based visualization platform can purely start a project from as-captured data without an as-designed model. Moreover, a point cloud-based platform allows us to easily register an as-designed model to a point cloud or even generate an as-built model from a point cloud. With the emergence of laser and UAV surveying techniques, obtaining high-resolution imagery and 3D scans becomes very convenient, which results in a migration from model-based visualization platforms to point cloud-based platforms or a combination of these two approaches (Ham *et al.*, 2016).

It is worth mentioning that the aforementioned platforms are not designed specifically for facility management tasks such as inspection and documentation. For example, ReCap (Autodesk Inc., 2015) only supports measurements on a point cloud and simple text box attached to a specific point, which is not sufficient for a detailed documentation. D4AR (Golparvar-Fard, Pena-Mora, *et al.*, 2009) allows users to register images to a point cloud and integrates construction schedules from BIM to support progress management, but it also lacks the functionality of documenting defects on infrastructure components. Therefore, the authors developed a novel visualization platform that specifically supports civil infrastructure use cases such as inspection and condition assessment.

The following section outlines the objectives of this research study and presents those in the context of overall research vision. Then, the proposed approach is detailed, clearly explaining how it helps in achieving each of the objectives mentioned in Section 2. Finally, this paper ends with the conclusion section and potential future directions.

2. OBJECTIVES

For this research, two case study bridges were used: (i) steel beam bridge, which had a suspended concrete deck (representative of most commonly found bridges in the US), and (ii) steel beam rail road bridge (had several less-observed features such as no deck and non-standard pier shapes, which add to complexity in 3D modeling and interoperability). For both these bridges, the authors collected necessary data from multiple sources such as design and as-built drawings, inspection reports and site photos. Information synthesized from these data sources was used for the purpose of achieving the objectives of this study, which are given below -

- Identify information requirements for formalizing bridge inspections; identify gaps in the existing bridge schema and develop new representations for the identified information items, in order to support development of integrated visualization environment
- Develop integrated visualization environment for immersive interaction
- Evaluate the performance of various platforms for immersive interaction to get feedback on preliminary use cases that were identified, and identify bottlenecks to integration of the immersive visual environments into real-life bridge inspection practice
- Develop immersive inspection platform integrating various data sources, including point clouds, so that it can serve as a valuable toolbox for inspectors while remotely assessing the condition of the structure

These objectives form the research vision of this study (illustrated in Fig. 1).

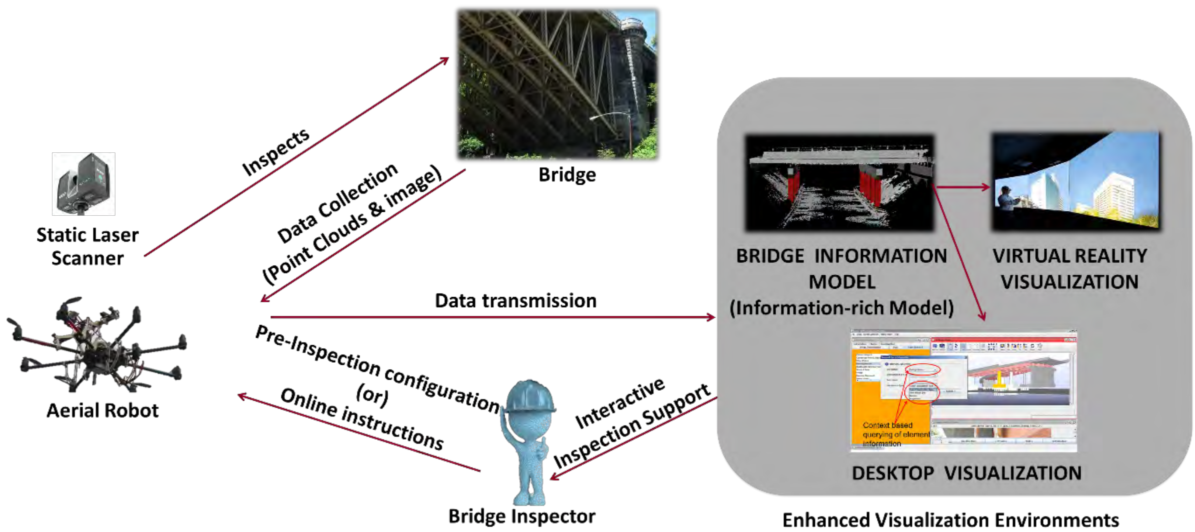


Fig. 1: Using enhanced visualization environments for interactive inspection support and assessment

3. APPROACH

The proposed approach receives as input (i) UAV and Terrestrial laser scans (ii) design and as-built drawings, (iii) inspection reports, and (iv) on-site 2D images captured using UAV and stand-alone cameras. Using these inputs, we initially developed a 3D design model of the bridge using the existing documentation. Then, registered scans were superimposed to identify and document changes, thereby resulting in a 3D as-built model. To add semantics to this 3D model, for the purpose of interoperability, we identified information requirements for bridge inspection/assessment use cases and investigated several schema to find a suitable one to accommodate these information requirements (see section 3.1). Once we identified a suitable schema, it is necessary to test it for its effectiveness. As this is an iterative process, during preliminary testing, we created a prototype of an integrated visualization environment and focused only on incorporating minimal semantics such as topological information, geometry information related to bridge elements, and other metadata, of the case study bridges (see section 3.2). As the ultimate goal is to come up with a *virtual immersive visualization* environment of infrastructure sites for use cases such as inspection and assessment, it is important to devise metrics and testing procedures to check for effectiveness from an end users' standpoint. Section 3.3 elaborates further on these procedures. Moving on in the iterative process, condition information was then extracted from prior bridge inspection reports and analysis of scans/2D images, and incorporated into the model to create an up-to-date as-is 3D model. Finally, we can import this model into the *virtual immersive visualization* environment and test it for infrastructure-related use cases (see section 3.4). Overall, the following sub sections provide details of the proposed approach that will enable us to achieve objectives stated in section 2.

3.1 Identification of information requirements and suitable schema for formalizing bridge use cases

By perusing through inspection reports and assessment standards, and by interacting with bridge inspectors, we identified several relevant information items. Following that, we grouped them into logical categories such as (i) spatial information, (ii) meta information, (iii) physical element information, and (iv) as-is condition information. Then, we evaluated various data schema such as Industry Foundation Classes (IFC), IFC-Bridge (Arthaud and Lebegue, 2007), TransXML (Ziering, 2007), CityGML (Kolbe, 2009) and OpenBrIM (Hu *et al.*, 2014), over their ability to represent these information categories. Additionally, to decide the most suitable schema for our case study, we also evaluated them on their ability to support interoperability of 3D geometric, semantic and other inspection data between different software systems, and whether the schema was adopted by widely used 3D modeling software. The results are presented in the table below, and it precisely conveys the ease with which each data schema is able to represent/support different information categories or development requirements.

Table 1: Tables summarizing the capabilities of different schema. [Color code: Black = possible or ease of modeling; White = not possible; Grey = indirectly possible/using workarounds]

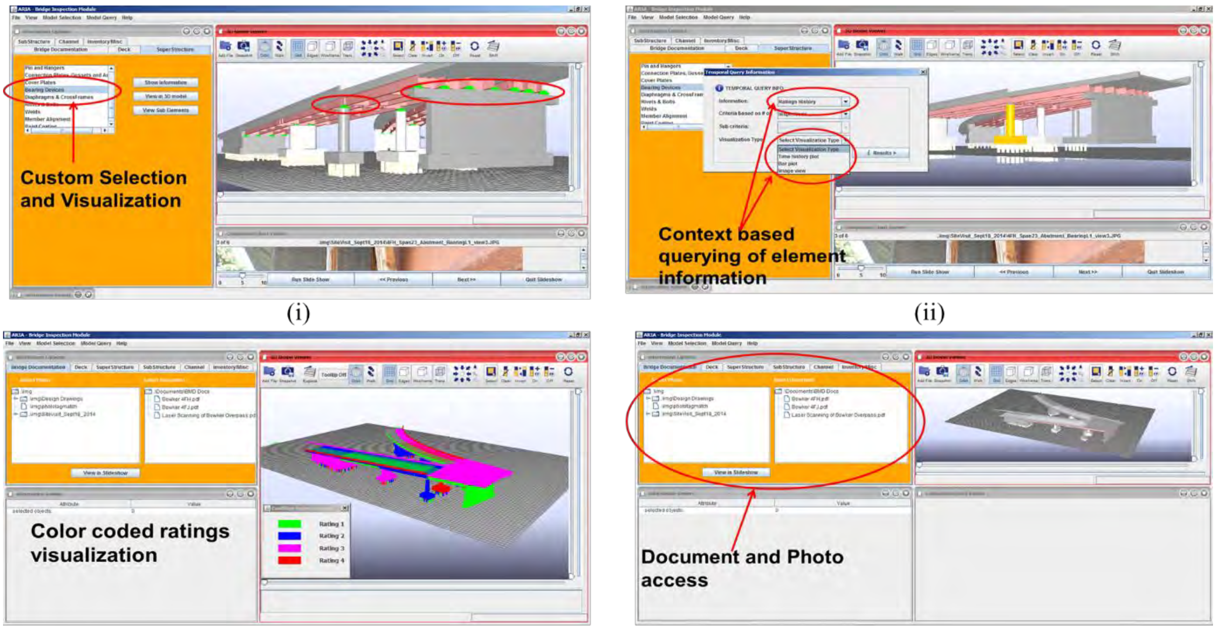
	Spatial and meta information.	Component information	Physical element information/ ease of 3D representation	As-is condition information.	Interoperability with 3D modeling software
IFC and IFC-Bridge	Black	Black	Grey	Grey	Grey
TransXML	Black	Black	Grey	Grey	
CityGML	Black	Black			
ISO TC211 – 19133 (geo-referencing standard)	Black				
OpenBrIM	Black	Black	Grey	Grey	

From the results table, it is clearly seen that IFC together with IFC-Bridge is currently the most suitable schema among the other. After identifying the most suitable data schema in the requirements analysis phase, we performed a gap analysis to understand what information items are already represented, what else need to be represented, and how existing schema can be extended to create an information model that cover the items which are not currently represented (Kasireddy and Akinci, 2015). This information model formed the backbone for inspection prototype (see section 3.2) developed during the case study.

3.2 Development of an integrated visualization environment using bridge information models

For the case study using real bridge data sources, we developed preliminary *desktop version* prototype for off-line virtual inspection support in a JAVA-based open source platform - IFCTOOLSPROJECT (Tulke *et al.*, 2010). Within this prototype, we augmented the semantic models with several data sources such as previous inspection reports, site investigation reports, and related inspection manuals. This is in addition to interactive modes such as context menus for visualizing condition photos and other information, and color-coded visualization, to quickly perceive existing bridge conditions.

As this was in the initial stage of iterative process, the prototype recognized only minimal semantics such as topological information, geometry information related to bridge elements, and other metadata, that were encoded into the 3D model. This encoded information intended to answer general queries pertaining to bridge-inspection use cases. For example, under ‘Custom Selection and Visualization,’ answers to questions such as ‘Show me all bearing devices associated with Pier 1 and Pier 2,’ can be visually represented on the 3D model inside the prototype (see Figure 2 (i)). Similarly, for ‘Context-based querying of element information,’ it is possible to answer queries such as ‘Show me the ratings history of the element that has been flagged as *Poor* at least twice in the last five inspections’ (see Figure 2 (ii)). Besides those, ‘Color-code ratings visualization’ provides a quick global perception of problematic areas that potentially require more attention during the next maintenance schedule (see Figure 2 (iii)). Finally, ‘Document and photo access’ feature allows the prototype user to retrieve relevant bridge standards, previous inspection reports, and site photos from previous visit, on an as-needed basis (see Figure 2 (iv)). Overall, this updated 3D semantic model (i.e. bridge information model) will be used as a base for importing into other immersive and non-immersive visualization platforms that will be developed thereafter.



(iii) (iv)

Fig. 2: Figure showing different features of integrated visualization environment

3.3 Development of approaches to evaluate the performance of various platforms for immersive interaction

Currently, several immersive visualization options, i.e. virtual reality and mixed reality platforms, are available commercially, and many more will be developed and released in the future. Due to the vast number of options available, it is a difficult task for infrastructure practitioners to decide which platform is appropriate. For this reason, the authors planned to develop a generic approach that will enable the practitioners to quantitatively evaluate the platforms they have at hand. As part of this study, the authors evaluated different immersive environments through a user study to identify which immersive environment was suitable for which type of inspection/assessment task on a virtual infrastructure site. The results of the study are out of the scope for this paper, and will be discussed in future publications. The test subjects chosen were experienced practitioners, who are familiar with the domain knowledge; however, they had no prior experience dealing with virtual sites on immersive environments.

In the user study, the tasks were designed to compare performance of the test subjects on different immersive environments, in the aspects of: (i) Information visualization and access, (ii) Site navigation, and (iii) Cognitive recall and recognition. A quick summary of the tasks is given below.

In the user task related to information visualization and access, the subjects had to answer five types of questions, which were related to infrastructure use cases. Some of them required a subject to simply extract categorical, temporal or descriptive answers from the provided information displays. On the other hand, other questions required the users to extract and organize scalar values based on specified criteria. The metric is the accuracy of responses normalized across different platforms for the same user. Some of the sample questions posed to the user are given below in Table 2 –

Table 2: Tables showing a sample set of questions for 'information visualization and access' task

	Question Type	Oculus (trial 1)
1	Spatial/ Categorical	Which element is on a higher elevation? Pier 1 or Pier 3?
2	Topological/ Categorical	Which section has higher number of floor beam connections - Spacing between girders (G-1 & G-4) in Span 1, or spacing between girders (G-7 & G-10) in Span 3?
3	Topological/ Scalar	What is the most recent repair date of the bearing device that connects Girder3 with Pier 1?
4	Temporal/Value sorting	Sort and arrange Girder G-2, Bearing BD-1 and Deck as per their future maintenance schedule dates (earliest to latest)
5	Descriptive	Which firm(s) painted Span 3 in last 10 years?

Similarly, for the user task related to site navigation, subjects were assigned an origin and a destination within the virtual bridge site. Each subject was expected to navigate between those points as efficiently as possible. The specific metric used is the ratio between the length of the user's navigated path and length of the shortest known path.

Finally, for the user task on cognitive recall and recognition potential, a subject is expected to navigate around each environment, and recognize all target condition instances (as well as recall their condition type) present on the site within a given time frame. For example, if the user is assigned a task to inspect a particular bearing device, she should recall different types of possible defects for that element type, retrieve condition images from previous inspections, and then identify the type of defect and severity of the current defect instance.

Further, evaluation can be improved by conducting comprehensive charette tests with both novice and expert inspectors to evaluate performance of inspectors in different immersive environments to the current inspection methods. The overall goal is same, i.e. to quantify the effectiveness of different visualization approaches for infrastructure use cases such as periodic inspections and condition assessment.

3.4 Development of a full-fledged immersive inspection platform for interactive inspection support and assessment

In this phase, the authors planned to improve off-line virtual inspection support with increased inspection functionalities such as point cloud visualization and temporal simulation/animation environment. Particularly, the focus was on using point cloud visualization as means to provide skeuomorphic objects in immersive environments. This would give the inspectors an ability to use natural gestures to make measurements of as-is conditions, and thereby use those measurements to do condition assessment.

Within the immersive visualization environment (comprising both virtual reality and mixed reality platforms), inspectors have the ability to access difficult parts of the bridge virtually and make measurements (see Figure 3). In addition, UAV images can be geo-tagged in 3D allowing inspectors to visualize images in perspective view, in addition to getting a sense of the inspection sequence conducted by the UAV in the previous inspection (see Figure 4). This can potentially help in planning the next inspection with improved efficiency (i.e. by reducing wasteful navigation) and more effectiveness (i.e. by minimizing occlusions and maximizing data capture).

For the condition assessment use cases, this environment provides inspectors with measurement and annotation tools that will allow them to use VR commands to geo-tag defects and make measurements of as-is conditions. As a result, these measurements can in turn be used to do element-level condition assessment (see Figure 5). Temporal aspect is also brought into the mix, wherein defect representations over multiple inspections can be animated to provide a perception about the rate of deterioration (or lack of). Within the mixed reality environment, the inspectors can use natural gestures to annotate problematic areas while inspecting a real infrastructure site, and those areas got automatically geo-tagged in 3D semantic models and corresponding point clouds (see Figure 6). Finally, after performing the condition assessment, inspectors can update the queryable 3D bridge information model (see Figure 7) with the latest condition information, from which data analytics can be performed for long term insights about the conditions and the required maintenance and repair actions.

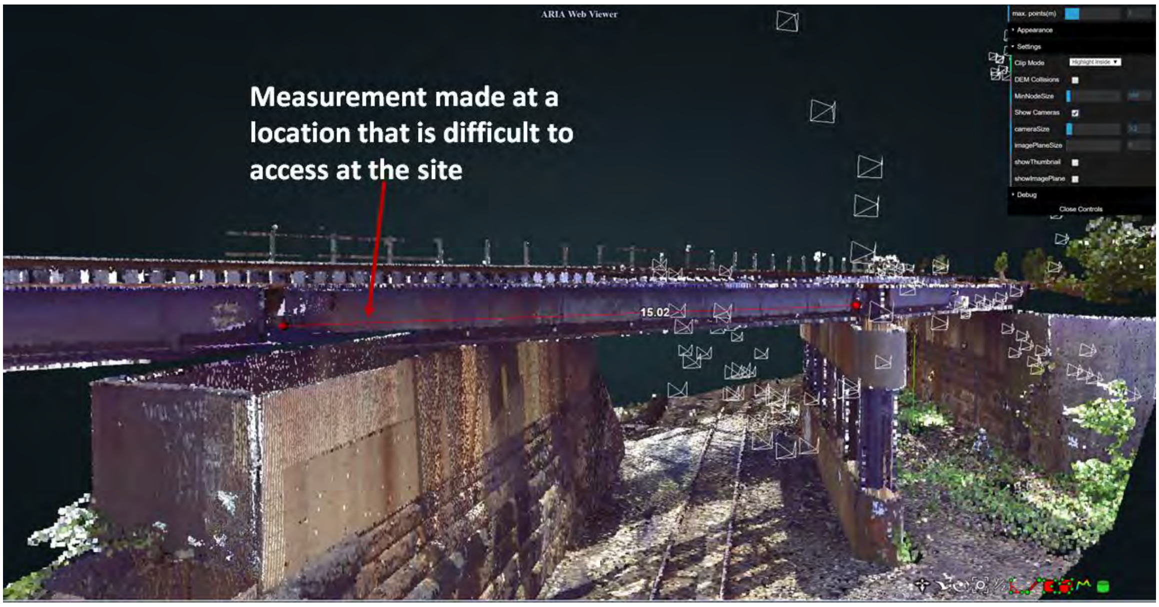


Fig. 3: Figure depicting how inspectors immerse themselves into the virtual site environment to access locations on the bridge that are typically difficult to access at a real site

These features were designed to support common infrastructure use cases such as inspection and condition assessment, although taking the entire experience into a virtual world or a mixed environment. With the additional capabilities (for example, point cloud integration and defect propagation) built into the immersive inspection platform, effectiveness of the platform from a user standpoint can again be tested using the procedures mentioned in Section 3.3 with a group of infrastructure inspectors.

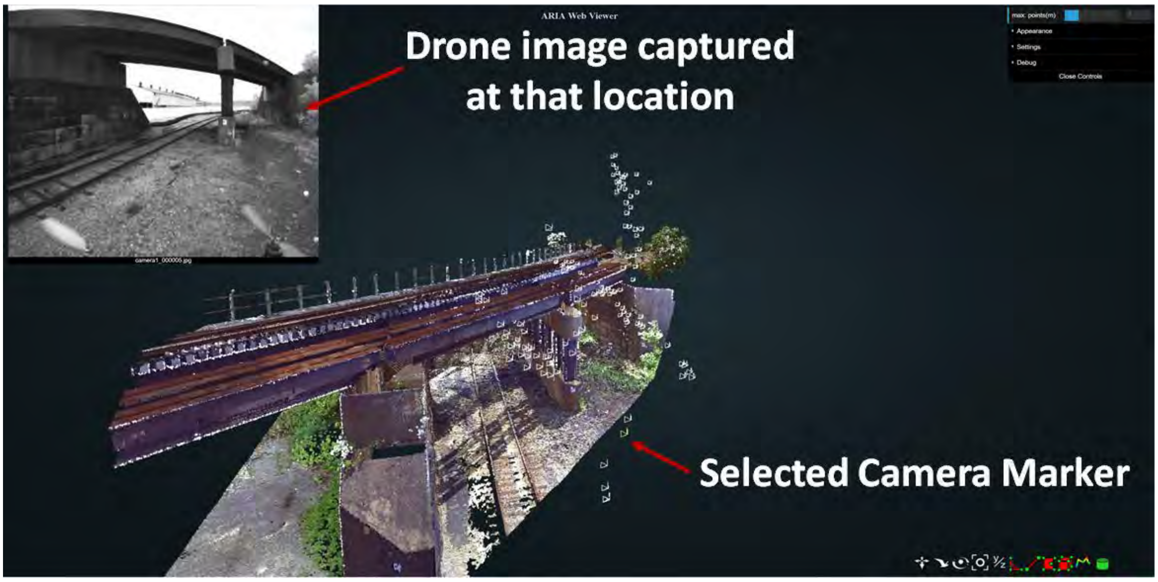


Fig. 4: Figure showing UAV camera markers that represent the position in 3D space from where a particular image is capture. These markers can also be used to perceive the inspection sequence during the data collection process.

Fig. 5: Figures showing geotagging and measurement annotation tools within the immersive environment

4. CONCLUSION

This paper presented an end-to-end and a structured approach to develop and evaluate 2D and 3D vision-based visualization platform for civil infrastructure. This platform makes use of 3D semantic models (i.e. bridge information models), that are enriched not just by traditional data sources such as inspection reports and 2D drawings/sketches, but also 2D imagery and 3D laser scans.

This approach can potentially transform the way infrastructure inspections are conducted in the future. Particularly, the usage of immersive visualization environments to virtualize most of the infrastructure inspection and assessment tasks, except the data collection process. Prominent features in the platform include (i) custom visualization using contextual queries; (ii) contextual retrieval of photos and relevant documents within the platform; (iii) color-code visualization; (iv) virtual access to difficult locations on a structure, and perception of the inspection sequence to improve planning for the next inspection; (v) virtual measurement of defects, contextual geo-tagging of defects/problem areas, and 4D visualization of defect propagation, (vi) using mixed-reality to automatically update real site observations to the 3D semantic model.

The authors envision significant benefits of using this approach, especially in terms of increasing the frequency of periodic inspections and reducing the number of errors made during the assessment phase. In the future, the authors plan to improve evaluation of this approach using comprehensive charette tests with both novice and expert inspectors by measuring their performance in different immersive environments. This will help quantify the benefits of adopting virtual immersive inspection over the current inspection methods. Overall, the research presented in this paper will also advance efforts to integrate 2D and 3D vision data into regular civil infrastructure management practice.

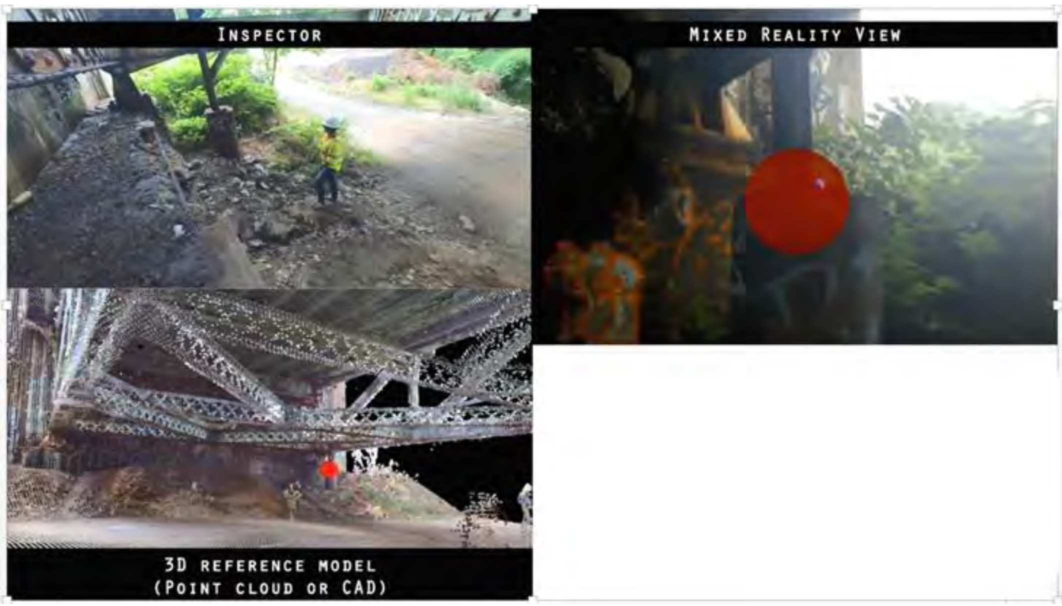


Fig. 6: Figure showing mixed-reality usage to automatically tag observations on a real bridge site on the 3D semantic model

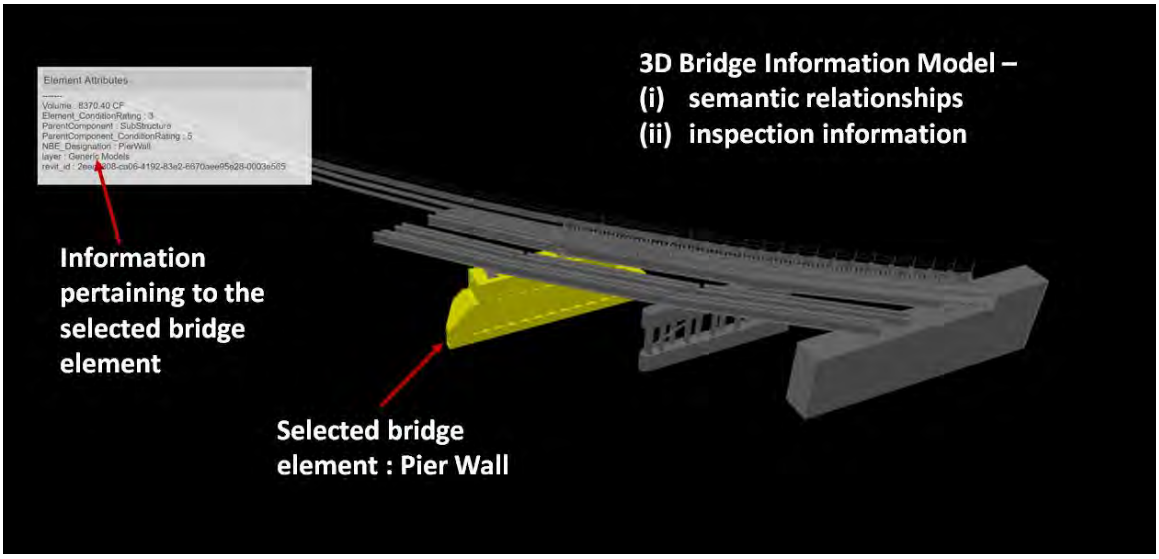


Fig. 7: Figure showing queryable 3D semantic model that be used for infrastructure data analytics

5. ACKNOWLEDGEMENTS

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A FRAMEWORK FOR VISION-BASED AUTOMATIC SCAFFOLDING PRODUCTIVITY MEASUREMENT

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ABSTRACT: Scaffolding is defined as a temporary structure erected to support access or working platforms for a work crew and materials. Scaffolding work includes erecting, altering or dismantling scaffolding components and is widely conducted during construction, maintenance and repair of man-made structures. Current productivity measurement for scaffolding work still relies on manual observation and record of work progress, making it subjective, inefficient and costly. An automatic method of measuring productivity is promising in construction management. However, automated activity recognition and measurement of scaffolding work have not been fully explored in relevant literature. This paper proposes a framework for an automatic method for interpreting scaffolding work productivities from onsite videos. The proposed framework includes steps including data collection of scaffolding videos, activity definition, data labelling and resizing, detection and productivity measurement. The proposed method uses convolutional neural networks (CNNs) to recognize scaffolder's activities related to scaffolding work, and then analyses work productivity based on the recognized activities. And a specific index will be developed to reflect the productivity of a scaffolder.

KEYWORDS: *neural networks, human recognition, productivity measurement, scaffolding.*

1. INTRODUCTION

Scaffold is defined as a temporary erected workplace to provide access for construction workers and materials. Scaffolds are widely used in the construction, maintenance and repair of man-made structures. Scaffolding work includes erecting, altering or dismantling a temporary structure erected to support a platform, which is a labour intensive task (Safe Work Australia, 2014).

Scaffolding has become a serious concern that cannot be neglected among building, infrastructure, oil and gas and other industries, due to its features of low productivity, lack of labour and high cost (Hou et al., 2014). In particular, liquefied natural gas (LNG) plants, mega sophisticated facilities in LNG industry that process natural gas into liquid state, require a large amount of scaffolding workload during both construction and maintenance. Especially for maintenance, regular scaffolding erection are required for facility inspection and replacement. Fluent operations of scaffolding or relevant delays directly impact the production of LNG plants (Moon et al., 2016).

The labour cost of scaffolding is believed to be a crucial area of total cost cutting of projects and a significant volume of resources are placed on scaffolding on industrial projects (Moon et al., 2016). According to Lei et al., the budget of scaffolding contributes around 12-15% of the entire project cost and it is projected to increase in the future. It is indicated that scaffolding operations influence to a large extent whether the current construction progress is able to fulfil the previous schedule since the scaffolding work has strong connections with other onsite activities (Hou et al., 2017).

Therefore, it is promising to develop an effective method to monitor and optimise the productivity of scaffolding labour. As a case study, in Darwin, Australia, the lean manager of a scaffolding company observed the progress of dismantling scaffolds and recorded the activities that the scaffolding crew implemented and the time period each activity took in order to optimise the scaffolding procedure and boost the scaffolding productivity. Inspired by this, an automated method of scaffolding activity recognition for labour productivity measurement and optimisation is proposed in this paper.

Productivity is deemed to be an important index in construction industry that it measures the conversion rate from input to output in a period of time (Measuring Productivity OECD Manual, 2001). In construction projects, interruption, waiting and other incidents often result in low efficiency in daily site operations (Gong and Caldas, 2011). Productivity reflects the execution of project schedules, which is crucial to time and cost managements in the implementation of construction projects. In order to enhance the productivity, the initial step is to capture and collect on-site data on labour or facility that are employed in construction operations to implement productivity measurement and analysis.

Labour productivity related to construction activities are generally defined as the ratio of installed quantities to labour hours. In current practice of construction research, the measurement of labour productivity commonly adopts hourly output that it takes a labour hour as the input unit and actual completed workload as the output.

$$Productivity = Output/Work\ hour$$

Sungkon et.al employed the amount of work time spent on one cubic meter (min/m3) of scaffold erection or dismantlement as the erection and dismantlement norms (Moon et al., 2016). Additionally, Marko adopted hr/m3 as the unit of scaffold erection in the man-hour manual for estimators (Bulic, 2003).In this paper, it is proposed to continuously adopt min/m3 as the unit to indicate the labour productivity of scaffold erection.

For productivity measurement and analysis, traditional methods of data collection mainly reply on project level information systems, direct observation methods, and survey or interview methods. However, the drawback of these methods is that the measurement task requires additional labour to track and record the process and results of operations and the results are susceptible to human errors and bias. (Peddi, 2008). Similarly, in the field of scaffolding work, the existing method of scaffolding progress and productivity monitoring still remains manual observation that not only extra manual work is required to record the scaffolding progress of a scaffolder, but also the result is subjective. Automated methods for measuring productivity of scaffolding work have not been fully explored in the literature.

Due to the rapid development of information and sensing technologies over the past decade, mega data can be generated and transmitted from various sensors for measurement and analysis. Through the human motion capture in construction operations, remarkable researches have been conducted to investigate a variety of fields in construction management.

Basically, human motion capture technologies can be divided into three options: electro mechanical, magnetic and optical. Electro mechanical system mainly attaches different kinds of electro mechanical sensors on human body parts to capture the motion or location shift of limbs (Guraliuc et al., 2011). Amendola et.al implemented the technique of passive radio-frequency identification (RFID) to classify several gestures by using wearable RFID tags and a RFID reader (Amendola, Bianchi and Marrocco, 2015). Additionally, accelerometers, gyroscopes and magnetometers are integrated as an Inertial Measurement Unit (IMU) which provides 3D information directly without the impact of occlusion. For the purpose of increasing precision, Alwasel et.al demonstrated a practical method of combining IMUs and video cameras to develop a classifier to identify poses of safe and productive masons (Alwasel et al., 2017). However, this type of technique requires workers to wear a suit of sensors attached to their major joints, which only shows feasibility under lab environment and does not present practical on construction sites where regular suit washing is essential.

Magnetic field can also be used as a feasible tool for motion capture (Aloui, Villien and Lesecq, 2014). Nevertheless, the magnetic approach is susceptible to surrounding metal objects, which restricts its application for scaffold installation.

Optical systems are proposed to extract human poses and motions directly from various images or videos. The

VICON system employs multiple cameras (eg. 6 or 8 cameras) to capture human motions by tracking the reflective markers attached to a human body. Han and Lee explored a motion recognition system with VICON and video camcorder to detect workers' unsafe behaviour on construction sites (Han and Lee, 2013).

With the appearance of Microsoft Kinect, RGB-Depth sensors have aroused great interest in motion capture research (Ijjina and Chalavadi, 2017). Ray and Teizer proposed a classification of ergonomic and non-ergonomic work activities in indoor environment using Kinects (Ray and Teizer, 2012). Yu et.al investigated a real-time system based on Kinect motion capture to identify construction workers' unsafe behaviours (Yu et al., 2017). Han et.al introduced a Kinect recognition system based on to detect unsafe actions that workers usually perform while working with a case study of ladder climbing (Han, Lee and Peña-Mora, 2013). Although Kinect shows huge potentials for indoor motion capture and analysis, its depth sensors are sensitive to sunlight and subject to outdoor environment, which may become an obstacle for the application of outdoor scaffold setup environment.

Video surveillance, as an economical convenient device for recording human and object status, has been widely used on construction sites for management purposes, it is easily accessible to the data of video. According to Gong and Caldas, video-based data collection has more benefits compared to RFID based methods as follows: 1) an intuitive and rich content; 2) convenient implementation and low cost; 3) use for training purpose and dispute mitigation. Also, by installing multiple cameras or stereo cameras, the drawback of video such as occlusion and lack of spatial data can be relieved (Gong and Caldas, 2010).

The traditional action recognition methods include directly extracting body angles from a sensor or indirectly implementing particular algorithms to recognise human joints from image frames and by analysing the change of angles and spatial locations of the joints to recognise specific actions. Ray and Teizer classified 6 typical postures, standing, squatting/sitting, bending and crawling, by analysing body joint angled computed from posture information from OpenNI (Ray and Teizer, 2012). Yu et.al investigated human body skeleton directly from Kinect to identify three unsafe behaviours of construction workers (leaning on handrails, dumping from height, climbing ladders) (Yu et al., 2017).

In recent years, Convolutional Neural Networks (CNNs) have drawn more and more attentions and have been proved to be an efficient class of models for image recognition because this technique does not require manually preset and extract default features for application purposes and is capable of high-accuracy recognition. Back to the early twenty first century, CNNs were applied successfully into the detection, segmentation and recognition of objects such as traffic sign recognition and the detection of faces, pedestrians and human bodies from images and deeper applications have recently dived into face recognition, self-driving cars and autonomous robots.

The ImageNet Large Scale Visual Recognition Challenge (ILSVRC), an annual competition to compare different algorithms for object recognition and image classification at large scale, which requires the competitors to train their algorithms with the ImageNet dataset of over 1.2 million images and classify 150,000 test images into 1,000 object categories, has triggered great interest worldwide and also has made remarkable progress especially the application of CNNs started to be adopted in 2012 that lowered the error rate dramatically (Krizhevsky, Sutskever and Hinton, 2017; LeCun, Bengio and Hinton, 2015).

Image-based Researches also have been implemented in the detection and recognition of other fields. Ammour et.al proposed a CNN system for car detection in unmanned aerial vehicles (UAV) images (Ammour et al., 2017). According to Maggiori et.al, CNNs were also investigated as a powerful tool for large-scale remote-sensing image classification (Maggiori et al., 2017).

The video-based detection and recognition stand at one of the cutting edges of CNNs research. Feng et.al processed videos as a series of still images and applied CNNs to recognise the developing embryos, however, this method focused on the classification of five biological categories and ignored the relevance among contiguous frames (Feng Ning et al., 2005).Wang et.al proposed a parallel algorithm based on MapReduce framework to enhance the performance and computational efficiency of CNNs for action event recognition in surveillance videos (Wang et al., 2016).

Unlike the ImageNet and other challenging complex classification problems that require mega images or videos to realise more than 10 classes action or object classification, Stern et.al achieved simple classification of egg-laying behaviour of insects by adopting CNNs to process video frames with a relatively small dataset (Stern, He and Yang, 2015). Inspired by this approach, it is also promising to develop a CNNs system to achieve simple classification of scaffolding activities and then productivity measurement would be conducted based on the results of activity detection and classification.

2. FRAMEWORK OF AUTOMATIC PRODUCTIVITY MEASUREMENT

The proposed framework starts from data collection and the collected data will be divided into testing data and training data two parts. Followed the step of action definition, the training data is required to be resized and labelled for training purpose through neural networks. Testing data is merged at the stage of detection and classification to test the effectiveness and accuracy of the system of neural networks. Finally, productivity measurement is conducted to link the results from the neural networks with productivity index.

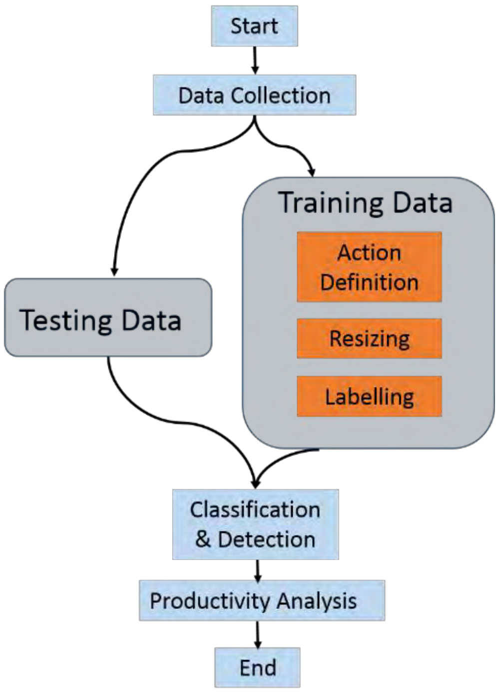

Figure. 1 Flow chart of the framework

2.1 Dataset collection

There is no video dataset of specific scaffolding installation process available online or from other sources for direct research, so it is necessary to manually collect video-based data on construction sites to provide sufficient information for classification and recognition. The proposed dataset is separated into two parts: training and testing. The training data accounts for 2/3 of the total video dataset and the testing data makes up the rest 1/3.

Regarding the content of video dataset, each video clip is proposed to explicitly record one scaffolder's activity during scaffolding erection and the length of video clip is controlled not shorter than 2 minutes. To ensure training effect, the maximum and minimum distances between recording camera and scaffolding work are 15m and 2m respectively.

Since a large quantity of dataset is crucial for training and testing, a large number of video clips are proposed to be collected in various angles, distance, backgrounds and illuminations on different construction sites. Besides, some of the clips are designed to capture multiple scaffolders' movements for future research rather than only capture and analyse one single scaffolder's activity at the first stage of research.

As a research partner and sponsor, KAEFER Integrated Services Pty Ltd, an industrial provider specialising in scaffolding, insulation and anticorrosion, would facilitate the onsite data collection and scaffolding practical guidance, including permission of video capture on their construction sites in Australia.

2.2 Activity definition

Activity identification of different work class is a complicated challenge since there is no widely accepted metrics to define the relation between construction activities and the corresponding productivity. Also, the boundary between each class of activity is ambiguous. In this framework, two methods of trial are planned to establish connections between activity recognition and the scaffolders' productivities in the video and be conducted to validate the effectiveness of activity definition.

The first approach divides scaffolder's activities into three sections: effective activities, contributive activities and ineffective activities. Effective activities denote those activities performed by scaffolders directly add values to the construction such as coupler installing and tube assembly. Contributive activities represent the necessary activities that contribute to the effective activities like transporting scaffolding materials and fetching tools. Ineffective activities include the activities are not contributive to the construction progress, for instance waiting, chatting and resting.

The second approach focuses on one specific activity that during scaffolding installation, scaffolders require both hands to hammer pins and wedges or to set up scaffold couplers that are fittings that connect the tubes together and stabilize the entire structure, which is regarded as a crucial step for the scaffolding process. Therefore the idea is raised that it is feasible to define and recognize this specific activity as "measurable activity".

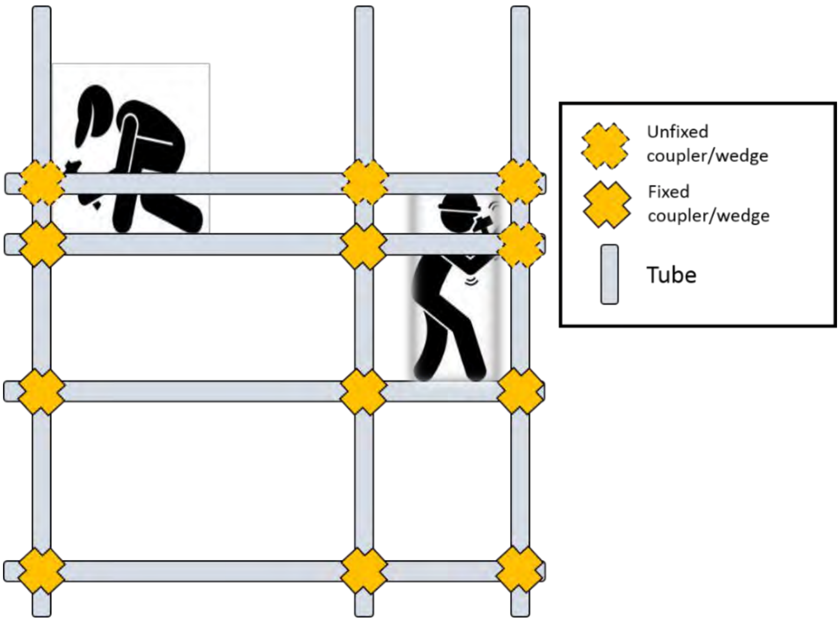

Figure. 2 Schematic diagram of scaffolding work

This activity of hammering wedges or setting up scaffold couplers only requires a scaffolder's both hands to work together to complete repetitive workload, however the scaffolder's body have to remain a stable and appropriate position (squatting, standing, facing upward). In the automatic recognition system, this activity with various body positions is proposed to be detected by machine correctly from other scaffolding activities.

2.3 Labelling and resizing

The training data is required to be labelled and resized into an identical form before the training data can be fed as an input into neural networks. For instance, if a type of neural networks is designed to distinguish between a cat and a dog through images containing a dog or a cat, the corresponding training images ought to be labelled such as "dog1.img" or "cat2.img" to clarify the content of each image. Also, as one step of pre-processing, it is programmed to extract the information of these labels to indicate computers which category each image belongs to.

Based on the activity definition above, the image frames from the collected videos that meet the relevant description of the effective activity will be annotated as "effective_activity.img", "contributive_activity.img", "ineffective_activity.img". However, all the labelling process have to be done manually, which is expected to be a tedious and time consuming task.

Videos collected from various device are stored in different formats, however, neural networks required an uniform image size, such as 100×100 pixels or 200×200 pixels, since an input to realize machine learning progress, so the video clips are required to undergo a resizing process through a computer program.

2.4 Classification and detection

Classification and detection are an integrated step of CNNs. After the training data is pre-processed (labelling and resizing), it is projected to input the training data into the designed. It is proposed to modify an existing CNN structure from open source to adapt the CNN structure for this scaffolding task. The training data is transmitted through a CNN system and relevant weights and parameters are trained and determined to ensure the classification and prediction to be optimized. Then, the trained CNN system will be verified with the testing data and the prediction accuracy and processing time are the major concerns that researchers aim to make efforts to enhance the prediction accuracy and reduce the processing time.

The automatic system is designed to detect the working scaffolder as the first step. When a working scaffolder appears in the video, a yellow bounding box on the top is designed to involve and track the scaffolder's appearance in real time. When the scaffolder in videos performs "effective activity", the CNN system is projected to recognize and detect this activity and results in colour change of the bounding box that it turns into green and display "effective activity" with a percentage of prediction confidence as an indication.

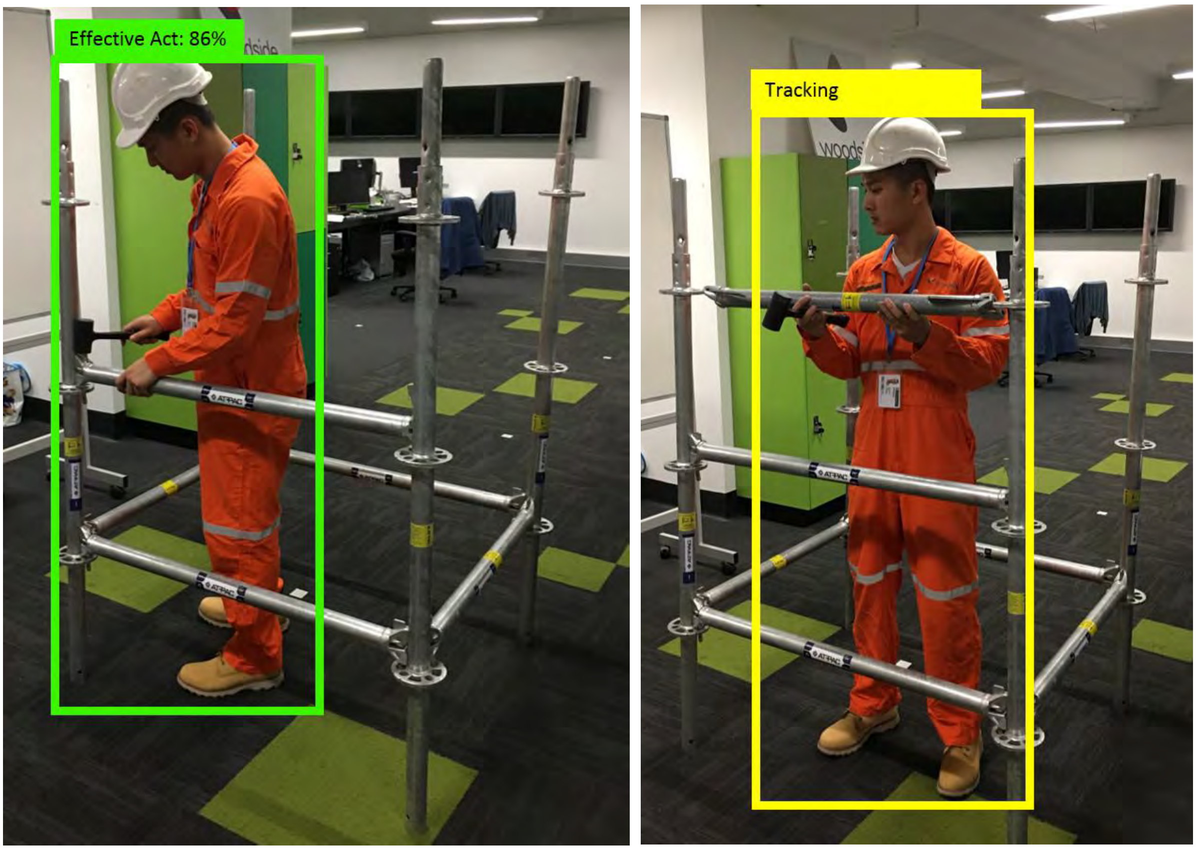

Figure 3. Detection demonstration

2.5 Productivity measurement

Following the first approach of activity definition, the scaffolding process is divided into 3 types of activities: effective activities, contributive activities and ineffective activities. According to Abhinav's research on the productivity measurement of tying rebar, the productivity of scaffolding can be calculated as below (Peddi, 2008):

$$P = (T_{effective} + T_{contributive})/(T_{effective} + T_{contributive} + T_{ineffective})$$

Where $T_{effective}$: Time of effective activities in scaffolding

$T_{constributive}$: Time of contributive activities in scaffolding

$T_{ineffective}$: Time of ineffective activities in scaffolding

For the second approach of activity definition, pins or wedges and couplers are vital components in scaffolding structures and they are viewed as main nodes in scaffolding modelling in this research framework. It is proposed to implement automatic recognition system to detect "measurable activity" described above from videos and calculate the number of these activities are performed which directly reflects the number of scaffold wedges or couplers are installed in a period of time (T) in order to analyse the productivity of scaffolding work that this activity reflects. The productivity (P) of wedges or couplers installation can be calculated as below:

$$P = N/T$$

Where P: Productivity of wedges or couplers installation

T: Scaffolding installation time, N: number of wedges or couplers installed in time T

Observations and records would be conducted to count manually the number of wedges or couplers installed in the same time period to compare with the results generated from automatic recognition system. Adjustment and iteration on automatic recognition system will be made in order to achieve better accuracy and efficiency.

Additionally, consultation in the form of interviews with scaffolders and onsite scaffolding supervisors will be deployed in order to establish an index E, which represents the productivity of scaffolding work and connects the progress of scaffolding with the number of wedges or couplers installed. The index E will be tested and iterated as a function of N and T based on a large number of onsite observations and onsite experience.

$$E = f(N, T)$$

Where E: Productivity of scaffolding installation

T: Scaffolding installation time, N: number of wedges or couplers installed in time T

3. FUTURE WORK

Future work will focus on the data collection and labelling as well as the design and adjustment of automatic recognition system. Manual data collection and labelling are believed to be costly and time consuming tasks and also as a feature of CNN, a large quantity of data and the variety of data ensure the CNNs' prediction effectiveness and accuracy so sufficient time have to be spent on the data collection and labelling.

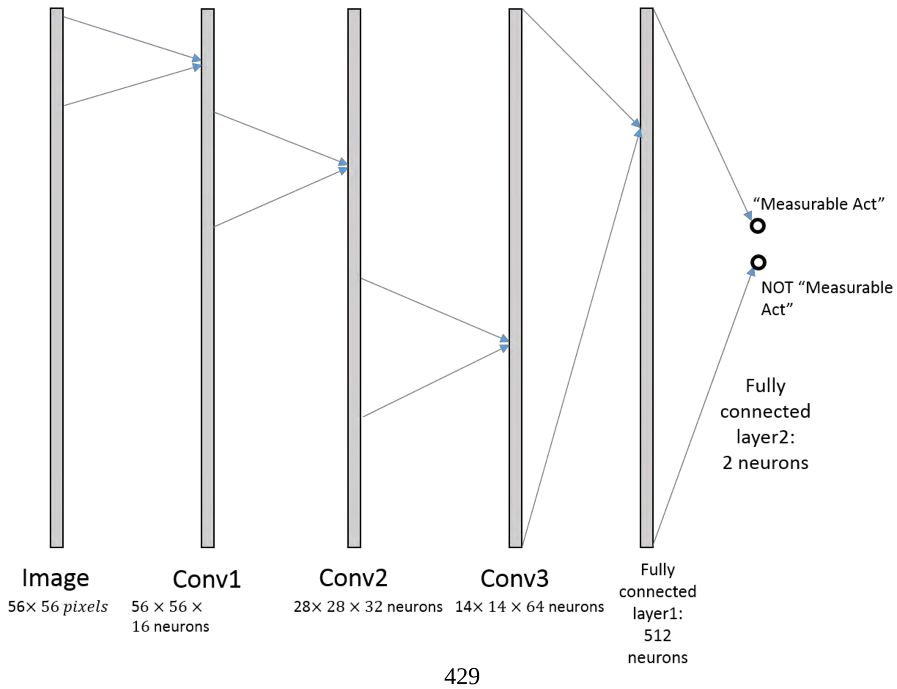

Figure 4. Proposed structure of convolutional neural networks

For the automatic recognition system, in order to achieve the application of classification of “Measurable Activity” and NOT “Measurable Activity”, it is proposed to modify and simplify the existing open-source CNN structure and program. Currently, a series of algorithm, such as CNN, Region-based Convolutional Neural Networks (R-CNN), Faster-R-CNN and You Only Look Once (YOLO), with different performance are available for implementation. Figure 4 displays a CNN structure model that produces the prediction results of “Effective Activity” or “NOT Effective Activity” with 3 convolutional layers and 2 fully connected layers. Additionally, it is essential to test and adjust the program iteratively for better performance. For example, if the automatic recognition system does not manage to detect the “effective activity”, the following actions might be taken to improve the system: 1) increasing the amount and variety of the dataset 2) adjusting the CNN structure 3) redefining the activity.

4. DISCUSSION AND CONCLUSION

This paper presents a framework for automatically interpreting scaffolding work productivities from onsite videos. The proposed framework includes data collection of scaffolding videos, activity definition, data labelling and resizing, detection and productivity measurement.

For the automatic detection of scaffolder’s activity, occlusion is expected to be a major difficulty inevitably, since in most circumstances scaffolders work inside the structure of scaffolding where vertical and horizontal tubes often partly block the image of scaffolders’ activity. Also, when a scaffolder is working with back to the camera, the scaffolding activity cannot be effectively captured. Deploying multiple cameras from different directions is expected to be an effective approach to solve this problem, but it still needs practical research. In future research, the validation of the theoretical activity definition requires further tests, which can be conducted with sufficient on-site practical experiments.

5. ACKNOWLEDGMENTS

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INFORMATION TECHNOLOGY AND NEW ZEALAND CONSTRUCTION INDUSTRY; AN EMPIRICAL STUDY TOWARDS STRATEGIC ALIGNMENT OF PROJECTS AND ORGANISATIONS

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ABSTRACT: *Modern construction processes are incrementally relying on information technologies at a significant rate. New Zealand is picking up on this movement and the following suit; specifically, tools and concepts such as Building Information Modeling (BIM), Cloud Computing, Group Decision Support System (GDSS) and 4D Modeling are gaining considerable attention. The main objectives of this study are to assess the impact and challenges of implementing information technology tools, concepts and applications on New Zealand construction industry performance. The study is significant as it is a step towards the strategic alignment of information technologies, construction projects, and organisations. The study follows a practical approach to understanding the requirements, reality and complexity of information technology implementation. Empirical data obtained through interviews conducted with senior engineers from different construction projects in New Zealand. The study concludes that For New Zealand construction companies, organisational infrastructure and information technology infrastructure are two domains specified as having the issue or the opportunity that can handle through the deployment of the main business as a strategic resource. However, the usage of the information technology may have a negative impact on employees, which will require further investigation, especially into organisational resources, infrastructure, integration models and strategic alignment.*

KEYWORDS: *construction industry; information technology; building information modelling; Construction Management; organisational culture; IT infrastructure*

STREAM: *Stream 3 BIM and GIS (Jack Cheng).*

1. INTRODUCTION

The construction industry is one of the largest fields of investment in the world and it is one of the most influential sectors for New Zealand economic growth; ranking in the top five most contributing sectors (Liu et al., 2017; MBIE, 2015; Wilkinson, 2012). However, this industry faces significant challenges including low productivity, chronic delays, cost overruns, and quality issues (Mbachu & Taylor, 2014; Poshdar et al., 2014). The studies show that the use of advanced project management methods combined with the modern tools and systems such as information technology can deliver a 30% enhancement in total industry performance (Jia & Min, 2010). This situation calls for a reassessment of the state of the project management knowledge and the level of penetration of modern methods and technologies (Jelodar et al., 2016; Jia & Min, 2010; Onyegiri et al., 2011). Information technology (IT) supports processing, storing, sharing and producing information (Bjork, 1997). Initially, it was mainly depended on the data processing. However, given its wide-spread adoption today, IT can offer a higher level of cooperation, coordination and information integration to enhance the construction performance (Forcada Matheu, 2005). All the construction phases including the initial project planning, the execution stage, and the operational development can be benefited from the implementing IT. A review of the reports on the penetration of IT in construction shows that the adoption has started in projects (Weippert et al., 2003). However, a full establishment of IT in construction remains subject to the institutionalization of strategic alignment between IT application and the business strategies adopted by the firm (Acar et al., 2005; Gaith et al., 2009; Stewart & Mohamed, 2003).

The concept of strategic alignment is mainly based on the theory an IT correspondent to the firm's business strategy can shape an effective and competitive border and provide strong solutions to the firm's strategic problems (Luftman, 1996). The alignments have traditionally linked with two determinants. It has either been linked to the *strategic fit* that is the scope to which the infrastructure support an organization's strategy; or the *functional integration* that is the scope to which IT approaches support the business plan (Izanec,1997). Effective implementation of the strategic alignment requires synchronization between the strategic fit and the functional integration (Henderson et al., 1996). This paper conducts an analyses of the existing connection between IT implementation strategy and the organisational and project strategies adopted by the construction industry in New Zealand. The following research questions have been considered: Do New Zealand construction firms have clear information technology strategy within the business initiative? How can the construction organisation in New Zealand achieve and manage the strategic alignment between information technologies, organizational infrastructure and business strategy? Answering these two questions will help in finding the routs to fit, align and integrate IT into the organisational and project business strategies of construction firms.

2. LITERATURE REVIEW

In the late 1960s, Japanese academia and industry emphasized on the concept of the information technology as a phase of economic development (Björk, 1999; Zhanglu & Wenwen, 2014). However, its application in engineering started in the 1970s as a computer-aided design (CAD) that facilitated engineering drawings (Forcada Matheu, 2005). However, this usage was restricted to large-size engineering projects. The development of personal computers (PC) in the 1980s increased the computational power, and facilitated its implementation in the medium-size projects (Forcada Matheu, 2005; Peansupap & Walker, 2005).

The requirement for information transparency and perfection in a competitive business calls for effective tools that could enable business efficiency. The alignment of business efficiency with supporting technologies is the main concept of strategic alignment. Strategic alignment proposed to support the integration of information technology into business strategy and processes. (Luftman, 1996) defined it as a concept that aligns information frameworks with the business strategy to shape a powerful competitive border and produce strong solutions for field and organisation issues. The Strategic Alignment Model has established on the idea of *"strategic fit"* which is the vertical linkage between external and internal domains and explains the business requirement to make decisions. Another linkage can be established in the *"functional integration"* between firm and technology domains which relates to information technology and the alignment of the business (Henderson et al., 1996) **(Figure 1)**. The concept of the strategic alignment model theorises the analytical scope of the firm strategy from the infrastructure and operation support (strategic fit) or business plans and information technology support (functional integration) (Izanec, 1997). On the other hand, Henderson (1996) concluded that the organisation should work on both strategic fit with functional integration for better results (Henderson et al., 1996).

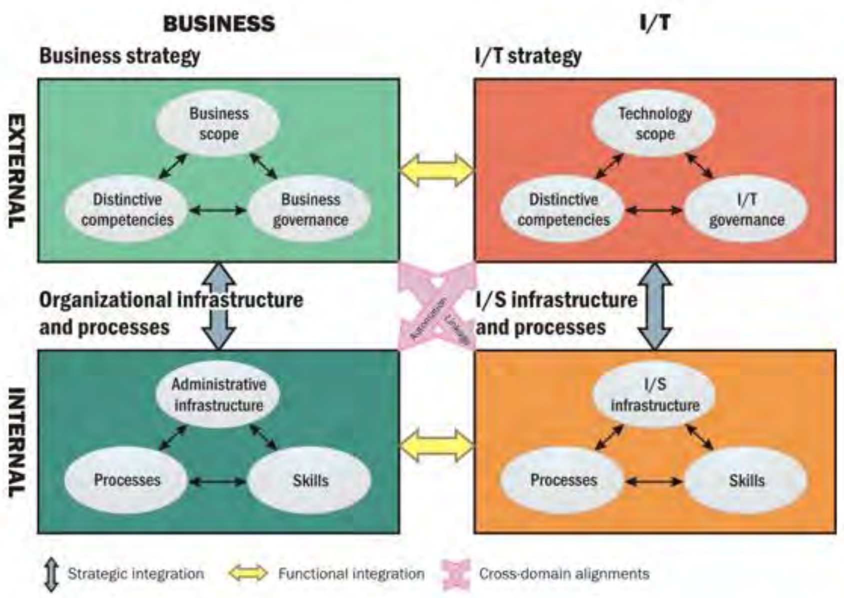

Figure 1: Strategic Alignment Model for Business. Source: Adapted from (Henderson & Venkatraman, 1989)

In 1999, Björk discussed the scope or the range of the study of the information technology applications in construction using an analysis technique based on a strong model of the information management in construction called IDEF0. The objective was to draw a clear border between the specific information technology research and other similar research in this area (Björk, 1999). The author found that in the previous studies about information technology in construction, there was a weakness in term of the information technology model identification (Björk, 1999). Other researchers have analysed the barriers that control the spread and the implementation of the information technology in construction organisations such as the nature of the application itself and considering the business strategy over information technology infrastructure (Henderson et al., 1996; Peansupap & Walker, 2005). Regarding the strategic alignment, they concluded that the business strategy, information technology strategy, firm infrastructure and information technology infrastructure should have a level of integration for best results **(Figure 1)** (Henderson & Venkatraman, 1989; Henderson et al., 1996; Peansupap & Walker, 2005).

As mentioned above, Henderson (1996) concluded that the organisation should work on both the infrastructure and operation support (strategic fit) with business plans and information technology support (functional integration) for better results and there are internal and external domains within each element (Henderson et al., 1996). The internal domain in the business strategy area described as "organizational infrastructure and processes", and it is mainly involved with options that determine the structure or restructure of pivotal business procedures, the executive structure and the development of resource skills. However, the external domain in this area described as "business strategy", and it is involved with governance decisions, business scope decisions and distinctive competency (Goh, 2006; Henderson et al., 1996). Correspondingly, the internal domain in the information technology strategy area described as "information technology infrastructure and processes", and it is involved with how to manage the information technology infrastructure in regard of its architecture, processes and skills. On the other side, the external domain in this area described as "information technology strategy", and it is involved with the organisation place in the information technology marketplace in regard of its technology scope, information technology governance and systemic competencies (Goh, 2006; Henderson et al., 1996). Various tools and techniques have been proposed to process the alignment issue using measurement methods or modelling techniques and one of the benefit models was the Strategic Alignment Model (Andres & Poler, 2017). The strategic alignment model works on developing the integration of the information technology domain and business domain at strategic scale - the relationship between information technology strategy and business strategy - and the operational scale - the relationship between organisational infrastructure and information technology infrastructure -. However, its required to consider one of the four dominant alignment perspective - which presented in **Figure 2** - to operationalise the model (Goh, 2006; Henderson et al., 1996).

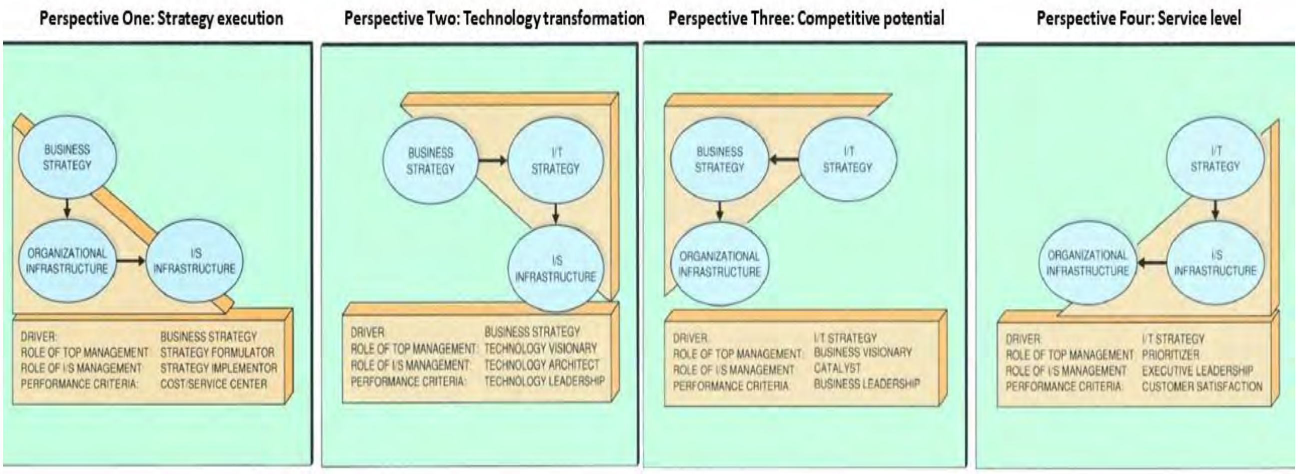

Figure 2: Four dominant alignment perspective of the strategic alignment model.

Source: Adapted from (Henderson et al., 1996)

The latter argument confirmed by Tulenheimo (2015) who demonstrated that the project budget and management culture have significant shortcomings and inabilities in implementing new technologies in the construction industry which is proven to be difficult to penetrate (Tulenheimo, 2015). Moreover, the level of organisation was considered as an obstacle in term of information technology implementation; especially if the national use of the information technology as a project management tool is relatively late(Jia & Min, 2010). Zhanglu and Wenwen (2014) have suggested that the impact of the information and communication technology implementation on project performance and cost saving is dependent on the hosting country's growth and organisational culture towards the information technology (Zhanglu & Wenwen, 2014). Thus, the effective use of the information technology starts from the structure and the development of the construction firms as mentioned by Wilkinson (2012) who performed a research to analyze the volume of information technology application; within construction project management of New Zealand during project phases and the acceptance of those organizations to invest in specialized information technology applications. It was found that the companies with a large number of employees are more likely to use the information technology application and considered it as strategic to their firm compared with the companies with fewer numbers of employees (Acar et al., 2005; Sarshar & Isikdag, 2004; Wilkinson, 2012; Poshdar et al., 2018).

Although there are obstacles and barriers to implementing the new information technology in the construction industry, there are direct and indirect relationships between the information technology implementation and project performance (Peansupap & Walker, 2005). Some researchers found that the information technology, in general, has a direct positive effect on the construction organisation performance by improving the efficiency of works and facilitating the project management. However, the positive impact of the information technology on the performance reflected a negative effect on the organisation workforce such as limiting the options for employment, the effect on work-life balance experienced by employees, the effect on workforce attitudes and create "technostree" which is stress results from working on technology for a long time. (Sun et al., 2008). According to Kang et al. (2013), there is a robust relationship between best practice or construction management and the project performance stronger than the relationship between the information technology implementation and the project performance or outcomes. However, the use of the information technology has a significant direct impact on the best practice or project management. In general, information technology implementation can directly affect the work progress without a direct relationship to the project performance (Kang et al., 2012). The latter argument was also supported by Onyegiri, Nwachukwu, and Jamike (2011) who found that the fast development of the information and communication technology has an indirect positive impact as it increases the communication efficiency, decreases data processing time, improves the decision-making and facilitates coordination works (Onyegiri et al., 2011). Thus, most researchers agree that implementing information technology has a positive impact on project performance and construction cost, but this still depends and also restricted by the study location and the local culture (Jia & Min, 2010; Kang et al., 2012; Peansupap & Walker, 2005; Zhanglu & Wenwen, 2014).

In this regard, many researchers have chosen to analyse and study the impact of the information technology implementation using empirical studies in different countries and geographical locations with specific cultures as the level of results vary and depend on the position of the construction industry in this country (Tulenheimo, 2015). In the last ten years, many researchers studied the effect of organisation information technology on the construction projects in different countries. A researcher such as Zhou and Min (2010) who studied and tried to recognise the barriers that impact the implementation of the information technology in Chinese construction projects and analyse the possible ways to eliminate those barriers. The author studied the incorporation of the impact of sophisticated information technology on the management of the project and the obstacles in information technology implementation to analyse the value of coping strategies in the Chinese construction industry (Jia & Min, 2010). Other researchers studied the challenges of implementing new information technology in the construction industry using the local practical study to analyze the level of spreading this technology in the construction firms nationwide (Jia & Min, 2010; Tulenheimo, 2015).

Some authors consider the breadth of application and volume of information technology implementation of the on New Zealand construction industry without considering its effect on the project outcomes. For instance, Wilkinson (2012) studied the usage and volume of the information technology application corresponding to the project management in the New Zealand construction organisations during project phases and the organizational acceptance towards specialised investments in information technology applications. Based on a survey, the researchers found that 58% of the construction companies in Auckland used the information technology application which related to project management during planning and monitoring works; around 21% of those construction companies created their project management applications which reflect the company needs (Wilkinson, 2012). Thus, there is a definite acceptance of using the construction-related information technology applications in New Zealand construction industry. However, more in-depth analysis and empirical evidence through industry, organization, and project based research are required to observe and identify the efficiency of using information technology tools and applications; in addition to determining the challenges around that (Liu et al., 2017).

3. RESEARCH METHODOLOGY

In order to analyze how information technology is integrated, fitted and aligned with the business strategies of construction firms in New Zealand, a two-phase methodology has been developed and implemented. In stage 1 the "Theoretical Review", an overall review of related literature from well-respected sources has been performed to recognize different characteristics and advantages of information technology implementation in the construction industry. For stage 2 known as "Practical Investigation", expert Semi-structured open-ended interviews selected as the most appropriate instrument for collecting the necessary data from large construction projects based in Auckland, New Zealand. The interviews conducted with the project managers, planning managers and senior engineers from each construction project. The semi-structured interview method provides an equilibrium between the elasticity of open-ended questions and the concentrate of a structured interview and the data during the semi-structured interviews can convert the study process from domains topics to more particular views (Harris & Brown, 2010). This type of qualitative study supplies key expert results which are in the same level of training and experience and can analyze multiple ways of problems management (Flick, 2009). Furthermore, using Expert Semi-structured interviews provides a foundation for the validation of other results from other research in the same field of study (Gubrium & Holstein, 2002; Jelodar et al., 2018).

Interview responses rate was based on the theoretical saturation principle which has been performed in similar research (Jelodar, 2016; Martin, 2011; Glaser, 2009). Accordingly, a total of thirteen expert interviews were conducted which are tabulated with complementary information in **Table 1**.

Table 1: Interviewees profile summary

	Role	Experience	Cur. Project	IT products/tools used	By-Product / Capabilities
Expert 01	Project Manager	21 years	Highway	BIM, Cloud, DSS, CAD	VR, AI
Expert 02	Project Manager	17 years	Airport	BIM, Cloud, DSS, CAD	VR, Wearable
Expert 03	Project Manager	31 years	Airport	BIM, Cloud, DSS, CAD	AR, AI
Expert 04	Project Manager	33 years	Infrastructure	BIM, Cloud, DSS, Sim, CAD	VR, Wearable
Expert 05	Senior Planning Engineer	12 years	Highway	BIM, Cloud, DSS, CAD	VR
Expert 06	Cost and Control Manager	30 years	Airport	BIM, Cloud, DSS, CAD	
Expert 07	Planning Manager	30 years	Airport	BIM, Cloud, DSS, CAD	
Expert 08	Planning Manager	16 years	Infrastructure	BIM, Cloud, DSS, Sim, CAD	VR, AR, AI
Expert 09	Senior Planning Engineer	13 years	Hotel	BIM, Cloud, DSS, CAD	VR, Wearable
Expert 10	Senior Civil Engineer	11 years	Highway	Cloud, DSS, CAD	VR
Expert 11	Senior Civil Engineer	10 years	Airport	Cloud, DSS, CAD	
Expert 12	Senior Civil Engineer	10 years	Airport	BIM, Cloud, DSS, CAD	Wearable
Expert 13	Senior Civil Engineer	23 years	Infrastructure	Cloud, DSS, CAD	VR, AR, Wearable

Experts were selected using the theoretical process as they are from different types of construction projects with purposive experience of using the information technology tools and systems in New Zealand construction work environments and projects. Therefore, the selection process considered that all the interviewees worked in four large size construction projects in Auckland New Zealand in the higher tier of management roles and used the information technology during their daily works. The sample population are holding high ranked positions in their organizations, making them well informed and experienced individuals. Therefore, the expectation that respondents must have a good understanding and demand of current practices and processes within their organizations and the wider construction industry is fulfilled. The expert face-to-face interviews structured with foundation questions related to the relationship between the information technology implementation strategy and construction organization strategy followed by complementary open-ended questions for better tangibility responses.

The answers from the foundation questions, the experts' comments and opinions have been categorised and classified using NVIVO software and then analysed - considering the software outputs - to be in the term of "agree" and "disagree". In this regards, the percentage of "agree" results has been calculated and distributed on the related domain considering the factors affecting the position of a specific domain in the organisation (Acar et al., 2005; Andres & Poler, 2017; Boddy et al., 2008). Thus, to achieve the main objective which is analysing the strategy of construction organisation to consider information technologies as strategic resources, the strategic alignment model has been selected as a framework for aligning the information technology with the business strategy. To apply the strategic alignment model on the collected data, it is required to analyse the data based on the main four elements or domains of strategic alignment which are business strategy, information technology strategy, organisational infrastructure and information technology infrastructure.

4. FINDINGS

The findings of this study have been presented in two sections. In the first section, the collected data have been summarized and organized on the four strategic alignment domains based on their impact on each domain, and the goal is to append statistical result from the interview to each part of the four domains. Thus, to apply the structure of the strategic alignment model, each domain level has been analysed separately and presented as “Strong”, “Mid” or “Weak” to determine the power of each domain in term of considering the information technologies as strategic resources. The full process of the first section presented in **Figures 3 and 4**. Based on the collected data, the business strategy of the large-sized New Zealand construction organizations exists, and it is in an optimal good position. Moreover, the information technology strategy responds to the business strategy and the information technology organizational culture is strongly present (**Figure 3**).

On the other hand, the organizational infrastructure is the weakest area in New Zealand construction organizations which indirectly effect on the information technology infrastructure and process (**Figure 4**). Hence, for large-sized New Zealand construction enterprises, organizational infrastructure and information technology infrastructure are two areas identified as having the issue or opportunity that can be classified through the deployment of the information technology as a strategic resource.

Therefore, and from the figures above, the business strategy is the driver element with the strongest level compared with the other domains then the information technology domain follows it with an accepted healthy standard as well. The information technology strategy reacts to the business strategy, and the performance criteria based on financial parameters considering a cost pivot concentrate. Looking at the right-hand side chart **(Figure 3)** of the external domain, which is an information technology strategy, the information technology in New Zealand construction organisation mainly concentrates on performance efficiency by financial savings and increased the productivity and efficiency of the organisation work process. The strategy execution perspective considered as the typically dominant alignment for the New Zealand construction organisation based on **Figure 4** as the organisation infrastructure is the weakest domain and lagging behind the development vision of the organisation due to a lack of investment on information technology facilities. Therefore, the information technology Infrastructure is impacted and need to be developed to support the firm or construction company infrastructure shortfalls.

However, the tested components have multiple effects with instances where they are reinforcing or balancing other potential components. For instance, creating more IT infrastructure will create requirements for more skilled professionals and if that may not be an option training facilities and workshops need to be included. This effects may disrupt cash flow issues or require more investment in other infrastructure which was totally unthought-of at the beginning of the process. These components and their collective interactions create systems and subsystems that are in the congregation with many different layers (Jelodar et al., 2015). The other observation made is the fact that a change in components makes the system unstable in a manner that different status changes are then experienced to reach more stability; however, this changing status is constantly happening especially with the fact the technology improvements and changes are rapidly taking place throughout the industry. On the other hand, the ultimate goal of IT systems and technology is to enhance quality and productivity which is a continuous process both at the project and industry level. On top of these complexities, a non-linear relationship exists leading to a range of dynamic variations in the system. Accordingly, a system dynamic model framework seems to fit into the findings of this study. The creation of the initial system dynamics model involved the problem statement, formulating a dynamic hypothesis, and formulating a simulation model (Jelodar et al., 2018). Based on this assessment a causal loop diagram is suggested to summarize and analyze the drives of information technology infrastructure based on the collective views of construction experts.

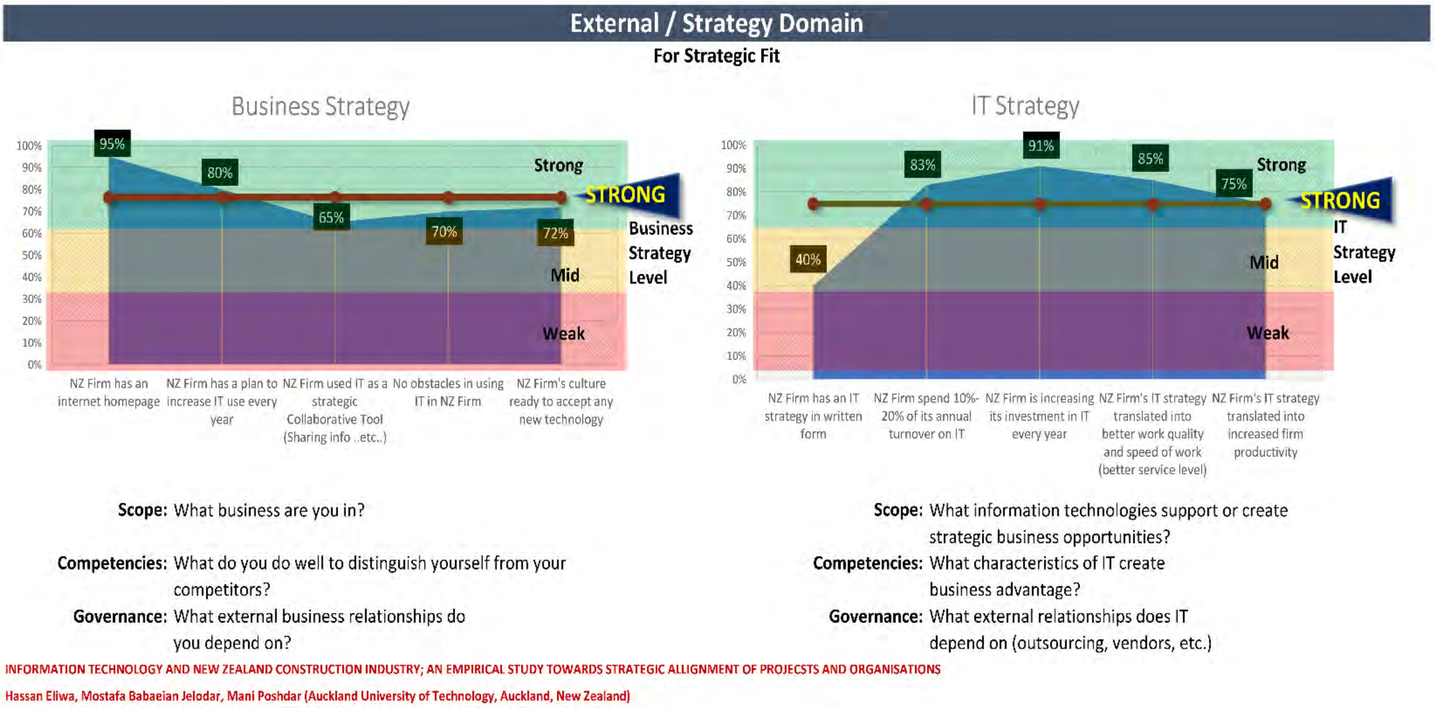

Figure 3: Results of analysis of New Zealand Organizations for Internal / Infrastructure Domains

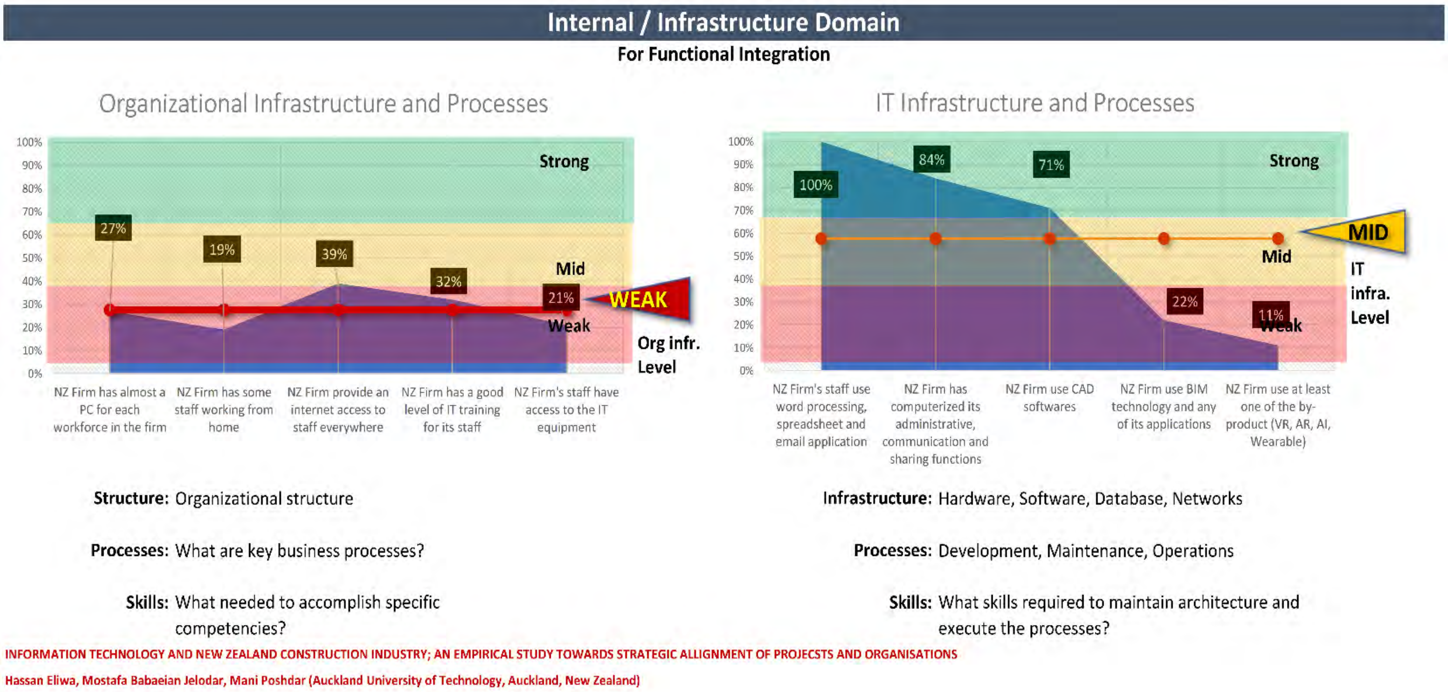

Figure 4: Results of analysis of New Zealand Organizations for External / Strategy Domains

This stage was performed via the application of a system dynamic Vensim PLE as a systems dynamic tool and presented in **Figure 5.** The method has been widely used in many interdisciplinary reassert area and similar complex construction oriented issues such as innovation instruction (Jelodar et al., 2018). In addition the diagram can isolate and identify the main factors to be considered as the weakest link or domain in the strategic alignment of technology and organizational infrastructure to the overall benefit of construction companies, and opens up roots to further idea development for future investigation for more efficient problem solving in such issues (Nguyen & Ogunlana, 2005; Sterman, 2000; Walrave & Raven, 2016).

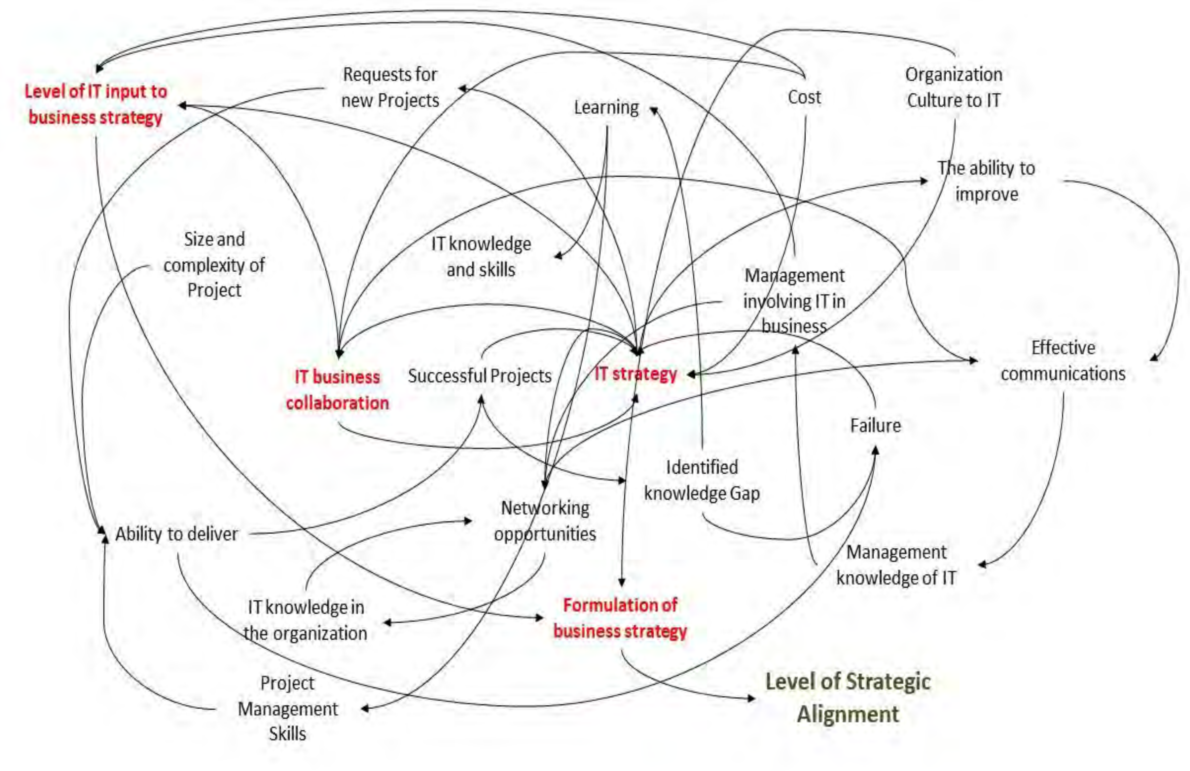

Figure 5: Causal loop diagram to summarize and analyse the drives of information technology Infrastructure

5. CONCLUSION

This research analyzed the quality of the information technology usage by New Zealand construction organization. It studied the alignment of business and information technology strategies by applying the structure of the strategic alignment model. In New Zealand construction industry, firms have common requirements relating to building information technology capability, and at the policy level, it is important to address domain-specific concerns. Based on this study, organizational infrastructure and IT infrastructure are two areas identified as having an opportunity that can be addressed through the deployment of information technology as a strategic resource. The findings assist policy makers as well as construction project management to better understand the New Zealand construction sector firms' information technology and strategic management orientations.

This research identified possibilities for New Zealand construction organizations in focus to increase their strategic alignment level. As it has proposed actions, the organizations can take by identified the weak domains in the strategic alignment model as well as the performance criterion. This paper has considered the experts' and the literature suggestions and discussed possible actions to take to effectively align the use of information technology with organization business strategy. The overall action that needs to be taken in order to align information technology with the business strategy is transforming the overall perception of information technology as a costly department toward information technology as a provider of competitive advantage.

6. RESEARCH LIMITATION

The scope of this research limited to large construction projects within the Auckland region in New Zealand as Auckland region mostly covers national construction demand in New Zealand. Thus, the study provides insights into what the impact and challenges of implementing information technology tools, concepts and applications on New Zealand construction industry performance.

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DYNAMIC AS-BUILT BIM UPDATING DURING CONSTRUCITON USING THERMAL IMAGES

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ABSTRACT: *Image-based systems are known as an affordable method for many construction companies to collect data every day. Numerous studies have been conducted to utilize and improve the image-based methods for construction project monitoring and management purposes. However, a notable downside exists in traditional image-based processing, for example, poor or undesirable ambient lighting conditions produce low quality images which significantly affect the accuracy of data extracted and lead to errors. In addition, BIM has been used for construction progress monitoring by comparing the as-designed model with the 3D reconstructed model based on images collected from the site. This research proposes a methodology to dynamically updating BIM model for construction by using thermal images, which adds extra information to identify materials with different thermal radiation, especially the higher temperature caused by hydration of cement. As a result, it is possible to distinguish newly constructed concrete component from other objects, such as scaffolding made of steel, guardrails made of wood, etc. Obstacles not relevant to the component of the main structure can be identified easily and removed automatically through thermal image processing. By using this method, a dynamic BIM model can be constructed following the updated construction progress.*

KEYWORDS: *Dynamic BIM, Thermal image, Construction*

1. INTRODUCTION

Monitoring and tracking the performance of construction projects play a significant role in achieving smooth construction project delivery but is often a complicated and challenging task due to the changes occurred on site. To get meaningful progress information, two features of a project are essential: an optimal level of project activity granulation, and an object-oriented activity structure, where each activity is associated with clearly distinguishable building elements that can be identified in real time. Due to the significant workload required, manual progress monitoring represents disproportionately high costs or may be ineffective, or even both. It is, therefore, not surprising that significant research has focused on digital construction progress monitoring.

There are two widely-used techniques, laser scanner based or image-based 3D model reconstruction, in project monitoring and tracking. By comparing the as-built 3D model with the as-designed 3D model, the change or error during construction can be identified. These as-designed 3D models, generally known as building information models (BIMs), are used throughout a building's lifecycle to provide semantically rich information for the designer, constructors and the facility managers. However, during the construction, significant design changes may occur together with undocumented changes or inadvertent errors. Consequently, creating an updated or dynamic as-built BIM model have significant meanings in project management.

However, either laser scanner based or image-based 3D model reconstruction methods can only present the spatial relationships as point clouds, and in most cases without any material properties information. In other words, the as-built BIMs require massive human intervention to justify these point clouds. In addition, image-based method has many limitations: (1) The fixed camera has limited the analysis to only the closest structural frame to the camera; (2) Lighting conditions and shadow issues significantly affect the image processing; (3) Dynamic occlusions make it difficult to analyze the components; and (4) Static occlusion may result in false detection (Golparvar-Fard et al., 2009).

2. RELATED WORKS

2.1 Laser Scanner based 'As-Built' 3D Model Reconstruction

The process of convert the point cloud data collected from laser scanner into an as-built BIM is known as 'scan-to-BIM'. Ideally, the 'scan-to-BIM' model should not only show the spatial relationships between nearby structures but also be annotated with identity labels (e.g. wall, door, column or beam) and meta-data, such as surface material (e.g. concrete) and functional relationships between nearby structures. However, these processes are done manually, and the results produced by different modelers may have significant differences even errors due to insufficient understandings between domains. A recent research done by Xiong et al. (2013), who proposed a method to identify the model's planar walls, floors, ceilings, and any significant rectangular openings, have a great progress in laser scanner point clouds process. However, how to convert the surface representation to a volumetric representation are still ongoing work. Additionally, the laser scanner based technology suffers from its high equipment cost, which is infeasible for small projects (Dai et al., 2013). Also, time spent for on-site scanning and pre-set (to reduce scanning noise manually such as sundries on the floors) are also importance factors that need to be considered for applying this technology.

2.2 Digital Image Based 3D 'As-Built' Model Reconstruction

The image-based 3D model reconstruction with over past year's development is considered as an affordable and an alternative for acquiring spatial data of infrastructures. Its basic principle is triangulation, whereby a target point in space is reconstructed from two mathematically converging lines from two-dimensional (2D) locations of the target point in different images. This digital image processing method has shown a great potential to replace the existing practice of 'scan-to-BIMs' technology if the high-quality BIMs are not required (Kim et al., 2013). Similarly, the digital image-based 3D model reconstruction has the similar problem in identifying the construction components. Fortunately, with several successful studies about automated defining the point clouds, this method became a strong candidate for automated construction progress monitoring. For example, Wu et al. (2010) have used the 3D CAD-based image processing techniques coupled with Canny-edge detection and watershed transformation to identify the relationships of existing objects with nearby structure components. Zhu and Brilakis (2010) have used machine learning techniques where hundreds of construction site images are divided into regions through image segmentation. Their study only focused on the concrete regions so far which cannot provide geometry and position information, and the combinate-materials detection is still undergoing. Even though Son et al. (2012) have provided an optimal combination of color space and machine learning algorithms to detect the concrete regions with high accuracy, however, it only focuses on the concrete material and without geometry and position information.

2.3 Thermal Image Based 3D 'As-Built' Model Reconstruction

This technique is relatively new, which still requires plenty of study to identify how to improve the accuracy of the object identification based on thermal images. Actually, the infrared thermography has proved to be an adequate technique for building inspection, since it is well used in construction defects (such as cracks) detecting and building energy efficiency. Hundreds of points can be measured by using thermography without direct contact (Lagüela et al., 2012). Since different construction materials present different temperatures in the same given condition on site, it is feasible to distinguish these components using a temperature filter (Zhang and Pazhoohesh, 2017). However, the measured construction material's temperature is significantly influenced by the location, time to exposure, intensity of the sunlight, measuring distance and atmospheric humidity on-site (Hoegner et al., 2016). Additionally, thermal images processing can be complicated, since it is mostly done individually without constant rules to follow. And without comprehensive view of constructions, the analysis will be limited (Maset et al., 2017). Meanwhile, the same problem exists that only spatial and geometric information can be obtained from these models.

3. PROPOSED METHODOLOGY

To realize the automatic construction process monitoring, the semantically rich as-built BIM which carries sufficient dynamic construction information is required. The as-built BIM is generated using multiple images-based 3D reconstructions. However, like the laser scanner-based 3D reconstruction technology, the traditionally images-based can only provide the spatial information with meaningless point clouds. Therefore, the solutions turn to take full advantage of point clouds and to redefine them. Consequently, once the system can automatically classify the points clouds extract from images semantically, with the 3D reconstruction technology, a semantically rich as-built BIM can be obtained. Based on the authors' previous research (Zhang and Pazhoohesh, 2017), thermal-image processing is proposed to automatically identify building components and compared with the as-designed BIM model so as to update the model.

As shown in Figure 1, there are several steps should be followed in the proposed methodology. First of all, the target components (columns, beams, etc.) should be decided according to the construction schedule. Secondly, determining the suitable potential locations for taking photos by combining the effective shooting distance of thermal camera and safety on site. Thirdly, recording the orientations and spatial information of the camera while taking photos to acquire the same view in the Revit model. The next step is to semantically segment the targeted objects from both thermal and optical images and cross-over registering the computer views with the thermal and optical images. Finally, extracting the features from optical and thermal images to form the semantic point clouds according to the object class. As a result, semantically rich 3D building models can be obtained.

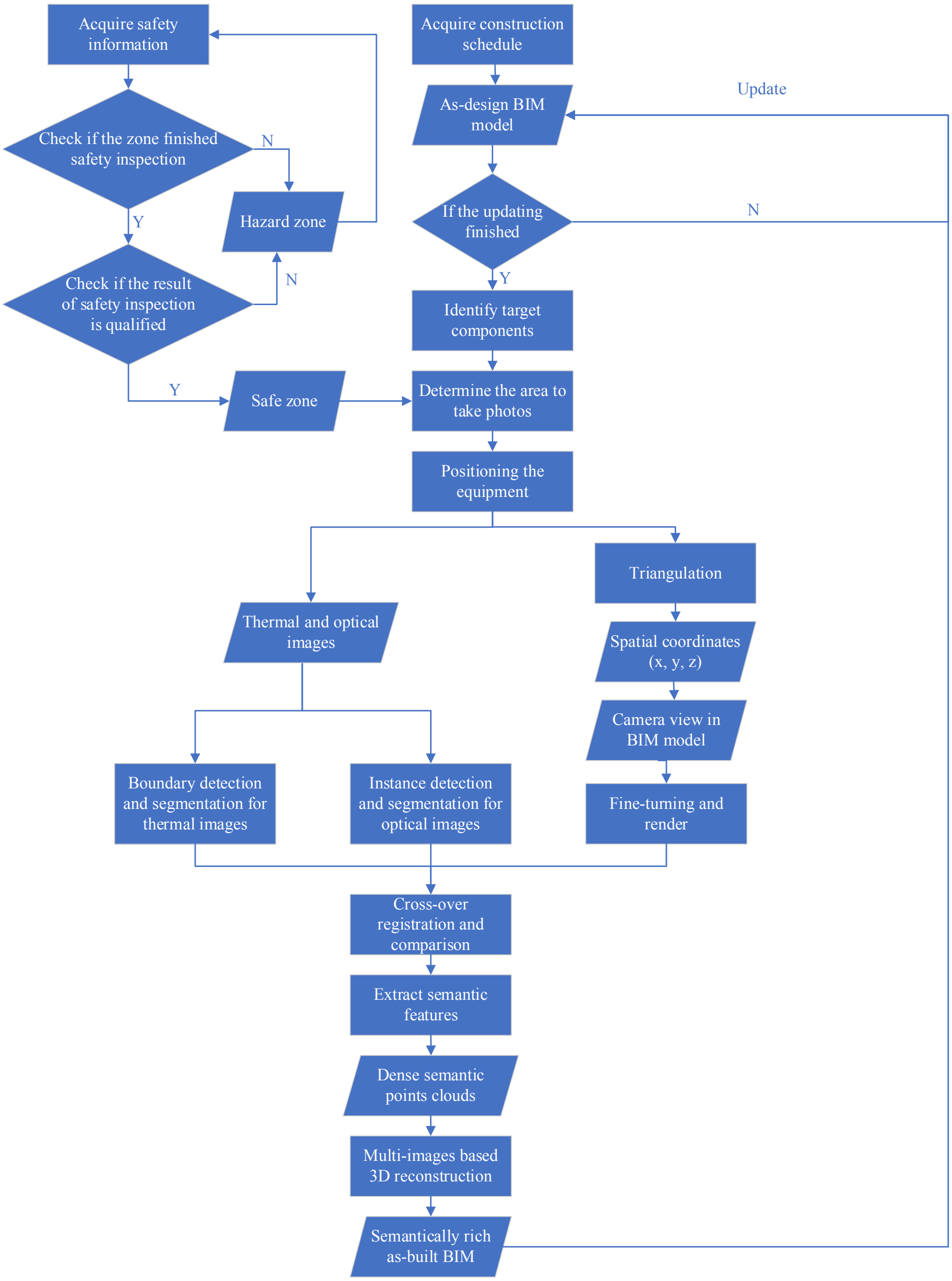


Fig. 1: Work Flow of the Proposed Methodology

3.1 Identify Locations to Obtain Onsite Pictures

To select the target components, construction schedules and the security zone planning should be carefully reviewed. The target components should stand within the effective shooting distance. The practical shooting distance of thermal camera is different from each type. For example, the effective shooting distance of FLIR E4 ranges from 2m to 30m (the valid range is a concept which specifies the area where the camera can measure relative accurate data). Additionally, when choosing the shooting locations, it is important to ensure the IR camera capturing various scenarios. For example, the scenarios should contain more than three different construction components (column, wall, and beam) or one component with the different thermal environment (under direct sunlight, in shadow area, and so on). Therefore, the potential locations for shooting can be identified after considering all the factors.

After that, when the pictures are taken on site, the real locations of the thermal camera should be recorded. To simulate the actual optical view, the external parameters (locations and rotation of view) and the internal parameters (field of view, focal length, aperture and shutter speed) should be recorded. The internal parameters can be directly obtained from the camera specifications, while the external parameters require further measurements on site, which include the horizontal orientation of the view (referring to North direction, taking clockwise as positive direction), the vertical orientation of the view, the relative elevation z (referring to both top beam and bottom beam) and the distances from nearby three columns (referring to the center of the surface at the same elevation which towards to the camera location). By using the external parameters recorded, the corresponding location of viewpoint can be identified in Revit model and the matching view can be obtained.

3.2 Thermal Image Segmentation

The thermal image obtained by the thermal camera is in the form of RGB (red, green, blue). An RGB color image is an M×N×3 array of color pixels, where each color pixel is a triplet corresponding to red, green, and blue components of an RGB image at a spatial location. The colorful image can be viewed as a mixture of these three colors with a color monitor. As mentioned before, different materials under the same environment condition will present different temperature. Consequently, they have different colors in view and can be identified accordingly. Color region segmentation is done by using a set of specified color range in an RGB image to represent an interest region. Then classify each pixel in the given RGB image by comparing with a specified range. One of the efficiency measures is Euclidean distance. Let $\boldsymbol{z}$ denoted an arbitrary point in the space and $\boldsymbol{m}$ is the mean value of specified color ranges. Also, then, the similarity can be represented as the distance between them is less than a specified threshold T, which is shown as follows:

$$\mathrm{D}(\boldsymbol{z},\boldsymbol{m}) = \sqrt{(\boldsymbol{z}-\boldsymbol{m})^T(\boldsymbol{z}-\boldsymbol{m})} \le T$$

Or

$$\mathrm{D}(\boldsymbol{z},\boldsymbol{m}) = \sqrt{(z_R-m_R)^2+(z_G-m_G)^2+(z_B-m_B)^2} \le T$$

By plotting the points that $\mathrm{D}(\boldsymbol{z},\boldsymbol{m}) \le T$, it forms a solid sphere with radius T. By definition points contained within, or on the surface of, the sphere satisfies the specified color criterion; points outside the sphere do not. In this research, the *k*-means clustering is adopted to segment the thermal images. The *k*-means clustering aims to separate *n* observations into *k* clusters in which each observation has the nearest mean distance to the center of cluster.

3.3 Optical Image Segmentation

The semantic segmentation as a complex and important task for computer to understand the scene is one of the most crucial tasks for further semantic 3D reconstruction. Various traditional computer vision and machine learning techniques have solved the autonomous driving, human-machine interaction, computational photography, and so on. However, the deep architectures, Convolutional Neural Networks (CNNs) usually, provided an entire new approach with incomparable accuracy and even efficiency. In the present research, the pre-trained Visual Geometry Group (VGG), a CNN model introduced by the Visual Geometry Group (VGG) from the University of Oxford, is applied to semantically segment the digital image coupled with thermal images. The VGG is also known as VGG-16 since it composes 16 weight layers. The VGG-16 follows the traditional architectures which contains the convolution layer, ReLU (rectified linear unit) layer, pooling layer, and fully connected layer, as shown in Figure 2. This research uses the pre-trained VGG-16 network to conduct the semantic segmentation. There are two main reasons for using pre-trained network: sufficient dataset and less time to reach convergence. By continuing the training process, weights can be fine-tuned through the pre-trained network. Higher-level of network and smaller learning rate are chosen to produce better results. Supervised learning is used for pixel level labelling (semantic segmentation), which provides the ability to learn appropriate feature representations for particular problem.

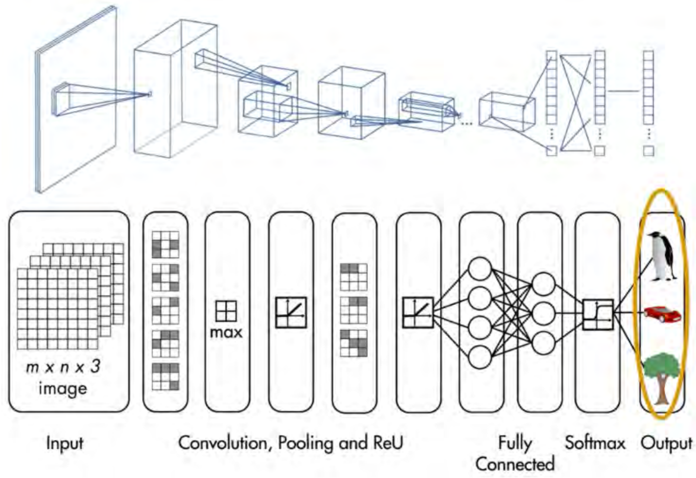


Fig. 2: Typical convolutional neural network

3.4 Image Registration

The image registration is carried out by overlaying three images, which are thermal image, optical image and BIM view image, for the same scene. In general, there are four steps:

1) Feature detection: The salient and distinctive objects of images, for example, closed boundary regions, edges, contours, line intersections, etc., are manually or automatically detected for further processing. The detected feature should have physical interpretability to ensure the reference and sensed images have enough common elements. In the ideal case, the same features should be identified in all projections of the given scene regardless of image deformation.
2) Feature matching: The correspondence between the features detected in the sensed and reference images will be established. However, due to the different spectral sensitivity of sensors, object occlusions or other unexpected issues, the corresponding features can be dissimilar. The ideal matching algorithm should be robust and efficient enough to overcome the effects caused by few features without corresponding counterparts.
3) Transform model estimation: This process uses the mapping functions to align the sensed image with the reference image. The exact mapping function is chosen according to the pre-known information about acquisition process and expected image degradations. If the priori information is insufficient, the model should be flexible and general enough to deal with all the possible degradations. This stage depends on the accuracy of the feature detection method, and the reliability of feature correspondence estimation. Additionally, the fault differences between sensed and reference image have to be removed, which makes this task extremely difficult.
4) Image resampling and transformation: This stage uses interpolation techniques developed form the mapping function established in previous stage to resample the sensed image.

Image registration methods can be categorized with respect to various criteria. In this research, the reference image is the BIM view while the sensed image is optical image. In feature detection stage, the region features which are developed from segmentation techniques are adopted to detect the high contrast closed-boundary regions (e.g., columns and beams). The result of the segmentation significantly influences the registration; therefore, the parameters used to define each object are required to be consistent and invariant.

4. CASE STUDY

The case study is conducted on a construction site located in Suzhou Industrial Park, China. The building has six floors above and three floors underground with a total construction area of 85946.6 m^2. The piled raft foundations are used in this project. At the time of applying the case study, the excavation is undergoing with temporary supporting structures. Parameters were identified including the emissivity of material ε, the distance between objects and IR camera d, the relative humidity RH, and the atmospheric temperature T_{atm}. The value of emissivity is the most critical parameter to evaluate the object radiation. For rough and dry concrete, $\varepsilon = 0.95$ as the same as the soil, while for rough and rusty latticed steel column, $\varepsilon = 0.92$. The distance between IR camera and objects is used to compensate the radiation loosed during transportation in the air. However, since there is generally more than one object within a scene, the value is usually taken as the distance between the center of the image to the IR camera. Compare to other factors the relative humidity caused fewer effects. Therefore, the value of RH usually is set as fault value, which is 50%. Table 1 provides the spatial information for the image registration, while Table 2 provides the environmental information for the case study.

Table 1. Spatial information

Shooting Spot		**Horizontal Orientation**	**Vertical Orientation**	**Height of Camera**	**General Camera Site**	**Column 1**		**Column 2**		**Column 3**	
						Distance (m)	Location	Distance (m)	Location	Distance (m)	Location
A	1	300	0	1.372	DF-D9	37.50	DG-D8	14.65	DE-D10	35.64	DE-D8
	2	30	0								
	3	135	0								
B	1	0	0		DE-D7	8.26	DD-D7	12.01	DE-D6	5.41	DE-D7
	2	330	0								
	3	115	0								
C	1	0	345		DG-D4	12.20	DG-DH, D2-D3	6.51	DJ-D3	15.34	DK-D4
	2	60	0								
	3	255	0								

Table 2. Environmental information

	Time	Atmosphere Temperature (°C)	Weather	Atmosphere Moist (%)
Start	10:00am	18.1	Partly Cloudy	50
End	12:00pm	20.3	Clear	

In Table 1, the horizontal orientation refers to the North direction, and the capital letter accompanied with a number represents the axis for the building. With the recorded information for each shooting spot, the corresponding views in REVIT are created.

(a)

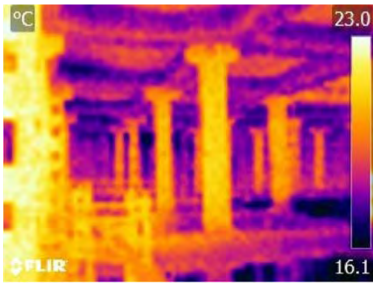
(b)

Fig. 3: Optical pictures with corresponding Revit view

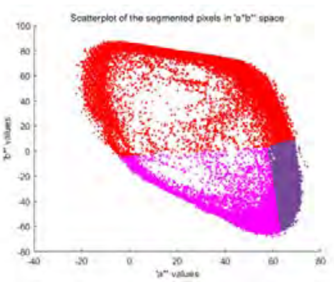
Figure 3 shows the optical pictures taken by the camera and the corresponding views in REVIT. It can be noticed that the REVIT model is not detailed enough to match the reality on site. For example, the safety guardrails are not created in REVIT model. In addition, soils, temporarily stacked materials do not exist in REVIT model, which increases the difficulty of accurate image processing.

4.1 Image Segmentation

Both thermal and optical images are segmented into identical components. Thermal images are segmented by using the L*a*b* color space and k-means clustering by using MATLAB. The L*a*b* color space consists of a luminosity layer 'L*,' chromaticity-layer 'a*' indicating where the color falls along the red-green axis, and chromaticity-layer 'b*' indicating where the color falls along the blue-yellow axis. All of the color information is in the 'a*' and 'b*' layers. With a k-means cluster, the difference between two colors using Euclidean distance metric is calculated. Figure 4 (a) shows the original thermal image which contains multiple colors. After using the k-means cluster, all the colors are clustered into three types, as shown in Figure 4 (b), where the pixels in yellow color taking more than half of the total pixels and the purple one has less percentage. The grey-scale map in Figure 4(c) shows how the cluster automatically classifies the image with three indexes, where black, grey and white are used. To present the segmentation results more visually, individual images are produced to represents the three different clusters, as shown in Figure 4(d)(e)(f).



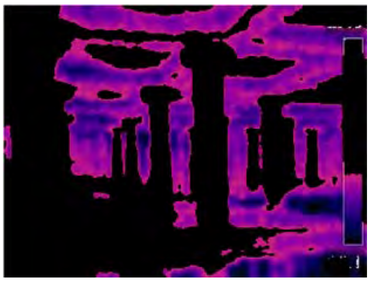
(a)



(b)

(c)

(d)



(e)

(f)

Fig. 4: Case study with 5 m effective shoot distance: (a) original IR image; (b) classification in a*b* space; (c) Classified image in grey-scale; (d) Segmented image – Cluster 1; (e) Segmented image – Cluster 2; (f) Segmented image – Cluster 3

The digital image semantic segmentation is implemented through the convolution neural network. To fine-tune the pre-trained VGG-16 networks, the pixel label base is required. In the current research stage, the label base is created either according to specific project or some public database. To ensure the system can adequately understand and learn, the database should have a large scale and represent information accurately. However, since most of the databases are used to classify the objects in a general approach (e.g., cats, dogs, streets, roads, signals, and buildings), a customized database for construction projects is demanded. Figure 5 represents two example of customized image label database developed in the present research project.

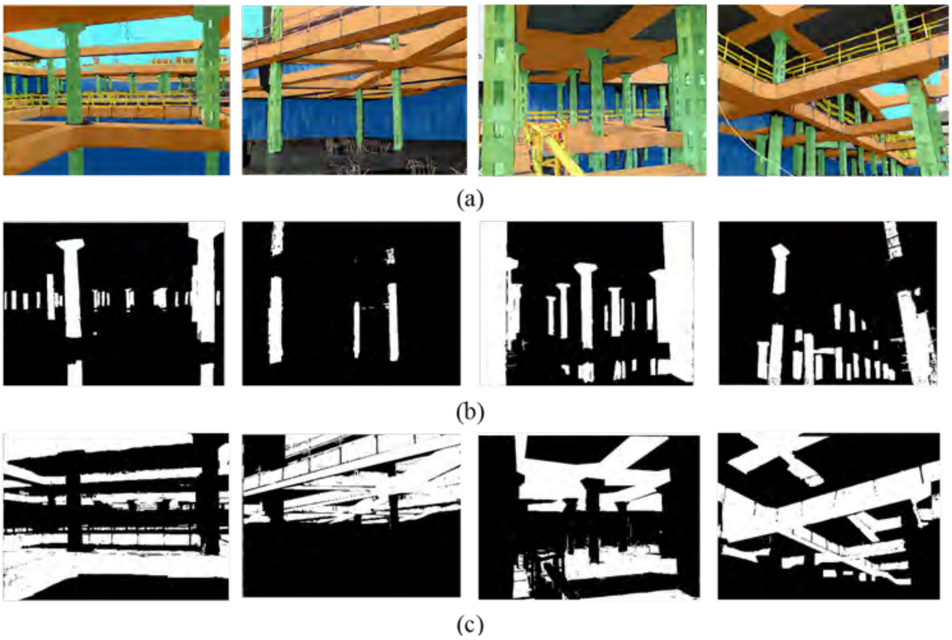


Fig. 5: Optical image segmentation

There are four elements (column, beam, safety guardrail and sky) highlighted in the images. They all have smooth edges and clear boundaries. Additionally, all the labeled pixel can be freely recalled in next steps in montage form, shown in Figures 5(b) and 5(c). With the customized image and fine-tuned networks, the system can automatically label the objects within small test samples. As it can be observed in Figure 6, the latticed steel column is wrongly labeled with the lower surface of beam and security fences. This problem is not able to be solved at this stage. However, it indicates that the probability to solve semantic segmentation using neural convolution network.

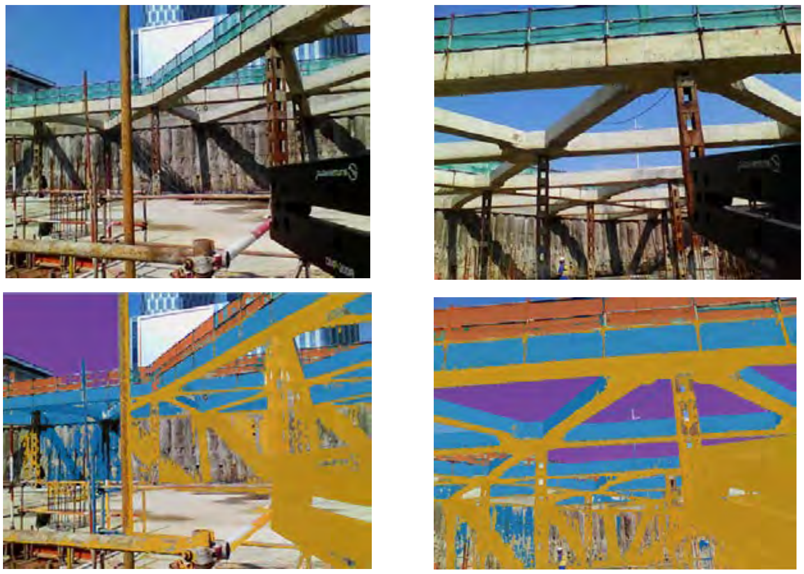


Fig. 6: Segmentation test results

4.2 Image Registration

Multiple photographs are taken from different sensors/cameras, at different time, from different viewpoints, which contain the same objects. The first step of registration is transforming the images from RGB form to grey-scale which will reduce the computation time since the RGB image has three tunnels while the grey-scale has one only. The second step is extracting the features from image. The features can be points, lines, and contours where the grey value has a suddenly change. After that, the coordinates of movable images are transformed using homeomorphic mapping or diffeomorphic mapping. Figure 7 shows an example of image registration.

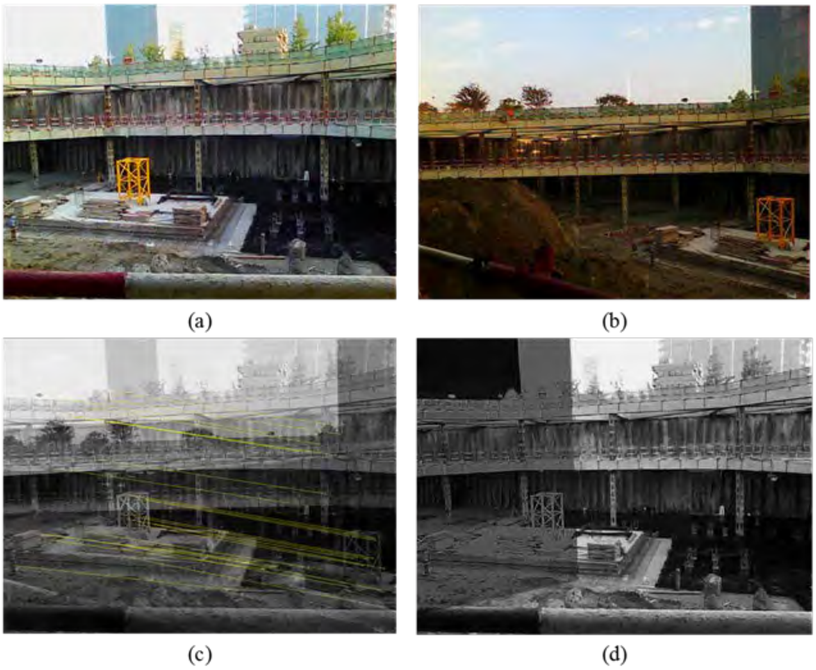


Fig. 7: Example of image registration

The image registration algorithm works well for the optical images with different viewpoint. However, it is unable to register the digital image taken by a camera and the REVIT model view in the current research stage. Figure 8 shows an example of the registration for camera view and corresponding REVIT model view. Even there are 749 features detected in the camera view and 119 ones in the REVIT model view, the images cannot be matched automatically. The main reason is that the features detected in REVIT model have no sense for the camera view. For example, the edges detected in REVIT view, where the grey values have a sudden change, have a significant difference with the edges detected in camera view. Since the reductions rate of grey value is different for the "same" object in the two views, they cannot be matched. Therefore, more research study will be carried in the future to address this problem.

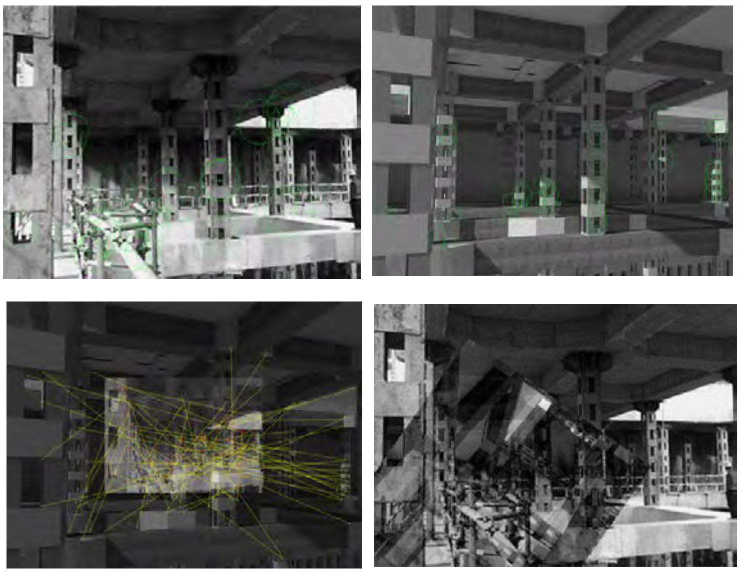


Fig. 8: Example of image registration between optical image and Revit view

5. DISCUSSION

This research has explored an innovative approach for automatically monitoring construction process by using thermal image processing techniques. This approach consists of four main stages: automatic segment the thermal image, semantic segment the optical image using convolutional neural networks, register the camera views with the REVIT views, and integrating all the information obtained from previous three steps to automatically compare the as-designed BIM model with the as-built construction site model. Case studies were carried out to explore the feasibility and effectiveness of the proposed method. A good potential has been proved to use thermal images providing extra information for 3D reconstruction and used to automatically monitor the construction progress in the future. Some limitations have been found, such as, the information extracted from IR thermal images is limited. By using thermal infrared imaging, it can only provide general spatial distribution of objects. Additionally, to achieve identifiable components in thermal images, enough radiation are required which means that the IR camera will capture more recognizable images during the sunny day than at the night or after rain. Therefore, combining additional image processing methods is necessary. Due to the limitation of thermal infrared imaging mechanism, considerations should be taken when taking thermal images to avoid complex micro-thermal environments, valuable radiation sources, and so on.

ACKNOWLEDGEMENT

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BIM EXTENSION TO INCORPORATE EMBODIED ENERGY INFORMATION

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ABSTRACT: *Assessment of the embodied energy of buildings provides an opportunity for reducing the use of energy consumption and improving sustainability performance. Building Information Modelling (BIM) provides a platform to incorporate sustainability information in the design of buildings. However, interoperability of BIM with Life Cycle Assessment (LCA) tools needs further investigation. Previous research in this area has either partially employed BIM; data was exported from the main BIM authoring tool and then auxiliary tools were utilized to evaluate the embodied energy content, or have ignored the importance of retaining embodied energy results within the BIM environment. The presence of embodied energy results give way to the potential of sensitivity analysis to optimize the embodied energy content. Therefore, there is a need for a formal and standard definition of embodied energy content in BIM. Such inclusion is necessary to perform related model sharing through main stream BIM data exchange protocols such as IFC. Therefore, this paper proposes an extension of the IFC model to incorporate embodied energy information. Matching the aspects of cost associated with the building elements and processes, a new resource of energy is proposed. Consequently, the abstraction of this energy resource is further embedded by establishing the relationship with other model entities.*

KEYWORDS: *LCA, Embodied Energy, IFC*

1. INTRODUCTION

The performance of construction projects is recently being tied with sustainability along with time and cost. Numerous sophisticated tools are available to control the traditional factors of cost and time. However, sustainability has not yet been properly quantified and a lot of research is being done to quantify the various aspects of sustainability. Building Information Modelling (BIM) has become the new standard of delivering projects and is based on Industry Foundation Class (IFC) schema for capturing and sharing data. Since cost had been a critical factor for assessing project performance at the time when the IFC schema was developed, therefore, cost was adequately mapped within the IFC schema. Albeit sustainability parameters are also mapped in the IFC schema but their effectiveness is not adequate, because unlike cost, the intention was just to set the physical properties of materials rather than input for decision making scenarios.

Embodied Energy, being an important aspect of sustainability and a direct trade-off for the operational energy optimization studies, needs to be thoroughly embedded in the BIM models. This is necessary because the post-construction or operation and maintenance energy is already being calculated in a fully automatic manner within tolerable error limits. Therefore, this paper proposes to extend the current IFC4 model to incorporate embodied energy values for construction resource such as material, equipment, transportation, labor etc.

2. LITERATURE REVIEW

Building sustainability refers to a building structure and the processes for its use that are environmentally responsible and resource-efficient throughout the building's life-cycle: from siting to design, construction, operation, maintenance, renovation and demolition (UEPA, n.d.). This encompasses the efficient utilization of resources (energy, water, etc.), reduction in environmental degradation due to pollution and waste, and the regeneration of resources through onsite mechanisms and treatment plants. Sustainability assessment can be defined as the process of identifying, predicting and evaluating the potential impacts of particular initiatives and their alternatives (Devuyst, 2000).

Forecasts of the U.S. Energy Information Administration (EIA, 2010), show that energy consumption in buildings is increasing at a rate comparable to those of the industrial and transportation sectors. As far as building energy is concerned, Embodied energy (EE) and Operational energy (OE) together constitute a building’s life cycle energy (LCE). EE involves the initial energy of the construction (material and energy burden associated with material consumption in buildings) and OE reveals the energy utilized in the building’s operating phase (Praseeda et al, 2016). There are two more types of building energy, namely demolition and disposal energy, but these are rarely addressed as together they form less than 1% of LCE (Sartori and Hestnes, 2007; Ramesh et al, 2010).

Building Information Modelling (BIM) is one of the most promising developments in the Architecture, Engineering and Construction (AEC) industries. According to National BIM standards, "BIM is a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition" (NBIMS, 2010).

Many studies have been conducted for the BIM-sustainability integration in general and for the estimation of embodied energy in particular. Shrivastava and Chini (2012) assessed the initial embodied energy of a building through BIM. This study criticizes the export of BIM quantity take-offs to other platforms for sustainability analysis and proposes the extension of material properties to incorporate sustainability data within the BIM environment. Another study (Abanda et al, 2014), analysed the embodied energy and CO2 emission of mud-brick and cement block houses, where building element was treated separately and manual calculations were performed to estimate the embodied energy. Shadram et al. (2016) proposed an integrated BIM-based framework for minimizing embodied energy during building design. Likewise, another effort to conduct LCA through BIM is done by Jrade & Abdullah (2012), which proposes to export the BIM model as an IFC file to a LCA tool. Abanda et al. (2017a) thoroughly integrated BIM with UK new rules of measurement and extended their study to incorporate LCA data (2017b). In addition, a famous commercial tool "Tally" also quantifies sustainability information for BIM model.

The previous studies mentioned have ignored the importance of retaining the LCA results within the BIM environment; the results are in the form of excel sheets or pdfs. This is probably because there is not adequate mapping in the underlying IFC schema which can hold these values and make them available for automated decision-making systems. On the other hand, cost is adequately mapped in the schema and thus it is represented in an orderly fashion. It is vital to examine the embedment of cost in the IFC model before proposing IFC extension for energy.

2.1 IFC Model

The Industry Foundation Classes (IFC) data model is intended to describe building and construction industry data in a standard way which enables various software platforms to exchange information throughout the life cycle of the project with minimum human interaction (Nizam and Zhang, 2017). IFC has four layers, (i) Resource Layer, (ii) Core Layer with Kernel & Extensions, (iii) Interoperability Layer and (iv) Domain Layer. Figure 1 shows these layers and the components within each layer (IFC4, a).

3. OBJECTIVES

The concept of embodied energy is similar to that of cost as far as calculation and abstraction is concerned. Therefore, the objectives of this paper include:

1. Thoroughly review the embedment of cost in the current IFC model and extract meaningful information in terms of entities and data types forming the cost model.
2. To propose the extension of IFC model for incorporating embodied energy information in the IFC model.

4. METHODOLOGY

To achieve the first objective, an extensive review of the IFC model was conducted. Primarily the most external and loosely bonded reference of cost was located and then its lead was followed to understand the weaving of cost model into the IFC architecture. Once the connection of the entities underlying all the layers was established, a table was generated to list all the entities and types with respect to its layer and corresponding layer component.

Once the embedment of cost model was extracted from the IFC Model, the cost related entities and types were adopted and modified wherever necessary to propose new entities for embodied energy. Since, the availability of cost information is usually from an external source such as a pricelist of materials and products, and the availability of embodied energy information is also from an external source such a Life Cycle Inventory (LCI) database pivoted on material or product information, a stark similarity is encountered in the way both these models work. Therefore, with minimal changes new entities and types were proposed for the IFC extension and the existing entities fulfilling the purpose of both the models (cost and energy) were left unchanged.

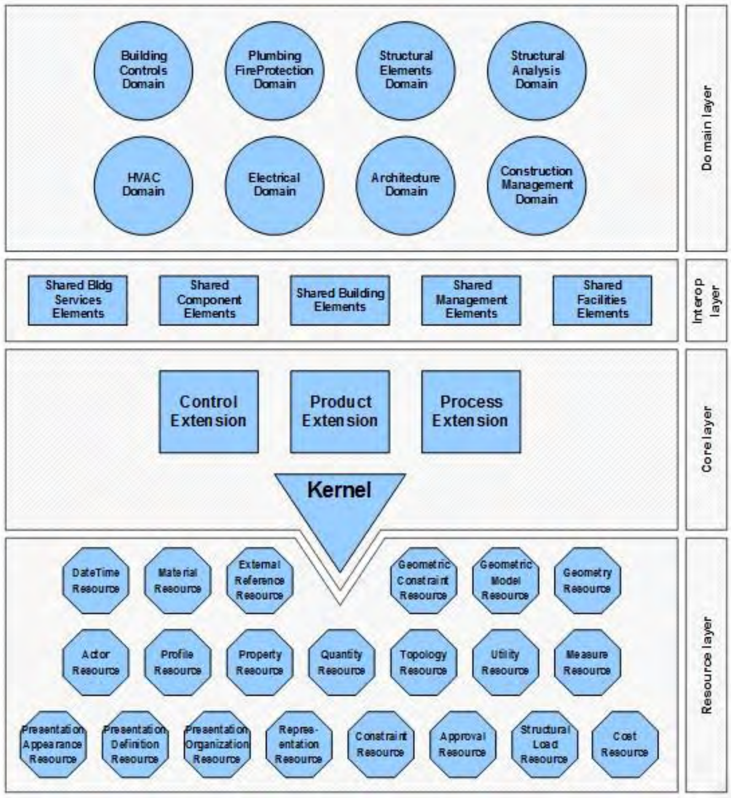

Figure 1. IFC data architecture schema with conceptual layers [15].

5. IMPLEMENTATION

The implementation of the proposed methodology starts with the review of the cost embedment in the current IFC4 model and then culminates in extending the IFC model for embedding the embodied energy information.

5.1 Cost Embedment in the IFC Model

Using a bottom-up approach for analyzing the IFC architecture (IFC4, b) primarily yields an independent *ifccostresource* which provides the basic schema to identify cost values. This *IfcCostValue* may be an absolute value or a multiplying factor for some other cost value. Usually this value is per unit quantity basis to be consistent with the prices available per unit quantity of an item. In this manner, the total cost can be calculated by combining a set of component values. This is achieved through the assertion of an applied value (*IfcAppliedValue*) relationship which acts as a container for applied value components. Apart from other text or numeric attributes, *IfcAppliedValue* class has two select attributes: *IfcAppliedValueSelect* and *IfcArithmeticOpertorEnum*. The *IfcAppliedValueSelect* constitutes of a combination of attributes while *IfcArithmeticOpertorEnum* is an enumeration of simple arithmetic operations such as add, divide, multiply and subtract. Another attribute of *IfcCostResource* is *IfcCurrencyRelationship* which deals with the exchange rate of currencies.

Moving up the hierarchal ladder of the IFC model, just above the Resource layer is the Core Layer. One of the schema of the core layer is the *IfcKernel*, which defines the most abstract part or core part of the specification. It captures general constructs, that are basically founded by their different semantic meaning in common understanding of an object model, like object, property and relationship. One of the object models of *IfcKernel* is *IfcControl*, which is the abstract generalization of all concepts that control or constrain the utilization of products, processes, or resources in general.

Two cost related instances are within the subset of *IfcConrol*: *IfcCostItem* and *IfcCostSchedule*. However, these entities lie within the shared management elements of the Interoperability Layer of the IFC architecture. The *IfcSharedMgmtElements* schema defines basic concepts that are common to management throughout the various stages of the building lifecycle. *IfcCostItem* is used for cost estimates, budgets, and other forms, where a variety of identification codes are used extensively to identify the meaning of the cost. To further clarify the context of *ifcCostItem*, an example is illustrated in the Figure 2.

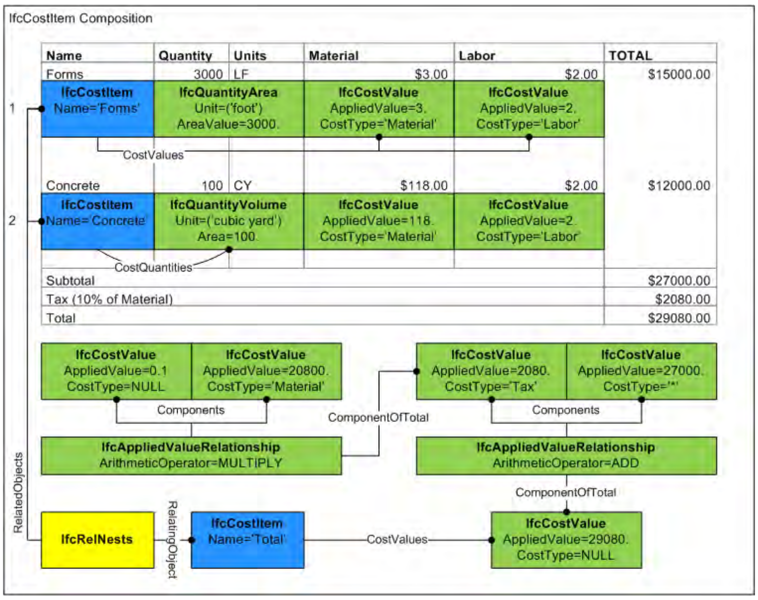

Figure 2. *IfcCostItem* Cost Composition (IFC4, c).

The previously discussed concept of *IfcCostValue* is used as a datatype for the value of *IfcCostItem*. *IfcRelNests* relationship is used to sum up the difference instances of *IfcCostItem* and retain the value in "Total" instance of the *IfcCostItem*. Moving on to the other cost related instance of *IfcControl, an IfcCostSchedule* consolidates the instances of *IfcCostItem* to generate estimates of constructions costs for various purposes. Apart from these entities, two cost related types also exist in the *IfcSharedMgmtElements*. These types are *IfcCostItemTypeEnum* (user defined or undefined type) and *IfcCostScheduleTypeEnum* (Budget, Tender, BOQ etc.).

The top most layer of IFC model, the domain layer constitutes of different domains such as Architecture, HVAC, Building Controls etc. The *IfcConstructionMgmtDomain* accounts for the costs incurred on the project due to different resources and these resources are represented by *IfcConstructionResource,* which is an abstract generalization of the different resources used in construction projects, mainly labor, material, equipment and product resources, plus subcontracted resources and aggregations such as a crew resource. *IfcConstructionResourceType* further determine the specialty of resource and provide classification related to the tasks it would be needed for.

Before summarizing the discussion of cost embedment in the IFC architecture, it is vital to elaborate another resource known as *IfcQuantityResource*. *IfcQuantityResource* defines a set of basic quantities that can be associated with products through the *IfcElementQuantity* (defined in *IfcProductExtension*). This *ifcElementQuanitiy* contains physical quantities such as Count, Length, Area, Volume, Time etc. To emphasize the importance of this resource, a diagram for cost assignment on elements is shown in the Figure 3.

To summarize the role of various layers and different components within these layers in embedding the cost information in the IFC architecture, a top down approach is employed. Table 1 shows the different layers of the IFC structure with the cost relevant components and the related IFC entities used to embed the cost information in the current IFC2X4 model.

5.2 Embodied Energy in the IFC Model

In the current IFC2X4 model, the embodied energy information is embedded as a property (*TotalPrimaryEnergyConsumption*) within a property set of *Pset_EnvironmentalImpactValues* lying in the core schema of *IfcProductExtension*. *IfcEnergyMeasure* is lowest level representation shared in the

IfcMeasureResource of the Resource Layer. To put things into perspective the other instances of *IfcMeasureResources* are *IfcForceMeasure*, *IfcAreaMeasure etc.* which are purely physical properties with no prospect of optimization or decision- making inputs in the larger context of a construction project. Interestingly, within the *IfcMeasureResource* there is a type of *IfcMonetaryMeasure,* which again is just a value with no relation with the above-mentioned concept of cost embedment elaborated in section 5.1.

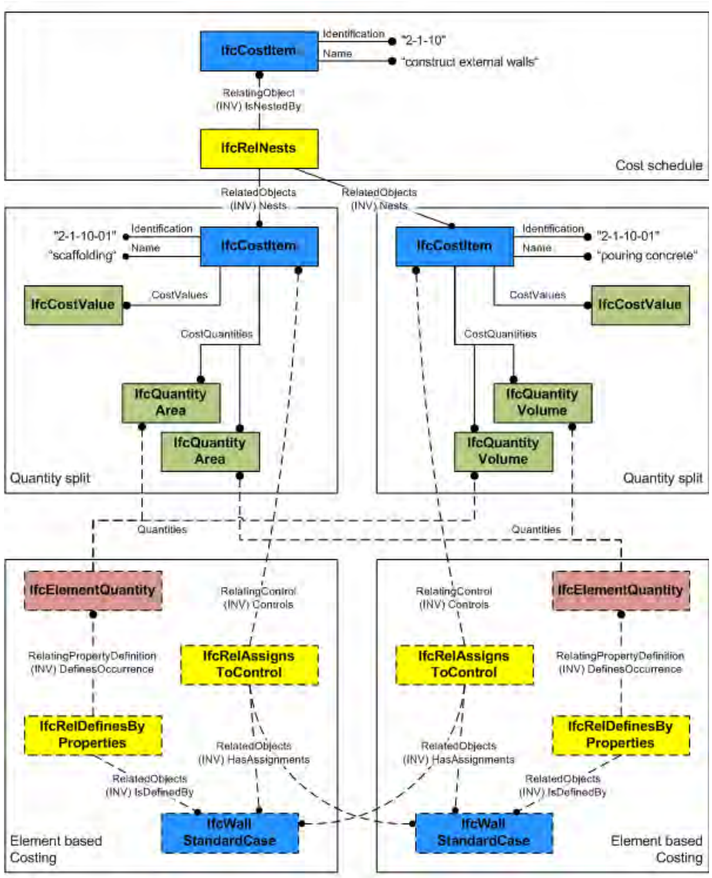

Figure 3. IFC Cost Assignment (IFC4, d)

Table 1 Summary of IFC cost embedment

IFC Layer	IFC Layer component	IFC Entity and Types
Domain Layer	*IfcConstructionMgmtDomain*	*IfcConstructionResource* *IfcConstructionResourceType*
Interoperability Layer	*IfcSharedMgmtElements*	*IfcCostSchedule* *IfcCostItem* *IfcCostItemTypeEnum* *IfcCostScheduleTypeEnum*
Core Layer	*IfcKernel*	*IfcControl*
Resource Layer	*IfcCostResource*	*IfcCostValue* *IfcCurrencyRelationship* *IfcArithmeticOperatorEnum* *IfcAppliedValueSelect*

5.3 Extension of IFC to Incorporate Embodied Energy Impact

Within the fundamental concepts of the IFC4 model, a concept of Resource Cost is defined as “Resources can have associated costs indicating financial costs and environmental impacts incurred according to a specified base quantity” (IFC4, e). However, this template is fully implemented only for the financial cost aspect throughout the breadth and width of the IFC model Nevertheless, this template paves way for integration of embodied energy concepts in the IFC model.

Looking at the lowest layer of the IFC Model in Table 1, an entity of *IfcCostValue* represents the basic unit of cost. A similar entity for energy with the name “*IfcEnergyValue*” is proposed to describe the fundamental energy unit. *IfcArithmaticOperatorEnum* remains same as with the cost concept, but the *IfcAppliedValue* is modified by removing the date time association as “time value of money” concept is not relevant in the context of energy. Also, the concept of *IfcCurrencyRelationship* is irrelevant in the current context. Figure 4 shows the Express-G diagram for this newly proposed entity of “*IfcEnergyValue*” under the new resource of “*IfcEnergyResource*”.

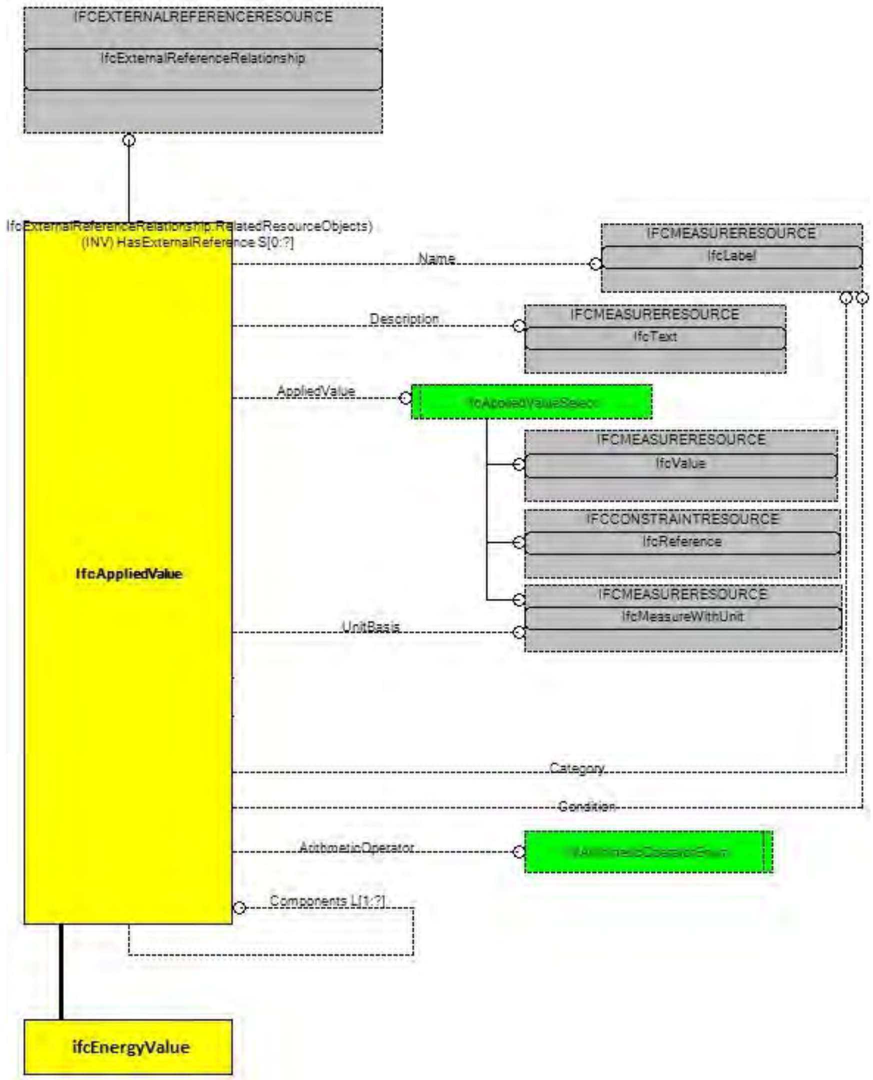

Figure 4. Express-G diagram of *IfcEnergyResource.*

The next layer is the Core Layer, with *IfcControl* entity. Since, energy controls or constraints the utilization of products, processes or resources; thus, fits well in the definition of *IfcControl*. Within the interoperability layer two new energy related entities are proposed: *IfcEnergyItem* and *IfcEnergySchedule.* Two new data types: *IfcEnergyItemTypeEnum IfcEnergyScheduleTypeEnum* are also proposed. The Express-G diagram for these newly proposed entities and types are shown in Figure 5.

The domain layer is the top most layer of the IFC schema. An extension in this domain is proposed to include

IfcEnergyResource as an optional attribute to account for the embodied energy impact of the construction resources. The Express-G diagram for the modified *IfcConstructionMgmtDomain* is shown in Figure 6.

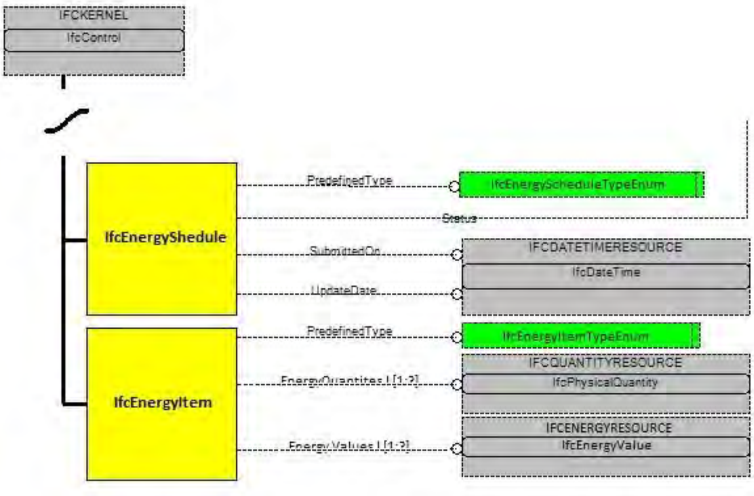

Figure 5. Express-G diagram for *IfcEnergySchedue* and *IfcEnergyItem*.

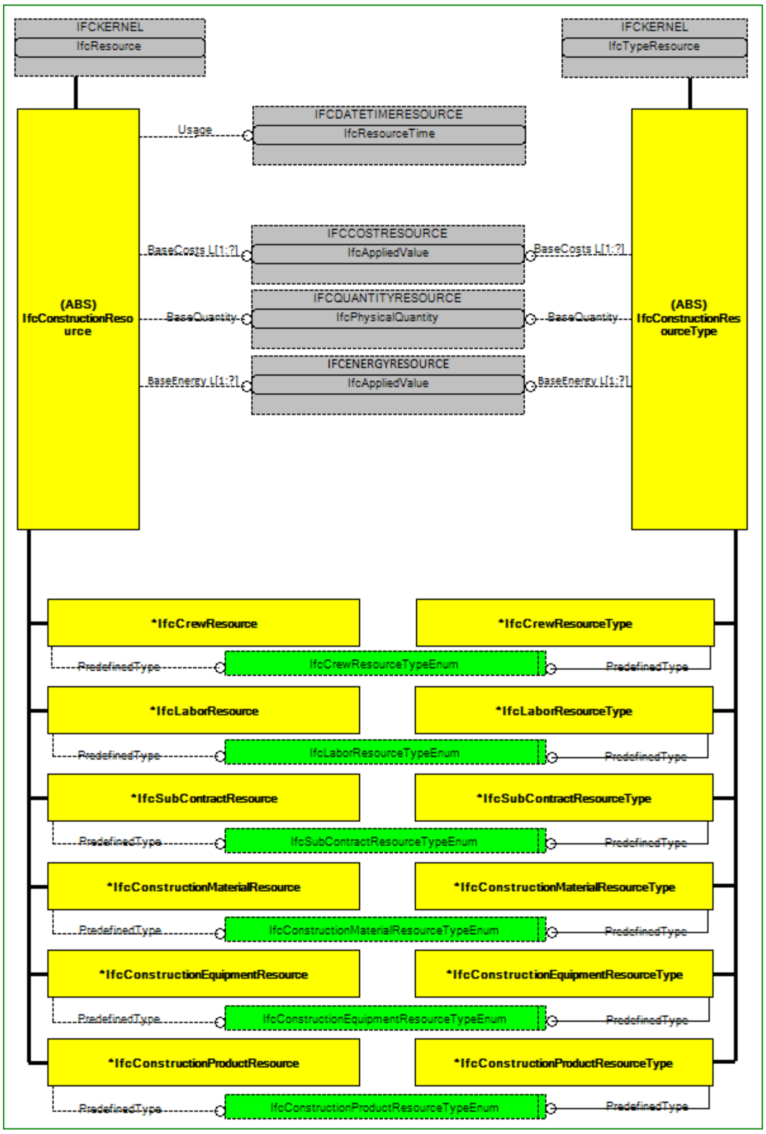

Figure 6. Express-G Diagram for the modified *IfcConstructionMgmtDomain*.

In this manner, the extension of the IFC model for incorporating the embodied energy impact is complete. The authors have already developed a plug-in for a BIM authoring tool to estimate the embodied energy of building products (Nizam and Zhang, 2018). The future step would be to map that embodied energy impact on this newly extended IFC Model and validate the data exchange with different BIM authoring tools.

6. CONCLUSION

Sustainability has become a high priority goal for construction projects. However, the availability of information to achieve and excel this goal is subjective and thus, incomprehensible for autonomous decision-making systems. This is in part due to the fact that the sustainability information is not quantified in an explicit manner or in some cases where this information is quantified, qualified and standard data management schemas fail to map this quantification. Therefore, this paper proposed an extension for the IFC standard to embed the embodied energy information in the IFC model. This was achieved by proposing a new resource "*IfcEnergyResource*" with a new data type "*IfcEnergyValue*". To assign this data type to different resources, two new shared management elements, "*IfcEnergyItem*" and "*IFCEnergySchedule*", are proposed. *IfcEnergyItem* hold the embodied energy impact of a material, while *IfcEnergySchedule* brings together different instance of *IfcEnergyItem*. The schema for *IfcConstuctionMgmtDomain* was also modified to embed the embodied energy information at the domain level so that it can be assigned to various resources abstracted by *IfcConstructionResource*. This extension will aid in bringing back the sustainability information in the BIM model from the LCA tools and restores the authenticity of the central BIM model as a knowledge base in the context of sustainability as well.

7. ACKNOWLEDGEMENT

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ESTIMATING NET COSTS OF IMPLEMENTING BIM AT DIFFERENT LOD – A NEURAL NETWORK APPROACH

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ABSTRACT: *Previous studies have focussed on evaluating Building Information Modelling (BIM) implementation performance through reporting case studies and assessing BIM model's maturity level. However, there is a lack of focus on predicting the benefits and costs of BIM implementation. This study aims to provide an ex-ante evaluation method to estimate the Net Costs of implementing BIM at different Level of Development (LOD) generically. An Artificial Neural Network (ANN) is used to predict the LOD that organisations are most likely to implement; this is then converted into the generic Net Costs of BIM implementation. Data used in ANN training was collected via a 7-point Likert scale questionnaire. Through examining the proposed method on a small sized infrastructure construction organisation, this study finds that implementing BIM at a higher LOD does not ensure more project savings. In the examined case study, the Net Costs of BIM implementation is quite sensitive to Adaptation Costs that have occurred during the BIM implementation.*

KEYWORDS: *Artificial Neural Network, BIM implementation net costs, ex-ante evaluation, Machine learning*

1. INTRODUCTION

Construction industry accounts for a large proportion of the national economy of many countries across the globe (Ruddock et al., 2006). As one of the key Information Technology (IT) developments in the construction industry, Building Information Modelling (BIM) has been gaining immense growth in its applications, particularly due to its potential capabilities in improving efficiency and minimising error (Eastman et al., 2011). Previous studies reported that integrating BIM in construction projects also can reduce overall project costs (Hammad et al., 2016) and improve real-time data management (Sun et al., 2015). This, however, does not mean that BIM implementation comes at no expense. Various challenges exist to its implementation, including interoperability issues (Haynes, 2009), lack of experienced technicians (Singh et al., 2015), and people's resistance in BIM adoption (Lu et al., 2012).

There are two types of evaluation methods adopted in the field of information technology system implementation; the first is referred to as ex-ante evaluation, while the second type is known as ex-post evaluation (Myrdal, 1939). Ex-ante (predictive) evaluation is performed to forecast and evaluate the impact of future situations on decision making, whereas ex-post evaluation assesses the value of existing situations on the decisions that are to be made (Remenyi et al., 2012). Ex-ante evaluation has been frequently used in assessing IT investment, including Enterprise Resource Planning (ERP) implementation (Stefanou, 2001) and social programs (Todd et al., 2008). In addition, ex-ante evaluation is frequently used in assessing Public-Private Partnership (PPP) projects from a macroeconomic perspectives (Liu et al., 2015). Ex-ante evaluation is an essential component in project preparation and initiation (i.e. objective definition) and project success evaluation (European Commission 2001). Ex-post evaluation of BIM implementation has been frequently reported via case studies, for example Kim et al. (2017) and Ham et al. (2018). However, there is a lack of ex-ante evaluation of BIM implementation.

Artificial Neural Network (ANN) can be considered as a type of information processing technology that simulates the human brain and the nervous system; it is commonly used to solve complex non-linear problems (Boussabaine, 1996). ANN has been attracting widespread interest in fields such as construction productivity estimation (Portas et al., 1997) and modelling the strength of high-performance concrete (Yeh, 1998). Because ANN can find a set of connection strengths and predict unknown data accurately (Rumelhart et al., 1994), this study uses ANN to predict the organisations' Level of Development (LOD) of BIM implementation. The LOD is defined as the detail level embedded in digital building models created via BIM. This paper aims to propose an ex-ante evaluation method for decision-makers to assess whether BIM should be adopted. Through using ANN as a prediction tool, a generic approach is derived to conduct cost-benefit analysis of BIM implementation. In addition, a sensitivity analysis is carried out to enable decision-makers to find which type of *Implementation Benefits* and/or *Implementation Costs* need to be addressed, in order to reduce the *Net Costs* associated with BIM implementation. Given the high expenses of BIM implementation and the low Return on Investment (ROI), the ex-ante evaluation method developed in this study can assist decision-makers to decide whether BIM implementation is profitable and at which LOD should BIM be implemented.

This paper is organised as follows: Section 2 categorises BIM implementation benefits and costs via an extensive literature review. This is followed by a methodology section which describes the analysis methods used in this study and data collection approach. Next, a case study is presented to test the proposed ex-ante evaluation method. A sensitivity analysis is then performed to find the sensitive factor of BIM implementation *Net Costs*. Concluding remarks are presented at the end.

2. CATEGORISING BIM IMPLEMENTATION BENEFITS AND COSTS

Benefits associated with BIM implementation are considered as one of the main motivations for many Architectural, Engineering and Construction (AEC) companies to adopt BIM (Xu et al., 2014; Doumbouya et al., 2016). The costs of BIM implementation however hinder BIM adoption (Li et al., 2017). Therefore, this study evaluates *Net Costs (Implementation Costs minus Implementation Benefits)* associated with BIM implementation, through evaluation of *Implementation Benefits* and *Implementation Costs*.

According to the available literature, benefits of BIM implementation could be categorised into two areas: *Productivity Improvements* and *Intangible Improvements*. “Productivity” is the amount of goods and services produced by a productive factor in a unit of time, which could be improved through improving construction planning and scheduling, site supervision and engineering design (Arditi, 1985). The most frequently mentioned *Productivity Improvements* associated with BIM implementation include cost reduction and time reduction (Cain, 2003; Eastman et al., 2011). In addition, it is believed that BIM usage could improve project information management, in particular, the data accuracy (Azhar, 2011). Moreover, the implementation of information technology is often associated with intangible benefits, which are difficult to be quantified in monetary values (Murphy et al., 2002). Differing than the tangible benefits which directly affect the company’s profitability (Remenyi et al., 1993), intangible benefits impact the company’s profitability indirectly. Improving project participants’ collaboration has been categorised as the most beneficial *Intangible Improvement* of BIM implementation (Aibinu et al., 2013; Hanna et al., 2013). There are other *Intangible Improvements* that can not be neglected when considering BIM implementation, including streamlined external information flow among project stakeholders (Aranda-Mena et al., 2009; Lu et al., 2010), and improved external relationships with other project participants (Poirier et al., 2015).

Although the benefits of BIM implementation are quite attractive, the costs for implementing BIM may hinder many AEC companies from adopting BIM. According to existing studies, there are 3 main types of *Implementation Costs* that have been reported frequently; these include *Training Costs*, *Installation and Maintenance Costs*, *Adaptation Costs*. *Training Costs* are important during BIM implementation because technology complexity would significantly affect technology adoption (Rogers, 2003; Ding et al., 2012). In addition, training staff from novice to intermediate or to a more advanced level is one of the major investments of BIM users in the short-term (Hanna et al., 2013). *Installation and Maintenance Costs* is one of the major costs in BIM implementation, which include license purchasing fees, costs of hardware and software upgrading, and ongoing maintenance fee (Allen Consulting Group 2010). Since BIM implementation relates to several subsequent matters including suitability and interoperability, the availability of technical support during BIM implementation is critical (Poirier et al., 2015). *Adaptation Costs* is considered as a type of indirect cost or loss of income in this study, which is most frequently reported to occur at the very early stage of BIM implementation. The occurrence of adaptation costs are caused by the change of workflow, learning curve’s influences, and people’s psychological resistance (Lu et al., 2012).

This study uses the categorised BIM implementation benefits and costs as proxies to measure the generic *Net Costs* associated with BIM implementation. The following section explains how these proxies produce the generic *Net Costs*.

3. METHODOLOGY

This study adopts ANN to predict an organisation’s selection of LOD to use when implementing BIM. Selection of the LOD to adopt can be formulated as a multi-class classification problem which assigns an instance with a single label from a set of disjoint labels (Trohidis et al., 2008). There are different versions in defining LOD, for example, Level of Details (The American Institute of Architect 2007) and Level of Development (British Standards Institution 2013). This study uses unsupervised clustering learning – k-Means analysis to determine organisations’ LOD, rather than asking respondents from different parts of the world where LOD terminology slightly differ, to identify their organisations’ LOD. In addition, it is known that k-Means analysis is a simple to implement partitional algorithm, that can converge to the local optima efficiently (Jain, 2010). This section starts with an overview of ANN, followed by the data collection and preparation process. Two assumptions related to producing *Net Costs* are presented in subsection 3.3, followed by a k-Means analysis to identify organisations' LOD. Table 1 summarises the notations involved in this study.

Table 1 List of Notations

Notation	Description	Dimension
x_j	Input unit(s), $j = 0,1,\dots,J$, with x_0 being the bias unit in the input layer	$J \times 1$
$\bar{x}_j$	The average value of input unit(s)	1×1
z_h	Hidden units, $h = 0,1,\dots,H$, z_0 is the bias unit in the hidden layer	$H \times 1$
Y_i	True (known) label of output unit(s), $i = 0,1,\dots,I$	$I \times 1$
$\hat{Y}_i$	Predicted (unknown) label of output unit(s), $i = 0,1,\dots,I$	$I \times 1$
$p(x_j)$	Predicted value of output unit(s)	$I \times 1$
w_{hj}	Weights in the first layer	$H \times J$
v_{ih}	Weights in the second layer	$I \times H$
$s(x_j)$	Threshold value in multi-class classification obtained from softmax function	$I \times J$
$r(x_j)$	Units of costs of instance $x_j$in LOD selection	$I \times 1$
$J(\theta)$	Value of cost function in k-Means	1×1
k	Number of clusters in k-Means	1×1
β	Scale of change in sensitivity analysis	1×1

3.1 Overview of ANN

This subsection aims to provide an overview on how ANN is used to predict an organisation's BIM implementation LOD. The key elements comprising an ANN include input units (x_j), hidden units (z_h), output units (Y_i), weights (w_{hj}, v_{ih}), and the activation function (Alpaydin, 2014; Boussabaine, 1996). A bias unit (x_0) is added to each pre-output layer, to increase the flexibility of an ANN (Rumelhart et al., 1994). This study used the tanh function as the activation function, which converges quicker when compared with the sigmoid function (Molas et al., 1995). The training process of an ANN includes two essential steps, namely forward propagation and backpropagation. Forward propagation aims to calculate the value of output units ($p(x_j)$) based on known input units (x_j) and randomly generated weights (w_{hj}, v_{ih}); while, , backpropagation, utilised in this study, carries the error from output units back to input units; the method minimises the total errors via Stochastic Gradient Descent (SGD) and in response the weights of the network are updated (w_{hj}, v_{ih}) (Rumelhart et al., 1986). Eq. (1) and Eq. (2) shows the calculation process of forward propagation:

$$z_h = x_j \times w_{hj} + x_0 \qquad \text{Eq. (1)}$$

$$p(x_j) = \tanh(z_h) \times v_{ih} + z_0 \qquad \text{Eq. (2)}$$

Richard et al. (1991) proved that the predicted value ($p(x_j)$) of an ANN trained with backpropagation and SGD can be considered as a posterior probability. So far, the well-trained ANN can produce the probability of an instance (organisation) to implement BIM at each LOD. However, this study aims to find the LOD that an instance (organisation) is most likely to implement. Therefore, softmax function is used in the final layer of ANN to find the instance's (organisation's) class from all 4 classes considered (i.e. LOD 200, LOD 300, LOD 350, LOD 400), because the outputs of softmax function represent a valid probability distribution (Mikolov et al., 2011). By feeding the output units ($p(x_j)$) into softmax function, the maximum value of $s(x_j)$ will be assigned with a positive label (Alpaydin, 2014).

3.2 Data Collection and ANN Tuning

Data used in this study were collected using a 7-point Likert scale questionnaire. The collected numbers of the 7-point scale were the source of neural network input. Research participants were asked to select a single number that best characterises their opinion/experience with regards to potential influencing factors related to BIM adoption (from 1 = strongly disagree to 7 = strongly agree). The following criteria relating to the involved participants were ensured: 1) they must have at least 5 years of work experience in the construction industry; 2) they must have some basic BIM knowledge. A total of 307 research participants were involved in this survey, where 62% are contractors, 19% are engineers, 18% are architects, and 1% are consultants. As a priori step, data preparation is important in ANN analysis. The collected data were separated into 3 datasets – train set, validation set, and test set. Since ANN is quite sensitive to data input (Rafiq et al., 2001), the collected data in 7-point scale needs to be normalised before feeding it into a neural network. To achieve an optimal ANN structure, this study used a constructive approach, which starts with a small structure and adds units/layers gradually to improve the

ANN performance (Alpaydin, 2014). The tuning process, as summarised in Figure 1, stops when the validation loss from validation set reaches minimum. Table 2 summarises the ANN characteristics of each type of *Implementation Costs/Benefits*.

Table 2 ANN characteristics of *Implementation Costs* & *Benefits*

	Productivity Improvements	*Intangible Improvements*	*Training Costs*	*Installation and Maintenance Costs*	*Adaptation Costs*
ANN structure	5-11-11-4	2-24-24-24-4	4-22-22-22-4	6-17-17-4	4-23-23-23-4
Cost function	Cross-entropy	Cross-entropy	Cross-entropy	Cross-entropy	Cross-entropy
Train loss (train set)	0.973	0.910	0.793	0.701	0.996
Validation loss (validation set)	1.319	0.923	0.717	0.791	1.177
Binary test accuracy (test set)	66.5%	76.0%	68.5%	72.5%	72.5%
Note: a '5-11-11-4' ANN structure refers to an ANN with 5 input units, two hidden layers with 11 hidden units in each, and 4 output units.					

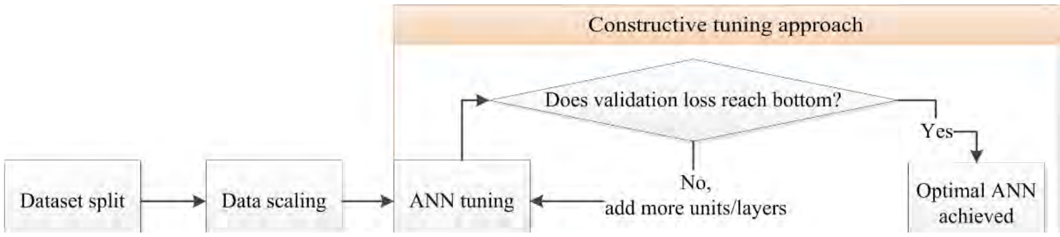

Figure 1 ANN tuning process

3.3 Assumptions

Since the ANN outputs cannot be interpreted as the generic costs of BIM implementation, several assumptions need to be made to convert the ANN outputs into the generic *Net Costs* of BIM implementation.

Assumption 1: As highlighted in subsection 3.1, the output of an ANN trained with backpropagation and SGD can be considered as the posterior probability (Richard et al., 1991). Therefore, this study assumes that the lower the costs (the higher the improvements) associated with BIM implementation, the higher the possibility that the organisation will implement BIM at a higher LOD.

Assumption 2: Given the inputs of trained ANN have been normalised, this study uses the average value of normalised inputs ($\overline{x_j}$) to determine whether the organisation finds it more/less challenging to invest in adopting BIM. If $\overline{x_j} > 0$, the selected organisation experiences greater challenges in *Adaptation Costs* compared to other types of costs (i.e. *Training Costs*), when contrasted against other industrial counterparts. Consequently, more costs to the organisation would occur.

Training Costs, *Installation and Maintenance Costs*, *Intangible Improvements*, and *Productivity Improvements* associated with LOD level implementation ($r(x_j)$) are expressed as follows, Eq. (3):

$$r(x_j) = [p(x_j) - s(x_j)] \times (-\overline{x_j}) \times 10 \qquad \text{Eq. (3)}$$

Adaptation Costs associated with LOD level implementation $r(x_j)$ are expressed as follows, Eq. (4):

$$r(x_j) = [p(x_j) - s(x_j)] \times (\overline{x_j}) \times 10 \qquad \text{Eq. (4)}$$

3.4 k-Means

As highlighted earlier, this study used k-Means analysis to determine organisation's LOD, to reduce the effects of respondents' misunderstanding of LOD (as it may differ across regions). The process of k-Means analysis can be summarised into three steps: **Step 1**, reviewing different versions of LOD definitions and identifying relevant features by using domain knowledge. **Step 2**, feeding the collected data and features into k-Means model and determining number of clusters k. **Step 3**, matching a level of development to a cluster by using domain knowledge. This study adheres to the LOD definitions proposed by British Standards Institution (2013) and Table 3 summarises the definition of LOD.

Table 3 LOD definitions (source: British Standards Institution (2013))

LOD	Definition

LOD 100	The Model Element may be graphically represented in the Model with a symbol or other generic representation but does not satisfy the requirements for LOD 200.
LOD 200	The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation.
LOD 300	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation.
LOD 350	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems.
LOD 400	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation with detailing, fabrication, assembly, and installation information.
LOD 500	The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation.

Through reviewing the definition of LOD, it is found that the key elements in determining LOD include the purpose to use BIM (i.e. as a modelling software) and the functionality of geometric information contained in BIM models. Therefore, this study assesses LOD of BIM implementation among BIM users by using 9 features, summarised in Table 4.

Table 4 Features used in k-Means

Features		Data type
F1	The implementation of procurement management	Boolean (0 = False, 1 = True)
F2	The implementation of facility management	Boolean
F3	The implementation of lifecycle maintenance	Boolean
F4	The implementation of 3D visualisation	Boolean
F5	The implementation of quantity take-off	Boolean
F6	The implementation of cost estimation and control	Boolean
F7	The implementation of clash detection	Boolean
F8	Willingness to integrate BIM for project communication purpose	Ordinal (from 1 = extremely unwillingly to 7 = extremely willingly)
F9	Organisation's understanding towards BIM	Nominal (1 = BIM is a 2D drafting tool; 2 = BIM is a 3D/4D modelling software; 3 = BIM is a database that stores project data; 4 = BIM can be used to manage building design throughout the lifecycle; 5 = BIM is a digital representation of the facility)

After identifying the inputs of k-Means analysis, the following step is choosing the reasonable numbers of clusters (k). This study used the oldest method – the elbow method - to determine k. In the elbow method, the moment when the cost function value $J(\theta)$ drops dramatically and reaches plateau afterwards indicates that the ideal k is reached (Kodinariya et al., 2013). Figure 2 presents the relationship between $J(\theta)$ and k. According to elbow method, four clusters are sufficient in this study.

Figure 2 Determining number of clusters (k)

Since k-Means analysis is classified as unsupervised learning, the analysis results do not directly refer to a specific LOD. Therefore, domain knowledge was involved to assign a LOD to each cluster. This study analysed and compared the mean and median values of features used in k-Means analysis to allocate a specific LOD level to a cluster (Table 5). As shown in Table 4, F1 to F7 are Boolean variables, while F8 and F9 are nominal/ordinal variables. Therefore, Table 5 observes the mean value of F1 to F7 and median value of F8 and F9. Cluster K1 has stronger preferences in implementing procurement management, facility management, lifecycle maintenance, and cost estimation and cost control than other clusters. Therefore, cluster K1 refers to the highest LOD level among these 4 clusters. In addition, cluster K2 does not have much interest in integrating BIM for project communication purposes; consequently, cluster K2 is labelled as LOD 200. Given the mean and median values of k-Means inputs, this study assigns LOD 300 to Cluster K0, LOD 400 to Cluster K1, LOD 200 to Cluster K2, and LOD 350 to Cluster K3.

Table 5 Mean and median values of features in different clusters

Features		Cluster K0	Cluster K1	Cluster K2	Cluster K3
F1 – mean	The implementation of procurement management	0.07	0.15	0.04	0.08
F2 – mean	The implementation of facility management	0.12	0.35	0.18	0.17
F3 – mean	The implementation of lifecycle maintenance	0.18	0.21	0.11	0.18
F4 – mean	The implementation of 3D visualisation	0.73	0.66	0.75	0.52
F5 – mean	The implementation of quantity take-off	0.45	0.58	0.57	0.45
F6 – mean	The implementation of cost estimation and control	0.29	0.60	0.39	0.33
F7 – mean	The implementation of clash detection	0.20	0.43	0.57	0.32
F8 – median	Willingness to integrate BIM for project communication purpose	6	5	1	5
F9 – median	Organisation's understanding towards BIM	3	5	3	2
Assigned LOD		***LOD 300***	***LOD 400***	***LOD 200***	***LOD 350***

4. CASE STUDY AND SENSITIVITY ANALYSIS

The case study examined in this study is a Grade 3 infrastructure organisation located in China, which has been implementing 3D visualisation at LOD 350 for 2 – 5 years. Around 30% of projects are involved with BIM integration. The case study's responses to questionnaire is presented in Appendix. This section starts with the prediction of ANN and the estimation of BIM implementation *Net Costs* based on Assumption 1-2.

4.1 ANN prediction

Table 6 summarises the *Implementation Costs* and *Benefits* for the case study to implement BIM at different LOD. As presented in Table 6, implementing BIM at LOD 300 is the most beneficial choice for the case study in terms of *Productivity Improvements* (2.98) and *Intangible Improvements* (1.13). While LOD 400 appears to be the most economical choice when it comes to *Training Costs* and *Installation and Maintenance Costs* (both 0). The *Adaptation Costs* associated with BIM implementation at any LOD are no greater than 0, which suggests that BIM implementation would not pose any temporary threats to projects, for example, project schedule delay due to lack of BIM experience. The *Net Costs* of BIM implementation suggest that implementing BIM at LOD 300 could maximise the organisation's benefits, followed by LOD 350. The results indicate that a higher level of LOD does not guarantee more benefits.

Table 6 Units of Costs in LOD Selection – Infrastructure Case Study

	Productivity Improvements	*Intangible Improvements*	*Training Costs*	*Installation and Maintenance Costs*	*Adaptation Costs*	*Net Costs*
LOD 200	1.87	0.43	1.25	2.32	0.00	1.27
LOD 300	2.98	1.13	0.53	1.34	-4.67	-6.91
LOD 350	0.00	0.76	0.61	0.53	-5.94	-5.56
LOD 400	1.46	0.00	0.00	0.00	-0.44	-1.9

4.2 Single Factor Sensitivity Analysis

This study conducted a sensitivity analysis with scale of change at 30% and 50%, to find which type of cost has the most significant impact on the *Net Costs*. It is believed that if respondent's feedbacks about BIM implementation (i.e. perceived *Productivity Improvements*) would directly affect the estimation of BIM implementation *Net Costs*. Therefore, in the sensitivity analysis, source of changes is respondent's answers to the questionnaire. This study presents the sensitivity analysis results of implementing BIM at LOD 300 and LOD 350, since LOD 300 and LOD 350 are the predicted and actual implemented level in this case study, respectively.

Figure 3 summarises the impact of *Implementation Benefits* (*Intangible Improvements* and *Productivity Improvements*) changes on the *Net Costs* associated with LOD implementation. When the case study is perceiving more *Productivity Improvements* (β increase), the *Net Costs* of implementing LOD 300 would increase, but the *Net Costs* of implementing LOD 350 would decrease. Hence, in order to minimise the *Net Costs*, an organisation is suggested to move to a higher LOD, if the organisation aims to maximise the *Productivity Improvements* associated with BIM. When the case study is perceiving more *Intangible Improvements* (β increase), the *Net Costs* of implementing LOD 350 would increase, while, the *Net Costs* of implementing LOD 300 would decrease at the beginning and increase later. Compared with *Productivity Improvements*, improving *Intangible Improvements* does not necessarily require a higher LOD.

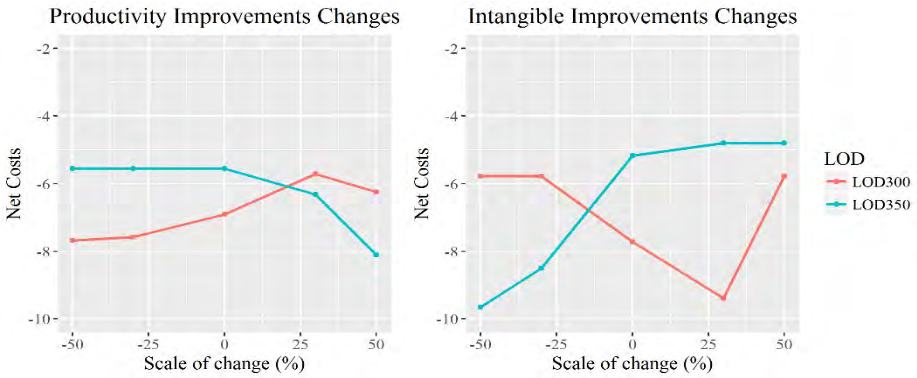

Figure 3 Impact of Implementation Benefits Changes on Net Costs of LOD Implementation

Figure 4 summarises the impact of *Implementation Costs* changes on the *Net Costs* associated with LOD implementation. The *Net Costs* of implementing BIM at LOD 350 will increase if the case study reports more investments in *Training Costs* and *Adaptation Costs* (β increase), and less expenses in *Installation and Maintenance Costs* (β decrease). On the other hand, the *Net Costs* of implementing BIM at LOD 300 will increase, if the case study experiences more investments in *Installation and Maintenance Costs* and *Adaptation Costs* (β increase), and less expenses in *Training Costs* (β decrease). Since the slopes of LOD 300 and LOD 350 related to *Adaptation Costs* in Figure 4 are steeper than others, *Net Costs* of BIM implementation is most sensitive to *Adaptation Costs* if the case study implements BIM at LOD 300 and LOD 350. Thus, in this case study, *Adaptation Costs* always need additional attentions, regardless of the BIM implementation LOD.

Figure 4 Impact of *Implementation Costs* Changes on *Net Costs* of LOD Implementation

5. DISCUSSION AND CONCLUSION

An ex-ante evaluation method was proposed in this study to assist organisations in estimating the costs and benefits to implement BIM at different LOD. Collected data was trained using ANN to predict the LOD level that was likely to be implemented by the organisations. Following that, a case study (a small infrastructure construction organisation) was selected to test the performance of the trained ANN. The examined case study had implemented BIM at LOD 350. Although the *Net Costs* of the current implementation level (LOD 350) is beneficial, the results suggest that LOD 300 is more economical. As a result, implementing BIM at a higher LOD does not secure more benefits. Results of a sensitivity analysis conducted indicate that BIM implementation *Net Costs* is quite sensitive to *Adaptation Costs* in the examined case study. Therefore, the organisation is suggested to pay more attention in change management during BIM implementation.

This study aims to provide decision makers a predictive tool to evaluate which LOD is more suitable to be implemented. The proposed method is practical, since it has reliance on the availability of project data. Future studies aim to design an embedded method (i.e. self-organising map) to embed the clustering of LOD with ANN prediction. Meanwhile, the accuracy of ANN prediction can be improved in the future by incorporating feature selection techniques (i.e. chi-squared test and decision tree), in order to improve the relevance of ANN's input features.

APPENDIX – CASE STUDY'S RESPONSES TO THE QUESTIONNAIRE

Question	Response
Productivity improvements	
BIM adoption reduces the project's overall costs.	4
BIM adoption reduces the project duration.	5
BIM improves project information management.	5
BIM improves stakeholders' understanding of the project scope.	4
Using BIM reduces conflicts in the project	4
Intangible improvements	
The decision of adopting BIM is/was strongly affected by building competitive advantage over other competitors.	6
The decision of adopting BIM is/was strongly affected by the need to streamline organisation's management process.	5
BIM improves project collaboration among participants.	5
Training costs	
No or little additional knowledge/training is invested to implement BIM in the organisation.	4
Costs and efforts required to link information from other sources are insignificant.	4
Costs and efforts required to create, annotate, and refine project documentation via BIM are insignificant.	4
The organisation will provide/provides proper training to staff before implementing BIM.	6
Installation and maintenance costs	
Costs and efforts required to upgrade BIM operation hardware are insignificant.	5
BIM implementation requires high investing expenses.	4
Professional guidance is/was available to the organisation in the selection of BIM tools.	6
Costs and efforts required to maintain BIM models are insignificant.	4
Costs and efforts required to maintain BIM central files are insignificant.	5
A specific technical centre (or a technician) is/was available for assistance with BIM implementation.	6
Adaptation costs	
BIM implementation is associated with the increasing of project cost, due to workflow changes;	2
The use of BIM gives rise to project communication issues with other project participants	4
The use of BIM brings about project schedule delays due to lack of experience in using BIM	2
The use of BIM reduces working efficiency temporarily due to people's resistance to change	4

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MONITORING DESIGN PRODUCTIVITY THROUGH PROCESS MINING OF BIM LOG DATA

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ABSTRACT: *Despite substantial investments in Virtual Design and Construction (VDC) technologies, the Architecture, Engineering, and Construction (AEC) industry have not improved productivity as much as other industries, such as manufacturing. The ultimate goal of this research is to improve understanding of the design process for the AEC industry to enable improvements in design productivity. The research objective of this paper is to test the individual preferences of designers in the execution of design tasks and explain the variability in design productivity. The research capitalizes on large volumes of data available in the event logs of computer programs used by designers from numerous disciplines to create building information models. We will connect the disciplines of design management and data analytics to take advantage of the fine-grained, objective and cost-effective data provided in electronic design logs. This research departs from the existing design productivity assessment methods that rely heavily on the manual collection of data, non-verifiable presumptions about the design process and often a narrowed view to analyze productivity data. This is the first attempt to reveal the relationship between the productivity and execution patterns of an individual designer using fine-grained, objective and cost-effective data captured non-intrusively from the actual design process.*

KEYWORDS: *BIM Logs; Process Mining; Design Productivity; Social Network Analysis*

1. INTRODUCTION

Good design is central to enhancing customer experience, improving product functionality, and increasing project quality (Oh et al., 2015; Vibæk, 2014). It provides significant opportunities for productivity improvement and time and cost savings in capital projects. Given the fact that design projects become larger and more complicated, BIM, as a new digital revolution in the AEC industry, provides a collaborative platform to facilitate information exchange and sharing among various specialty design participants for better decision-making (Zhang et al., 2016). However, successful collaboration does not emerge by accident, but rather as a result of a managed process that involves several participants from different disciplines and backgrounds (Homayouni et al., 2010). Several studies have shown that poor management of design process is the primary cause for rework in construction projects (Becker et al., 2013; Park et al., 2013). This problem is rooted in the lack of understanding about the complexities of the design process and how it influences design productivity. The significance of this research lies in (1) It extracts novel design productivity knowledge from cost-effective data sources that are produced as the by-product of the design process; (2) Better understanding of the dynamics of the design process can create long-lasting positive impacts on an industry which has traditionally suffered from chronic productivity problems.

Despite substantial investments in Virtual Design and Construction (VDC) technologies, the AEC industry has not improved productivity as much as other industries, such as manufacturing (Iwamoto, 2018). Design errors and omissions and poor design performance are major reasons for growing project costs, delays in project delivery, and low-quality project outcomes (Love et al., 2014; Simpeh et al., 2015). While the design phase typically accounts for about 5 to 10 percent of the total project cost (Tizani, 2011), rectifying conflicts resulting from faulty design decisions accounts for an additional 5.1 to 7.6 percent of the total project cost (Lee and Peña-Mora, 2016). To the state of the practice, this research contributes to providing insight into the design process through a better understanding of relationships between network characteristics and production performance of designers for enhancing productivity. The new knowledge created by this research include (1) a new non-intrusive data collection approach to monitor, measure, and analyze design productivity; (2) a novel data-driven modelling methodology of perceiving collaborations among designers to discover social networks; and (3) an intelligent model for productivity measurement, prediction, and benchmark.

2. STATE OF THE ART

Collaboration in design is essential for project success but the circulation of incomplete and erroneous information among project stakeholders makes design issues inevitable (Ren et al., 2013). Availability of comprehensive information from all disciplines, as well as learning from past projects is necessary for project managers to anticipate problems in design development and take corrective actions in a timely manner (White et al., 2005).

Early research in collaborative design management was usually qualitative in nature and often based on a single project (Emmitt and Ruikar, 2013). Complex Networks Research aims to better understand collaboration in organizations (Gao et al., 2016) and shed light on its decision-making process (Ruths and Ruths, 2014). In today's electronically connected world, executing work processes commonly leaves behind historical traces that can be stored in several electronic formats. There are promising opportunities to use emerging data acquisition methods to capture the information required to model and analyze complex social networks. This departs from recent research by investigating the possibility of extracting data on inter-organizational collaborations and social networks from design log data in BIM applications.

Social network mining is the main approach the field has adopted to identify and analyze relationships, social roles and social structures in collaborative organizations (Scott, 2017; Van Noorden, 2014). It can be used to create a sociogram from information embedded in event logs and determine relations among a large number of performers acting in the process (De Leoni et al., 2016). We will capitalize on the availability of event log data for items such as login accounts, timestamps and comment flows in these design applications. More specifically, we will explore the social context of design processes based on large event logs. A better understanding of social networks could reveal a misalignment between the information system and its users, and thus, provide insight into increasing efficiency and effectiveness of processes and organizations.

3. METHODOLOGY

This research attempts to use tremendous volumes of design logs as a non-intrusive data collection approach to capture human-computer and human-human interactions and investigate linkages between process behaviors and productivity for new knowledge discovery in BIM collaborative design. Fig. 1 illustrates the overall framework of the proposed approach, which consists of three main modules, as elaborated as follows:

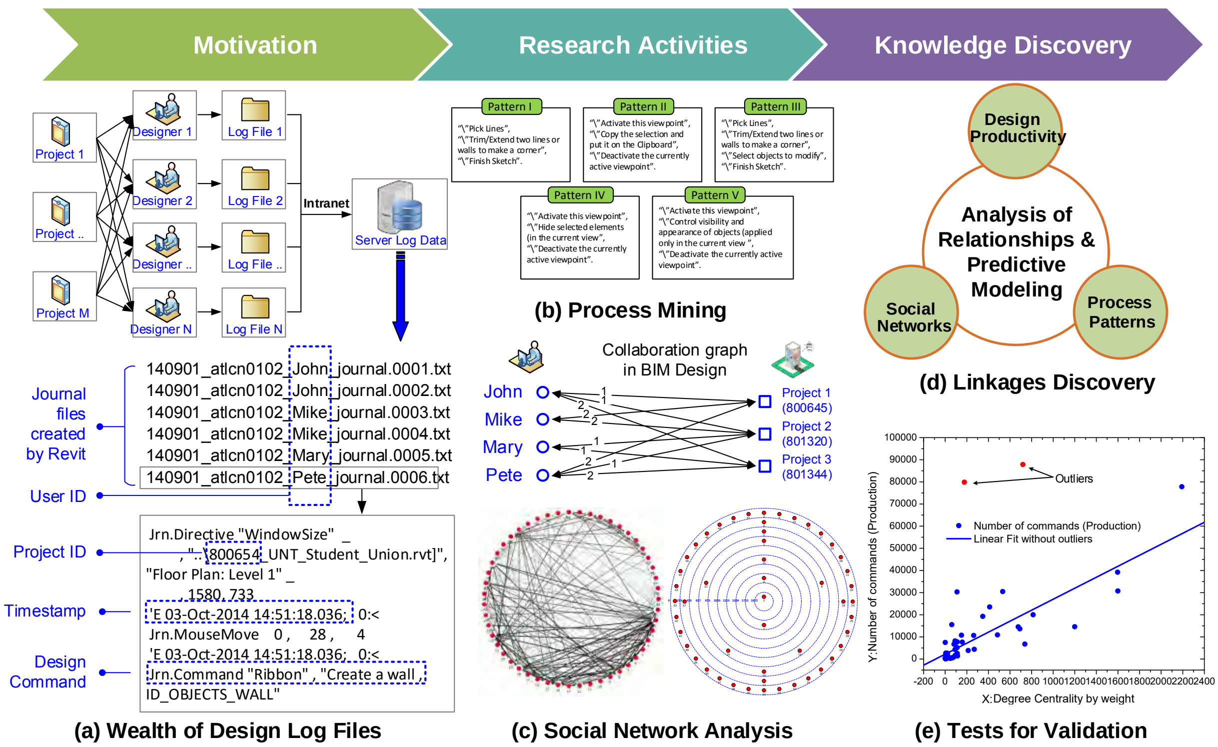

Fig. 1. Overall framework of the proposed approach.

(1) Data collection and process mining

We are planning to create a database of design logs of a substantially large number of designers working on multiple projects. Fig. 1 (a) shows a workflow of the data organization and processing. Statistical tests will be conducted to ensure the statistical significance of findings. We are familiar with the data collection challenges through our successful preliminary work in Zhang et al. (2018).

We will use pattern mining (Aggarwal and Han, 2014) as a means of understanding characteristics of the design process as followed by individual designers in the execution of various design tasks. Frequent pattern mining is a means of retrieving sequential patterns in a text dataset (Aggarwal and Han, 2014). The focus of the pattern discovery will be on user operations identified as design commands. The goal is to identify command sequences that appear repeatedly in the log dataset. One of the challenges with pattern mining is to establish a set of context-driven assumptions to assure the identification of meaningful patterns. For instance, we need to assume that a pattern does not cross the boundary of multiple sessions. Each design command is treated as an independent event. In order to establish these context-driven assumptions, we will use methods such as model-based reasoning (Mislevy et al., 2017), which have been proven to be helpful to retrieve and represent assumptions in similar contexts.

A Patricia tree (PAT) algorithm will be applied to retrieving all possible sequences and their respective frequencies from the design log dataset. Before applying the PAT tree on the BIM log dataset to extract patterns, each design command will be mapped into a unique non-zero number. The number of occurrences of each node will be tracked in the constructed PAT tree. The identified patterns will be classified based on pattern length and placed in a descending order according to the number of times that they appear in the design log dataset. The proposed pattern analysis algorithms will be applied to the entire design log database to identify the most frequently used patterns of commands among all the designers. The algorithm will also be applied at the level of individual designers to identify the most frequently used patterns individually, which are interpreted as designer’s preferences. Fig. 1 (b) shows an example of the mined design patterns from event logs. The results will be compared to explore how designers differ when executing the most common patterns of commands (which are interpreted as designers’ preferences). These differences will be explored further to establish links between the preferences of designers in executing commands and design productivity.

(2) Social network modeling and analysis

Social network modeling will be conducted to measure and analyze structural characteristics of the discovered BIM-based collaborative network at macro, meso, and micro levels. It develops a weighted sociogram (P, R, W) representing relations among multiple performers (Scott, 2017). Three components, performers, relations, and weights of relations, will be used to identify a social network in BIM design. Fig. 1 (c) shows an example. Social Network Analysis (SNA) will be applied on the developed sociogram to investigate the design network structure configuration at the following three levels:

1) SNA at Macro-level: Research at the macro-level aims to analyze and measure characteristics of the entire network found in a design organization. Measurements at the macro-level will be network size, density, average degree, mean distance, diameter, and clustering coefficient (Scott, 2017). Information can flow more easily in dense networks compared to sparse networks, as there are multiple paths between the nodes in the dense network. Measurement results can be used to manage the design process, as they show how connected design team members are in the project.

2) SNA at Meso-level: Analysis at the meso-level attempts to demonstrate structural characteristics of the network at the level of a subset of nodes called a clique. Such a clique has at least three nodes which are directly connected with each other, and no node outside the clique is directly connected with all nodes in the subgraph (Hogan, 2008). Common nodes in different cliques play an important role in linking sub-groups as boundary spanners (Kapucu et al., 2010). In this research, a clique represents a group of designers who have considerable collaborations with each other over the course of multiple projects.

3) SNA at Micro-level: Investigation at the micro-level aims to (i) evaluate the position of a single node in the whole network through calculating the centrality, betweenness, and closeness of the node, and (ii) determine whether these measurements are significantly correlated with the production performance of designers. We will try to discover whether designers at the center of the interaction map are those most reachable for others and assess the correlation between designers' expertise and their design task assignment. We will also investigate whether the designers with high productivity records in historical projects will gradually grow to be placed in core positions in the design process.

(3) Linkages discovery and validation

We will stratify our database into several groups based on several control variables. The list of these control factors include but not be limited to: (i) main project characteristics (e.g., location, project type, project size, site area); (ii) project team features (e.g., experience level of team members, and BIM competency); (iii) project goals (e.g., energy efficiency, design quality, LEED certification, user satisfaction, and security); and (iv) design strategies (e.g., mechanical/electrical/plumbing (MEP) coordination, and outsourcing). For each group, we will measure and analyze temporal relationships between the identified design pattern attributes and the discovered sociological network properties at the individual, team, and organization levels. Since the design productivity, social network properties, and design patterns are time-stamped, we will use time series methods to examine the hypothesis that a designer's centrality measure is a leading indicator of his/her productivity performance. Fig. 1 (e) shows a regression model (demo).

To choose the correct type of multivariate time series models to examine whether design productivity is cointegrated with the design patterns and social network properties, it is necessary to use a cointegration test. A group of variables with a specific order of integration is cointegrated if a linear combination of the variables has a lower order of integration. Vector Error Correction (VEC) models are recommended for multivariate time series modeling, in which the variables are cointegrated (Pfaff, 2008).

We will validate the identified temporal relationships, predictive models, and the hypothesis itself by statistical examination of the accuracy of the predictive models applied on several independent design log datasets (that were not used in creating the original models). The accuracy of the predictive models will be measured based on two well-established error measures: Mean Absolute Prediction Error (MAPE) and Mean Squared Error (MSE) (Zhang et al., 2017). We will also use diagnostic tests to investigate whether the residuals of the predictive models follow the underlying modeling assumptions. Moreover, the variance of the residuals of the multivariate models should be constant. Statistical tests, such as the Breusch-Godfrey serial correlation Lagrange multiplier test, will be used to determine the serial correlation among the residuals, while other tests, such as the Autoregressive Conditional Heteroskedasticity (ARCH) test, will be used to ensure that residuals have a constant variance.

4. DATA COLLECTION

We aim to obtain BIM Revit log data from several designers over the course of working on multiple projects. Revit log data are design event logs that record all modeling activities of designers in executing commands, which are stored in the Program Files directory under the Revit Product version folder called Journals (Revit, 2017). Several information items related to design activities can be captured from Revit logs, including user ID, project ID, timestamp, design command, etc. Fig. 2 illustrates a workflow of the data extraction process from BIM design event logs. There are three main steps in data collection: (i) data harvesting; (ii) data parsing; and (iii) data cleaning.

(1) Data Harvesting: In any design project, a team composed of several designers work together on the BIM Revit platform. Each designer generates thousands of access logs to Revit throughout the whole project. Most of the times, several projects run in parallel within a design firm, leading to the generation of a large number of journal files. To streamline design logs across different projects from numerous designers, a cloud-based database is developed to regularly harvest the distributed log files onto the Server Centre via the firm's Intranet.

(2) Data Parsing: BIM Revit logs are stored in a text format, which makes it challenging for data analysis. A journal file parser is developed to automatically parse through a folder of journal files and read Revit logs (Revit, 2011). Several information items, such as user ID, project ID, timestamp, and design command, are pulled out and stored in a Comma Separated Values (CSV) format.

(3) Data Cleaning: In the parsed CSV file, each line represents a design command that is executed by a designer at a point in time. A number of lines are involved with noise, such as empty or meaningless commands, which creates a need for removing noisy commands. For instance, in Lines 5 and 12 in Table 1, the command "Cancel the current operation" shows that the designer presses the "ESC" key while moving the mouse or in the middle of the execution of a command, which has no specific meaning for the design and should be removed from further analysis. Command lines must be continuously evaluated, and those containing valid commands without any null values or errors will be kept as new data are placed into the clean logs file.

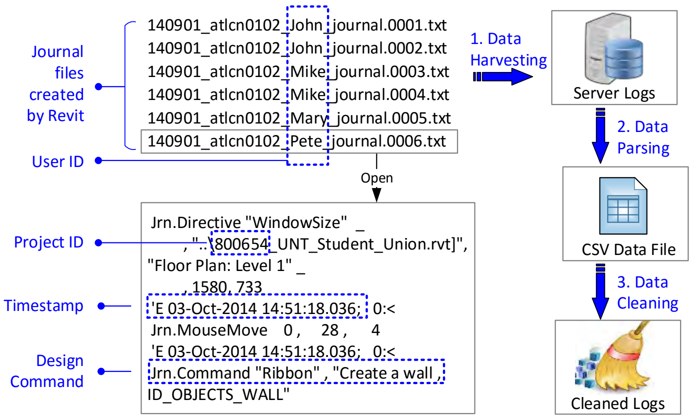

Fig. 2. Workflow of the data extraction from BIM event logs.

5. APPLICATIONS

Based on the captured BIM event logs and the developed methodology, there are several applications in order to facilitate the monitoring, modeling, and analyzing the design process performance in BIM-enabled collaborative design. This section will briefly present such application cases.

5.1 Measuring design productivity

In order to find out what different or similar designers are when executing the most common patterns of commands, the productivity performance is compared between different designers. The baseline of the design productivity in the selected organization is first identified. Then, the productivity performance of the targeted group is extracted. The average process durations and the associated standard deviations at the discovered sequential patterns among those six designers can be obtained. Fig. 3 shows the comparison of productivity performance among different designers via the discovered five sequential patterns in a visualization manner.

It is clear that productivity performance within the discovered sequential patterns varies significantly among different designers. As shown in Fig. 3, regarding each sequential pattern, the red hollow cycles "○" that are located on the left of the blue filled cycle indicate that the productivity performance of the designer(s) is higher than the baseline, while those on the right of the blue filled cycle indicate that the productivity performance of the designer(s) is lower than the baseline. For instance, in Pattern I, the performance of four designers (6#, 5#, 2#, and 1#) overpasses the baseline, while two designers (3# and 4#) fail to pass the baseline. In Pattern II, the performance of all the designers, except the 2# Designer, overpasses the baseline.

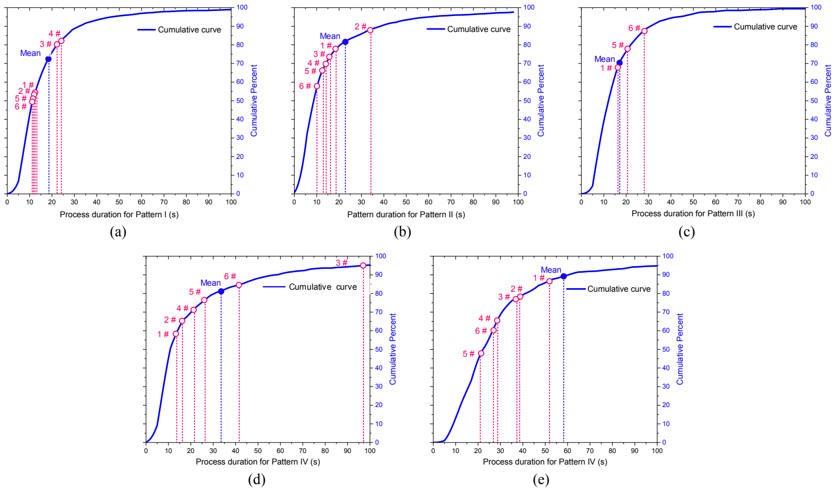

Fig. 3. Comparison of productivity performance among different designers via the discovered five sequential patterns: (a) Pattern I; (b) Pattern II; (c) Pattern III; (d) Pattern IV; and (e) Pattern V.

5.2 Identifying outliner performers

The identified patterns can also be as a project control mean to identify outlier performers that may require additional attention from project leaders. An outlier performer is an observation that lies an abnormal distance from other performers in a sense of the productivity. This definition leaves up to whose design performance should be considered abnormal. The boxplot provides a useful graphical display for describing the behavior of the data and its distributions, where the median and the lower and upper quartiles (defined as the 25th and 75th percentiles) are employed. Given the lower quartile is denoted by Q1 and the upper quartile is denoted by Q3, the difference (Q3 - Q1) is called the interquartile range or IQ. The following quantities, denoted by fences, are needed for identifying extreme values in the tails of the distribution, including lower inner fence (Q1 - 1.5*IQ), upper inner fence (Q3 + 1.5*IQ), lower outer fence (Q1 - 3*IQ), and upper outer fence (Q3 + 3*IQ). A point beyond an inner fence on either side is regarded as a mild outlier, while a point beyond an outer fence on either side is regarded as an extreme outlier.

In this research, taking the Pattern I as an example, Fig. 4 illustrates the results of the identified outlier performers when executing Pattern I. It seems that each designer has a possibility of becoming a mild or extreme outlier performer, except for the designers coded as I, K, and S. Considering the frequency of becoming an outlier performer, particularly an extreme outlier performer, the designers coded as N, R, and J should require additional attention from project leaders, as they are considered as extreme outlier performers for more than five times. It is suggested that an early training and education to the identified outlier performers, particularly focusing on their design tasks, can reduce their learning cost with experience and help enhance their design productivity, to a large extent.

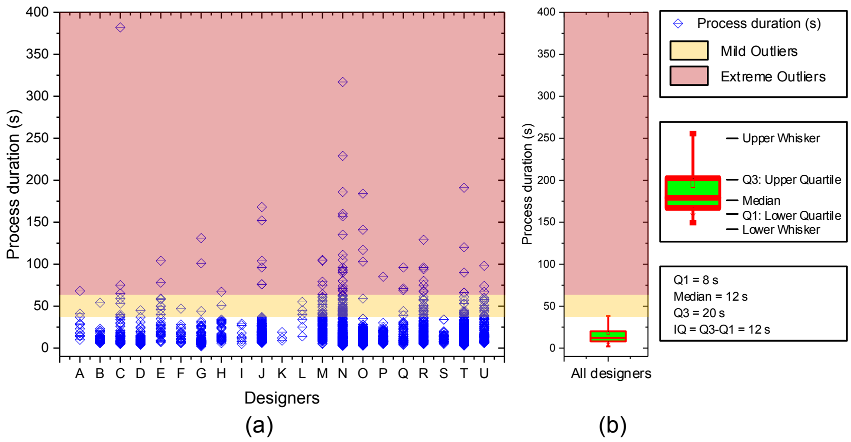

Fig. 4. Identification of outlier performers when executing Pattern I: (a) Scatterplot of process duration at Pattern I among different designers; and (b) Boxplot of process duration at Pattern I. (Note: A, B, C, …, U refer to the code of designers involved in executing Pattern I.)

5.3 Modeling social networks

At the level of the entire design firm, the cleaned event logs contain information about the executed commands by 51 designers who work on 82 projects and contribute 620,492 commands to the projects. The metric that is based on joint cases is used to define the relationship among designers in BIM-based collaborative design. The metric measures weight of the relation between two designers, as the total number of all commands that the two designers have contributed to all projects (where they have worked together). Fig. 5 shows the social network built based on this metric that characterizes the relations among 51 designers in the design firm. Herein, the collaboration network is an undirected network, red points represent all the designers involved, and the width of edges represents the weight of the relation.

From a perspective of degree centrality, the results of two measures in this type, including degree centrality by link and weight, are computed. Degree centrality by link measures the width of the collaboration between a designer and others, while degree centrality by weight measures the depth of collaboration. Fig. 6 illustrates the concentric map of centrality analysis among 51 designers by degree centrality and link centrality. The top three designers ranked in the degree centrality by the link are designers “#24”, “#2”, and “#18”, while the top three designers ranked in the degree centrality by weight are designers “#2”, “#7”, and “#4”. This indicates that these designers are highly active and interact frequently with other designers in the network. These designers are located in the center of the concentric map (as seen in Fig. 6 (b)) and other designers would be likely to build up interactions with them. For instance, designer “#2” is considerably active not only in the width but also the depth of the collaborative network. In general, all these designers, including designers “#2”, “#24”, “#7”, “#24”, and “#4”, can be regarded as “stars” in the network of BIM-based collaborative design.

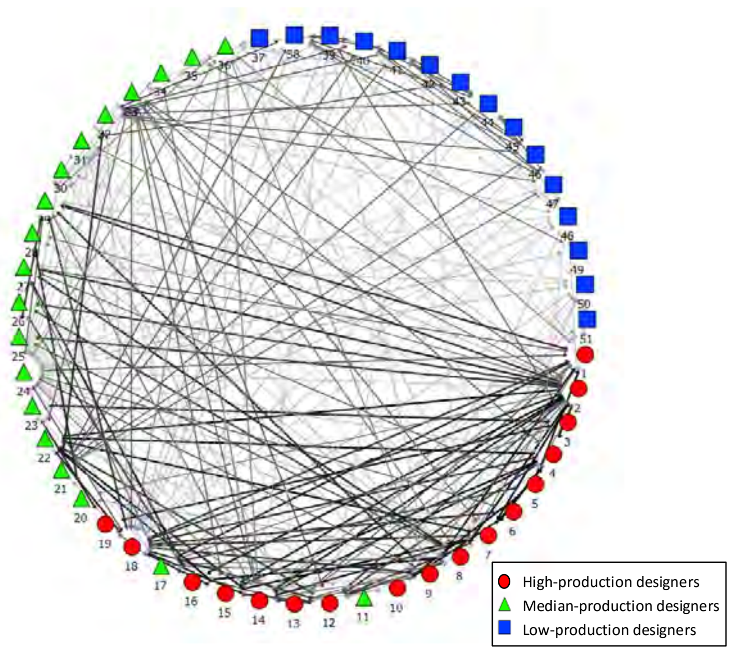

Fig. 5. Map of the discovered social network among 51 designers in BIM-based collaborative design.

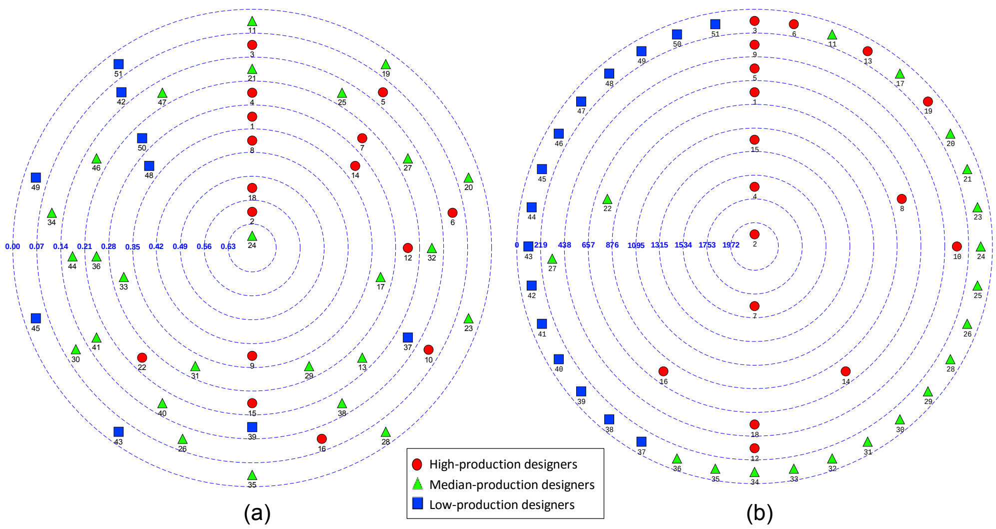

Fig. 6. Concentric map of centrality analysis among 51 designers by (a) degree centrality, and (b) link centrality.

5.4 Performing predictive analysis

In order to further investigate relationships between network characteristics and production performance of designers, correlation analysis is conducted between the measured node centralities and the recorded commands of the involved designers within the organization. Considering the nature of the underlying data, nonparametric Spearman correlation analysis is used to assess the relationships between network characteristics and production performance of designers.

Strong positive correlations exist among all centrality measures calculated based on the discovered social network of BIM-based collaborative design. The calculated degree centrality by weight has the greatest association with the production performance of designers with a correlation coefficient of 0.805 at a 1% significance level. A linear regression test is performed between these two indicators. Fig. 7 illustrates the results of the linear fit. When all data points are considered, an increase of one unit in the degree centrality by weight leads to an increase of 26.73 units in the production performance, associated with an adjusted R-Square of 0.3790 (see Fig. 6 (a)). When two outliers (marked in red in Fig. 7 (b)) are masked, the value of the adjusted R-Square is sharply increased to 0.7113, indicating a strong interpretation for the regression fit. Therefore, the measured node degree centrality by weight is capable of explaining the greatest percentage of variations (71.13%) in the production performance of designers. An increase of one unit in the degree centrality by weight probably leads to an increase of 24.82 units in the production performance of designers.

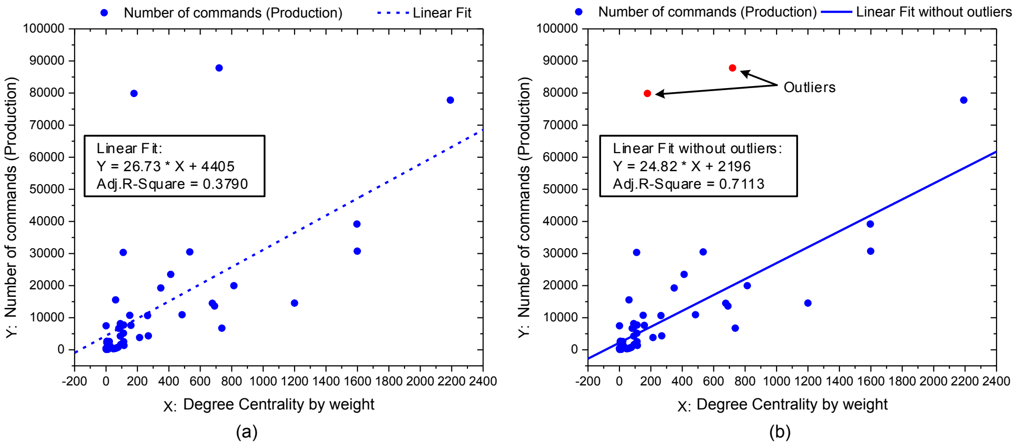

Fig. 7. Linear fits between network characteristics (Node degree centrality by weight) and production performance of designers (Number of commands executed): (a) with all data points; and (b) with outliers masked.

6. CONCLUSIONS

Tremendous volumes of computer-generated event logs are available as a result of the massive growth of BIM in the AEC industry. There is a good opportunity to make good use of these event logs to extract valuable information for enhancing project performance in design firms. This research develops a novel and systematic approach to deeply mine design event logs from BIM Revit platforms to perform process mining and discover social networks in BIM-based collaborative design. The proposed approach consists of three main steps: (i) Data collection and process mining; (ii) Social network modeling and analysis; and (iii) Linkages discovery and validation.

This project attempts to improve understanding of building design development process enabling improvements in design productivity. This research takes tremendous volumes of design logs as a superior alternative source of information for discovering social networks in collaborative design practices and examine the relationships between the characteristics of the design social network and production performance of designers. The main interesting findings of this research include: (1) Identify attributes describing individual designers' preferences in the execution of design tasks, (2) Analyse structural features of collaborative networks at different levels within a design organization through social network analysis, (3) Measure and analyse the effects of design pattern attributes and social network properties on design productivity at individual, team and organization levels using multivariate time series analysis tests, and (4) Explain and validate the variability in design productivity through the creation of predictive models based on the measured design patterns and the quantified design network attributes.

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FREQUENCY-DOMAIN ANALYSIS FOR WI-FI BASED HUMAN ACTIVITY RECOGNITION SYSTEMS IN SMART HOMES

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ABSTRACT: *Effective human activity monitoring has become essential for an intelligent eldercare system in a home environment. Recently, device-free activity recognition using Wi-Fi signals has been the focus of human activity monitoring systems. This approach analyzes Channel State Information (CSI), the fine-grained information of the Wi-Fi fingerprint system. Human activities affect the propagation paths of Wi-Fi signals, which change the CSI. A CSI-based activity recognition system exploits these CSI variations in the time domain. However, the amplitude of the CSI can be diminished in Non-Line-Of-Sight (NLOS) conditions, and the CSI can also contain various activities performed by multiple subjects, which reduces the system's recognition performance. In this context, this paper examines the effect of human body movement on the CSI in the frequency domain and analyzes the energy distribution in a common frequency range for human body movement. Experiments were conducted in both Line-Of-Sight (LOS) and NLOS conditions, and two subjects also performed different activities at the same time. The experiment results show the correlation between body movement and CSI in the frequency domain. Such an established correlation presents an opportunity to detect various activities from the weak signal, as well as to detect simultaneous activities by multiple subjects.*

KEYWORDS: *Smart Home, Activity Recognition, Device-free Sensing, Fine-grained Wi-Fi Signal, Channel State Information, Frequency Fingerprinting*

1. INTRODUCTION

According to the World Health Organization (WHO), the elderly population (those over 65 years of age) is rapidly growing, and 17 percent of the world's population will be aged 65 or over by 2050 (Majumder et al., 2017). As members of this elderly population need regular assistance and healthcare in their daily lives, the demand for healthcare services for the elderly continues to grow. Monitoring human activity has always been a part of an intelligent eldercare system in a home environment. Device-free activity recognition approach using off-the-shelf Wi-Fi devices has been the focus of human activity recognition systems, because it does not require additional equipment (e.g., wearable devices) and has fewer privacy issues (Yousefi et al., 2017). This approach exploits Wi-Fi signals propagating indoors. When Wi-Fi signals propagate inside a static home environment, the signal is stable. However, human activity may affect the propagation paths of Wi-Fi signals, which results in a signal change at the receiver. Previously, Wi-Fi-based activity recognition approaches mostly analyzed signal variances in the time domain (Wang et al., 2014; Arshad et al., 2017; Wang et al., 2017; Ali et al., 2015). However, this approach has limitations regarding signal attenuation and mixed signals generated by activities of multiple subjects. First, when signals are transmitted, they frequently reflect off of or pass through walls. A signal that has passed through a wall is much weaker than one that is reflected. For example, if a 2.4 GHz Wi-Fi signal passes through a reinforced concrete wall, the signal power is reduced by 40dB (Adib & Katabi, 2013). Also, as signals pass through walls, the higher the signal frequency is, the more power the signal loses (Tesserault et al., 2007). The decreased signal power reduces the signal variation caused by activities, making it difficult to distinguish from noise (Wang et al., 2017). Second, the Wi-Fi-based approach may not distinguish between different activities at the same time. If multiple subjects simultaneously perform different activities, the signal contains multiple activity information as a variance. However, the mixed variance of the signal may register as a new activity rather than multiple overlapping activities.

To cope with the limitations of the Wi-Fi-based approach relying on the time domain, we examine the effect of human activity on Wi-Fi signals in the frequency domain. Some researchers have shown that channel state information (CSI) in the frequency domain correlates with activity (Wang et al., 2017; Yousefi et al., 2017). They employ frequency-domain analysis (i.e., power profile patterns from the Short Time Fourier Transform (STFT) analysis) as one of the features of their classification algorithms, but whether and how CSI correlates with human activities in the frequency domain has not been empirically examined. This paper seeks to fill that gap by investigating the correlation between human body movement and Wi-Fi signals in the frequency domain through empirical data obtained from laboratory experiments. We believe that this correlation between CSI and human activity in the frequency domain can be exploited for increased efficacy in Wi-Fi-based activity recognition approaches.

2. BACKGROUND

As Wi-Fi signals pass through physical space, environmental effects on the signals can be expressed by Channel State Information (CSI). The Wi-Fi-based activity recognition approach exploits this CSI. If a person performs an activity in a static home environment with an operating Wi-Fi device, the Wi-Fi signals are scattered by the body's movement, causing the signals to become fluctuated (Wang et al., 2017). Off-the-shelf Wi-Fi devices using commercial network interface cards (e.g., Inter NIC 5300) continuously monitor and quantify the channel state, and the CSI values can be collected by the Linux CSI 802.11n tool (Halperin et al., 2011). The CSI can be expressed as $Y = HX + \mathrm{N}$, where Y and X are the received and the transmitted signal vectors. H denotes the CSI matrix for a packet, and N is the noise vector. Current Wi-Fi standards, such as IEEE 802.11n/ac, supports Orthogonal Frequency Division Modulation (OFDM). The OFDM divides the bandwidth (20 MHz) into multiple orthogonal subcarriers (Yousefi et al., 2017). Thus, the CSI matrix, H, contains a total of 30 subcarriers which have amplitude and phase information. Figure 1 shows the raw CSI amplitude data of these 30 subcarriers. The bar graph shows ground truth, and Pause and Activity on the bar imply no activity and the movement of a hand ("hand-moving activity"), respectively. The Wi-Fi-based approach recognizes human activities by analyzing these amplitude variations.

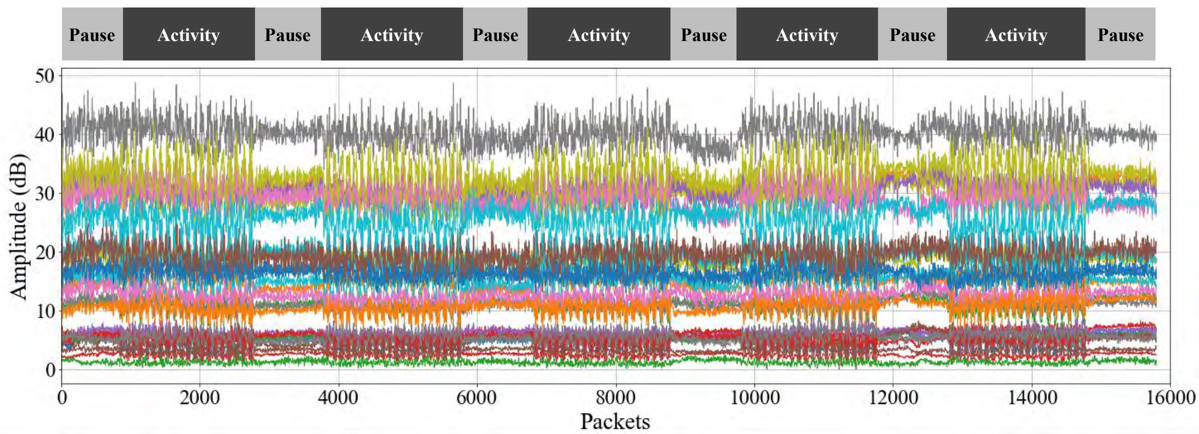

Fig. 1: Raw CSI amplitude data of 30 subcarriers captured during the hand-moving activity. Colors indicate different subcarriers, and bar graph indicates the ground truth.

3. METHODOLOGY

This study examines the correlation between human body movement and CSI in the frequency domain. The acceleration of body movements was recorded by an accelerometer. The accelerometer data and CSI in the time domain were then converted to the energy distribution in the frequency domain using the Fast Fourier Transform (FFT).

3.1 Data Collection

The test was performed in a United States home, and Figure 2 shows the floor plan for the testbed. We used one transmitter-receiver pair to retrieve CSI. The transmitter, Access Point (AP), remained in a fixed location in the living room, but the location of the receiver changed according to the location of the subjects. We used an AC1750 MU-MIMO Gigabit Router for the AP and a laptop Lenovo T400 with Intel 5300 NIC for the receiver. During the test, Internet Control Message Protocol (ICMP) packets were set to 100pkts/s, and the CSI was captured and extracted by the Linux CSI 802.11n tool.

During the test, subjects repeatedly waved their right hand for 20 seconds, wearing an accelerometer on the hand by keeping their hand moving at a constant rate. The hand-moving activity was performed in five rounds, with 10 seconds intervals between each period of activity. In the first part of the test, one subject waved their hand in the living room, Line-Of-Sight (LOS), and then the bedroom, Non-Line-Of-Sight (NLOS). In the bedroom, the subject performed the test with both the door open and the door closed. Data from these experiments show how the CSI reacts to human activities in the LOS and NLOS conditions. In the second part of the test, two subjects in the living room waved their hands at the same or different rates, as directed, in order to simulate multiple subjects simultaneously performing the same activity or different activities. In addition, to examine the effect of the subject alignment on the FFT result of CSI, two subjects performed the test by sitting side-by-side ("horizontally") or front-to-back (vertically) while facing the direction of the signal propagation. The experimental conditions are summarized in Table 1.

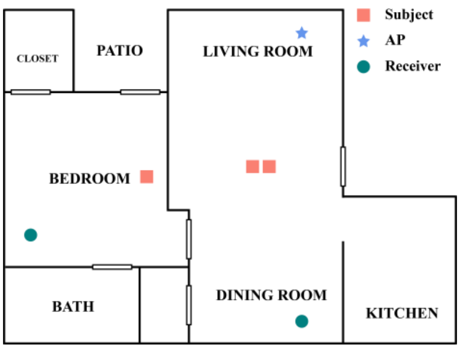

Fig. 2: Floor plan for the testbed.

Table 1: Summary of experimental conditions: Tests 1–6 evaluate the effect of LOS and NLOS conditions and Tests 7–10 evaluate the effect of simultaneous activities by multiple subjects.

	Number of Subjects	Subject Location	Notes	Activity Frequency
Test 1	1	Living room	-	1 Hz
Test 2	1	Bedroom	Door open	1 Hz
Test 3	1	Bedroom	Door closed	1 Hz
Test 4	1	Living room	-	1.7 Hz
Test 5	1	Bedroom	Door open	1.7 Hz
Test 6	1	Bedroom	Door closed	1.7 Hz
Test 7	2	Living room	Horizontal-align	1 Hz, 1 Hz
Test 8	2	Living room	Vertical-align	1 Hz, 1 Hz
Test 9	2	Living room	Horizontal-align	1 Hz, 1.7 Hz
Test 10	2	Living room	Vertical-align	1 Hz, 1.7 Hz

3.2 Data Filtering

The raw subcarrier data is firstly filtered out for the data processing. As shown in Figure 1, the subcarriers show similar patterns for an activity, but their amplitudes have different ranges. Firstly, the CSI amplitude of the 30 subcarriers were normalized. We next removed noise that may not be due to the hand movement. To remove the low-frequency and high-frequency noises, we used the fifth order low pass and the first order high pass Butterworth filters. The cutoff frequency was 10 Hz and 0.2 Hz for the low and high pass filters respectively, as this frequency range is the expected range for human activities at home (Wang et al., 2017). Figure 3 shows the filtered CSI amplitude of the 30 subcarriers.

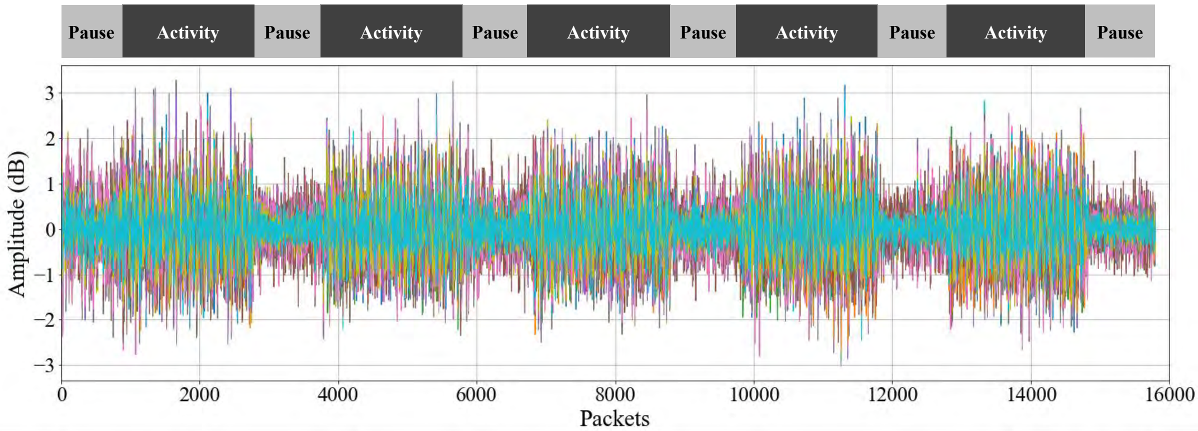

Fig. 3: Filtered CSI amplitude data of 30 subcarriers captured during hand-moving activity. Colors indicate different subcarriers, and bar graph indicates the ground truth.

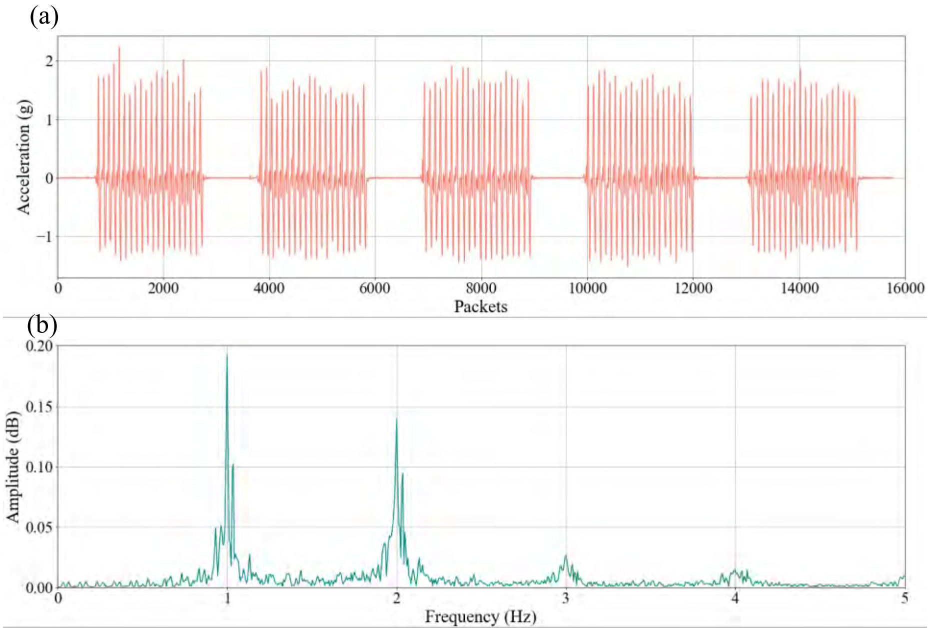

Fig. 4: Acceleration of hand-moving in (a) the time domain and (b) the frequency domain.

3.3 Fast Fourier Transform

A Fast Fourier Transform (FFT) converts signal data in the time domain into the frequency domain by breaking down the original waveform data into a series of sinusoidal signals, which each have a unique amplitude and frequency. Thus, FFT can identify the significant contributors to the signal. Figure 4 shows the acceleration data collected at the subject's hand during the test. The FFT result of the acceleration data indicates that the hand-moving contains most of the energy in 1 Hz, along with its harmonic frequencies at 2 Hz and 3 Hz. When a signal consists of multiple sine waves, its FFT results usually have multiple harmonic frequencies, which are multiples of the fundamental frequency (Smith, 1997). Figure 5 shows acceleration of the first round of hand-moving. The signal shows the peak values every second, which means that hand moving is performed at 1 Hz. The CSI of a single subcarrier for the test in both the time and frequency domains is shown in Figure 6. The FFT result of the CSI also shows major components in 1 Hz, along with the peak values in 2 Hz and 3 Hz harmonic frequencies. The CSI and the acceleration of the hand-moving show similar energy distributions in the frequency domain.

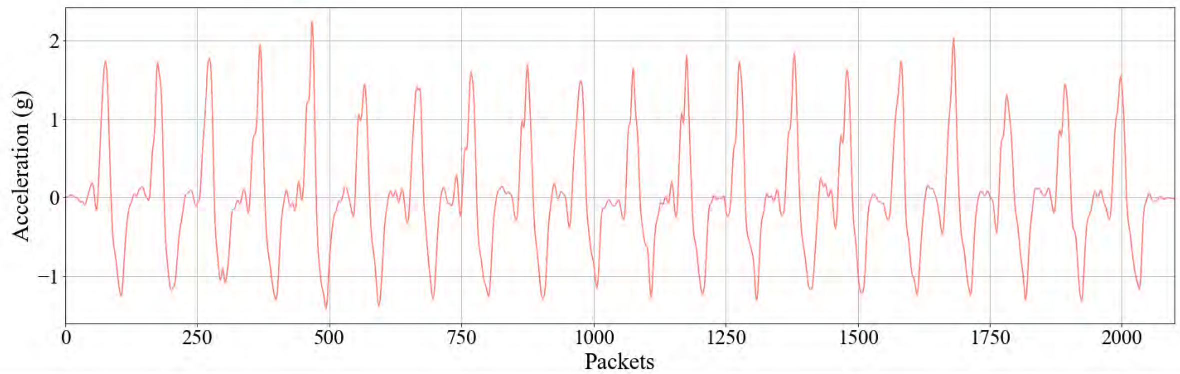

Fig. 5: Acceleration of hand-moving in the time domain for the 20 rounds.

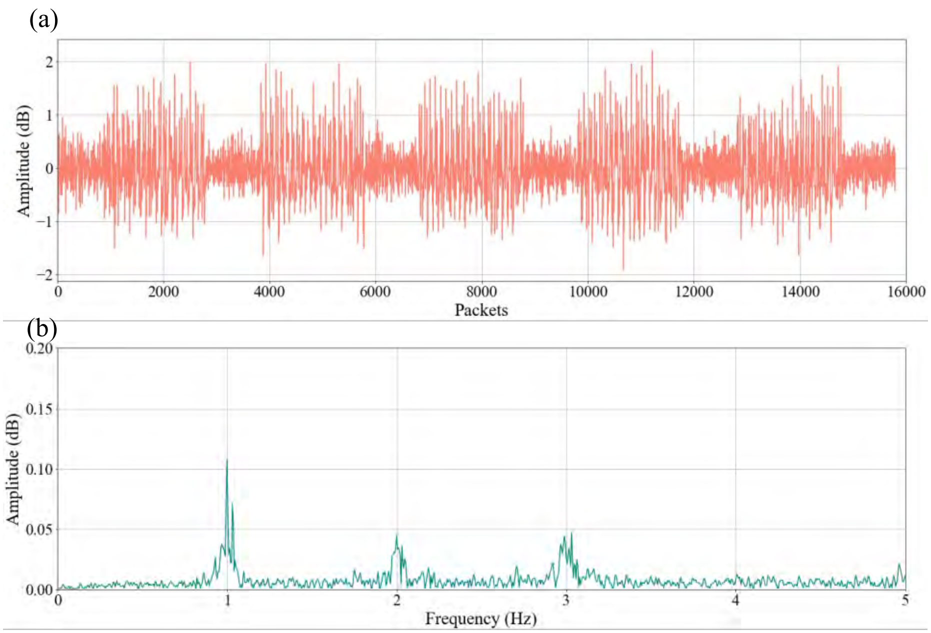

Fig. 6: CSI of the 20th subcarrier in (a) the time domain and (b) the frequency domain.

3.4 Subcarrier Selection

As shown in Figure 1, the extracted CSI contains data from 30 subcarriers. The CSI-based approach can exploit a single subcarrier (Wang et al., 2017) or all subcarrier data in various forms, such as variance (Arshad et al., 2017), moving variance (Wang et al., 2014), or Principal Component Analysis (PCA) (Ali et al., 2015). The transformation of data also changes the frequency characteristics of the data, generating different FFT results. Therefore, we first select the single subcarrier that has the most sensitivity in the time domain. Each subcarrier has a different sensitivity for a given human activity due to the different wavelengths displayed by each subcarrier. Figure 7 shows the variation in the amplitude of the subcarriers. A brighter color indicates a larger amplitude, which in turn means a higher sensitivity. The neighboring subcarriers of the 11th, 19th, and 28th subcarriers have higher sensitivities to hand-moving. To measure the sensitivity of each subcarrier, we used the mean absolute deviation of the CSI amplitude. Generally, a larger mean absolute deviation implies higher sensitivity (Wang et al., 2017). The mean absolute deviation of the CSI amplitude data has relatively large values in the 12^{th}, 20^{th}, and 28^{th} subcarriers, as shown in figure 8. However, even though the 12^{th}, 20^{th}, and 28^{th} subcarriers have the highest sensitivity in the time domain, it may not adequately contain the frequency properties. For example, Figure 9 shows the FFT result of the 12^{th}, 20^{th}, 28^{th}, and 13^{th} subcarriers. The CSI was collected when two subjects moved their hands at two different rates, 1.0 Hz and 1.7 Hz. The FFT result of the 12^{th}, 20^{th}, and 28^{th} subcarriers, which have higher sensitivities, show that some energies are concentrated at 1 Hz and 1.7 Hz, but their magnitudes are not high. However, even if the 13^{th} subcarrier has the lower sensitivity than the 12^{th}, 20^{th}, 28^{th} subcarriers, it has clearer energy distribution which has strong energy at 1 Hz and 1.7 Hz. This result indicates that the even subcarriers which are sensitive in the time domain may not be sensitive in the frequency domain. Thus, we decided to plot all subcarrier data in a figure to exploit all subcarrier information for estimating the correlation between body movement and CSI in the frequency domain.

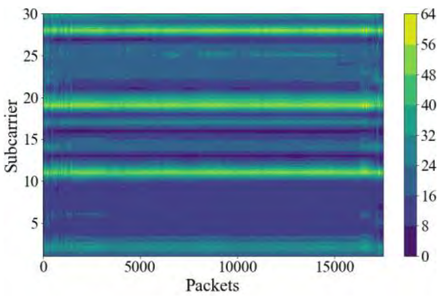

Fig. 7: Variation in amplitude of subcarriers.

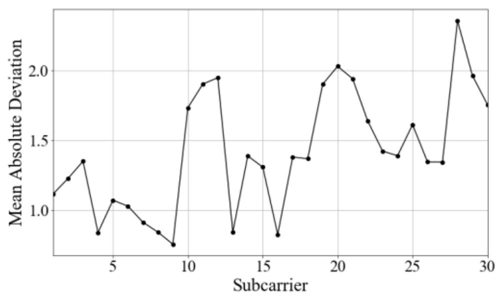

Fig. 8: Mean absolute deviation of CSI amplitude.

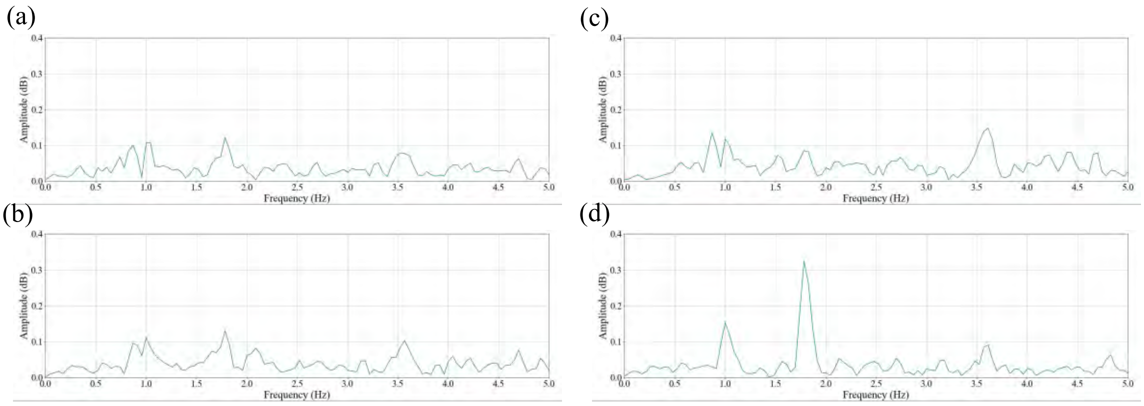

Fig. 9: Result of FFT: (a), CSI amplitude of the 12^{th} subcarrier; (b), CSI amplitude of the 20^{th} subcarrier; (c), CSI amplitude of the 28^{th} subcarrier; and (d), CSI amplitude of the 13^{th} subcarrier.

4. RESULTS AND DISCUSSION

This section presents the comparison of FFT results between the acceleration data and CSI. The hand-moving activity was performed in five rounds, and the FFT results of each round are plotted in a figure. Thus, the figure for the CSI contains 150 graphs (5 rounds × 30 subcarriers), and the figure for the acceleration data contains 5 graphs.

Figure 10 shows the FFT results from Test 1 to Test 6. In Tests 1, 2, and 3, the subject performed hand-moving at 1 Hz in the living room and bedroom, which indicate LOS and NLOS conditions, respectively. Although the CSI variation in NLOS is reduced, the FFT results of the CSI clearly show the identical energy distribution in a frequency range in both the LOS and NLOS conditions. Also, the acceleration data retrieved at the hand displays the same energy distribution frequency range as that of the CSI. In Tests 4, 5, and 6, the subject performed hand-moving at 1.7 Hz, but it was unable to repeat hand-moving at the constant rate of 1.7 Hz. The FFT result of the acceleration data for Test 5, Figure 10(h), shows that the peak point of energy distribution has variant ranges. The CSI for Test 5, Figure 10(f), also has variances at the peak values, the same as Figure 10(h), indicating that the CSI is quite sensitive to small activity changes.

Figure 11 shows the FFT results from Test 7 to Test 10. In Tests 7 and 8, two subjects performed hand-moving at the same rate, 1 Hz, in the living room. Figures 11(c) and 11(d) show the acceleration data of the two subjects for Test 7. During Tests 9 and 10, the two subjects waved their hands at different rates, 1 Hz and 1.7 Hz. Figures 11(g) and 11(h) show the acceleration data for the two subjects for Test 10, and the FFT result for the CSI for Test 10 contains the energy distributions of the two distinct hand-moving activities. These results provide new information about the relationship between human body movement and CSI that is not visible in the time domain. This information can be exploited for recognizing human activity in the NLOS conditions and for discriminating between various activities generated by multiple subjects.

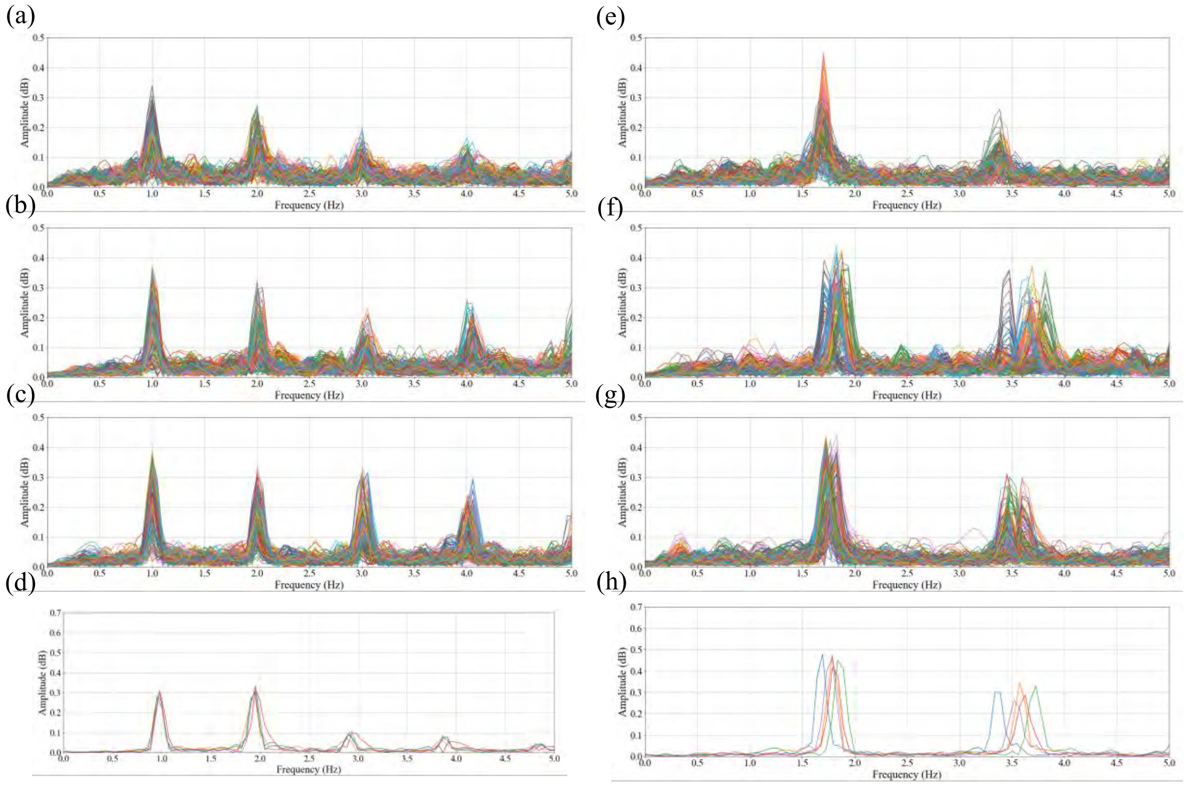

Fig. 10: FFT results from Test 1 to Test 6: (a) CSI for Test 1, (b) CSI for Test 2, (c) CSI for Test 3, (d) acceleration data for Test 1, 2, and 3, (e) CSI for Test 4, (f) CSI for Test 5, (g) CSI for Test 6, and (h) acceleration data for Test 4, 5, and 6.

5. CONCLUSION

This study analyzes the correlation between CSI and human body movement in the frequency domain. The results indicate that CSI is sensitive to human body movement in the frequency domain, so that the correlation can be used for recognizing activities in the NLOS conditions and differentiating activities from mixed signals. This frequency-based approach can help mitigate the limitation of the Wi-Fi-based activity recognition approach in the time domain. As next research steps, we will study how to exploit all subcarrier data to retrieve a single FFT result. As shown in the subcarrier selection section, not all subcarriers have proper frequency characteristics. Additionally, subjects in this study performed simple hand-moving, which is not regular activity in a home environment. We will examine the energy distribution in the frequency range of the various common household activities to utilize the correlation between human activity and CSI in the frequency domain for greater efficacy in human activity recognition.

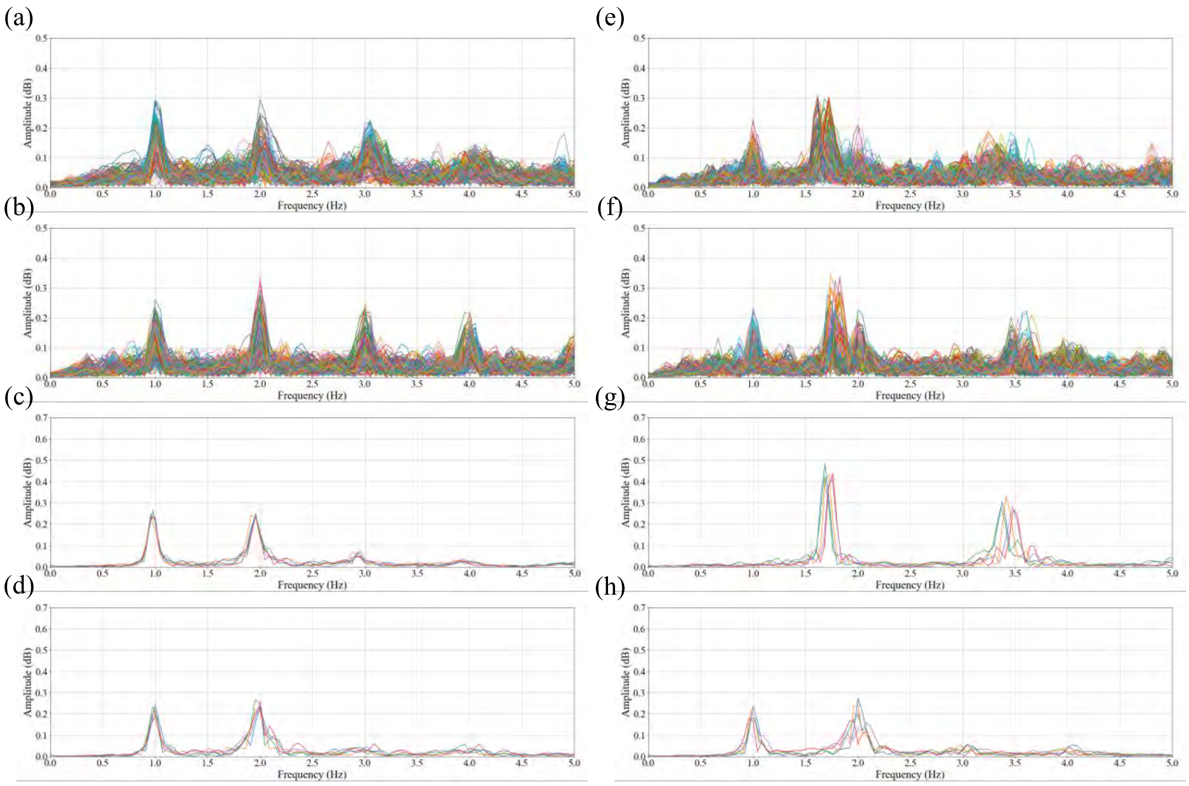

Fig. 11: FFT results from Test 7 to Test 10: (a) CSI for Test 7, (b) CSI for Test 8, (c) Subject 1's acceleration for Test 7, (d) Subject 2's acceleration for Test 7, (e) CSI for Test 9, (f) CSI for Test 10, (g) Subject 1's acceleration for Test 10, and (h) Subject 2's acceleration for Test 10.

6. ACKNOWLEDGEMENT

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VISUALISATION OF INDUSTRIAL FACILITIES FOR OPERATIONS AND DECOMMISSIONING

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ABSTRACT: *The late life and decommissioning stages of Oil and Gas and other industrial facilities have received an increased attention in recent years. Over the next 30 years, it is expected that over 400 offshore installations in the North Sea's UK Continental Shelf (UKCS), will need to be decommissioned. However, there are currently many challenges in information management which impact on the availability of the needed data to support operations and decommissioning processes of industrial facilities. In particular, the availability of 3D and other visual models, which could support maintenance tasks and decommissioning decisions is typically limited. In this research, a framework is proposed for the development of Engineering Project Management (EPM) software solutions to support the late life and decommissioning stages of industrial facilities of the energy sector. We propose the integration of the Owner/Operator's documents, GIS data, as well as a variety of reality capture and visualisation methods to capture the interior and exterior of facilities. The adopted survey and visualisation methods include: Unmanned Aerial Vehicle (UAV) survey to capture the exterior of facilities using photogrammetry; Laser scanning, 360º photography and use of a Matterport camera to capture the interior of the facilities, and; the development of 3D parametric models for subsea assets of oil and gas facilities. A case study is presented to demonstrate the integration of the resulting models with an EPM system currently in development. The case study highlights how the integration between the various survey and visualisation approaches and the underlying EPM data can be used to assist facility owner/operators in operations and decommissioning tasks by providing the relevant Tag data in interactive walkthroughs. The development of the case study revealed a number of limitations which will be tackled in further developments of the proposed framework.*

KEYWORDS: *Industrial facilities, Decommissioning, CFIHOS, Visualisation, Reality capture, Photogrammetry, GIS*

1. INTRODUCTION

Over the next 30 years, it is expected that over 400 offshore installations in the North Sea's UK Continental Shelf will need to be decommissioned (OGA, 2018). There are currently many challenges related to information management of these existing facilities, including their management and operation during their late life stages.

Information management for industrial facilities has been the focus of research for many years. Various engineering data management standards and specifications have been proposed to streamline the access and delivery of data throughout the lifecycle of industrial assets (Kim et al., 2011; USPI-NL, 2011; Rasys et al., 2012; Fiatech, 2017a; Fiatech, 2017b).

The most notable efforts include the ISO 15926 standard and the Capital Facilities Information Handover Specification (CFIHOS). The ISO 15926 standard provides a Reference Data Library (RDL) to enable the integration, sharing, exchange, and handover of data about process industry assets between disparate computer systems (ISO, 2004). Several projects based on this standard are currently under development to enable its adoption by the Oil & Gas industry (USPI-NL, 2011; Fiatech, 2017a; Fiatech, 2017b). CFIHOS is an ongoing industry effort that will provide a practical implementation of the ISO 15926 standard. CFIHOS proposes the definition of several information management specification templates to support the whole lifecycle of process plants, including the specification of a Reference Data Library, which defines the required documentation at each phase of the assets' lifecycle (USPI-NL, 2011).

Fiatech has developed guides as well as various tools for the implementation of the ISO 15926 standard by the process industry, including the development of information patterns for ISO 15926 to enable standardised information access and data exchange between software applications (Fiatech, 2017a; Fiatech, 2017b).

The International Association of Oil & Gas Producers (IOGP) is coordinating the implementation of ISO standards by Oil and Gas companies, through the definition of a series of templates which take into account additional Owner/Operator requirements, through the development of the JIP33 initiative (IOGP, 2018).

It is expected that these efforts will foster the adoption of standards by the process industry, enabling facility lifecycle management. However, due to their complexity, and the industry's current business processes, their adoption has been limited and the industry remains fragmented. For existing facilities coming out of commission, data is typically unstructured, unreliable and incomplete, which introduces significant challenges during the late life of industrial facilities, in particular for the planning and development of decommissioning programmes.

In the UK, increased attention has focused on the decommissioning of Oil and Gas facilities. Government institutions such as Business, Energy and Industrial Strategy (BEIS) and the Oil and Gas Authority (OGA) provide a variety of guidelines to ensure that owners decommission their facilities according to the international regulations (OSPAR, 1998). The current decommissioning process across the North Sea involves extensive planning and consultation with regulators several years before cease of production (CoP) (OGUK, 2017). This includes the selection of accredited shipyards to decommission the facilities (ISO, 2009). In the UK, decommissioning activities are partially publicly funded through tax relief (HM Treasury, 2012), so there is a strong focus in minimising costs and environmental impact, while facility owners are focused in maximising the production capacity of their facilities during the late stages of their lifecycle. Decommissioning programmes for the United Kingdom Continental Shelf (UKCS), along with the corresponding environmental assessments, have to be approved by a government representative (Secretary of State), and are available for public consultation (OGA, 2018). Various standards and guidelines have been proposed in recent years to support the decommissioning of Oil & Gas facilities in the UKCS (BEIS, 2017; OGUK 2015; HIE, 2017; OGUK, 2017).

Key requirements for decommissioning include assets condition and an inventory of hazardous materials by asset. These requirements will inform the future use of the facility (e.g. repair, replace, reuse or recycle) and also provide key information for planning maintenance and decommissioning tasks. The availability of 3D models and other visual models, such as photo-based walkthroughs, could provide valuable inputs to evaluate facility condition and decommissioning options (Cheng et al. 2017).

This paper proposes a framework for the development of EPM solutions focused on the late life and decommissioning lifecycle stages. The framework proposes the combined use of Geographic Information Systems (GIS), reality capture methods for preliminary assessment of facility condition, and the development of 3D models of subsea Oil and Gas assets, to support the decommissioning of wells and pipelines. Visualisation can provide an important role in operations and decommissioning of energy facilities since it can provide input to inventory mapping and condition assessment, reducing the time and expenses associated with on-site visits, and offshore trips. A variety of survey and visualisation methods are proposed including: UAV survey to capture the exterior of facilities using photogrammetry, and; Laser scanning, 360º photography and use of a Matterport camera (Matterport, 2018) to capture the interior of the facilities. Documents management is provided by an in-house proprietary EPM software solution. A case study was carried out consisting in the development of an exterior 3D model of an industrial facility using photogrammetry resulting from a UAV survey, and the development of an interior interactive walkthrough of the facility using a Matterport camera. The models are integrated and accessible via a custom EPM system that is currently being developed. The resulting models can be used to plan maintenance tasks and for the early stages of decommissioning planning, reducing costs and risk associated with time spent onsite.

2. PROPOSED FRAMEWORK

One of the main requirements for operations and decommissioning of energy facilities, is the reduction of time spent onsite, both for safety and economic reasons. In this research, a framework is proposed to streamline the planning of operations and decommissioning processes, which is expected to provide accurate data to enable decisions regarding the optimal use and fate of the assets. The proposed framework will be used as a basis for the development of a EPM to manage the late life and decommissioning of energy facilities, including cost control, execution scheduling, capacity planning and also track the actual results of the execution.

The adoption of visualisation methodologies can be used to plan maintenance and decommissioning activities, and to evaluate the condition of assets and decide their fate (e.g. repair, replace, reuse or recycle). We propose the combined adoption of a variety of reality capture methodologies to capture the exterior and the interior of industrial facilities in the energy sector. The resulting models are used for the development of interactive walkthroughs, linked to the underlying facility data. This provides facility owner/operators with the ability to identify and locate assets, as well as provide preliminary condition assessment of the assets. For decommissioning, this can be used to identify assets that can be reused, as well as assets that might contain hazardous materials from an early stage of the decommissioning planning process.

In this framework, visualisation is adopted for the interior and exterior of industrial facilities, through the use of a variety of reality capture methods (Table 1). We propose the development of 3D parametric models for subsea assets, which can be integrated with GIS data and used to evaluate pipeline decommissioning options and well plug and abandon (P&A) operations. 3D model visualisation can be integrated with the relevant data and documents about assets, provided that they have been structured in a common format. An overview of the framework proposed in this research is provided in Figure 1. In the following sections, the methods proposed for the capture and visualisation of the exterior and interior of the facilities will be detailed.

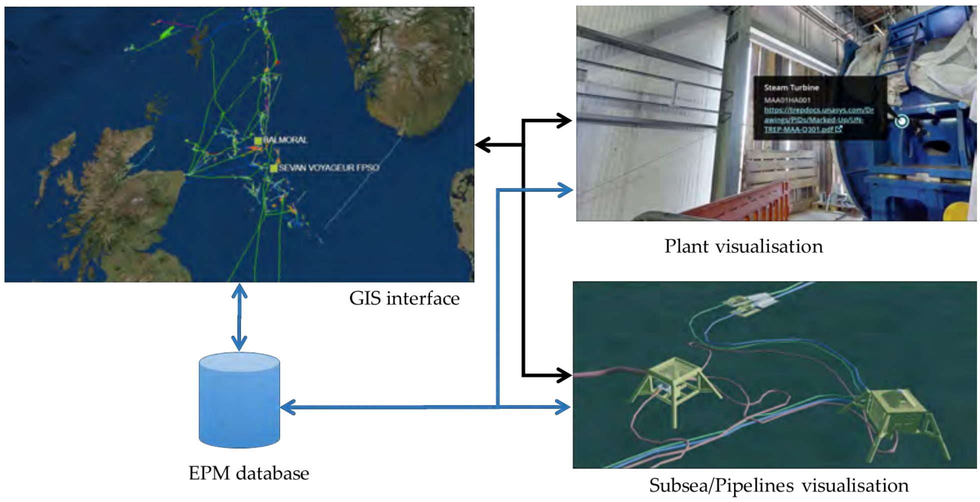

Fig. 1: Framework for visualisation of Oil and Gas & industrial facilities for operations and decommissioning

Table 1: Overview of reality capture, modelling and visualisation approaches adopted in the proposed framework

Plant visualisation		*Subsea/Pipelines visualisation*
Exterior	Interior	
Aerial survey (drone - photogrammetry)	Laser scanning	3D modelling from as-built drawings
	360º photos	
	Matterport survey	

2.1 Reality capture and visualisation of industrial facilities

In this research we propose the adoption of a variety of reality capture methods for existing industrial facilities in the energy sector. For many existing facilities, visual data in the form of 3D models and drawings is currently not available. Therefore, it is fundamental to investigate how reality capture methods can be used effectively to obtain a visual representation of these facilities, and how they can be used to support maintenance tasks and removal operations during the late lifecycle stages. The use of reality capture methods can provide valuable inputs regarding assets' condition, and can also be used for the preliminary identification of hazardous materials, and to identify assets to be repaired, replaced, reused or recycled. Previous research efforts have explored the application of reality capture and visualisation methodologies in the Oil and Gas sector (Rasys et al. 2014; Hou et al. 2014; Wang et al. 2014). In this research, various methods were considered to survey and develop walkthroughs and 3D models of energy facilities.

2.1.1 Development of exterior facility models from UAV surveys using photogrammetry

UAV surveys can be used to capture the exterior of the existing facilities, and build a 3D model using photogrammetry. This can be achieved through the execution of a pre-determined flight plan in which the UAV camera captures a series of photographs. The resulting photographic survey can then be used to build point cloud and mesh models using specialized photogrammetry software (e.g. Pix4D). The resulting 3D model can be linked to the underlying asset data and documents in the EPM system using a game engine or a 3D model viewer, providing interactive web-access to the 3D model and related asset data (Fig. 2).

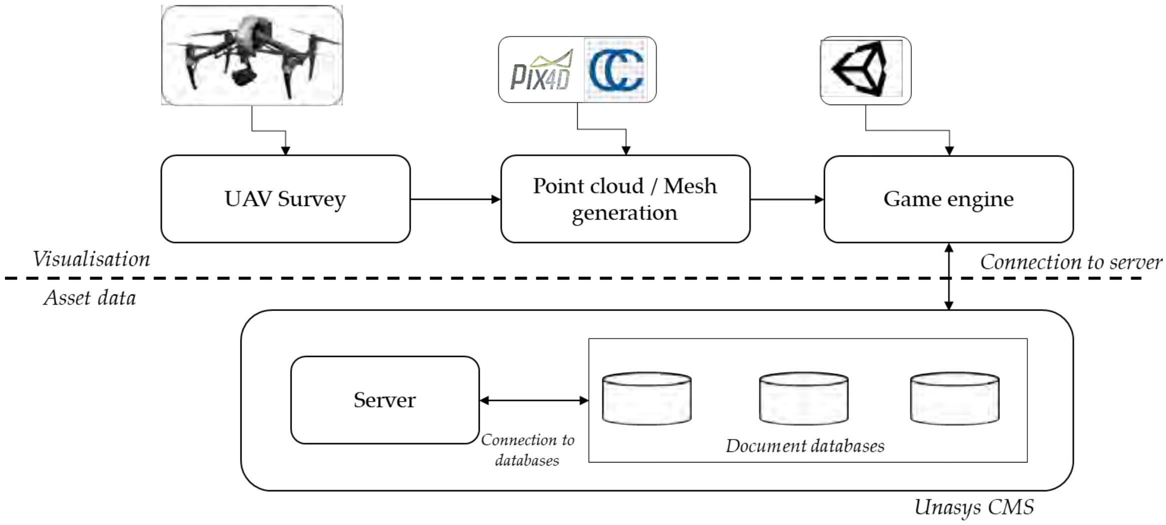

Fig. 2: Workflow for surveying and visualisation of the exterior of industrial facilities and linking with associated documentation data

2.1.2 Development of walkthroughs for the interior of industrial facilities

Previous research has explored and detailed the development of walkthroughs from a laser scanning survey using game engines and the development of walkthroughs from 360º photos in related research papers (Patacas et al., 2017; Patacas et al. 2018). While the use of a laser scanner provides the highest quality of surveyed data, in practice it is not always possible to perform laser scanning surveys in industrial installations, due to safety restrictions. 360º cameras, on the other hand, are affordable, extremely portable, and provide the opportunity to quickly capture existing spaces. If the device supports in-camera stitching (i.e. a feature in 360º cameras in which 360º panoramas are generated by the camera), post-processing time is greatly reduced. The resulting photographic surveys can be used for the development of walkthroughs in which specialised software tools (e.g. Panotour Pro) are used to link the different panoramas together. Photographic surveys can also be used for the development of 3D models using specialised photogrammetry software. Due to complexity of industrial assets, it is challenging to obtain accurate geometric features of the assets, however this process can be used to provide general spatial measurements of areas and rooms within the facilities. Another alternative is the use of a Matterport 3D camera, which combines the capture of 360º panoramas with a basic 3D model. While the resulting 3D model is not accurate enough to provide precise asset dimensions, it can be used in combination with the 360º panoramas to provide walkthroughs with smoother transitions, when compared to 360º-based walkthroughs. The Matterport SDK is used to provide the integration of the resulting walkthrough with the existing EPM system, enabling the user to interact with assets and retrieve their associated data and documents.

Each of the methods can be used for the development of interactive walkthroughs and 3D models to provide navigation of the facilities using a web browser to access a web-based EPM solution. Users can interact with existing assets and access their related data and documents. The workflow for each of the proposed methods is summarised in Fig. 3.

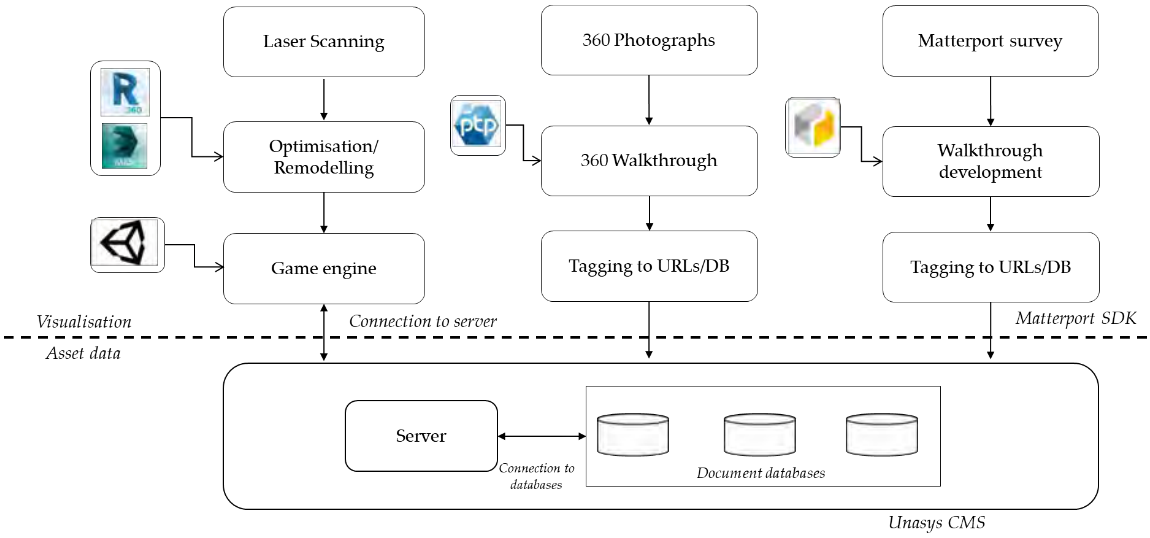

Fig. 3: Workflow for visualisation of the interior of industrial facilities and linking with associated documentation data

2.1.3 Development of 3D models for Oil & Gas subsea and pipeline assets from existing as-built drawings

Pipeline and subsea assets are of utmost importance for Oil & Gas owner/operators. For older facilities, 3D models of these assets are typically not available. In this research we propose remodelling the assets from the 2D as-built drawings and survey data. 3D models can then be linked to the underlying asset data and documents in the EPM system using a game engine or a 3D model viewer, providing interactive web-access to the 3D model and related asset data (Fig. 4).

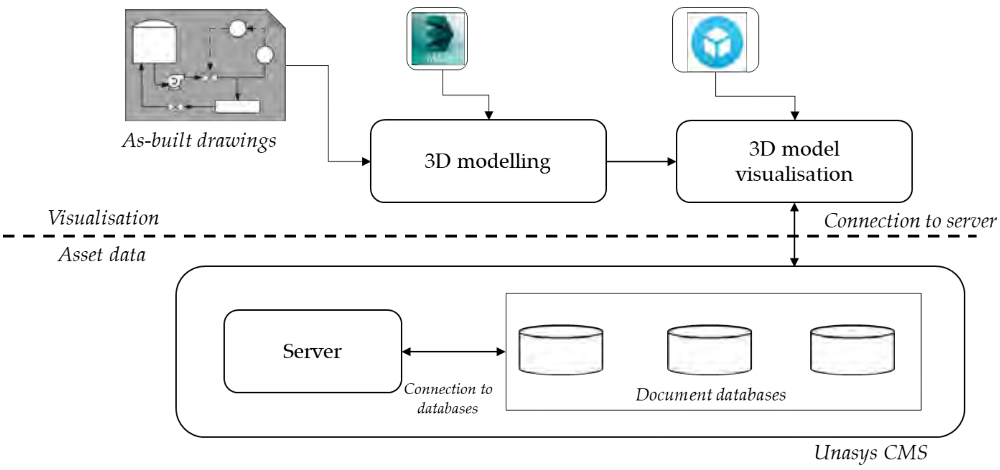

Fig. 4: Workflow for visualisation of Oil and Gas subsea and pipeline models and linking with associated documentation data

3. CASE STUDY

In this section we describe the development of a case study, consisting of the application of two reality capture techniques to survey and develop models for an existing energy facility. The goal of the case study is to develop interior and exterior models of the facility and link them to the underlying asset data in the EPM system to support the owner/operator during the operational stage of the facility lifecycle. To capture the exterior of the facility, a UAV survey was carried out, and a 3D model was obtained using photogrammetry. To capture the interior of the facility, a survey was performed using a Matterport camera. The resulting Matterport model was integrated with the EPM system using the Matterport SDK.

3.1 Exterior facility model

A UAV survey was carried out with the objective of obtaining a 3D model of the exterior of the facility. A DJI Inspire 2 drone with Zenmuse X5S camera was used in the survey, and the Pix4D Capture application was used to plan and fly a circular mission around the main building of the site. A total number of 419 photos were taken over an area of approximately 25000 m^2 at a height of 50m. The survey was completed within a single drone flight (circa 20 min.). The average Ground Sampling Distance (GSD) was 0.69cm. In this survey, Ground Control Points (GCPs) were not used.

After performing the survey, the Pix4D Mapper application was used to generate point cloud and mesh models of the facility, using photogrammetry. Generation of the point cloud and mesh models using the highest settings took around 14 hours using a laptop powered by a Quad core i7 CPU, 16 GB RAM, and a Nvidia GeForce 1050 graphics card. The resulting point cloud model included around 100 million points, resulting in an approximate density of 4000 points/m^2. The point cloud model was optimised using the Cloud Compare application, in order to provide a good user experience when accessing the model through the web-based EPM. Finally, the model was uploaded to Sketchfab and embedded in the EPM web interface.

An overview of the workflow adopted for the development of the exterior model of the facility is summarised in Fig. 5. The optimised point cloud model is provided in Fig. 6.

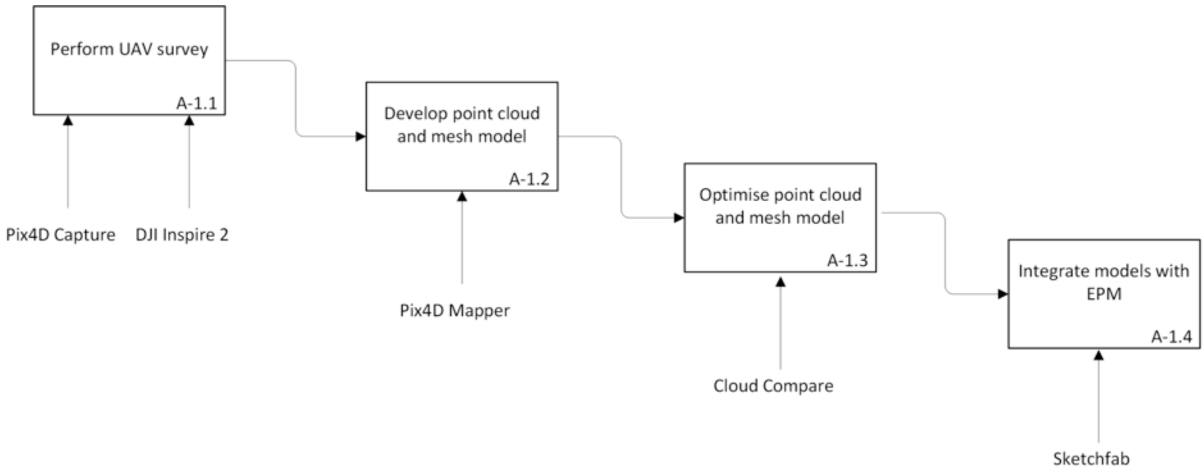

Fig. 5: Performing UAV survey and linking 3D model with underlying asset data – IDEF0 diagram

Fig. 6: Resulting point cloud model for the facility

3.2 Interior facility model

Within the framework proposed in this research, we consider a variety of methods to survey and develop interior models and walkthroughs of industrial facilities.

Previously we performed a laser scanning survey of a small Normally Unmanned Installation (NUI) (Patacas et al., 2017), and two 360º panoramic photographic surveys of a NUI and a Floating Production Vessel (FPV) (Patacas et al., 2018). For this case study, we used a Matterport Pro 2 3D camera to capture the interior of the facility's main building. As part of the planning process for the survey, we identified critical Systems and assets of the facility. Due to a limitation in the development of Matterport models (currently limited to a maximum of 200 scans per model) it was not possible to capture the entire facility within a single model. Therefore we focused the survey and model development on a single area of the facility.

After the survey was performed, a walkthrough was generated via the Matterport cloud service. The generated walkthrough was then linked to a custom in-house EPM solution, which contains all the corresponding facility data and documents. Using the Matterport SDK, integration is achieved at various levels, namely: Systems, Areas, and Tags. The relationship between these entities is summarised in Fig. 8. The walkthrough is embedded in the EPM system interface, allowing the user to navigate the facility walkthrough and interact with the assets in order to retrieve asset data. The user can also navigate the model structure and select the assets, which will highlight the asset within the walkthrough. An overview of the methodology is provided in Fig. 7. The users can interact with critical assets and retrieve the associated Tag data for the assets (Fig. 9).

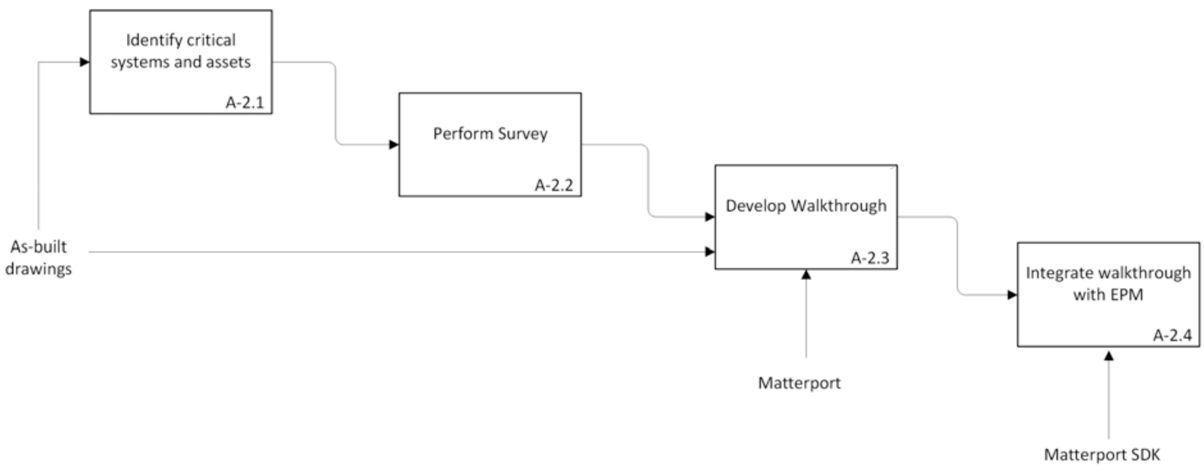

Fig. 7: Performing Matterport survey and linking Matterport Models with underlying asset data – IDEF0 diagram

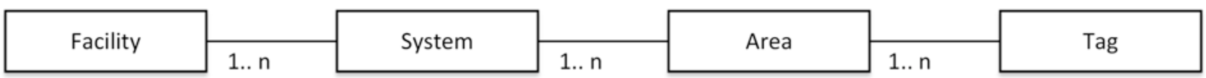

Fig. 8: Overview of relations between Facility, System, Area and Tag entities in the EPM system

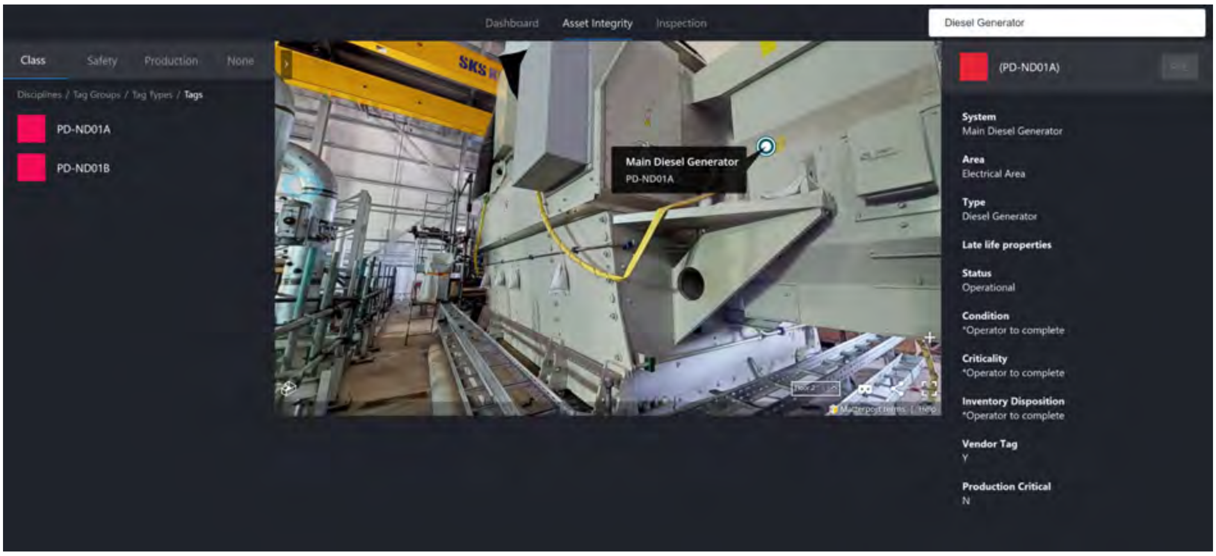

Fig. 9: Integration of Matterport walkthrough with EPM solution – visualisation of Tag data from an asset

4. DISCUSSION

4.1 Exterior facility model development

The execution of the UAV survey resulted in a very dense point cloud model (circa 100 million points). However, it must be noted that since we didn't use GCPs, the absolute accuracy of the model cannot be determined. Nonetheless, this methodology can be used to quickly capture and build a point cloud and 3D mesh model of existing facilities. In fact, while we used a laptop for generating the models, it is possible to use a cloud service (e.g. Pix4D cloud) for this task, which would speed up the model generation process.

In order to display the resulting point cloud model online, while providing a good user experience, we had to optimise the point cloud using the subsampling tool from Cloud Compare. This process consists of eliminating series of points, by specifying a minimum distance between points. In our methodology, we opted to use the point cloud model for visualisation, since the resulting mesh model resulted in visible loss in dimensional accuracy.

4.2 Interior facility model development

The use of the Matterport 2 Pro 3D camera and software allowed us to quickly perform the survey of one of the facility's modules, and generate the walkthrough model using the Matterport cloud service. Set up and execution of the survey takes a similar amount of time when compared with a 360º camera survey (considering the same amount of scans/photos), and is easier and quicker when compared to a laser scanning survey. Walkthrough development is provided by Matterport as a service, and is typically finished within a few hours after uploading the model. As a result it is easier to obtain a working model from the survey when compared to laser scanning and 360º photography survey methods. Since the walkthrough combines 360º imagery with a 3D model in the background, walkthrough navigation and transitions between 360º panoramas are much smoother than typical 360º-based walkthroughs.

There are however, a number of limitations regarding this approach. Since the walkthroughs are generated by Matterport as a service, the user can't edit the model and correct errors. Regarding accuracy, while the Matterport camera generates a 3D mesh model of the scene, this model is not accurate enough to provide asset measurements at the same level of detail as a laser scanning survey. Additionally, there is a limit in the number of scans that can be used in each model, making it unfeasible to capture entire industrial facilities in a single model.

Using the proposed walkthrough development methodology, it was possible to integrate the survey of part of an industrial facility with its underlying asset and documentation data, linking a Matterport model to a custom EPM solution. Integration was achieved at the System, Area and Tag levels. To enable navigation through the entire facility, URL links can be established within each module walkthrough to link the various facility modules together.

5. CONCLUSIONS

The framework proposed in this research identified key requirements to provide owners of energy facilities with an EPM to manage the late life and decommissioning stages of their facilities. These requirements include an overarching GIS interface, and visual, interactive models of the interior of facilities which can be used to retrieve Tag data about specific assets.

The framework proposes the integration of various visual data sources with a custom EPM solution to provide Owner/Operators with detailed information on how to maximise the use of their facilities during the late lifecycle stages and decommission the facilities safely and efficiently. The framework proposes the adoption of reality capture methods including: UAV survey to capture the exterior of facilities using photogrammetry; Laser scanning, 360º photography and use of a Matterport camera to capture the interior of the facilities, and; the development of 3D parametric models for subsea assets to support the maintenance and decommissioning processes of pipelines and wells for Oil and Gas facilities. The integration of GIS data is also highlighted as essential for planning maintenance and decommissioning tasks.

The reality capture and visualisation of exterior and interior facility models was demonstrated through the development of a case study. This was achieved by carrying out a UAV survey to generate a 3D model using photogrammetry, and; through the development of a walkthrough of the interior of an industrial facility using the Matterport camera and software, and their integration with an existing EPM system. The case study demonstrated how the proposed system can be used to retrieve Tag data about assets for operations and decommissioning procedures.

The proposed framework provides a roadmap for the development of dedicated EPM software solutions to support the operations and decommissioning of industrial facilities. Its implementation will provide facility Owner/Operators with a single interface where they can access and manage the various sources of facility data, including GIS data, visual interactive models, and asset data and documents needed for the late life and decommissioning stages.

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DEVELOPMENT OF A BIM-BASED PROGRAMME FOR THE FACILITIES MANAGEMENT OF CARE AND ATTENTION HOMES OF ELDERLY AND DEMENTED ELDERLY

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ABSTRACT: *In recent decades, hundreds of care and attentions (C&A) homes have been constructed to accommodate elderly and demented elderly in Hong Kong (HK). However, the facilities management (FM) of the C&A homes was often unsatisfactory due to the lack of deep understanding of elderly and demented elderly needs for facilities in their living environment in realistic situation. The poor FM has long been causing negative consequences to the society (e.g., elderly illness and accidents). Hence, the current study aimed to address this critical issue through the development of a Building Information Modeling (BIM) programme to support the FM of the C&A homes of elderly and demented elderly. To facilitate the FM for both normal elderly and demented elderly in the C&A homes, a number of BIM-based FM family members have been created, embracing different types of windows, doors, lighting, mobility aids, cabinets, etc. All the FM family members have been integrated into the BIM programme, which are displayed in two browsers (i.e., project browser for building components, and property browser for detailed information). A demonstrating case was also reported to show the efficiency of the developed BIM-based FM(C&A) programme in the design and management of the C&A homes. The work reported in the article mainly contributed to the further development of BIM Revit (i.e., the BIM-based FM(C&A) programme and various elderly specific family members, all of which are expected to facilitate the FM of the elderly C&A homes.*

Keywords: *BIM; Care and Attention Homes; Demented Elderly; Elderly; Facilities Management*

1. INTRODUCTION

With the increase in life expectancies, Hong Kong (HK) has long becoming an aging society. It was expected that the number of elderly in HK will account for 38% of the total population in HK in 2035 (i.e., a rise by 1.2 million from 2015 to 2035 to reach around 2.86 million) (Census and Statistics Department 2017). To accommodate the big elderly population, a lot of care and attention (C&A) homes have been constructed (Subcommittee on Retirement Protection 2012). It was necessary to ensure that the elderly are able to live their golden years in safe environments and enjoy healthy social lives, which make a good facilities management (FM) practice in C&A homes critical and essential.

However, it is reasonable to infer that the FM of the elderly C&A homes should be often unsatisfactory for the elderly. On one hand, the designers of the elderly C&A homes may be lack of experience in terms of both the knowledge and practices for the design of elderly C&A homes, and thus, are not able to fully understand the special needs of elderly and demented elderly in the C&A homes. On the other hand, C&A homes operators also found it difficult to imagine the proposed design simply based on the traditional technical drawings. In fact, there was also lack of efficient tools supporting the design and management of the C&A homes for satisfying the specific needs of elderly and demented elderly. Based on a preliminary FM guideline which was established with an extensive literatures and a group of experts for the elderly C&A homes (Leung 2017), current study reports the efforts to develop a BIM-based FM(C&A) programme which incorporated various BIM-based FM (C&A) family members specific for the elderly C&A homes by using the BIM Revit as a basis.

2. FACILITIES MANAGEMENT OF ELDERLY C&A HOMES

In HK, there were over 700 C&A Homes constructed to accommodate elderly (Hong Kong Social Welfare Department 2015). In general, C&A homes should offer residential, personal and certain cares to the elderly residents (The Hong Kong Society for the Aged 2011), through the provision of function rooms (i.e., space), adequate building services (e.g., ventilation & lighting), and other supporting facilities (e.g., handrails, and furniture). Indeed, the FM of C&A homes is of critical importance to ensure quality of life of the elderly in the

C&A homes.

FM are the practices to coordinate the various aspects of built environment with the elderly needs in the C&A homes in order to ensure their health and well-beings (Alexander 1996; Leung et al. 2016). The FM included three main aspects, namely space management, building services and supporting facilities components (Leung et al. 2014, 2017). The space management of C&A homes concerns about the needs of elderly for space, including the size of function rooms, distance between function rooms, and overall home layout. The building services perform certain functions in order to ensure the normal operation of the C&A homes, including lighting, ventilation, water supply and so on. Supporting facilities are also necessary to be in place to support the needs of the residents, especially the elderly one whose physical strength and health conditions keep deteriorating with aging. The general supporting facilities in C&A homes include furniture, recreational facilities, windows, signals and doors, while special considerations should be given to elderly when providing the supporting facilities to them.

3. BIM FOR THE FACILITIES MANAGEMENT OF ELDERLY C&A HOMES

The concept of Building Information Modeling (BIM) was proposed in 1990s, and, it is gradually becoming one of the hottest techniques applied in construction industry (Victor 2012). BIM provides a digital representation of the physical and functional characteristics of a facility. It extends the concept of 3D modeling to include three primary spatial dimensions as well as a fourth dimension (time) and a fifth dimension (cost). In addition, BIM accounts for spatial relationships, light analysis, geographic information, and the quantities and properties of building components (Vanessa 2012).

For its application in construction industry, BIM can be used to represent various aspects of construction projects by multiple-disciplines professionals, including architecture for architectural presentations, engineers for structural and building services engineering design, quantity surveyors for cost control and bill quantities, project managers for construction programme scheduling and material flow, and facilities managers for facility management. BIM can also serve as a platform to allow all professionals to efficiently and effectively communicate with each other for projects, and to prevent conflicts /clash among different disciplines (e.g., the common clashes between building services layout (drainage pipe) and structural members (beams).

The C&A homes are traditionally displayed by floor plan drawings that are composed only of lines and arcs, and the floor plans cannot show items installed in ceilings or walls, such as wall-fans, air conditioning systems, fire safety systems, and so forth. It was often difficult and time consuming for end-users (e.g., C&A homes managers) to understand an entire facility of a C&A home. With the BIM that allows for 3D demonstration of the C&A homes, the user can easily and quickly understand the entire condition of a C&A home by enabling all items to be shown for better understanding. BIM also allows users to insert unlimited information into the software. Hence, the FM tools can be included as add-ons to establish new BIM programmes, encompassing various aspects, including energy consumption, maintenance and life cycle cost for FM.

4. BIM-BASED FM(C&A) PROGRAMME

4.1 The Framework

It was envisaged that the developed BIM-based FM(C&A) programme will be used to effectively and efficiently produce C&A homes with appropriate FM for the elderly and demented elderly. There were several professional software provided by different companies that can be used to establish BIM models, including Allpan, ArchiCAD, Microstation, Revit, and Vectorworks (Epstein 2012; Graphisoft 2013). Despite the differences in functions between the software, the Autodesk Revit is the most commonly used BIM programme in the construction industry. Therefore, Revit was used in current study to develop BIM-based FM(C&A) programme and various elderly specific family members in the elderly C&A homes.

A conceptual framework for the BIM-based FM(C&A) programme was shown in below Figure 1. It includes a user interface section consisting of project and property browser, and a database section with a number of FM(C&A) family members.

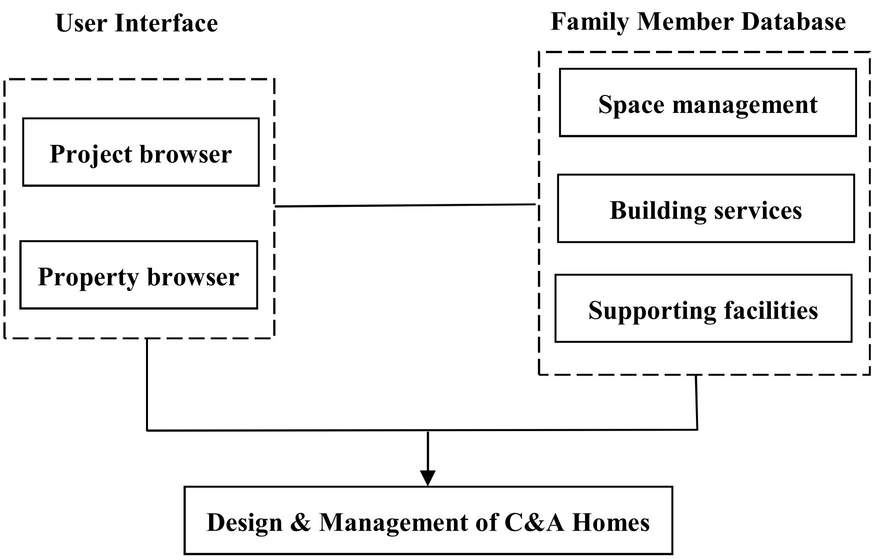

Fig. 1: Conceptual Framework for BIM-based FM(C&A) Programme

4.2 User Interface Section

All the developed BIM-based FM (C&A) family members have been integrated into a BIM programme, which comprises two browsers (i.e., a project browser for building components such as architectural floor plans, ceiling plans, structural plans, etc.; and a property browser for detailed information on building components and family members) (see Figure 2).

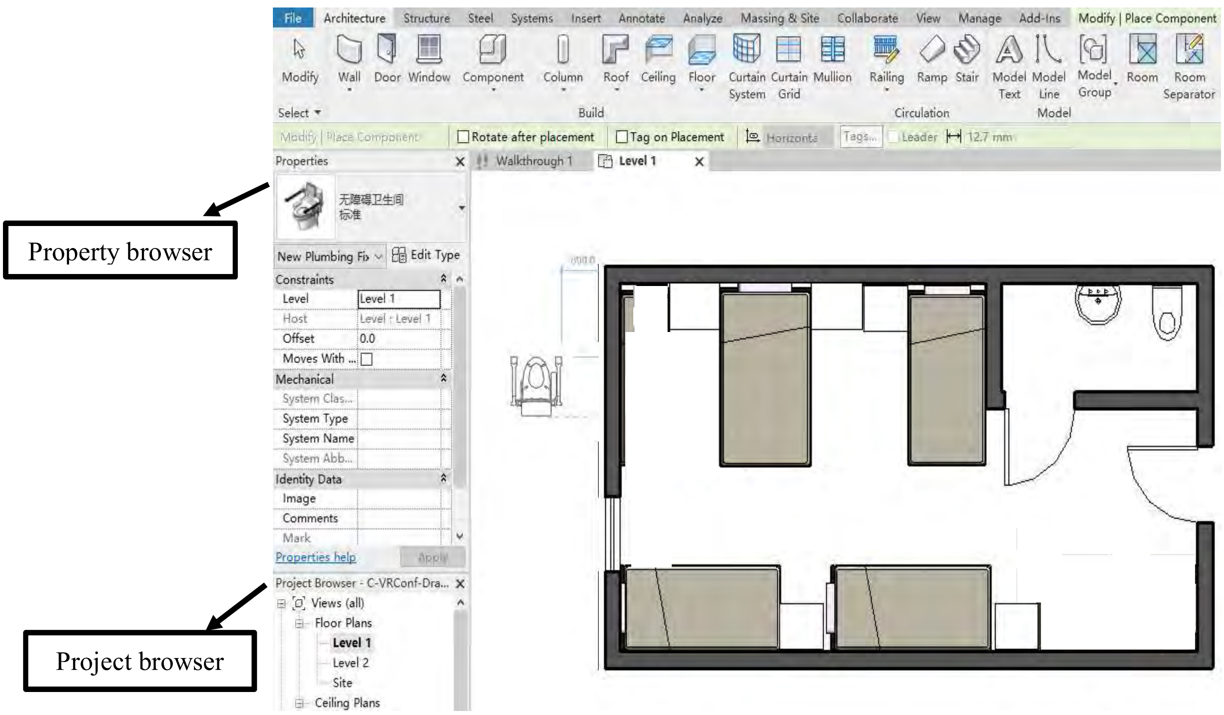

Fig. 2: BIM-based Programme for FM(C&A) Homes

4.3 Family Members Database Section

In total, eighty-eight FM family members, including 12 space management-related members (i.e., internal and external space management family members), 11 building services-related members (e.g., lighting, ventilation and air-conditioning, lifts, pumping and CCTV) and 65 supporting facilities-related members (e.g., windows, fixtures and furniture, signage, hygiene services, mobility aids, and creation and fitness), were created and incorporated into the BIM-based FM(C&A) programme.

1. **Space Management**
   Internal (e.g., doors, staircases, etc.), External (e.g., chairs, bench, planter, etc.)

2. **Building Services**
   Lighting, Ventilation and air-conditioning, Lifts, Pumping, CCTV

3. **Supporting Facilities**
   Windows, Fixtures and furniture, Signage, Hygiene services, Mobility aids, Creation and fitness

Facilities for normal elderly and demented elderly with different mobility capabilities may be varying (i.e., able elderly without dementia, disabled elderly with walking assistance but without dementia, disabled elderly with wheelchair but without dementia, able elderly with dementia, disabled elderly with walking assistance but with dementia, disabled elderly with wheelchair but with dementia). Therefore, the FM family members in the C&A homes have to be designed according to their specific mobility and cognitive capacities (see Table 1 for part of the list of the BIM-based FM(C&A) family members).

Table 1: Examples for the BIM-based FM(C&A) Family Members

BIM-based FM(C&A) Family Member		
Family members	**Non-Dementia elderly**	**Demented elderly**
Door	DR1, DR2, DR3	DR1, DR5, DR6
Lift	Lift-1, Lift-2	Lift-1, Lift-2
Wardrobe	WDE-1c, WDE-2	WDE-1a, WDE-1b
etc.		

For example, doors with the size of 2,150 x 1,050 x 50 mm (i.e. DR1b in Figure 3) and 2,150 x 1,200 x 50 mm (i.e. DR6b) were designed for able elderly and disabled elderly respectively. For the disabled elderly with dementia, alarm should be placed on the door (i.e. DR6a) in order to alert caregivers for demented elderly leaving the homes.

DR1b (able normal elderly) | DR6b (disable normal elderly) | DR6a (disable demented elderly)

Fig. 3: Doors for Different Elders (able/disable ; normal/demented)

5. APPLICAION FOR ELDERLY ACCOMMDATIONS

To check the efficiency the developed BIM-based FM(C&A) brought, a redesign case for the elderly bedroom was presented in this study. The layout plan of the bedroom was shown in below Figure 4, which included three beds for the normal able elderly (1-side open for individual movement) and one bed for disable elderly (2-sides open for helpers) along with some basic facilities including cabinet, and sanitary facilities. It was found that the bedroom door was not suitable for the disable elderly with mobility issues (i.e., narrow doors preventing use of wheelchair, lack of barrier-free facilities, etc.).

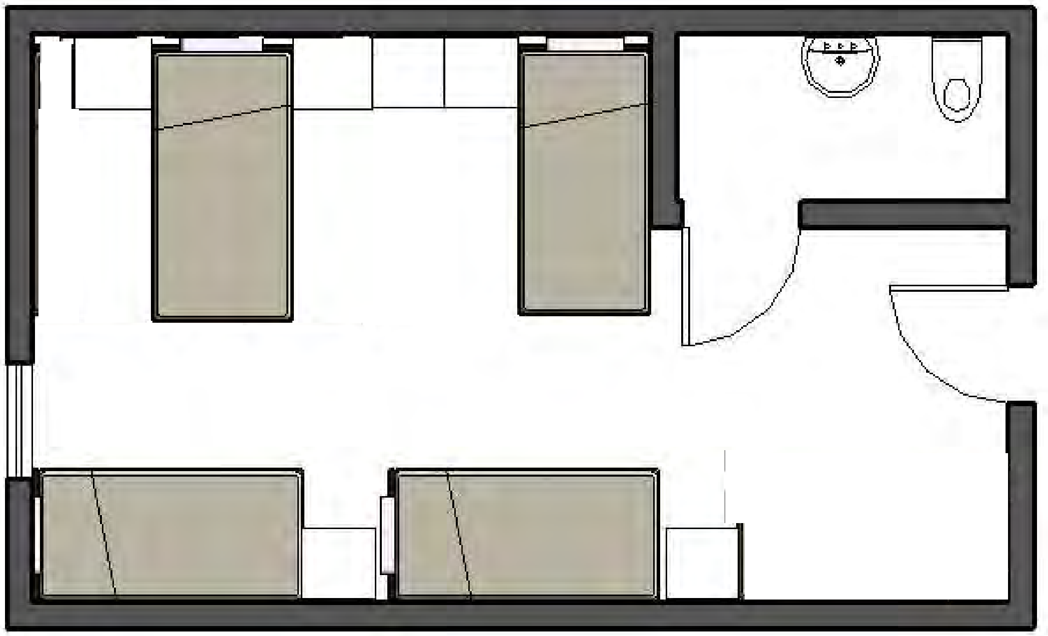

Fig. 4a: Dormitory with DR1 for Able Elderly

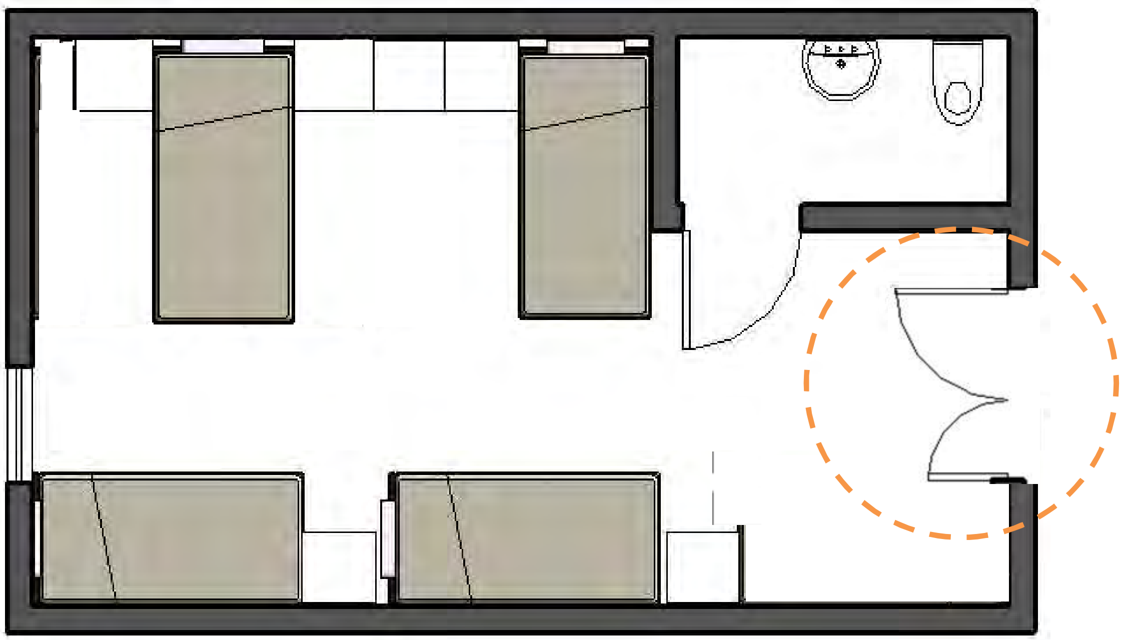

Fig. 4b: Dormitory with DR6 for Disable Elderly

In addition to provide appropriate door, the elderly and demented elderly should be allowed for more space and elderly-specific facilities (e.g., barrier-free stationary). Therefore, in the current demonstrating case, two beds were moved away, and more elderly-specific facilities were added. These revisions were made by simply calling out family members from the created BIM-based FM (C&A) family members database and loaded into the BIM model, and placed at appropriate location of the bedroom. It was also allowable for the user of the BIM-based FM(C&A) programme to check their design against the incorporated FM (C&A) guideline. The floor plan of the redesign was shown in below Figure 5. After loading the double-leaf door in the model and redesign the floor layout of the dormitory, the designers and end-users were able the view the characteristics of the bed. It was also allowable to check the bed and the whole bedroom environment in 3D view, which definitely enhanced the understanding of the entire FM of the elderly bedrooms (see Figure 6).

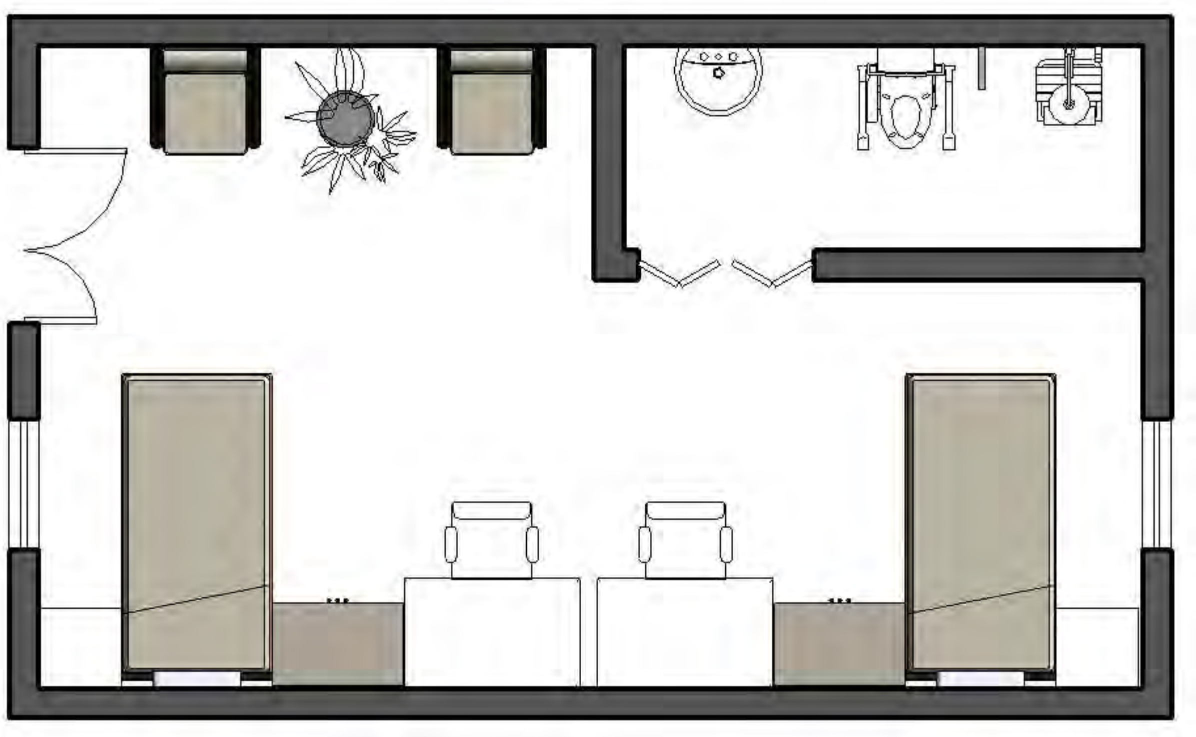

Fig. 5: Redesign of the Bedroom Using the BIM-based FM(C&A) Programme

Fig. 6: 3D Demonstration of the Redesigned Elderly Dormitory

As demonstrated by the case, the BIM-based FM(C&A) programme could greatly improve the work efficiency of the designers, as it saved the time for tailor-made elderly specific facilities one-by-one. As a whole, the further developed BIM-based FM(C&A) programme was able to enhance the communications between designers and end-users (e.g., facilities managers and elderly), which was fundamental to ensure a friendly and safe environment for the elderly in the C&A homes.

6. SUMMARY

Nowadays, a number of C&A homes have been constructed in HK to accommodate elderly citizens. To better design and manage the C&A homes for the health and well-beings of elderly and demented elderly, it was necessary to enhance mutual communication and understandings between the construction professionals and end-users of the C&A homes (staff and elderly). Applying the Autodesk Revit software, a BIM-based FM (C&A) program comprising project browser and property browser, and a number of BIM-based FM(C&A) family members were created to cater the diverse needs for the facilities of elderly with different mobility and cognitive capacities. It was definitely sure that the developed BIM-based FM(C&A) programme will support professionals (architects, building services engineers) and staff in the C&A homes (superintendents, social workers, care givers, etc.) to effectively and efficiently design and manage the facilities for elderly and demented elderly in the C&A homes.

7. ACKNOWLEDGEMENT

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THE PERCEPTION OF RETURN ON INVESTMENT OF BUILDING INFORMATION MODELLING AMONGST MALAYSIAN DEVELOPERS

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ABSTRACT: *Building Information Modelling (BIM) was introduced in the Malaysian construction industry in 2007. However, Malaysian developers are reluctant to implement BIM because they could not see the benefits in monetary terms. This paper aims to determine the impact of BIM towards Return on investment (ROI) from the developer's perspective. A literature review was carried out to review the linkage between BIM and ROI. The study engaged four (4) respondents who were experienced in BIM for primary data collection. Data was collected through face-to-face semi-structured interview sessions and was analysed using the qualitative content analysis technique. The findings show that BIM had impacted on the ROI of both the project and organisation. At present, these findings support the argument that BIM impacts ROI, both positively and negatively. However, the findings prove that BIM is worthy of its pricey initial investment. It is therefore suggested that Malaysian developers invest in BIM in spite of the pricey initial investment.*

KEYWORDS: *Building Information Modelling (BIM), Return on Investment (ROI), Construction Industry, Malaysia*

1. INTRODUCTION

The construction industry plays an important role in the growth of Malaysia's economy and had showed a steady growth in performance over the years. This industry is one of the productive industries that has contributed significantly to the Malaysian economy to enable the growth of other industries (Department of Statistics Malaysia, 2016). The importance of the construction industry was recognised and has been incorporated into the Eleventh Malaysia Plan. Furthermore, this industry provides jobs for professionals such as architects, engineers and surveyors, and to others such as main contractors, subcontractors, and suppliers (Ofori, 2015). Therefore, the construction industry can be described as an important cog in the wheel that propels the Malaysian economy.

Building Information Modelling (BIM) can be viewed as both a process and technology that can improve the construction industry. Its implementation is said to provide benefits to construction projects and the parties involved (Succar and Kassem, 2015). BIM is said to provide benefits to the construction projects (Succar & Kassem, 2015) and parties involved (Azhar, Khaflan & Maqsood, 2012). The benefits derived from BIM include better design, problem reduction and increases in project profitability (McGraw Hill Construction, 2014). Better design produced allows designers, contractors and developers to have a better understanding of the design through the 3D or 4D models. Through the 3D or 4D models, BIM is able to detect several problems at the preliminary stage (Martins & Monteiro, 2012). For example, design clashes and cost overrun. Doumboya, Gao and Guan (2016) had summarised some benefits which are, better design assessment during the preliminary stages, reduced financial risk due to accurate cost estimation including better project profitability in terms of return on investment (ROI). However, developers are still reluctant to implement BIM into their projects (CREAM, 2014). This is because the cost-savings benefits such as ROI is yet to be proven (Giel & Issa, 2013). The lack of data on ROI through BIM is mentioned as one of the top factors, which halts its implementation (Zahrizan *et al*., 2013).

This study aims to observe the impact of BIM on ROI as BIM is said to increase the ROI of a project, as suggested in several research. However, the reliability of most of the analysis for ROI through BIM is doubtful (Lee, Park, and Won, 2011). The results lack details of methods used for analysing the data that weaken the reliability on the ROI through BIM. The benefits of BIM were directly proportional to the level of experience of the developers (McGraw Hill Construction, 2014a). New users tend to record negative ROI due to lack of knowledge of BIM. However, BIM could be counter-productive if the level of experienced users were low (Eisenmann and Borinara, 2012). This study directly address issues like disagreement on the reliability of studies on ROI through BIM from the perspective of developers. A brief summary of BIM and ROI is provided in the next section, followed by the methods used, results and discussion, and lastly conclusion.

2. LITERATURE REVIEW

This section discusses on the BIM and ROI to show the its linkage.

2.1 Building Information Modelling (BIM)

In the Malaysian context, BIM is defined as a modelling technology and its associated set of processes to produce, communicate, analyse as well as apply the usage of digital information models throughout the life-cycle of a construction project (CIDB, 2016). The Government is very keen in increasing the adoption of BIM and thus, making it compulsory for all public projects through a mandate (Rogers, Chong & Preece, 2015). The Malaysia Government had taken initiatives to increase awareness of BIM and encourages developers to implement it. These initiatives could only be successful through the collaboration of multiple players in the construction industry. A BIM committee was established to identify the suitable platforms for construction projects (Ahmad Latiffi, Mohd & Brahim, 2014). A BIM Unit Project was established by the Construction Industry Development Board (CIDB) to prepare BIM Standard Manuals and Guidelines (Ahmad Latiffi, Mohd & Brahim, 2014) and a BIM Roadmap as a standard guideline to make BIM compulsory in Malaysia for design-and-build and conventional projects based on contract values (Ahmad Latiffi, Mohd & Brahim, 2014).

Furthermore, CIDB also developed a BIM Portal that contains a good deal of information regarding BIM (CIDB,2016). On top of that, CIDB has developed a training syllabus and has since offered training on BIM Tools for those who are interested or intended to use BIM. There are many construction projects initiated by the Government to implement BIM. In fact, there are very few projects in Malaysia that had successfully adapted BIM such as the National Cancer Institute in Putrajaya and the ELITE Pavillion in Kuala Lumpur (Ahmad Latiffi, Mohd & Brahim, 2015).

2.2 Return on Investment (ROI)

Return on Investment, ROI, is sometimes referred as the rate of return, and is one of the many ways used to evaluate proposed investments (Sen, 2012). Management uses ROI to measure the performance of an investment by evaluating the capital expenditure proposals (Ang, 2012). ROI calculation for BIM investment allows users to reach an agreement regarding money spent and expected earnings (Autodesk, 2007). However, when applying ROI to BIM, ROI is measured as net savings to the costs because the potential savings from this technology is considered as profit to contractors, designers and other involved parties (Sen, 2012).

2.3 BIM on ROI

BIM and ROI are interrelated as the benefits of BIM are directly proportional to the level of experience of developers (McGraw Hill Construction, 2009). The potential savings in a BIM project is estimated to range from 15% to 40% (Holness, 2006). Another research had also indicated the average ROI gained from BIM ranges from 634% to 1633% (Azha, Hein & Sketo, 2008). These findings prove that BIM has positive effects towards the ROI.

However, BIM does not always increase the ROI (Bercerik-Gerber & Rice, 2010). A survey shows that 11.9% of respondents had calculated a decrease in ROI (McGraw Hill Construction, 2009). This is because investment is made during the first few years of BIM implementation. Thus, it impacts negatively on performance, which will produce a negative ROI. Hence, it can be concluded that BIM does not necessarily increase ROI.

Furthermore, a survey shows about 69% and 80% of developers in the United States of America (USA) and The United Kingdom (UK) respectively who have experienced using BIM had gained a positive impact in ROI (McGraw Hill Construction, 2014). This shows that different levels of expertise have a different perceived ROI from BIM (Ahmad Latiffi, Mohd & Brahim, 2015). Experienced users are said to be most impressed with the potential reduction in cost and the ROI gained. It can be concluded that the higher the level of expertise of developers, the higher the perceived ROI gained (McGraw Hill Construction, 2009).

3. METHODOLOGY

This section discusses the method selected for this research. It is divided into two (2) parts; methods and tools, and the respondents.

3.1 Methods and Tools

This study used the qualitative approach as it focuses on the meaning, experiences and understanding (Ezzy 2013) as well as allowing the researcher to interact with individuals or groups whose experiences are what the researchers want to know (Parkinson & Drislane, 2011) This is because BIM is a comparatively new concept among developers in Malaysia and that most of those contacted are assumed to be not obliged to share understandably 'sensitive' data.

The method chosen was a qualitative survey, which is about the exploration of thoughts (Smith, 2015). It involves open-ended questions with no direct numerical values. This study was conducted through an in-depth interview or explorative expert interview. In-depth interviews allow interviewees to state their opinions regarding the topic and it enables the interviewer to understand the interviewees' view (Parkinson & Drislane, 2011). The parts that emerged from the interviews will be:

- Part A – The effect of BIM toward ROI
- Part B – Potential Improvement

These respondents were selected based on their understanding and experiences in managing BIM projects. All respondents worked as BIM managers in developer companies that had implemented BIM. Though the number of respondents was only four (4), the results gained are valid and able to act as a preliminary study on the developers understanding of BIM and ROI, that could be further expanded.

The data collected was analysed using the qualitative content analysis method. In adopting this method, the initial phase of analysis focussed on the written interview transcripts and summarised stories produced from the raw data (Smith, 2015). Content analysis involved the transformation of data into text, such as reducing the data collected into a manageable and informative database.

3.2 Respondents

A total of four (4) respondents, who were BIM Managers, representing four (4) different organisations participated in this study after several selections. Table 1 shows the background of organisations, respondents and their classification.

Table 1: Organisation Background

Respondent	Organisation	Years of Experience in BIM	Classification
R1	A	2	BIM Beginner User
R2	B	7	BIM Experienced User
R3	C	7	BIM Experienced User
R4	D	5	BIM Moderate User

R1 work in Organisation A that had implemented BIM for 2 years, and can be classified as a BIM Beginner User. Both R2 and R3 worked in Organisation B and C that had implemented BIM for 7 years and R4 worked in Organisation D that had implemented BIM for 5 years. These organisations were classified in accordance with the years of experience in BIM (McGraw Hill Construction, 2014a).

These organisations had been implementing BIM on multiple types of project, more specifically high-rise buildings. As these organisations are developers, BIM is often used as a managing tool. For example, BIM is used to manage the design of the projects, simulation of planning and facility management. All respondents were experienced in terms of managing BIM projects. Therefore, the respondents and organisations chosen are suitable for this study based on their position and years of experience with BIM.

4. RESULT AND DISCUSSION

This section discusses the usage of BIM among respondents and the effect of BIM towards the ROI in the organisation that implemented BIM.

4.1 BIM Effect on ROI

The evaluation of ROI of BIM projects is always a concern of construction parties especially developers (Giel, 2009). One of the reasons that slows down the usage of BIM among developers is, the lack of a detailed exploration on the ROI of BIM projects (Becerik-Gerber & Rice, 2010). Though lacking in information, developers who implement BIM can notice some differences in the ROI (Ahmad Latiffi & Ng, 2017). Table 2 shows the opinion of respondents towards the effect of BIM on ROI.

Table 2: Effect of BIM on ROI

Respondent	Annotation
R1	*"We noticed a slight difference in the ROI of a BIM project and non-BIM projects."*
R2	*"Of course there would be differences. The ROI for BIM projects will be higher than non-BIM projects in terms of profit, time, quality and productivity. For us, BIM saved up the most during design and planning stage because we only use BIM in these two stages."*
R3	*"There will be differences but it depends on the type of the project. Over the time, we can slowly see the improvement of ROI of BIM projects."*
R4	*"So far we could see that the ROI of a BIM project is a little higher than non-BIM projects, especially during the designing stage because it cuts out most cost and time. For example, the clashes are fixed during the design stage resulting in less to no reworks needed during the construction stage."*

All respondents except R1 agreed that the ROI of projects using BIM is higher than conventional projects. This is because R1 did not fully implement BIM in their project. R1's explanation is given below.

"We are currently implementing BIM in one of the construction stages, namely the designing stage. Still, we managed to notice some differences though not significant."

(R1)

However, the percentage of increments of the ROI depends on how well the performance of the management team is and the level of understanding of BIM as explained by R2. The ROI increases because the cost is reduced. The statement is agreed by R2 and R4. R2 revealed that ROI of a project increases the most in the design and planning stage. The viewpoint is supported by R4 who stated that BIM helps to reduce the cost and shorten the time of the design stage. R4 stated that BIM reduces the cost through reducing reworks based on clashes solved during the design stage. This viewpoint is in line with the statement that costs are saved during the construction stage (Barlish & Sullivan, 2012). Furthermore, the amount of material needed will be lesser, which will reduce cost as well (Mitchell, 2013). The benefit of cost reduction as explained by R4:

"Clashes are usually the ones that cause the increase in the cost during the construction stage. With BIM, clashes can be reduced, subsequently, reduces reworks during the construction stage. All the reduction also means that cost is maintained. We do not need to fork out extra money just to fix the clashes."

(R4)

The findings are in line with the findings of Giel & Issa (2013) and Barlish & Sullivan (2012) that, ROI for projects using BIM are higher than conventional projects (McGraw Hill Construction, 2014b). Though BIM project's ROI are said to be higher, the organisation's ROI is affected (Ahmad Latiffi & Ng, 2017), which appears to be true. Table 3 shows respondents' opinion on the perceived ROI gained.

Table 3: Perceived ROI gained

Respondent	Annotation
R1	*"There is. It usually decreases within the first few years after implementation because it needs an amount of investment, which is not a small amount. In my opinion, it may take up to 3 to 5 years to see an improvement in ROI, but for our company we are currently seeing a slight decrease in ROI due to buying licenses software and upgrading our hardware."*
R2	*"It will be ridiculous to say that you could see an increase in ROI right after the first year. Usually, it will decrease in first to two years due to investment such as hiring professionals and training, but it took a range of time maybe will take up till 5 years' times to see an increase of ROI. Our organisation is currently recording an increment in ROI."*
R3	*"All of us have to go through a learning curve. After you pass the first step, you may have stuck at the second stage, which is why there will a drop in the first few years. During the first few years, we had suffered from investments and failure of pioneer projects. At least a range of 3 to 5 years needed to an increase in the ROI. We are finally able to see some increment in the ROI."*
R4	*"Yes of course. The learning curve actually will tell you that it takes time to see improvement. And we have to take the risk to invest in new technologies. Our company had just started using BIM like in June 6th, 2012. It was launched officially by our Prime minister. So to say it increase or decreases, to us, it's currently breaking an even. Means, we are just recovering our ROI back to the previous state after implementing BIM which is a good motivation for us to keep continue using BIM."*

Based on the findings, all organisations had unanimously recorded a decrease in ROI during the first few years of BIM implementation. R1 revealed that the ROI for their organisation had recorded a decrease because many investments such as purchasing software and upgrading hardware are made during the first few years of implementation of BIM. This viewpoint is agreed by R3 that BIM implementation requires an amount of investment. R3 states that investment is needed to implement BIM, especially on hardware and software (Jupp, 2013), which was supported by R1 and R2.

"In order to implement BIM, a large sum of investment is needed. All the hardware upgrades and software need money, even sending staff for training need money or employing professionals also need money."

(R3)

"It usually decreases within the first few years after implementation because it needs an amount of investment. The investment is not only in terms of monetary but also the time to change the whole conventional management into BIM."

(R1)

"Usually, it will decrease in first to two years due to investment. We have to continuously convince the top management that these investments are worth."

(R2)

"We just have to take the risk to invest in new technologies. Though it is not as smooth as we think so, in order to move forward, we have to endure these profit lost until we successfully implemented BIM."

(R4)

On top of that, a higher level of expertise of BIM users is said to be have better benefits in terms of ROI (McGraw Hill Construction, 2014a) and that the ROI recorded is directly proportional to the level of expertise of the BIM user (Holness, 2006). Thus, the higher the level of expertise of users, the higher the perceived ROI gained. Table 4 shows the ROI of the organisation in the first year and current year of BIM implementation.

Table 4: Variation of ROI of Organisations

Org	Respondent	Classification	1st Year ROI	Years of Implementation	Current ROI
A	R1	BIM Beginner	↓	1 and ½	↓
B	R2	BIM Experienced	↓	5	↑
C	R3	BIM Experienced	↓	5	↑
D	R4	BIM Moderate	↓	3	Break-even

Note: ↓ indicates reduce; ↑ indicates increase

As in Table 4, Organisation A, which has been classified as a BIM Beginner is still recording a decrease in ROI after 1 and ½ years of implementation.

"We are currently seeing a slight decrease in ROI. We have yet to see any profit gained from BIM, though we have invested heavily in implementing BIM. But, our hopes are high and looking forward on the future ROI once our BIM unit had stabilised."

(R1)

On the other hand, Organisation B and C, which are classified as BIM Experience have seen an increment after 5 years of implementation. R2 explained that the decrease in the ROI in the first year was due to investment made on the BIM tools and the hiring of professionals to train their employees (Johansen & Shahrin, 2013) while R3 stated that their organisation had suffered from some failed projects during the first year of implementation, which caused them to suffer losses. Both R2 and R3 statements are shown below.

"Our organisation is currently recording an increment in ROI. Throughout our BIM journey, we always have our ups and downs. A piece of advice to all Malaysian developers, BIM is all about investments. The earlier you invest, the earlier you will taste the sweetness of the fruit."

(R2)

"We are finally able to see some increment in the ROI and prove to our top management that all the BIM benefits that were mentioned out there are true. There are times where our management team almost gave up because of the past failure BIM projects. However, we have finally managed to overcome the hard stage."

(R3)

Organisation D had recorded a break-even result in its third year of implementation, which means neither reduction nor an increment. A further explanation is shown below.

"It's currently breaking even. It means that we are just recovering our ROI back to the previous state after implementing BIM."

(R4)

This finding is in conformity with Jones (2011) that ROI will continue to increase once the new investment has been stabilised (Jones, 2011). All respondents agreed that it takes about three (3) to five (5) years to see improvements in the ROI of an organization. Therefore, the ROI of an organisation will start to see an increment after a range of three (3) to five (5) years. The findings differ from Becerik-Gerber & Rice (2010) that, it takes up to six (6) to eight (8) years to see improvements in ROI.

5. CONCLUSION

Malaysian developers have some understanding towards BIM and are aware of the benefits. However, they are reluctant to make investments in BIM. The findings indicate that, the ROI of BIM projects are higher than conventional projects. This is because BIM saves cost and time as well as improve the quality of the project. Apart from that, BIM is said to affect the ROI of the organisation both negatively and positively based on their experience in managing BIM.

BIM is the current trend in construction and is undeniably able to push the construction industry forward. In future, there will not be "What is BIM?" but "how to implement BIM". Many studies have proven and demonstrated the uses and benefits of BIM. Therefore, developers are advised to adopt BIM before they are labelled as incompetent and eventually left out. This study on the perception of ROI through BIM is indispensable to encourage and increase the awareness amongst construction parties to implement it in the construction industry.

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AR REPRESENTATIOM OF HANDWRITTEN NOTE FOR INFORMATION SHARING AT WORKSITE

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ABSTRACT: *Recent years, mobile devices prevail in many on-site workplaces. Writing a working paper with a mobile device while the fieldwork leads to effective collection and sharing of work records. This paper aims efficient sharing of working information by AR (Augmented Reality) representation for the on-site work so that the handwriting notes show the essential instructions and directly indicate the physical points to pay attention through a mobile device in realtime. We store the hand-written contents on the mobile device display as an image, from which we extract natural feature points. Using the feature points to estimate the camera position relative to the physical object in a 3D coordinate, markerless AR can be achieved to appear the handwritings float on the physical space. This AR representation allows not only handwritten input other than typed texts, but also intuitive instructions and recordings for the other workers in real space through a smart device camera. We prepare two types of AR representations; one is to stick the message on a specific object, the other is to keep facing the user like a billboard style. This paper reports the implementation and performance evaluation of the proposed method, assuming a warehouse-like working place usage.*

KEYWORDS: *Handwritten Note, Markerless Augmented Reality, Worksite, Information Sharing*

1. INTRODUCTION

The social capital stock of the country was intensively developed in the period of high economic growth in the 1950s and 1970s in Japan, and there is concern that rapid deterioration will occur in the near future. In the next 20 years, the proportion of facilities that are 50 years old or more after construction is expected to increase at an accelerated pace, and it is required to strategically maintain and update the aging infrastructure all at once. In addition, while the maintenance and management work of those continues to increase, the number of employed workers continues to decrease. In Japan, the aging of workers has also progressed, the baby-boom generation that has been supporting the site until now has retired and the technical ability cannot be passed down, so the problem is that the work depends on personal skill. Since early entry of workers who are not so experienced in the field is necessary, transmitting and sharing detailed information is crucial for each work site. To improve the work quality and improve the work on site efficiently, use of portable smart devices is expanding. It incorporates drawings and photographs into tablets to browse materials, various inspections at the site, leading to more efficient education at the time of new entrance and paperless. Since it can be used even in places without a network, it is also applicable to outdoor sites and huge factories.

Therefore, in this research, we focus on free handwriting manner to make notes by using a flexible smart device suitable for the site and show the notes with AR (Augmented Reality) display, which will allow the different users to share in different time. It is possible to instruct and record intuitively by virtual memo on the site where direct memo cannot be written on target objects. Besides, "handwriting" can handle various spatial information to indicate points, position, and directions by drawing lines, circles, arrows and the like, other than key-typed text. To hand over at a workplace where workers frequently change, we believe that it will lead to information sharing such as communication and instruction/education among experienced workers and inexperienced workers.

2. RELATED WORK

2.1

KDDI Research Institute, Inc. provides a remote operation support system that transmits images shot by smartphones and others from remote locations (KDDI Research). Among them, intuitive by using AR function to support work efficiency and mistake reduction by handwriting instructions written on terminal on the work instructor side closely follows real-time video in real time Remote indication is possible. In this research, we focus on how to display handwritten contents.

As for the inspection site of the public structure, if the destruction of a certain element exerts a large influence on the safety of the whole bridge, it is important to conduct an inspection as an important element (Fig. 1). In continuous high bridges and long bridges with a large number of spaces, in order to simplify the inspection site, it is necessary to check the upper bridge surface, the abutment, and the piers with numbers. The number is mainly marked with a spray. In addition, regarding the position to be numbered, it is done with the confirmation of the supervisor staff. (Osaka municipal bridge checking procedure). This number is also used to establish the direction of the structure. The direction of the path is determined by the number and this direction are used to distinguish the beginning and the end of the bridge inspection.

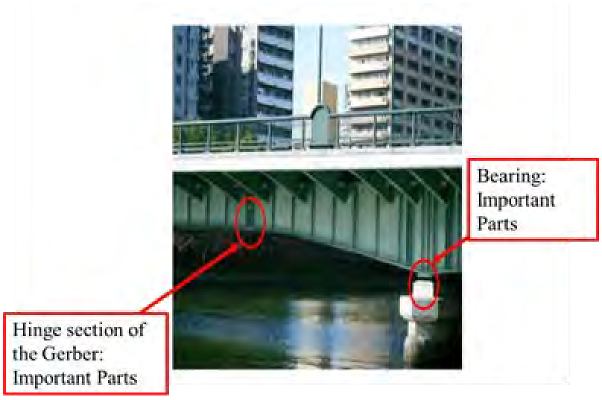

Fig. 1: Example of the important elements.

In recent years, building information modeling (BIM) and augmented reality (AR) technology have been introduced in outdoor infrastructure maintenance workflow (Marianna, 2016). BIM is a so-called database of buildings based on 3-dimensional (3D) digital data, which integrates information related to the planning, design, maintenance, etc. of constructions there. The information that BIM integrates mainly includes form information, elements of buildings, elements of buildings, equipment, cost, maintenance history, and the like. There is also a database that is responsible for civil engineering structures such as bridges and dams, called Construction Information Modeling (CIM). We think that sharing information becomes efficient by accumulating inspection results for maintenance and management on such a database. In this research, we aim to intuitive information sharing by sequentially displaying such information as AR as necessary.

There are several methods for AR alignment technology. There are sensor-based methods such as GPS and vision based using markers. (Woodward et al, 2010) acquires the user's position and orientation information using the global positioning system (GPS) However, there are problems with accuracy such as the error of several meters in GPS, etc. Kwon et al, 2014) are studying support systems for reinforced concrete using black-and-white reference markers (fiducial markers). In reference markers it is necessary to paste markers in specific places. It may be difficult to stick the civil engineering structure etc. So, we considered a markerless AR using natural feature points.

3. METHOD

3.1 Overview

In this research, memos written directly by the worker on a tablet screen is registered together with the actual imagery in the workplace where the worker cannot write down any memos on the target objects. Also, the hand-written memos can be derived and displayed in AR representation, when the same and/or another worker visit the same object to see through it with a tablet. Various places can be considered as work sites, but in this research, we propose to inspect with a bridge. As a method of checking at a bridge, numbers are given by spraying and the inspection points are recorded. Used in this conventional inspection Using AR number as the feature point, AR display is done. The natural feature points are also used for the place such as the side of the bridge pier with the number and the back side, and sharing information with high degree of freedom.

Also, the method of AR display of handwritten notes is prepared in two ways: a display in which the memo is fixed to the marker (hereinafter referred to as fixed display) and a display always facing the direction of the camera (hereinafter referred to as billboard display). In the fixed display, the handwritten memo displayed in the AR is stuck in the designated direction, and the way it looks differently from the viewpoint, so you can use it like a general sticky note such as the position and direction indication. Moreover, in the billboard display, since the handwritten memo displayed in the AR can always be seen from the front even if viewed from any angle, information transmission can be expected as a three-dimensional instruction / recording such as guidance or message at the bird's eye view

3.2 AR System with Registered Natural Feature Points

Memos written directly by the worker on the screen of the tablet displaying live-action images are automatically superimposed on the live-action screen and reproduced, so that the handwritten notes are displayed in AR at the work site. An arbitrary photograph of the work site scenery including the target object to be registered is registered as a marker image. The handwritten memo is separately stored as an image and can be superimposed on the camera image by using it as a texture for mapping to a polygon. The process flow is shown in Fig. 2. First, in the camera image capturing the marker in the field scene, some memo related to the work is written by the worker. A marker image is detected from this image and the display position of the handwritten memo is determined by calculating the coordinate transformation of the camera and the marker. Also, the handwritten memo contents are registered as image data. At this time, the user also selects from two kinds of AR display methods. Next, when displaying the registered information on the AR, a camera image is acquired by the user tablet, and similar feature points are found between the marker image and the photographed image by detection of the marker. By estimating the position and orientation of the camera and the marker based on the correspondence, the AR display is realized by preliminarily registering the information by calculating the coordinate transformation.

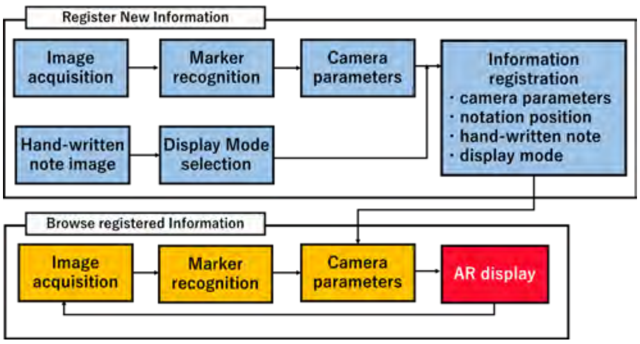

Fig. 2: Process Chain of the system.

3.3 AR Presentation Modes

As shown in Fig. 3, the marker gives the coordinate system to the physical object and shows the relative geometric relation with the camera coordinate system. By registering part of the camera image as a marker image, it is used as a 3D landmark. A large number of feature points are extracted from the marker image. The coordinate transformation from the camera coordinate system to the world coordinate system is obtained by this marker, and the handwritten memo is displayed. This transformation consists of a rotation matrix R and a translation vector t at the origin of the camera coordinate system shown in Eq.1. When a three-dimensional coordinate system is set in the real world, it is possible to estimate the position and orientation of the camera with respect to the coordinate system. A plurality of feature points are extracted from the camera input image and matching between three-dimensional and two-dimensional coordinates can be performed by matching with feature points of the registered marker images.

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \begin{bmatrix} R_{3\times3} & t_{3\times3} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_m \\ Y_m \\ Z_m \\ 1 \end{bmatrix} \quad \text{(Eq 1)}$$

By projecting the image coordinates of the handwritten memo on the X_m - Y_m plane of the world coordinate system, the AR display position of the memo is calculated. In this research, two kinds of AR indications; fixed display and billboard display are used. In the case of fixed display, the AR display is fixed at the marker coordinate system obtained by conversion with the rotation matrix R and the translation vector t.

In the case of a billboard display, even if the camera moves, only the translation vector t is applied so that it always points to the viewpoint of the camera. Since the rotation matrix R is included in the transformation matrix obtained by the API, after converting to the marker coordinate system once, in the implementation, by multiplying by the inverse matrix of the rotation matrix R, only the attitude of the memo display is matched with the camera coordinate system.

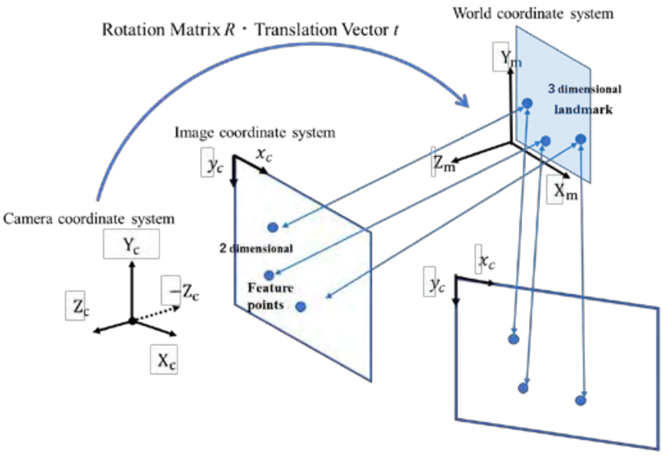

Fig. 3: Coordinate Systems of camera and the marker(s)

4. EXPERIMENTS

4.1 Implementation

In this research, the surface book 2 was used for drawing handwritten memos, and the built-in camera of surface book 2 and ELECOM UCAM-DLL 300 T were used as cameras for marker registration. We used OpenCV for image processing of saved handwritten memos, detection of feature points by natural feature points, estimation of camera position and orientation and marker recognition. Also, we used OpenGL for AR display, texture mapping of images, polygon rendering processing. As a target, a concrete pillar in the university campus was used as an inspection record targets of a bridge pier. On that side, marking as "P 5" with spray painting is used as a part of target, and the photograph of the scenery was used as an image marker. (Fig.4) As for the development environment to develop the proposed system program, C/C++ language in Microsoft VisualStudio 2015 was used.

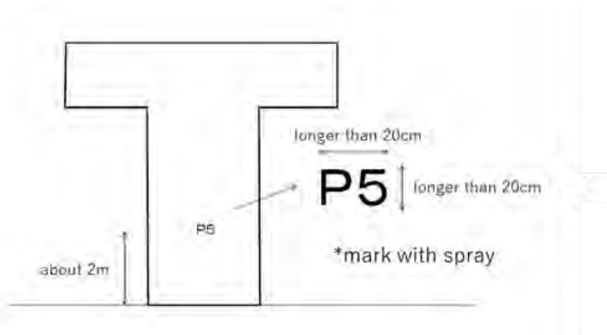

Fig. 4: Schematic target object for the experiment, assuming a bridge pier

4.2 Experimental Setup

We marked the number on the pillar assuming the bridge piers of the bridge by spray. (Fig. 5). Additional information such as inspection results can be displayed in AR by using the number used in recording of the inspection point as a characteristic marker image. In addition to numbers marked with spray, images taken with markers such as sides and backside of the pillar are registered as a marker, and when used together, the degree of freedom of the display range increases (Fig. 6).

We aim to share information of inspection record by AR without going against conventional work flow. Fig.7 shows the AR display results. With the marking "P5", you can see at a glance which part you would like to share inspection records even when similar bridge piers are lined up. If you hold "P5" on the tablet, you can share that the instruction to guide the inspection part etc. is recorded on the side as shown in Fig.7. Fig.8 shows the AR display on the side after moving the viewpoint according to the guidance.

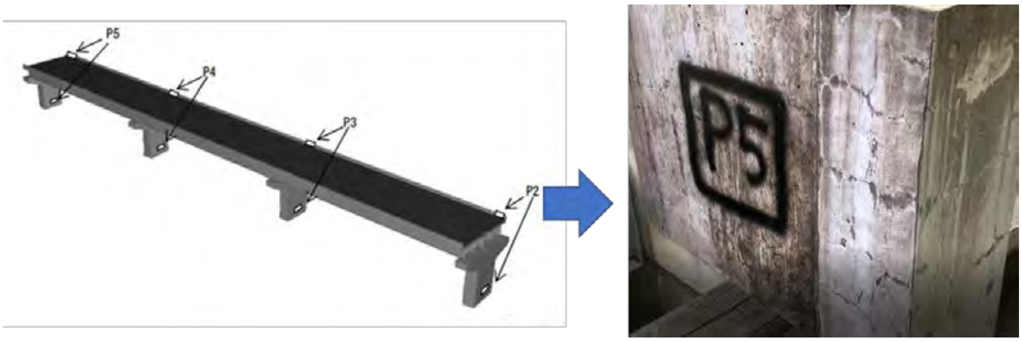

Fig. 5: Spray marking example, assuming the bridge piers inspection.

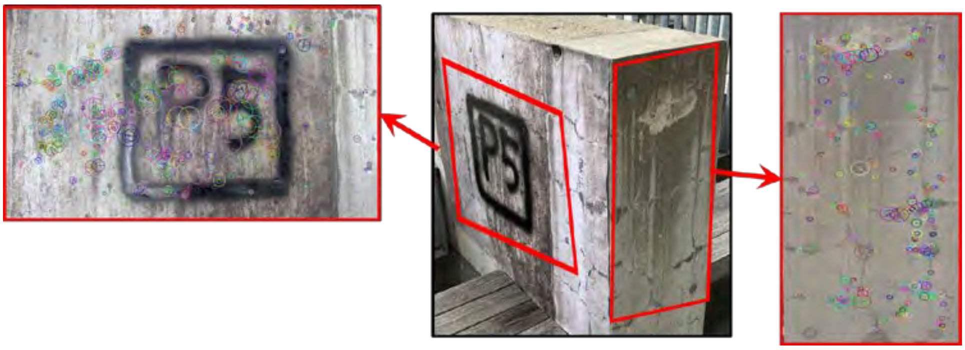

Fig. 6: Registered marker images around the spray marking

Fig. 7: Resultant AR representation of a hand-written note

5. DISCUSSION AND CONCLUSIONs

5.1 Discussion

In this research, we implemented two kinds of different indications in the AR display of memos handwritten by workers on site. By handwriting, it is easy to handle information transmission that uses a place instruction and a message together. Particularly with respect to billboard display, since the AR display rotates when the camera viewpoint moves, the expression of the handwriting instruction and the contents of the actual photograph may be misaligned, so the function of adjusting the rotation center is necessary. Also, marker recognition is poor due to the distance from the marker and AR display becomes unstable. Recognition of feature points outdoors is also different from indoor, due to the influence of environmental light such as sun and other shadows caused by obstacles and clouds in the sky. It is difficult to achieve the same display performance, so in future, we plan to be able to recognize landmarks widely in the field of view of the camera.

Fig. 8: Another result of AR representation, which leads to far from the spray marking

5.2 Conclusion and Future Work

In this research, information is registered in advance from the camera image and the handwritten content image, and by calculating the position and orientation from the marker in the image captured by the camera, the registered handwritten memo is superimposed on the work site We proposed a system.

In the future, if markers are registered as planar images, it is difficult to recognize if the viewpoint shifts, so improving how to register marker images and creating a shared database system for handwritten information are issues.

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4D SITE INSTALLATION PLANNING IN VIRTUAL REALITY

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ABSTRACT: *The site installation for a construction site should be optimized for the environment, the construction itself and the construction methods. To support the process of site installation planning a perspective projection in combination with head tracking of the participants in the planning process is helpful. By this, clashes between the construction and site installation equipment can be avoided. However for planning a site installation the different perspectives of involved parties at the same time are needed. But in a perspective projection one cannot point out things so that others can see what is pointed at, because all get the same perspective projection. Therefore a multi-user environment with perspective projection is helpful. Furthermore the interaction between different experts is needed to find the optimum. A perspective projection in combination with head tracking for multi-users can solve this problem. Since quite some time product models like building information models can be visualized in virtual reality. Only placing the objects of site installation within this BIM model is not enough because a typical construction site changes dynamically during the construction time. Therefore a product model linked with a time schedule to 4D construction model is needed as base for the planning of the construction site. Based on that, the site installation can be developed according to the requirements of the construction process. Furthermore, the objects of site installation have to be modeled with their parameters. Thus movements and processes flows can be check.*

KEYWORDS: *Site Installation, Multi User, Virtual Reality, 3D, 4D*

1. Introduction

Work planning of construction projects is dealing with preparing the complete construction process to build a construction. Building elements are generated by processes to produce them. The processes' sequence is depending on different constraints which describe the interdependencies. The process duration is depending on the construction method and the availability of resources. The environment also has a significant impact on the execution of the construction process. Therefore the design of a site installation is an important factor. The location, size and parameters of site installation elements are depending on the construction, on the construction environment and on the construction method. Therefore a planning environment is needed, which encompasses all these factors and at the same time gives a realistic imagination of the construction flow and all its elements within the site installation. This allows involving also participants in the planning process, which have different backgrounds.

2. site installation planning

Site installation of a construction site consists of site installation elements like machines, equipment, temporary constructions and supply utilities. Furthermore, the site installation has to support the construction process. Site installation must be compared with a permanent factory, with the exception, that it is only a temporary working place for some months or a few years.

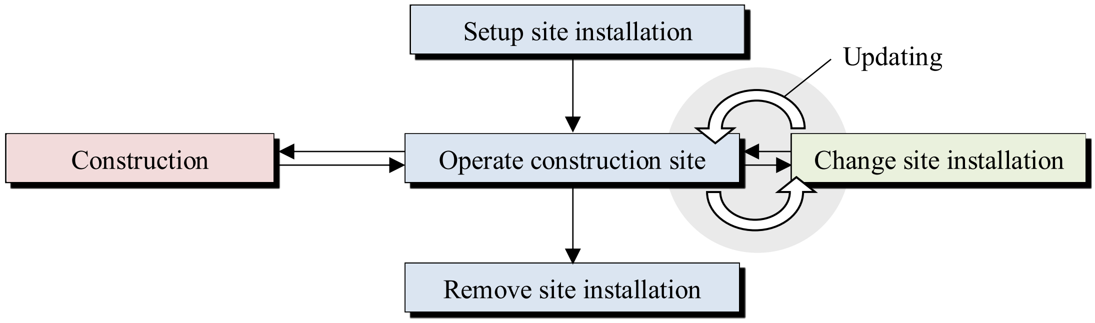


Figure 1: Site installation (Bargstädt and Steinmetzger, 2010)

Planning, acquisition and setup, operation and removal are the main phases of site installation. Furthermore, the site installation has to be adapted during construction time, if different processes require different site installation elements. The conversion of a site installation is an activity within the construction flow. Thus the construction flow model and the site installation model are linked with each other.

Furthermore the site installation is depending on the construction. There are three different types of construction: one-point sites like high-rise building and towers, line-oriented sites like tunnels, roads and waste water channels, and spread-out sites like development area, water dam, factories, shopping malls and surface mines. Figure 2 shows an example of a sketch for a one-point site installation.

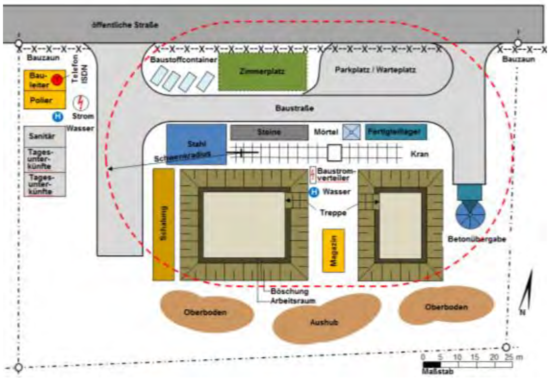


Figure 2: Example for a site installation

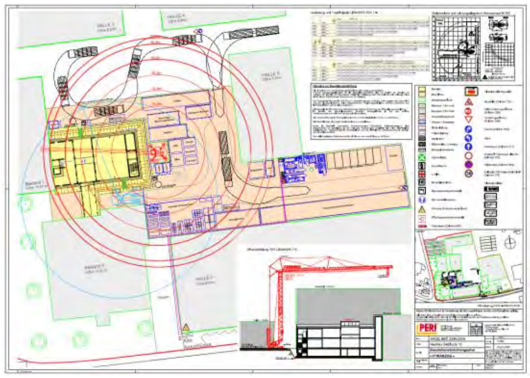


Figure 3: Examples for a site installation plan, Source: PERI GmbH

Different regulations and laws have to be considered for the planning of site installations. Traffic flow arrangements and job safety regulations are the most frequent. The major impact factors for site installation are identified as being:

- Type of construction project (design, construction, etc.),
- Size of the construction project (dimensions, construction materials, etc.),
- Production-related factors (design, construction methods, equipment),
- Material flow (type, quantity and weight of the material, their storage requirements),
- Local conditions (construction site environment, water and electricity supply, soil conditions, etc.),
- Construction time (milestones, handover) and
- Execution period (calendar-related, relevant weather conditions)

Today site installations are displayed on 2D drawings as shown in Figure 2 and Figure 3. Other than in Figure 2, Figure 3 shows a more detailed site installation. Several parameters of site installation elements like lifting capacity of the crane and range of the concrete pump are illustrated. Also an overview drawing of the surroundings and an explanation for symbols are given. And the drawings show the title block with general information as author of the plan, date of issue etc.

Equipment / Machines	Temporary constructions	Supply
• Crane • Concrete pump • Formwork • Excavator	• Scaffolding • Construction roads • Stair tower • Guardrail	• Container • Water supply • Waste container • Electricity supply

Figure 4: Examples for site installation elements

Yet this work procedure is stationary. It focuses only on one given moment of the construction flow, but it neglects the constantly changing site environment. Therefore a methodology is needed which considers the construction flow as well. Currently different models for the construction, i. e. a building information model and another model for the time scheduling are available. Through linking of these models, a 4D-Model of the construction flow can be generated. 4D-models of the project support the process of modeling the construction flow (Hartmann and Fischer, 2007) (Tulke and Hanff, 2007). However these models do not consider all the temporary elements of the site installation. Furthermore they do not consider the requirements for site installation elements, which result out of the construction process. Therefore, the site installation planning should be modeled in parallel with the construction flow. Thus, the site installation elements have to be modeled as objects and with their parametric behavior. In this research three different categories of site installation elements are identified. Figure 4 shows these categories and gives examples of the corresponding site installation elements.

3. Building Information Modelling

3.1 Building Information Model

A building information model is an object-oriented, three dimensional product model. The geometrical shape, the position and orientation is described by parameters. A building information model can include other information besides geometric information. Material could be such an attribute of an object. Requirements for an integrated product model are described in (Abeln, 1995).

The three dimensional building information modeling has benefits for the construction projects (Abeln, 1995). Building a BIM is object-oriented construction modeling. In several countries standardization of BIM is going on, for example in the US. The supplementary information is attached to the model at the right place. It can easily be communicated in this context. Different messages can be conveyed by using different perspectives or layers of the building information model. This kind of modeling is well established (Eastman, 2011), (Weygant, 2011), (Jernigan, 2008).

Kaminski analyzed the capability of BIM in infrastructure projects (Kaminski, 2010). Liebich analyzed the changes through BIM for the planning processes and job descriptions (Liebich *et al.*, 2011). A more detailed analysis of the implications which BIM brings for civil engineers, is given by Strafaci (Strafaci, 2008). Kohls shows how to use BIM as a base for a construction flow simulation of building construction (Kohls *et al.*, 2010).

The Industry Foundation Classes (IFC), developed by building SMART (International Alliance for Interoperability, IAI), is a neutral and open specification for building information models. It is registered as the international standard ISO 16739. The base class IfcProduct relates to a geometric or spatial context of objects. The IFC base class for processes, IfcProcess, is subdivided into tasks, events and procedures.

3.2 4D – Construction flow

The Mefisto research project proposed using BPMN (Business Process Model and Notation) models as a formal description for construction processes. A process-based simulation library can be established. Process templates can be used to break the project schedule down into more levels of detail (Scherer *et al.*, 2010). The proposal requires a Build Information Model, which is manually linked with a project schedule and with other information about available resources.

Within the research project of Mefisto, Benevolenskiy et al. discussed the ontology-based model and the use of process patterns and rules in the configuration of construction processes (Benevolenskiy *et al.*, 2012). Therefore, they develop a process configurator. It provides the defined ontology specifications, an initial knowledge base of process patterns, basic process rules and a set of construction process rules for the subdomain “structural concrete works”.

Huhnt proposes a process pattern for a more detailed construction flow model (Huhnt and Richter, 2010). The construction process must be modeled with its activities and events. Process patterns are linked to building elements for 4D visualization. A 4D visualization of the schedule helps to check the workflow. A methodology to break down a building into components and to assign processes is shown in (Huhnt *et al.*, 2010). Different colors help to understand the contents of the 4D visualization.

For 4D visualization, a three dimensional object-oriented product model must be available and linked to activities of schedule. A construction flow animation based on BIM is called 4D BIM. The objects in an object-oriented construction model have additional attributes for the start, end and duration of each process. By use of a time slider the different objects appear according to their scheduled execution dates.

4. 4D site installation planning

4.1 Perspective projection in combination with head tracking

3D television and stereo display are perspective projections with a fixed point of view. Therefore the perspective projection is only right for one single perspective. In all other points the perspective is wrong and the stereoscopic effect does not appear. Head Tracked systems can adjust the perspective to the individual view point. But when several users are using such a system at the same time, all will have the perspective of the head-tracked user as shown in Figure 5.

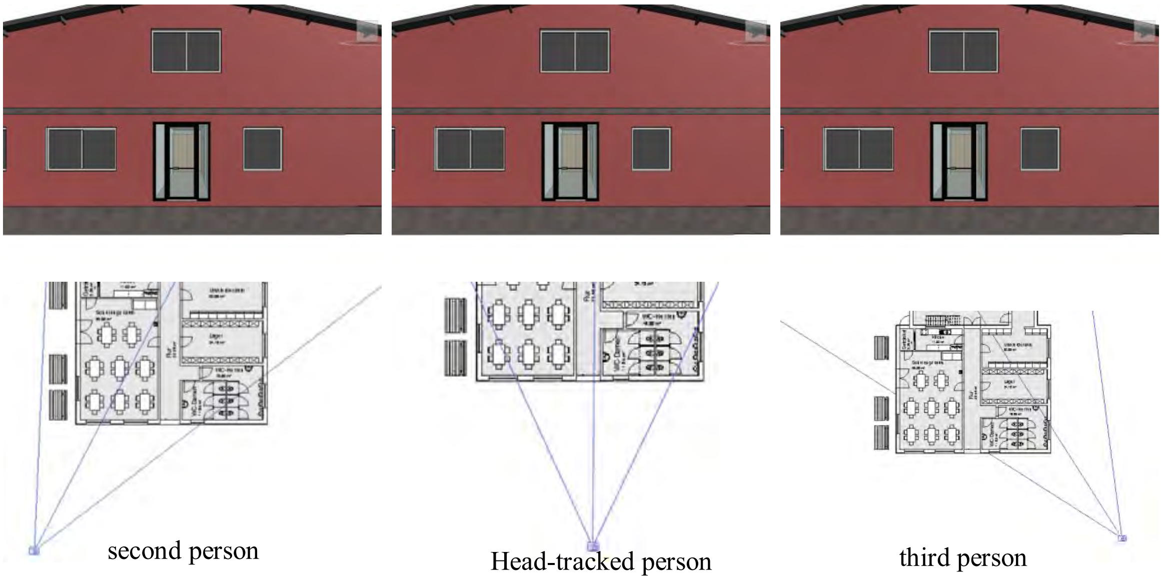


Figure 5: Single-user head tracking perspective projection

If all users would have the same perspective like in Figure 5 they could not point at some specific coordinate to each other because their fingers would not meet in space. Therefore, every user should be head-tracked, as shown in Figure 6. This stereoscopic multi-user system has been developed by Kulik et al. (Kulik *et al.*, 2011).

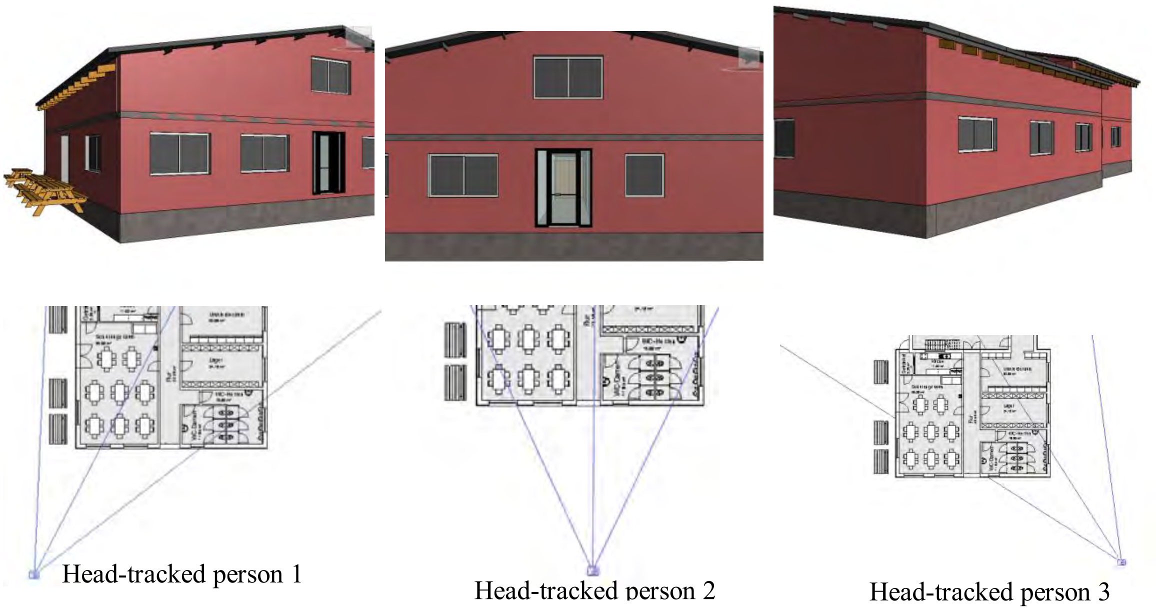


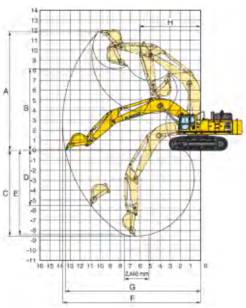
Figure 6: Multi-user head-tracking perspective projection

A group-to-group interaction is possible through the coupling of two or more of these multi-user systems (Beck *et al.*, 2013). As a result face-to-face meetings in a virtual environment are possible. Furthermore site-by-site coupling and exploring in a virtual environment as one group but placed in different places in real world are another application of such a system. For the planning of site installations the independent navigation is most interesting, because different groups of works can place their needed site installation elements at the same time like on a construction site. If the site installation from one group affects the work of another group of workers, in such a virtual environment this would be immediately detected and could be changed to a better or not conflicting solution. The detection of problematic site installations and processes which affect others can not only be used during planning but also as a training environment. For the placing of site installation elements in space there is need to point out to others in space where it should be placed.

In this research the building information models are used to be shown as a perspective projection. The file formats ifc and cpixml are used with the construction model. To show the construction model with the multi-user systems, the models have to be converted to obj files. Building information models are object oriented and therefore can be converted to a scene graph.

4.2 Object oriented site installation planning

Objects of site installation have different parameters. Performance, geometry and working range are examples for parameters of site installation elements. Figure 7 shows the parameters for the working range of an excavator.



	MODEL	PC800LC-8	PC800-8
	Boom length	8,0 m	7,1 m
	Arm length	3,6 m	2,9 m
A	Max. digging height	11.955 mm	11.330 mm
B	Max. dumping height	8.235 mm	7.525 mm
C	Max. digging depth	8.445 mm	7.130 mm
D	Max. vertical wall digging depth	5.230 mm	4.080 mm
E	Max. digging depth of cut for 2,44 m level	8.310 mm	6.980 mm
F	Max. digging reach	13.660 mm	12.265 mm
G	Max. digging reach at ground level	13.400 mm	11.945 mm
H	Min. swing radius	5.985 mm	5.645 mm
	Bucket digging force (ISO)	40.500 kg	48.000 kg
	Arm crowd force (ISO)	33.300 kg	38.100 kg

Figure 7: Work range parameters of an excavator Source: KOMATSU, www.komatsu.eu

For site installation planning the information about working range, geometry and performance has to be modeled. Figure 8 and Figure 9 show examples for such smart objects of site installation elements. The geometry and material of the site installation elements is modeled like building elements. The working range is displayed as colored area.

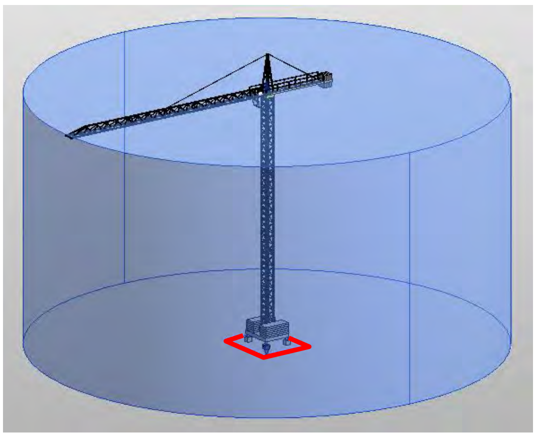


Figure 8: Visualization of site installation elements

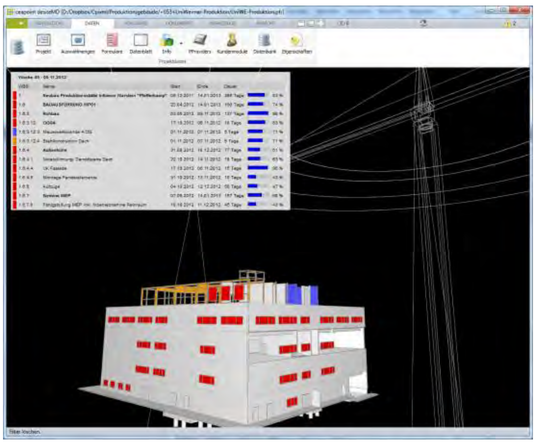


Figure 9: Visualization of site installation elements in a construction flow model

Site installation objects can be displayed in a construction flow visualization, as shown in Figure 9. Furthermore, for site installation planning it is necessary to place site installation elements in space. Therefore the user has to point out in space. To point out where in space elements shall be positioned, is especially important if a group of users work simultaneously on-site installation elements in space. Furthermore site installation elements have to be placed in space according to the processes of the construction flow which is in progress. With the linking of site installation elements to the construction flow in a virtual reality, clashes between different site installation elements and between site installation elements and the ongoing construction can easily be avoided, because several perspectives can be easily checked. Therefore real size perspectives are very helpful.

The stereoscopic multi-user system supports the transfer of information from planner to supervisor and worker as well as to the client and other third parties. Drawings, however, require an understanding of what the points and lines mean. The proposed stereoscopic multi-user system does not require a special knowledge of interpreting. This is a major advantage for a stereoscopic multi-user system in communication and planning of site installation, because in the process of site installation planning different parties with very different construction experience are in involved like the client, authorities, third parties and suppliers.

The design process of the site installation is based on the BIM construction model and on the construction flow in a 4D-visualization. Several common methods are known for the planning of the construction processes. These methods assist in solving questions like which and when a process starts or which kind of site installation to choose and where to place these elements. As shown in Figure 10 the possible methods of construction planning can be randomly, rule based case based, by constraint simulation and beforehand (pre-election) or interactive by a user. Furthermore combinations of these methods are possible. Most common in construction planning is the method, that a user just designs it beforehand. But in a virtual environment, as proposed in this paper, other methods like based on constraints or in an interactive environment seem to be more powerful.

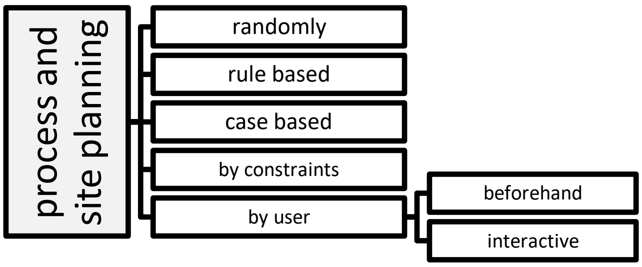


Figure 10: Methods of construction planning

4.3 4D site installation

By linking smart objects of site installation to a construction flow, the processes and building elements are linked to the site installation elements. In Figure 11 a sequence of a construction flow model together with the construction and time schedule is linked with the site installation elements. The visualization of the site installation elements in the construction flow is realized like the construction flow by showing, hiding or highlighting the site installation elements in the scene graph (obj-file). The links of processes to building elements and the links of site installation elements to processes and building elements are stored in an xml-file. The time schedule is stored in a separate xml-file. The objects of site installation elements can be stored as separate obj-files or can be included in the construction model.

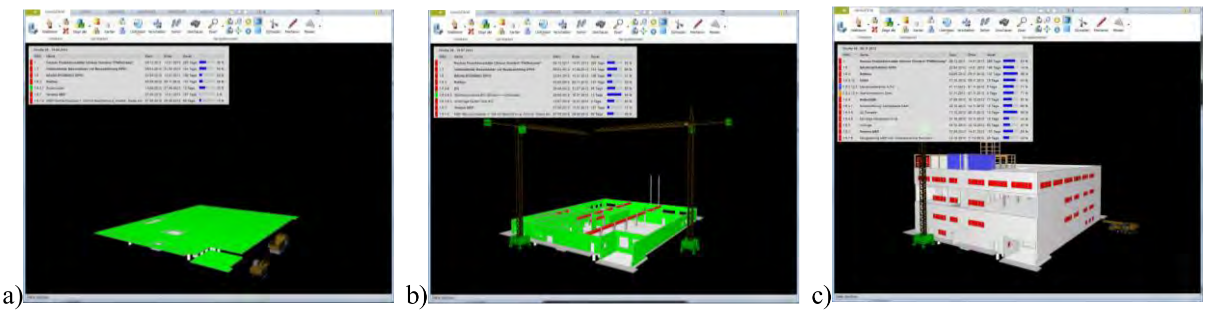


Figure 11: Construction sequence

Then the site installation can be interactively developed in the stereoscopic multi-user system. In the described virtual environment the construction flow can be visualize. When a construction process requires a site installation element this will be shown in a list. Then, users can choose this site installation object and place it in space. The place in space and the time when it gets installed are stored in the xml-file. Whenever the site installation element will be moved or removed, this information will also be stored in the xml-file. The xml-file is a resource schedule for the site installation. Thus for site installation elements a resource graph can be generated.

For the interactive process of site installation planning, a "cockpit" for the construction process is needed as shown in Figure 12. This construction control panel gives an overview about the important information of the construction flow. Therefore it has to display:

- Processes not started
- Processes ready to start
- Processes in progress
- Processes finished
- Resources
- Recourse graph

- Construction (3D-Model)
- Building elements not started
- Building elements ready to start
- Building elements in production
- Building elements finished
- Properties

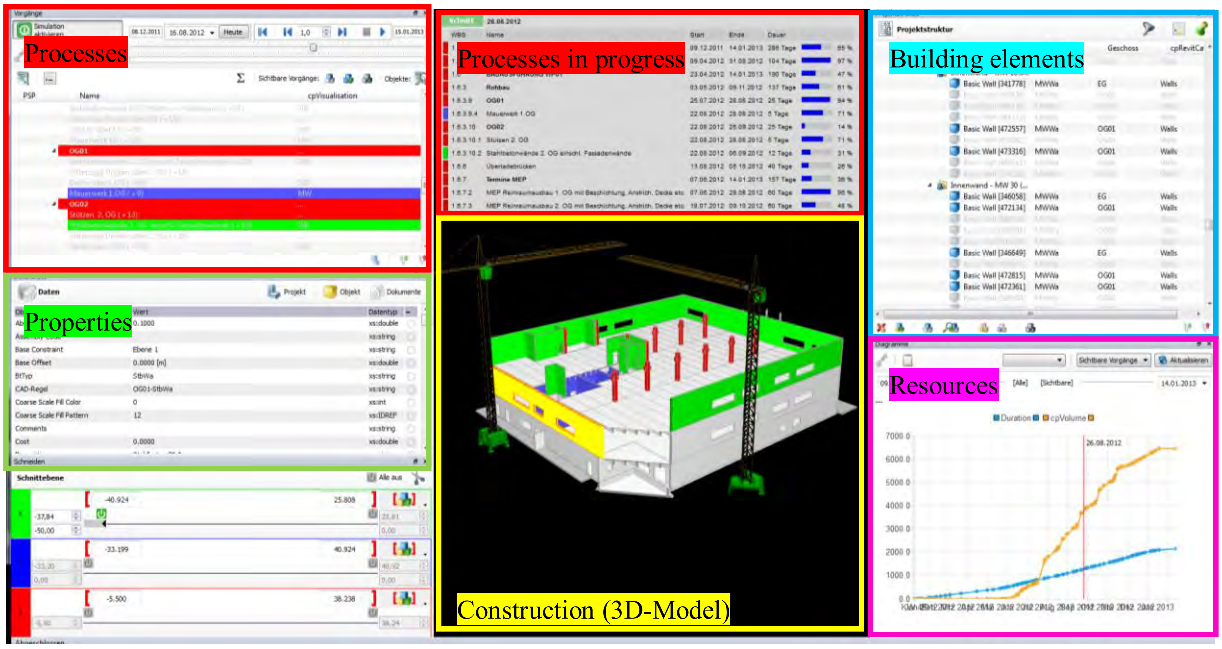


Figure 12: Construction control panel

Working on this construction control panel and by means of the stereoscopic multi-user system, an interactive site installation planning is possible. Tools for interacting with building elements in the stereoscopic multi-user system are developed by Argelaguet et al. (Argelaguet *et al.*, 2011). In this research, however, it is shown, how the construction control panel is integrated into the stereoscopic multi-user system. The object-oriented way of modeling then allows an allocation of all site installation objects.

5. CONCLUSION AND OUTLOOK

In this research a product model is linked with a time schedule to a 4D construction model and visualized in a stereoscopic multi-user system. This environment supports the process of planning of the construction site. Based on that, the site installation can be developed according to the requirements of the construction process. Therefore the objects of site installation have to be modeled with their parameters. Furthermore site installation elements can be allocated in the virtual environment during the 4D construction flow visualization. Clashes between site installation elements and with building elements can be detected in the virtual environment. As it is required in professional construction, these analyses can be done by working in groups of different parties, where every person will have his individual perspective on the project.

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THREE-DIMENSIONAL LANDFORM MODEL BASED ON POINT CLOUD DATA USING TERRESTRIAL LASER SCANNER AND UNMANNED AERIAL VEHICLE

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ABSTRACT: *Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in Japan is promoting the intelligent construction policy "i-Construction" for productivity improvement, quality assurance, and cost reduction. Three-dimensional landform data are generated by using laser profiler (LP), mobile mapping system (MMS), Terrestrial laser scanner (TLS), and camera on Unmanned Aerial Vehicle (UAV). There are no standards for representing and drawing three-dimensional landform data.*

In this study, a representing and drawing method of three-dimensional landform data based on point cloud data was proposed. The point cloud data are generated by LP, MMS, TLS, and camera on UAV. This study evaluated the density of point cloud data and display level for representing point cloud data based on various measurement hardware. The results were classified by the density. The density was evaluated for as-built management of road earthmoving. It should be one hundred points per square meter for as-built management. A three-dimensional landform representing and modeling guideline was proposed. It standardizes the notation of view, and proposes to define the contents of conformance class, level of detail, management information, an-notation, used point, line, surface and solid, and features.

KEYWORDS: *Three-dimensional Data, Standardization, Landform, Visualization, Point Cloud Data.*

1. INTRODUCTION

Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in Japan is promoting the intelligent construction policy "i-Construction" for productivity improvement, quality assurance, and cost reduction. Three-dimensional data of civil infrastructure is being promoted for planning, survey, design, construction, maintenance and operation for improving productivity and ensuring quality. Regarding topographies closely related to the three-dimensional data of the civil infrastructure, it is necessary to acquire it in three dimensions and promote its use, taking into consideration the close relationship between the facility and the topography. Three-dimensional landform data are generated by using laser profiler (LP), mobile mapping system (MMS), Terrestrial laser scanner (TLS), and camera on Unmanned Aerial Vehicle (UAV). It is necessary to standardize the three-dimensional landform data to utilize them with the topography across business phases. In order to establish the standard of three-dimensional data, it is necessary to consider standardization of the notation and standardization of data exchange. There are no standards for representing and drawing three-dimensional landform data. It is necessary to develop the standard to represent and draw landform data for distributing and utilizing them.

In this study, a representing and drawing method of three-dimensional landform data based on point cloud data is proposed. The point cloud data are generated by LP, MMS, TLS, and camera on UAV. This study evaluates the density of point cloud data and display level for representing point cloud data based on various measurement hardware. The results are classified by the density. The density is evaluated for as-built management of road earthmoving. It should be one hundred points per square meter for as-built management. A three-dimensional landform representing and modeling guideline is proposed. It standardizes the notation of view, and proposes to define the contents of conformance class, level of detail, management information, an-notation, used point, line, surface and solid, and features.

2. METHOD

In this study, an existing landform data included road, river, and so on are represented and drawn using point cloud measured by LP, MMS, TLS, and camera on UAV. There are several research subjects: three-dimensional representation rule, display level of each feature, representation of features using point, line, surface, and solid, representation of brake line, and annotation item of each feature.

A method of this study is shown in Fig. 1. In this study, there are three steps to accomplish the objective: (1) Representation of landform corresponding with density of point cloud, (2) Density and display level of point cloud based on use case, and (3) Registration of point cloud by several measurement instruments.

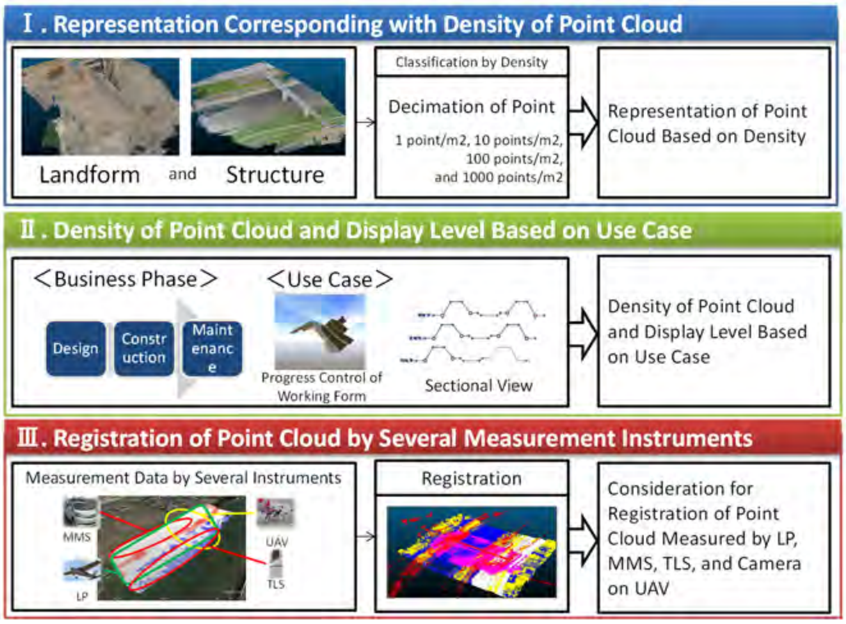


Fig. 1: Method of this Study.

3. REPRESENTATION CORRESPONDING WITH DENSITY OF POINT CLOUD

Point cloud of existing landform are represented based on its density. A density of point cloud is affected to display and processing speed of computer. A landform is displayed by two and three-dimensional data to test the comprehension by engineers. In this study, the measurement instruments are LP, MMS, TLS, and camera on UAV. TLS is Pentax S-3180V and UAV is DJI F550. This trial will be used for engineers to reduce the original point cloud and display them using computer. Fig. 2 and Fig. 3 represent the density of 1000 or 260 points per square meter, 100 points per square meter, 10 points per square meter, and one point per square meter. And, the representation of point cloud, TIN (Triangulated Irregular Network), and section of landform. According to the figures, the display of 1000 points and 100 points per square meter is represented the point cloud in an intimate manner and is able to be understood the original landform. However, the display of 10 points and one point per square meter is not represented precisely. In TIN display, the landform shape can be grasped at all densities of point cloud. In 10 points and one point per square meter, the edge part becomes smooth. In sectional display, the cross section of TLS is similar all densities. In camera on UAV, focusing on the edge portion, one point per square meter is found to be several tens of centimeters away from the other density.

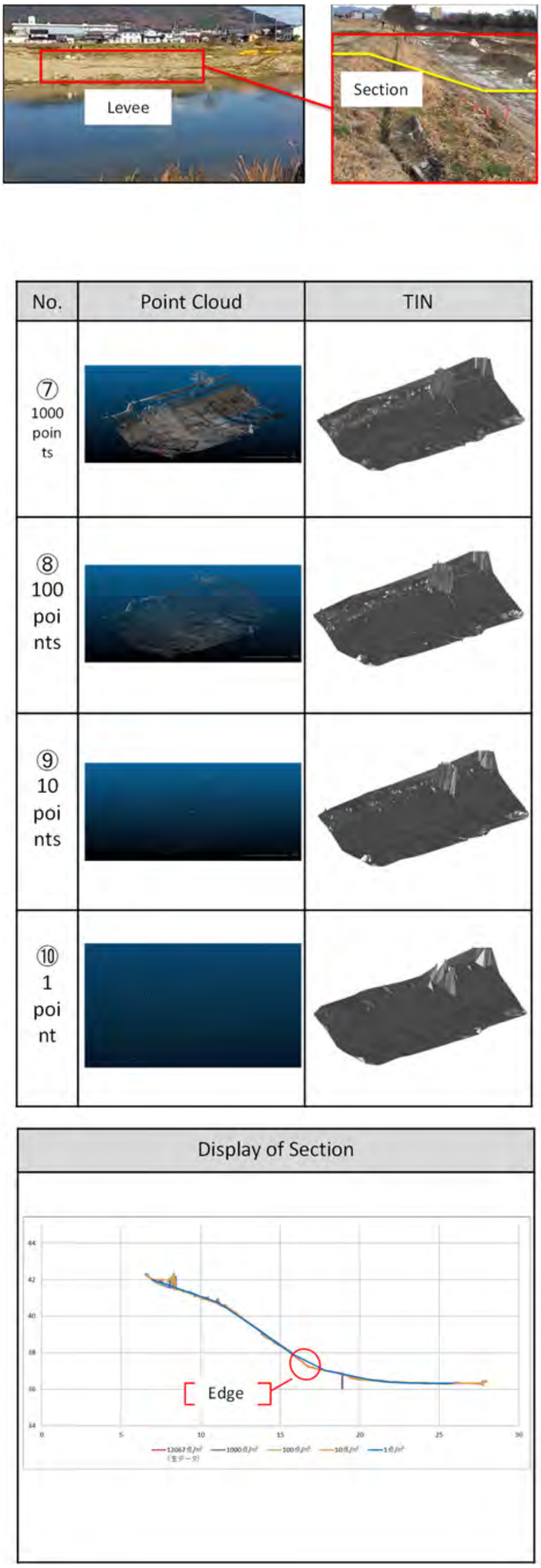


Fig. 2: Display Based on Density using TLS.

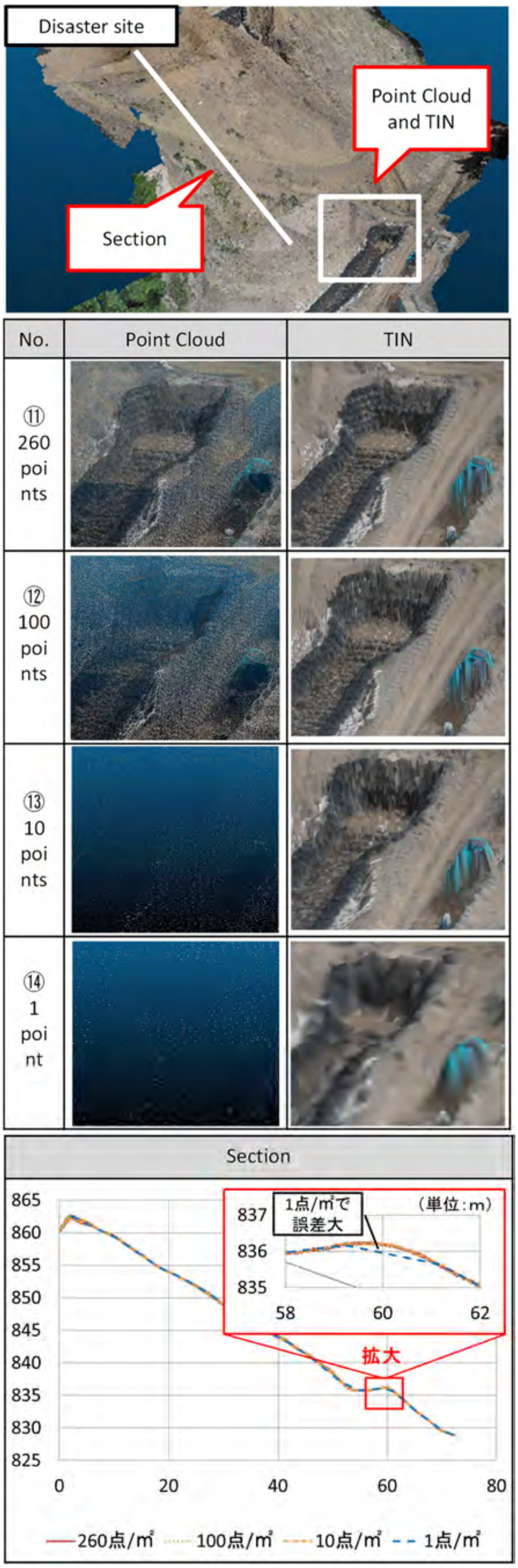


Fig. 3: Display Based on Density using Camera on UAV.

4. DENSITY AND DISPLAY LEVEL OF POINT CLOUD BASED ON USE CASE

In this chapter, the representation by density and display level of point cloud based on use case is displayed. The use case is progress control of working form in road earthworks. The density of point cloud is studied in this use case as shown in Fig. 4. Point cloud were measured by TLS and camera on UAV in the site of Fig. 5.

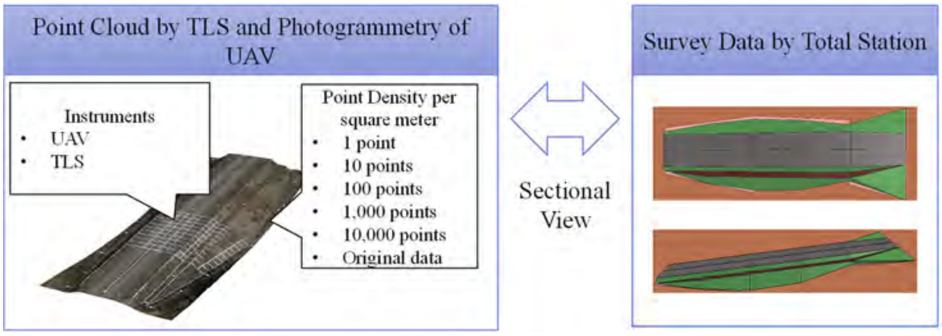


Fig. 4: Usage of Point Cloud in Progress Control of Working Form.

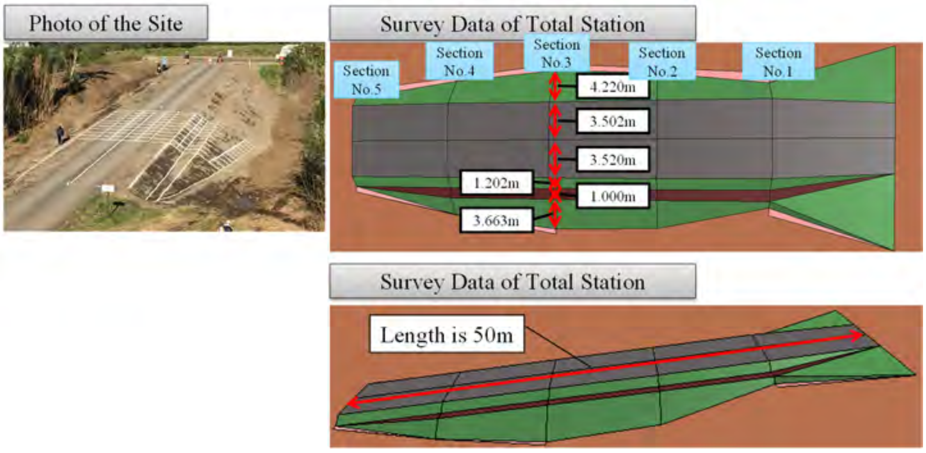


Fig. 5: Measurement Site.

The evaluation process is as follows:

Step 1: The cross section is created by acquiring a certain range of points from the point cloud at section No. 1, 2, 3, 4, and 5.

Step 2: The difference in elevation is calculated by lowering the perpendicular at intervals of one centimeter from the cross section and calculating the difference from the cross section of the correct data. The correct data are the survey data by total station.

Step 3: The calculated elevation difference is evaluated base on the average plus and minus 5 cm of standard value of point cloud in the working form management method.

The data used for evaluation is shown in Fig. 6 and Fig. 7. Fig. 6 is the data created by camera of SONY α6000 on UAV. Fig. 7 is the data created by TLS of RIEGL LMS-Z420i.

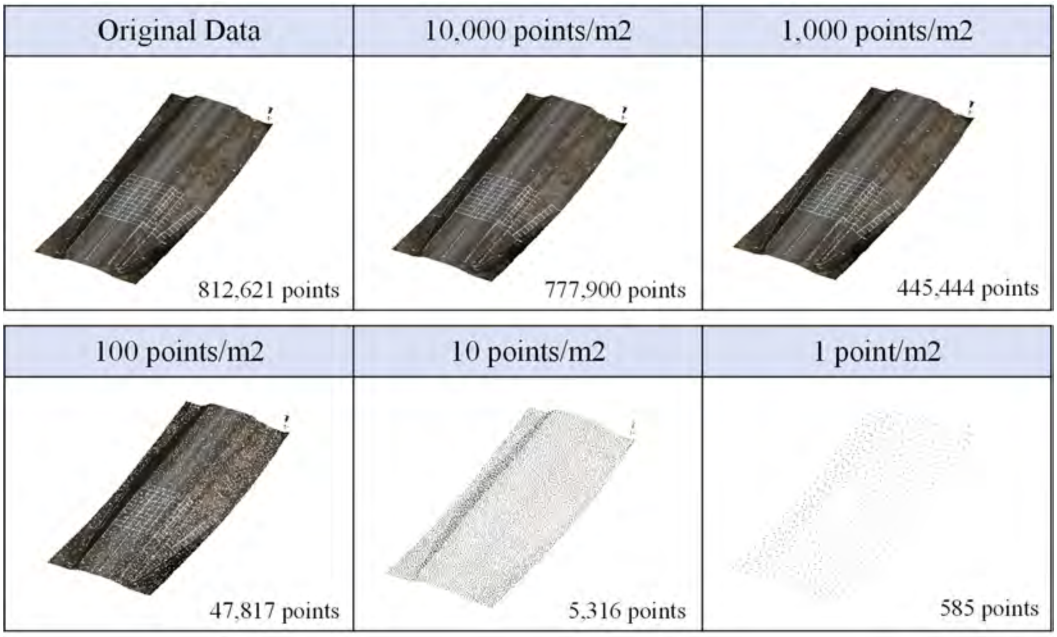


Fig. 6: Point Cloud by Camera (SONY) of UAV.

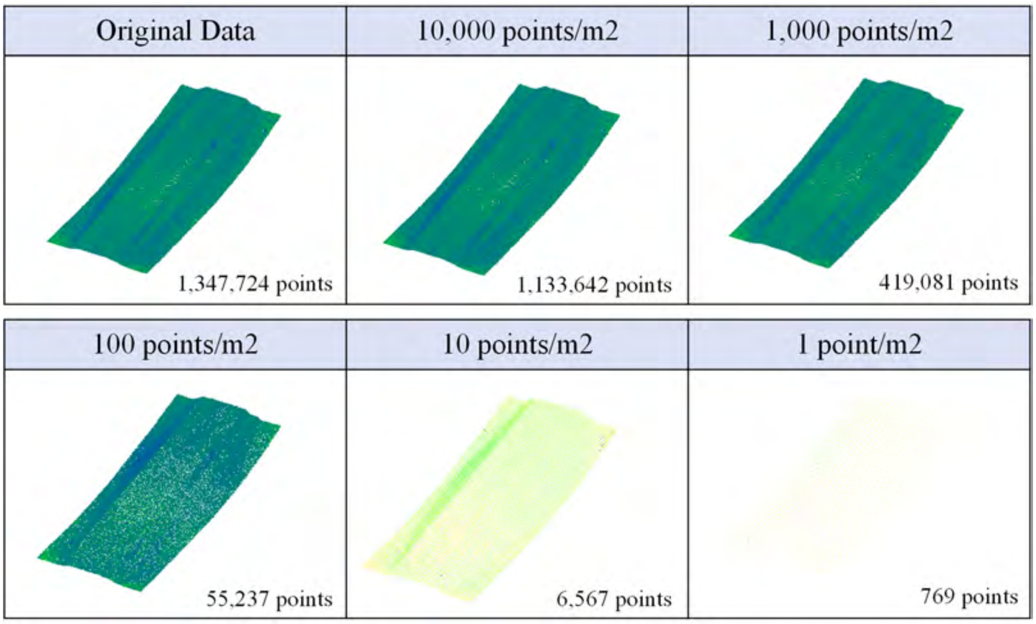


Fig. 7: Point Cloud by TLS.

Fig. 8 and Fig. 9 show the evaluation results of point cloud at the cross section No. 4. Fig. 8 shows the result of camera of SONY on UAV. Fig. 9 shows the result of TLS. The evaluation results for each measuring instrument are shown in Table 1 and Table 2. When the density of point cloud is 10,000 points to 100 points per square meter, it is similar to the proportion within the standard value of original data. For density of 10 points and one point per square meter, it is significantly different from the ratio within the standard value of original data. It is considered to set the density of point cloud to 100 points per square meter or more in progress control of working form.

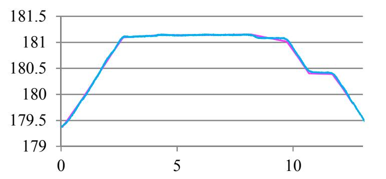
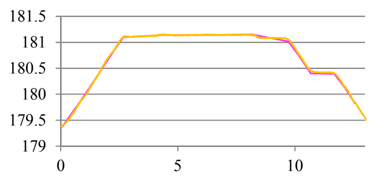
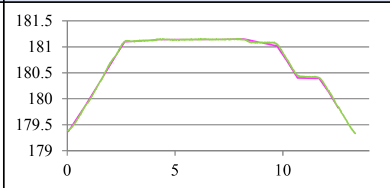
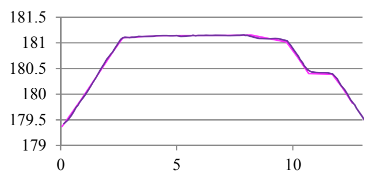
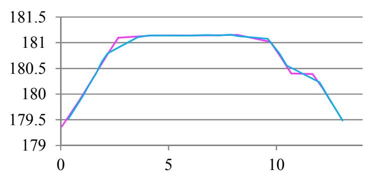
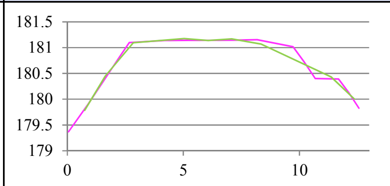
Original Data		10,000 points/m2		1,000 points/m2	
					
In Standard value	Out of Standard	In Standard value	Out of Standard	In Standard value	Out of Standard
1231 (98.4%)	20 (1.6%)	1231 (98.4%)	20 (1.6%)	1224 (97.8%)	27 (2.2%)
100 points/m2		**10 points/m2**		**1 point/m2**	
					
In Standard value	Out of Standard	In Standard value	Out of Standard	In Standard value	Out of Standard
1235 (99.4%)	8 (0.6%)	1039 (85.1%)	182 (14.9%)	760 (65.5%)	401 (34.5%)

Fig. 8: Evaluation Results of Point Cloud by Camera (SONY) of UAV.

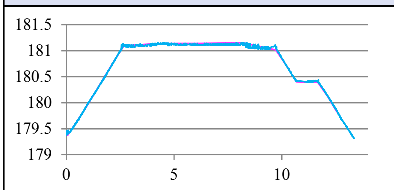
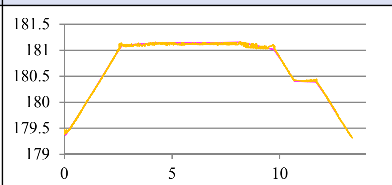
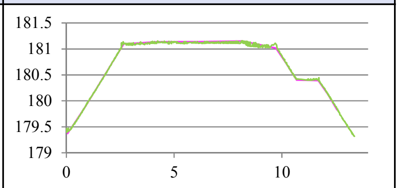
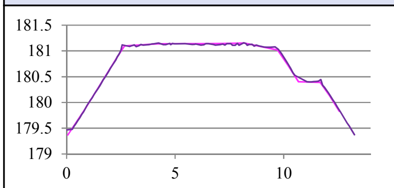
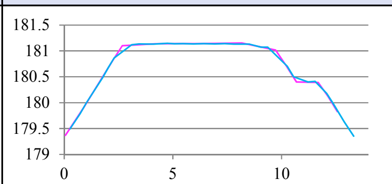
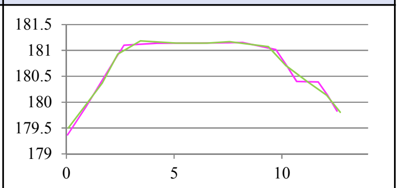
Original Data		10,000 points/m2		1,000 points/m2	
					
In Standard value	Out of Standard	In Standard value	Out of Standard	In Standard value	Out of Standard
1207 (96.5%)	44 (3.5%)	1207 (96.5%)	44 (3.5%)	1205 (96.4%)	45 (3.6%)
100 points/m2		**10 points/m2**		**1 point/m2**	
					
In Standard value	Out of Standard	In Standard value	Out of Standard	In Standard value	Out of Standard
1200 (96%)	50 (4%)	1127 (91.7%)	102 (8.3%)	358 (77%)	107 (23%)

Fig. 9: Evaluation Results of Point Cloud by TLS.

Table 1: Evaluation Results Based on Standard value (SONY Camera of UAV).

In Standard Value of 5 cm

Section	Density (points per square meter)					
	Original	10,000	1,000	100	10	1
1	1055 (96.4%)	1055 (96.4%)	1056 (96.5%)	1050 (97.8%)	969 (94.1%)	1014 (96.5%)
2	1306 (89.6%)	1305 (89.5%)	278 (98.2%)	1318 (90.6%)	278 (98.6%)	1071 (78.4%)
3	1458 (94.2%)	1457 (94.1%)	1460 (94.3%)	1461 (95.1%)	1116 (78.5%)	823 (55.9%)
4	1231 (98.4%)	1231 (98.4%)	1224 (97.8%)	1235 (99.4%)	1039 (85.1%)	760 (65.5%)
5	851 (96.2%)	505 (89.2%)	854 (96.5%)	507 (89.6%)	629 (77.2%)	554 (97.9%)
Total	5901 (94.6%)	5553 (93.8%)	4872 (96.3%)	5571 (94.9%)	4031 (84.5%)	4222 (75.2%)

Out of Standard Value

Section	Density (points per square meter)					
	Original	10,000	1,000	100	10	1
1	39 (3.6%)	39 (3.6%)	38 (3.5%)	24 (2.2%)	61 (5.9%)	37 (3.5%)
2	152 (10.4%)	153 (10.5%)	5 (1.8%)	136 (9.4%)	4 (1.4%)	295 (21.6%)
3	90 (5.8%)	91 (5.9%)	88 (5.7%)	75 (4.9%)	305 (21.5%)	650 (44.1%)
4	20 (1.6%)	20 (1.6%)	27 (2.2%)	8 (0.6%)	182 (14.9%)	401 (34.5%)
5	34 (3.8%)	61 (10.8%)	31 (3.5%)	59 (10.4%)	186 (22.8%)	12 (2.1%)
Total	335 (5.4%)	364 (6.2%)	189 (3.7%)	302 (5.1%)	738 (15.5%)	1395 (24.8%)

Table 2: Evaluation Results Based on Standard value (TLS).

In Standard Value of 5 cm

Section	Density (points per square meter)					
	Original	10,000	1,000	100	10	1
1	556 (50.8%)	564 (51.6%)	632 (57.8%)	894 (81.7%)	719 (66.1%)	3 (0.9%)
2	1182 (81.1%)	1180 (81%)	1201 (82.5%)	1346 (93.1%)	1277 (88.5%)	1093 (78.9%)
3	1497 (96.7%)	1498 (96.8%)	1501 (97%)	1499 (97.5%)	1348 (89.4%)	1335 (88%)
4	1207 (96.5%)	1207 (96.5%)	1205 (96.4%)	1200 (96%)	1127 (91.7%)	914 (73.3%)
5	809 (91.3%)	808 (91.2%)	815 (92.1%)	834 (95.8%)	818 (96.5%)	478 (71.7%)
Total	5251 (84.2%)	5257 (84.3%)	5354 (85.9%)	5773 (93.2%)	5289 (86.5%)	3823 (74.1%)

Out of Standard Value

Section	Density (points per square meter)					
	Original	10,000	1,000	100	10	1
1	538 (49.2%)	530 (48.4%)	462 (42.2%)	200 (18.3%)	369 (33.9%)	336 (99.1%)
2	276 (18.9%)	276 (19%)	254 (17.5%)	99 (6.9%)	166 (11.5%)	293 (21.1%)
3	51 (3.3%)	50 (3.2%)	47 (3%)	38 (2.5%)	160 (10.6%)	182 (12%)
4	44 (3.5%)	44 (3.5%)	45 (3.6%)	50 (4%)	102 (8.3%)	333 (26.7%)
5	77 (8.7%)	78 (8.8%)	70 (7.9%)	37 (4.2%)	30 (3.5%)	189 (28.3%)
Total	986 (15.8%)	978 (15.7%)	878 (14.1%)	424 (6.8%)	827 (13.5%)	1333 (25.8%)

5. DATA FUSION OF POINT CLOUD

5.1 Consideration points

Consideration points for fusion of data acquired by LP, MMS, TLS, and UAV photogrammetry were examined. It is necessary to devise various schemes of graphic design to generate shape data from point cloud. Different point cloud densities are required depending on the drawing method. Point cloud has only information that something was at that point at the time of measurement. In order to construct shape data from the point cloud, it is necessary to consider not only the accuracy and density of the point cloud but also the interpretation information and drawing method. The point cloud density for shape data creation needs to be experimented repeatedly by actually setting the objects based on the graphic method.

5.2 Display and drawing guideline

The three-dimensional landform display and drawing guideline were formulated to utilize point cloud acquired from various measurement instruments with different characteristics of LP, MMS, TLS, and UAV photogrammetry for design and construction work. The contents are as follows. 1) General provision: This chapter shows the outline and scope of the guideline and definition of technical terms. 2) Dimension of landform: The guideline defines the display rule of three-dimensional landform data. However, it is not necessary to make all landform data with three dimension depending on its usage. 3) Conformance class: This is defined by AP203 of ISO 10303 (Standard for the exchange of product model data). CC3 to draw contour lines and break lines and CC4 to draw the ground surface and consider the connection of surfaces are defined. 4) Display level of three-dimensional landform data: it includes display by point cloud density, density and display level based on use case, and data fusion of point cloud measured by various measurement instruments. 5) Level of detail: In LOD 100, elements are represented by symbols or schematic shapes. In LOD 200, the quantity, size, shape, position, and arrangement are represented by approximate values. In LOD 300, three-dimensional landform data are represented by unique shape and arrangement. In LOD 400, the data are represented by specific shapes and arrangements, as well as representing manufacturing and assembly information. In LOD 500, size, shape, position, and placement are expressed in the same way as on site. 6) Management information: it defines data updating time for maintaining latest landform data. 7) Number of significant digits and size value. 8) Annotation: It is held as the attribute information of the figure element. Its display depends on each software. 9) Display and drawing of points: It defines reference point with longitude and latitude. 10) Display and drawing of lines: It defines structures of road, railway, and building, landform, boundary, and brake line. 11) Display and drawing of surfaces. 12) Features.

6. CONCLUSION

In this study, a representing and drawing method of three-dimensional landform data based on point cloud data was proposed. The point cloud data were generated by LP, MMS, TLS, and camera on UAV. This study evaluated the density of point cloud data and display level for representing point cloud data based on various measurement hardware. The results were classified by the density. The density was evaluated for as-built management of road earthmoving. It should be one hundred points per square meter for as-built management. A three-dimensional landform representing and modeling guideline was proposed. It standardized the notation of view, and proposes to define the contents of conformance class, level of detail, management information, an-notation, used point, line, surface and solid, and features.

7. ACKNOWLEDGEMENT

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USING VIRTUAL REALITY TO DESIGN A SECOND LIFE FOR MINING CENTRES

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ABSTRACT: *In the construction design of mining centres, a major challenge faced is the inability to accurately predict air, land, and water conditions. This is as a result of limited availability of applicable examples that relate to similar environments. While current construction training of designers within mining contexts is vital, the process is expensive, time-consuming, and safety is a primary concern.*

This case study recommends that virtual reality (VR) be explored as a tool in the training of designers, with the aim of streamlining workflows by providing interactive simulations relating to navigation and circulation analysis within mines. The research indicates that users are better prepared for tasks when training is carried out in virtual environments – under the conditions which they would be expected to apply this knowledge. VR increases efficiency in communication and expands effectiveness in design analysis.

The proposed workflow from the training simulations aims to show that educating users in VR leads to an increased level of engagement and therefore a cognitive application of knowledge. Additionally, it is an objective to have this acquired knowledge go beyond analysis, by purposing to assist miners and mine operators to detect gas-leaks and therefore abate fatal explosions.

KEYWORDS: *construction analysis, communication, engagement, gas-leaks, safety training, mining, virtual reality*

1. INTRODUCTION

Safety training has become increasingly important for nearly all extraction industries operating in today's environment, and especially so for establishments involved in major mining and construction projects (Hancock, 2002). This is because in mining construction, failure to accurately identify and make appropriate allowance for risks being assumed under complex arrangements can have dire consequences (Squelch, 2001). We have seen in recent times many examples of such consequences and the fallout which may result in the event that risk is not carefully managed, and safety concerns are not addressed. These consequences extend beyond the immediate parties to the construction project, and they have economic and social impacts ranging from public hostility to future projects right through to the burden placed upon judicial resources, as a result of the inevitable disagreement that arises because of risks escalating (Hutchison, 2012). In the history of Australia, the worst mining disasters occurred as a consequence of an inability to accurately predict air, land, and water conditions (Brune, 2010). This led to undetected gas-leaks causing deadly explosions. This paper will provide an overview of a safety training case study. VR is used in place of physical navigation in construction projects, and the methods adopted by various participants to manage that risk is in an always dynamic environment. The paper presents a rationale for a pilot study to answer the question, "How can virtual reality be used as a tool of safety training to influence navigation in construction of mining centres?"

Table 1: The table shows the worst mining disasters in Australian history, in chronological order. In the three cases, inquiry into the disaster indicated that mine operators were unaware of the gas leaks and prevailing land conditions.

Location	*Year*	*Fatalities*
Bulli Mine, NSW	1887	81
Mt. Kembla Mine, NSW	1902	96
Mt. Mulligan Mine, QLD	1921	75

Table 2: The table shows recent mining accidents in Australia, as a result of parts of the mines collapsing. In the three cases, the weakest point of collapse was not known after the accident.

Location	*Year*	*Incident*
Gretley Mine, NSW	1996	Break in flooded workings (abandoned mine)
Northpakes, NSW	1999	Windblast (void collapse)
Beaconsfield Mine, TAS	2006	Mine collapse

2. CASE STUDY APPLICATION

The increasing accessibility to VR hardware and software has led to an exponential increase in VR users, especially in education and training sectors. Historically, the technology has been used primarily in the entertainment industry, but as the technology advances and VR headsets become more affordable, it is becoming increasingly common in other industries as well. For the mining industry, where plants are complex, remote, and unsafe when unknown, this immersive technology improves efficiency, safety, and productivity (Validakis, 2015).

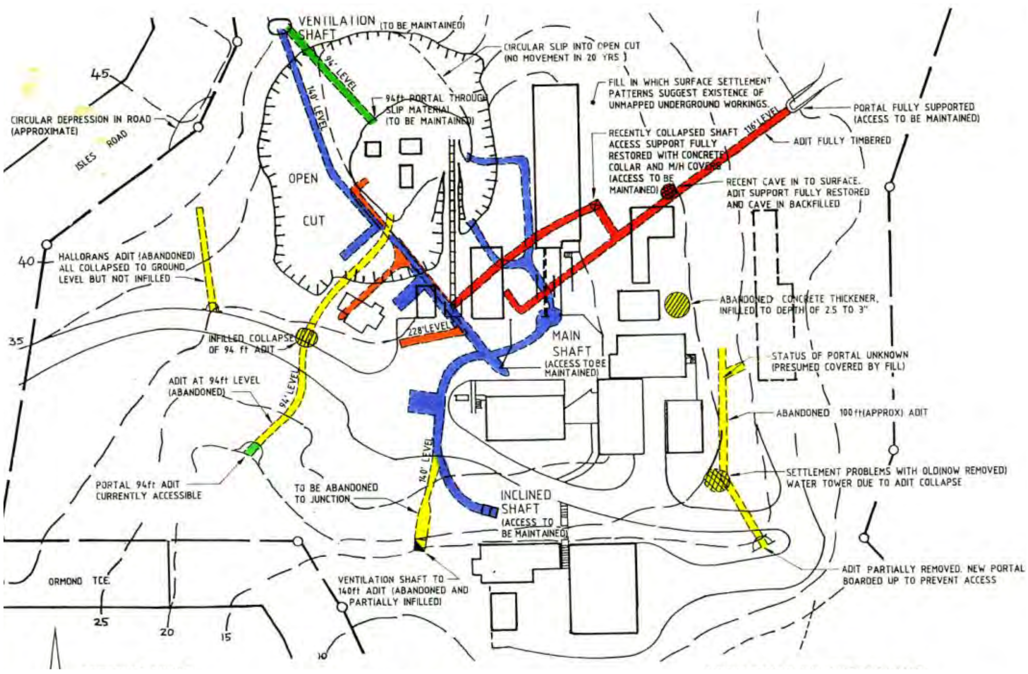

Fig. 1: The figure above shows a 2-D plan of the UQ Experimental Mine.

In Figure 1, the image depicts the current existing conditions of the mining centre. This is the current method used to carry out training exercises and to teach about emergency exits during an event of construction failure. From the image, it is evident that two-dimensional drawings are difficult to understand – both by experienced users and new trainees – and user confusion may be inevitable.

Using the UQ Experimental Mine (Indooroopilly, Australia), this case study examines three main means of application.

2.1 Training mine operators to improve compliance with safety standards

Dependent mine operators comprise much of the workforce in mining environments, and these workers must be properly trained and certified before they enter plants or perform maintenance and repair tasks (Wan, 2013). Traditionally (Filigenzi, Orr & Ruff, 2000), this is done through classroom training, video tools, and images such as the one seen on the previous page. Using the Unity 3D and Unreal Engine software platforms to create virtual models of plants and work areas is a simple and effective way for new employees and contingent workers to assess safety requirements and get an engaging first-hand view. The three-dimensional model and virtual reality view of a facility improves general understanding, making it easier for workers to practice safety requirements in plants and work areas and better able to respond to potentially unsafe situations. The learning theory of situated cognition is applied, where learners and trainees are seen to perform more effectively when their training is carried out in environments that are similar to those in which they would be expected to demonstrate their acquired knowledge. In this case, the experimental mine is modelled to match the physical mine in Indooroopilly.

2.2 Training maintenance technicians off-site

Mining centres are usually found in remote or offshore locations, and many of these facilities are difficult and expensive to access (Filigenzi et al, 2000). To help address the cost and ensure that maintenance is done in a timely manner, technicians in the study will use VR simulations to familiarize themselves with facilities prior to physically attending to the site (Kelly, 2017). Improving awareness and reducing maintenance times will offset the cost of creating virtual 3D models that clearly highlight the complex assemblies and sections within facilities.

2.3 Providing detailed diagnostics to improve maintenance efficiency

In the event of an equipment failure, technicians at the experimental mine must perform the first level of assessment to identify all necessary parts and tools (Foster & Burton, 2004). This first-level diagnostic can take time, as technicians must obtain safety clearance and permission prior to visiting the site (Foster & Burton, 2004). Using VR and an integrated virtual view of the facility with real-time data from operational systems, technicians can assess the extent of the problem before they physically visit the site. This can significantly reduce the time required to complete the maintenance, and more importantly, ensure that technicians are better prepared before performing the work. By integrating data from operational systems, VR can be augmented with real-time historical data of key parameters, which can help technicians make better decisions (García-Hernández, 2016).

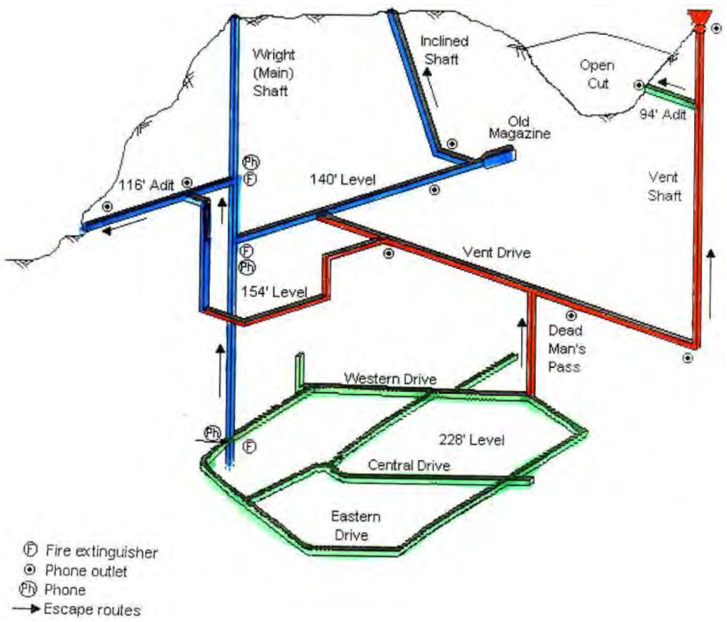

Fig. 2: The figure above shows a 3D plan of the UQ Experimental Mine, highlighting the main access and escape routes.

In the Figure 2, a three-dimensional image of the UQ Experimental Mine is used to indicate the locations of the regular and emergency access points. Additionally, it shows the position of the main mining shafts in relation to the drives. This proposed method of multi-dimensional visualisation in virtual reality enhances the level of engagement from the trainees, as they are able to visualize the position relative to the mine conditions.

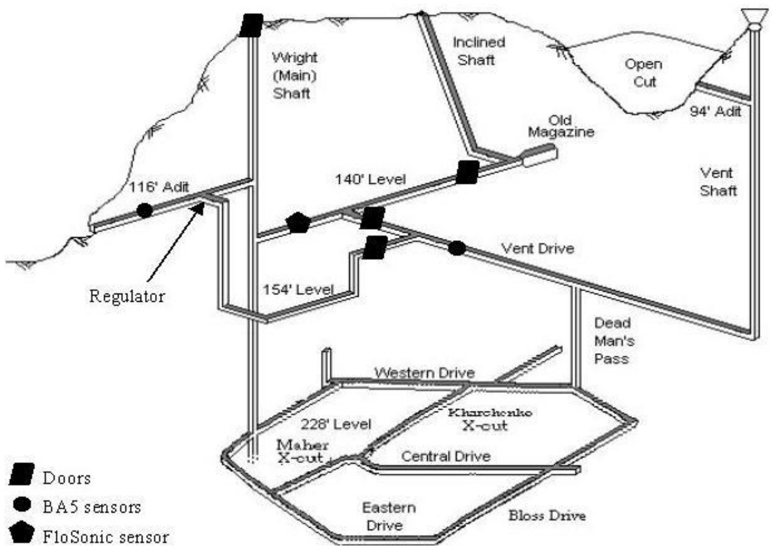

Fig. 3: The figure above shows a 3D plan of the UQ Experimental Mine, highlighting access points and sensors.

In the Figure 3, the Experimental Mine is depicted, showing the position of the main mining shafts in relation to the drives. This proposed method of multi-dimensional visualisation in virtual reality enhances the level of engagement from the trainees, as they are able to visualize the position relative to the mine conditions. With this knowledge, it is possible to conduct a training session in real-time where gas-leaks are detected and parts of the mine are isolated or sealed before the situation becomes fatal. The sensors, after detecting sudden changes in air pressure or gas leaks, illuminate a path to the closest exit within the simulation.

3. CASE STUDY EXECUTION – WORKSHOPS

The training and research will utilize case studies structured as immersive workshops. These case studies will require construction workers and construction managers of mining centres to navigate through the circulation of proposed mines, in virtual reality. These circulation spaces are unfamiliar to them, as they proposals that are yet to be constructed, and they will be required to acknowledge and respond to simulations of real life possibilities. These will include:

Guiding themselves and other users through circulation paths in proposed mines that are unfamiliar, under normal conditions, and

Guiding themselves and other users through circulation paths in proposed mines that are unfamiliar, during a time of crisis (such as in the sudden event of a fire or an explosion). The information gathered from these VR workshops will be used to determine whether the construction of a proposed mine will be feasible, given the level of difficulty faced when exploring the virtual simulation of the same.

The information is vital in determining whether a proposed mine will be safe and usable under normal conditions, and just as importantly, whether safe evacuations will be possible in the event of a crisis, even in the absence of construction drawings.

4. CONCLUSION

The key to driving adoption and maximizing the benefits of VR in construction is to move from the visual virtual view to a more analytic data-led view. VR will not serve to replace real-world experiences; instead, it will be used to enhance these experiences. This enriched virtual view provides access to both historical information, which can be accessed from three-dimensional modelling and visualization systems, and real-time systems.

Trainees learn in different ways, thus making multiple forms of media useful tools for interactive learners. Combined with this is a push towards simulation and VR to teach complex concepts in construction design, including the concept of spatial navigation, which is currently taught using static two-dimensional images.

The case study acknowledges that the system is initially expensive to set up, and the learnability of multiple systems is difficult. From the perspective of the author, much additional work is needed to simplify the current cumbersome workflows between software platforms and industry-specific methods towards these platforms. A simplified workflow will facilitate increased uptake in both training and professional setting, further adding to the value of these VR visualization, construction and navigation methods. It is intended that these issues will be addressed in future work.

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A REVIEW: HARNESSING IMMERSIVE TECHNOLOGIES PROWESS FOR AUTONOMOUS VEHICLES

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ABSTRACT: *Emerging immersive technologies comprising Virtual, Augmented and Mixed Reality (VAMR) and Electroencephalography (EEG) environments are creating a revolutionary and non-invasive Brain Robot cum Human-Computer interaction paradigms. The burgeoning rise of autonomy in the vehicles and expected introduction of self-driving vehicles will underpin the interesting use of such technologies creating a "brain to vehicle" connectivity, digitalization, efficiency, improved situational awareness, portable environment for riders and provision of safe testing grounds in real time conditions. Harnessing the collective prowess of these technologies will be at the forefront of predicting, developing and deployment of autonomous vehicles. Despite the increased industrial interest, there is very less attention being paid by the academia in the use of these immersive technologies in the testing, operation and users' perception of autonomous vehicles. This exploratory research study being part of a larger study is an attempt to venture into these emerging immersive technology applications and explore their recent role in a wider AEC industry setting with a special focus and linkages to driverless technology through optimally designed in-vehicle user's interfaces. Moreover, through an appropriate synthesis of recent and systematic literature review, an effort has been made to highlight the development of new brain-computer interaction paradigms that assist in the successful implementation of this technology and improving the users' trust, comfort, and safety.*

KEYWORDS: *Virtual, Augmented and Mixed Reality, Electroencephalography, Autonomous Vehicles, Human Computer Interaction.*

ABBREVIATIONS: *Brain Computer Interfaces (BCI), Virtual, Augmented and Mixed Reality (VAMR), Electroencephalography (EEG), Autonomous Vehicles (AV), Human Computer Interaction (HCI), Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), Head Up Displays (HUDs), Laser Ranger Finder (LRF), Global Position System (GPS), Information transfer rate (ITR), Building Information Modelling (BIM), Battlefield Augmented Reality System (BARS), Autonomous Intersection Management (AIM), Forward Collision Warning Alert System (FCW), Stop Distance Algorithm (SDA), Graphical User Interface (GUI), Human Machine Interface(HMI), Artificial Intelligence (AI), Machine Learning (ML)*

1. INTRODUCTION

Digitalization has a dynamic imprint on global markets paving the way towards human progress and ever-increasing appetite to control the surroundings. Rüßmann et al. (2015) identified that we are in the midst of the fourth wave of new digital industry technology referred as Industry 4.0 fueled by nine technological advances where cyber physical systems including sensors, IT systems, machines and work pieces are connected in a single enterprise with standard internet based protocols. The Augmented Reality (AR) and Autonomous Robots are among these nine pillars of this advancement and much to gain from each other. Increased focus on vehicle autonomy and advent of self-driving cars has led to explore another vista of research domain investigating the role of Human-Robot Interaction (Meschtscherjakov et al., 2018), use of immersive technologies, shared situational awareness, shared control and authority, virtual assistance and controlled transition procedures from the vehicle to the human driver and vice versa (Politis, Brewster & Pollick, 2015; Walch, Lange, Baumann & Weber, 2015). Nowadays, brain-computer interfaces detect neural activation patterns and control the devices by brain signals. Such BCIs comprise EEG headset in combination with vehicle dashboard systems and other optimally designed user interfaces can be employed to interact with vehicular systems in conjunction with VAMR platforms (Cernea, Olech, Ebert & Kerren, 2012). A systematic review of literature suggests that there is a research gap of how to make computers smart enough to assimilate non-verbal signals and natural gestures from humans in a real-time and communicate to autonomous vehicles using immersive technologies, mind controllers, sensors, wearables, photogrammetry, 3D scan capture, EEG, BCI, and HMI (Stergioulas, n.d.). Despite the increased industrial interest in these technologies, there is very less attention being paid by the academia in their use in the testing and operation of autonomous vehicles.

2. RESEARCH METHODOLOGY

This exploratory research is based on conceptual literature review of quality assured peer review publications and industry reports between years 2000 to 2018 from Web of Sciences database using key words "Immersive Technologies", "Autonomous Vehicles Interfaces", "Augmented Reality", "Electroencephalography "Mixed Reality" and "Virtual Reality application in Architecture Engineering Construction", and recent industry reports regarding use of VAMR and EEG applications in a wider AEC industry settings and then to identify and explore their emerging linkages with autonomous vehicles. This study is an early stage of a larger sequential research process to address holistically the impact of immersive, non-invasive and other emerging technologies in garnering the trust, comfort and safety of the users in driverless shuttles thorough optimally designed innovative interfaces. The aim at this stage is to explore these technologies and their emerging roles in the context of human computer cum brain robotic interaction paradigms to realize their futuristic role in driverless technology through appropriate and systematic literature review and longitudinal analysis. This research study will assist in achieving a reliable platform for further investigation.

3. SIGNIFICANCE OF AUTONOMOUS VEHICLES

The advent of AVs is expected to transform the future of the world in many ways (Geng et al., 2017). This disruptive yet beneficial technology will assist in shaping the future mobility, transport infrastructure, urban landscape, ensuring vehicle safety with less congestion, improved environmental outcomes, efficiency and productivity (Fagnant & Kockelman, 2015). AVs can help to reduce the human error contributing up to 90% of vehicles collision (Bonnefon, Shariff, & Rahwan, 2015; Gao, Hensley, & Zielke, 2014). AVs technology is one of "23 technologies providing new insights into the emergence of seamless intelligence" which was identified by nine IEEE Computer Society technical leaders (Alkhatib et al., 2015). Moreover, these can prove a test bed for various advanced technologies including AI, Computer Vision and Machine Learning (Katrakazas, Quddus, Chen & Deka, 2015) and this research study's immersive and non-invasive technologies. The term 'autonomous vehicle' is used here to refer to a vehicle that has the capacity to sense its environment and navigate without human input (Gehrig and Stein, 1999). The design of AVs is comprised of three layers, i.e., a perception, planning and a trajectory control layer (Geng et al., 2017). AVs combine various sensors to perceive the surroundings, including radar, laser light, GPS, odometry and other in-vehicle systems and have great potential to improve the transportation safety, mobility, customers' satisfaction while reducing the transportation costs, energy consumptions, and crime rates (Ross and Guhathakurta, 2017). In Construction Industry, autonomous vehicles, robots and self-driving construction equipment have their applications in mining, brick laying and glazing, concrete printing, digging and grading, efficient organization of job site, safety and productivity (Alderton, 2018; Bouge, 2018;Kirkpatrick, 2018).

4. IMMERSIVE AND NON-INVASIVE TECHNOLOGIES

Immersive technologies blur the boundary between the physical and the virtual, simulated, digital or cyber world thereby creating a sense of immersion for end users (Suh & Prophet, 2018). The use of immersive technologies including AR, VR and MR foster learning experiences, collaboration and increases creativity in various fields of education, marketing, entertainment and health care. These technologies allowing users to connect real and digital world for better decision making and efficient work procedures (Altinpulluk, 2017; Rüßmann et al., 2015) have been researched in both academic and the automotive industry alike. The proliferation of advanced computer technologies comprising AI and ML in conjunction with immersive technologies of VAMR and non- invasive EEG can prove to be vital in testing and operation of the autonomous vehicles. Nowadays, considerable and fruitful discussion into the use of VAMR and EEG technologies in driverless vehicles is taking place beside testing vehicles in controlled environments. The non-invasive use of EEG technology can significantly influence the decision-making module providing safe and reasonable abstract driving actions and collision avoidance strategies. These state-of-the-art technologies can provide a forward-looking capability to decision-making system of AVs, and their interface with VAMR can be used to predict future driving behaviors (Wei, 2016).

4.1 Mixed Reality (MR) Applications in Engineering and Construction.

Mixed Reality (MR) is one of the advanced computer technologies integrating physical and virtual spaces (Yoo & Bruns, 2006). Mixed Reality (MR) technologies are becoming increasingly relevant for human interaction in various fields of construction (Milgram & Kishino,1994; Riexinger, Kluth, Olbrich & Bauernhasl,2018) by connecting the on-site real work environment with digital information or virtual objects. MR instruments connect the virtual environment for self-inspection and self-instructions to check working processes and get interactive onsite guidance for preventing incorrect actions. Moreover, the thermal and acoustic evaluation of buildings and equipment can be enabled using MR through BIM based process simulation for self – instruction. Also onsite workers can visualize how to fix, install remove elements for refurbishment works. Lee, Soonhung and Jeongsam (2011) developed the idea of virtual factory layout planning system using mixed reality based digital manufacturing equipment integrating real images with virtual objects. Dunston (2008) described a vision for using MR systems in the AEC industry. This largely increases the efficiency for scheme explanation.

4.2 Virtual Reality, Augmented Reality and Mixed Reality (VAMR)

VR is a powerful method to immerse the end users into simulated situations and tasks where accurate control of the state is provided (Innocenti, 2017). VR has the potential to enhance the effectiveness and efficiency during the project lifecycle, from initial conceptual design through planning, preparation, and detailed design, to completion (Thabet, Shiratuddin, & Bowman, 2002). Shi, Du, Lavy, and Zhao (2016) indicated that VR enables real-time interactions of remote stakeholders in the same environment, with a shared immersive walkthrough experience, which can largely increase the design intent's understanding, improve the project's constructability, and minimize changes. VR can be applied to the majority of the economic sectors where 3D explanation or training is engaged, such as construction (Thabet et al., 2002), education (Sampaio et al., 2010), healthcare (Ford et al., 2018), etc. With the help of Building Information Modelling (BIM), the creation of a VR environment could be easier as the 3D model will be available as soon as the BIM-based design is completed. In the education sector, VR emerges as an effective tool for motivating students (Sampaio, Ferreira, Rosário, & Martins, 2010), thus making the learning process into an interactive game. It brings a change from passive learner attitudes into action. AR refers to the real-time perception of an environmental setting that has been enhanced by means of computer-generated virtual components (Raja and Calvo, 2017). It is a real time live view of the world environment whose elements are "augmented" by computer-generated visual information (Ruggiero, 2018). It has a specific place in the reality-virtuality spectrum as shown in Figure 1, in which AR position itself in the left hand side as main component of reality and computer generated visual information is a secondary component augmenting the reality.

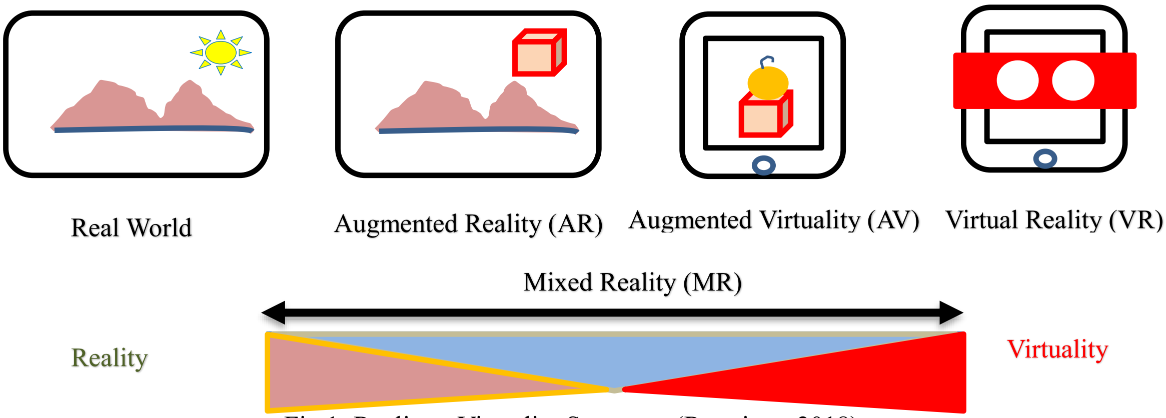

Fig 1: Reality – Virtuality Spectrum (Ruggiero, 2018)

AR can provide direct as well as indirect real-time view of the augmented environment. AR is referred as an integrated technique of image processing and display system of complex information which generates virtual objects over real objects to produce a mixed world (Jiao et al., 2013, Yang et al., 2013, Irizarry et al., 2013). According to Azuma et al. (2001), it could combine real and virtual objects in a real environment, run interactively in real time, and align with each other. Using the AR technique, integration between 2D and 3D can be achieved. With the 2D drawings, QR codes or even real-world views, virtual objects could be shown from 3D model using the mobile device. AR has been adopted in many fields of science and engineering. In game entertainment, Thomas et al. (2000) researched outdoor/indoor AR first-person application ARQuake, an extension of the desktop game Quake. In the military, Livingston et al. (2002) developed the Battlefield Augmented Reality System (BARS) for military operations. In medicine, Birkfellner et al. (2002) presented a simple design of the modified head-mounted display for AR visualization. In addition, AR is also considered as one of the advanced computer technologies which has potential to provide significant advantages through visualization to the AEC industry (Dunston, 2008). Kuo, Jeng, and Yang (2013) stated that AR has been gaining extensive applications in the construction field, such as real-time 3D display of on-site construction progress (Woodward et al., 2010), introduction of objects assembling procedures (Behzadan, Khoury, & Kamat, 2006), design and revitalization in existing built environments (Donath, Beetz, Grether, Petzold, & Seichter, 2001). Ruggiero et al. (2018) recently explored AR applications in building evacuations regarding training purposes, navigating and visualizing building evacuation simulations. Compared to AR, MR performs more interactivity. The end users can directly make interactive operations by using their body languages. MR mixes everything more seamlessly and offers a greater amount of user interaction. This is widely used in video games, and entertainment, but also present in education, healthcare, and engineering (Juraschek et al., 2018). For educational use, Ke et al. (2016) developed an MR platform for training teaching assistant in universities. Ford et al. (2018) utilize MR in burn care therapy as he found that merging in MR can reduce the pain for the patients.

4.3 Non-Invasive Electroencephalography (EEG)

A trend is emerging to use EEG in smart controls in buildings or transportation sector. Luo, Han & Duan (2015) explored EEG applications in smart home systems by designing a BCI control based on EEG for elderly and disabled people self-care. It included six functions of light on, light off, withdraw curtain, draw curtain and turn off and on the air conditioning system integrating android software. EEG is the measurement of brain electrical fields via electrodes (which act as small antennas) placed on the head (Cohen, 2017). EEG is widely used in neurophysiology research. It has proven effective in providing a more comprehensive understanding of the neural mechanisms underlying human cognition. Besides, EEG is an emerging biomarker of pathophysiology. Traditionally, the use of Graphical User Interface for smart control aims to enhance environmental accessibility yet it is challenging for many disabled users (Sirvent Blasco, Iáñez, Úbeda, & Azorín, 2012). Additionally, Conventional VR interfaces need more complex manipulation in Human-Computer Interaction (HCI) and physical features to assist disable people. EEG technology depends on a BCI, which processes the data received from an enhanced or wired brain and sends signals to external devices. Such a friendly interface eliminates the dependence on finger operations. Therefore, a sync of VAMR and EEG might prove to be a way forward, where a disabled person's mind can control the physical cum virtual world. It has other wide-ranging application in medical, education, self-regulations, production, marketing, security, gaming and entertainment (Abdulkader, Atia& Mostafa, 2015).

5. EXPLORING VAMR AND EEG LINKAGES WITH AUTONOMOUS VEHICLES

With regard to human-robot interaction, instance-based learning approach has been successfully employed in dynamic decision making and transfer of job knowledge from a human to a robot (Gonzalez, Lerch & Lebiere, 2003; Park, & Howard, 2015). AR can be a significant tool in enforcing conviction in autonomous driving by allowing the vehicle to perceive objects, generating a rationale for decisions and conveying its intent to the driver for manual intervention (Ng-Thow-Hing et al., 2013). It can also show a planned lane change to the driver to augment its situational awareness. Additionally, AR Head Up Displays are likely to be the future of car navigation and enhanced control mechanisms to improve traffic safety (Palladino, 2018) through 3D navigation overlay on road geometry and outside objects including pedestrians, bikers, and wheelchair users. Figure 2 below depicts how AR heads-up displays navigational images directly over what the driver observes from the windshield, thus reducing the mental energy of applying the information, avoiding distraction and reducing driver error.

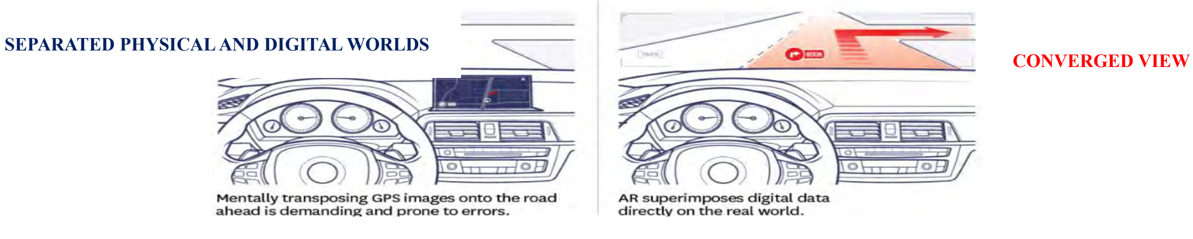

Fig 2: Augmented Reality in Autonomous Vehicles (Porter & Heppelmann, 2017)

VR windshields application will remove the requirements of road signs, traffic lights, road paintings and reconfigure multi-lane road based on demand. In the industry context for introducing innovative technologies, there is always a need to address cost reduction, speeding up of processes and quality improvement. AR fulfils all these requirements by reducing production times and costs, less training efforts and reduction of errors. This research identifies that AR and VR technology will assist in transition towards autonomous reality. AR world market could reach $90 billion by 2020 (Medal, 2018). AR promises enhanced navigation, safety, adaptive cruise control and lane keeping. An AR display system was developed in a vehicle to provide all the necessary information for the drivers during the travelling (Kim, 2015). Besides, MR was also applied to develop an immersive remote driving interface (Tarault, Bourdot, & Vézien, 2005). Ng-Thow-Hing et al. (2013) stated that AR has the potential benefits towards driver enhancement by "providing better situational awareness towards driving hazards" whereas AR can also enhance the communication between the driver and AVs. As mentioned before, VR can provide an immersive scene for the drivers in the call centers. First of all, the drivers can be immersed in a VR navigational environment. However, they might not be able to perceive the outside world. The VR system only keeps on receiving the end user's position and orientation data through its embedded accelerometer. Upon this, AR adds another input from the camera, which is capable of recognizing the outside world. AR performs better in overlaying 3D navigation instructions onto road geometry. This is more convenient for the drivers who makes remote control for the autonomous vehicles. By using AR, global awareness and local guidance by conveying the right information at the right moment can be enhanced (Pokam et al., 2015). Besides, the safety of both autonomous driving and human driving can be facilitated. In a typical MR system, more interactivity can be accrued though interactive tools, including motion controllers, leap motion. The drivers are able to make a remote connection with the vehicles efficiently in a physical-virtual-mixed world and carry on the pre-defined tasks by using a steering wheel and pedal combo. MR is adopted for Autonomous Intersection Management. According to Quinlan et al. (2010), it is possible to make intersection control for autonomous vehicles much more efficient than the traditional control mechanisms such as traffic signals and stop signs. It is highly likely that AR integration with driverless technology will inculcate a level of trust among consumers from navigation to increased awareness and translating into acceptance of autonomous future (Medal et al., 2018).

Autonomous Vehicles technology is likely to change significantly in the backdrop of "brain to vehicle technology" utilising VAMR and EEG technologies, thus controlling the vehicles with human mind. In the application of EEG based BCI architecture to control robotic devices, a non-invasive Brain Robotic Interface technology is becoming popular to control robot systems through brain waves while considering the dynamics and kinematics of robots (Mao et al., 2017). The Dynamics explores the motion characters involving speed, acceleration, and stability thus, finding the time cost of each motion of robot, resultantly giving guidance for choosing the corresponding ITR. The Kinematics study involves path planning, path optimization and global path planning. Similarly, autonomous vehicle has a sophisticated control architecture comprising sensor fusion, path planning, motion control, GPS and different sensors such as sonars, cameras and bumpers. Modelling an autonomous vehicle architecture with appropriate mechanical kinematics and dynamics embedded with VAMR and EEG technology can greatly enhance its performance. It is to be noted that brain signals can only be used in supervising the process and giving guidance in case of emergency and rarely in path planning which is realised by camera and GPS. In an emergency, the brain signals can overrule the path planning instructions to the autonomous vehicle. Zhao, Zhang, & Cichocki (2009) used motor imagery to control EEG as well as a car in VR environment. Cernea et al. (2012) used a BCI to control an unmanned vehicle. In an another project developed by F U Berlin, Germany, an EEG headset in combination with LRF and GPS data is used to control the car (Waibel, 2011) Furthermore, in – vehicle secondary control tasks with BCI can be performed through EEG based portable headsets. Measuring the driver state during various stages of cognitive workload under influence of affective sensing (emotions) with facial analysis and EEG can assist to envisage the break reaction time of a driver which is a fundamental input in designing of collision warning systems for autonomous vehicles (Govindarajan, & Bajcsy, 2017). The underlying theory is that during time constrained and real time conditions, human mind shift from a heuristic approach to lessons learnt from past experiences. The time of alert is crucial to the driver's recognition of Forward Collision Warning Alert System and same is applicable for autonomous vehicles under similar set of conditions. Therefore, VAMR and EEG technologies can be used for performance monitoring of autonomous vehicle and to improve upon vehicle reaction time to tune the distance of threshold used in Stop Distance Algorithm for collision warnings. Thus, an instance based learning approach can be used to mimic and model human behaviour. MR Prototyping can provide a safe testing ground for autonomous vehicles.

MR Lab at the University of Southern California has been successful in exploring human-machine teaming (USC, 2017). Most of the design algorithms in VAMR space used for human-drone pairing can be used for testing of autonomous vehicles where engineers can test, educate and carry out risk analysis in a virtual space besides allowing collaboration with other virtual systems since the virtual and physical space can be tied together in real time. This research study concentrated on the use of VR on autonomous vehicles. As a result, there are three points identified: 1) *Training*. With a pre-configured VR environment, both of the vehicle driver and the autonomous algorithms can be trained. When the automated vehicles conditionally reach its functional boundaries, the drivers are required to respond. However, such training largely depends on practice. Written knowledge can hardly get driving skills across to the learners and similarly, a real-world practice can hardly give all the circumstances to the learners. With this in mind, researchers attempted to simulate all the training scenarios in VR environment and emerge the learners within (Sportillo et al., 2018), thus it can efficiently establish environments that safely allow drivers to relearn their driving habits to towards a future operation of AVs. The research points out that AVs need to be capable of making informed, rational decisions on reacting the changing environments. With this in mind, the autonomous algorithms need to be trained on the input of video records from driving in real roads, with real driver behavior and real weather conditions. That is to say, the algorithms can also be trained in a VR environment, which provide a training environment close to reality. Such training system provide a scalable input for the autonomous algorithms; 2) *Testing*. Before real-world road testing, the prototype system can be tested in the VR environment. In a VR environment, dangerous scenarios can be simulated. This largely reduces the risks while avoids the impact from real-world weather condition. Likewise, the proposed system is potential to reduce the time consuming and costs for the testing processes; 3) *Interacting*. When the phase of autonomous driving begins, a driver-vehicle (or a human-machine) interface is needed. When the CAVs encounter with the edge cases, VR is a good tool for engaging the drivers with remote control. To make this work, a call center with a number of drivers will be established. These drivers keep on watching the whole vehicles' state. Once any vehicle is in trouble, the drivers can take control of it. In the call center, a VR environment is used for representing the scenes recorded in the cameras; and a steering wheel and pedal combo are deployed to allow the driver control the vehicle in trouble remotely. Once the vehicle back to normal, the autonomous driving system will resume control. Hence, VR tools are potential to reduce the training and testing cost and time consumption for the autonomous system development while promote the driver-vehicle interaction in the autonomous driving phase. In order to improve driver situational awareness and safety, innovative forms of visual displays based on computer vision such as lane departure and auto breaking combined with aural and haptic feedback can lead towards lesser accidents and fatalities. Additionally, VAMR applications could assist in responding to traditional phone calls thus significantly reducing the accident rates besides ending up as a "portable environment for passengers" in conjunction with AI. AI takes into account highly optimized computer vision algorithms, next-generation path planning, and traffic flow metering (Williams, 2018).

Car makers including Ford, Hyundai, BMI, Mercedes-Benz, and Audi have already started using AR in HUD systems, navigation, maintenance, and servicing, virtual test drive to purchase a vehicle (Jarvis, 2017), "Civil Maps" are crowdsourcing maps to let people into the brain of autonomous vehicles through visual representation of vehicle sensor date and Lincoln and Kia have tested their self-driving vehicles on 32 acres of simulated roads in the University of Michigan (Eisenberg, n.d.). Similarly, "WayRay" technology can convert car's windshield into a giant screen for movies, and "Navdy" equipped car connects the driver with the road. PSA Peugeot Citroen's is working towards built-in augmented reality in the cockpit where the driver can view data while looking at the road with a built-in transparent display projected on the windscreen (Eiges, 2017). Nissan Car manufacturers are ready to arrange a showcase in a driving simulator in 2018 (Alphr, 2018). The brainwave technology comprising EEG not only detects the level of comfort in the passenger and displays calming visuals using augmented reality to enhance the journey experience but also assists the vehicle to respond to dangerous situations much faster than humans. However, it would be interesting to note how these technologies unfold and interpret between instinctive reactions and sensible reasoning since human mind approach a problem in a more sensible way while giving a second thought. Chinese researchers have also developed a first mind-controlled car, where a driver can control the car's various movement wearing brain signal reading equipment comprising 16 sensors from the driver's brain (Crabbe & Wang, 2018). It was first conceived for the disabled people, and now this technology is being explored for driverless cars.

In this research, we propose to use AR tools for promoting the driver-vehicle interaction. Besides, Immersive technologies of V and MR can be used for performance analysis of autonomous vehicles including simulated testing and perfection, visual displays to improve situational awareness and as a portable environment for passengers. Head-mounted VR/AR in combination with EEG based neuro-monitoring and neuro-feedback is expected to unravel an innovative dimension of human interaction with virtual, digital and cyber world creating a way forward for driverless technology (Jung, Zao & Chang, 2016).

Conclusion

Use of immersive and non-invasive technologies including VAMR and EEG facilitates HCI paradigms in the context of autonomous vehicles and provide a right platform to realize the futuristic role of driverless technology in terms of its operation, testing, safety and users' acceptance. This research study finds out that users' level of comfort and trust, confidence in service, traffic safety, ease of use and in-vehicle security can be improved through innovative interfaces. In this research paper, the performance of EEG and VMR based systems have been explored to understand the impact of these immersive technologies to facilitate human computer cum brain robot interaction with autonomous vehicles. This study is a first step towards a larger study to deliberate upon formation of a framework for realizing trust dynamics in human-autonomous vehicles interaction through optimally deigned user interfaces thus essentially exploring how to humanize driverless technology for autonomous shuttles in a smart city context and to make it more attractive for prospective users relative to current means of transportation. The aim at this stage is to venture into the prospective applications of above mentioned technologies in driverless vehicles seeing their significance in wider AEC industry and find out their further merger in shape of suitably design user interfaces. Future merger of VAMR technologies with Neuroscience cum EEG functionality can unleash infinite possibilities of human machine interaction where vehicles functionalities and the automotive value chain will change significantly in the backdrop of mega-trends of autonomous driving, connectivity, digitalization and efficiency. However, this merger of VAMR and EEG interfaces once moved from controllers, swiping and voice activation to brain activity, it might invade personal space leading to tech-social, ethical and privacy challenges which also need to be revisited.

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VIRTUAL TRIAL ASSEMBLY OF HIGH-RISE AIR CORRIDOR USING BIM AND TERRESTRIAL LASER SCANNING

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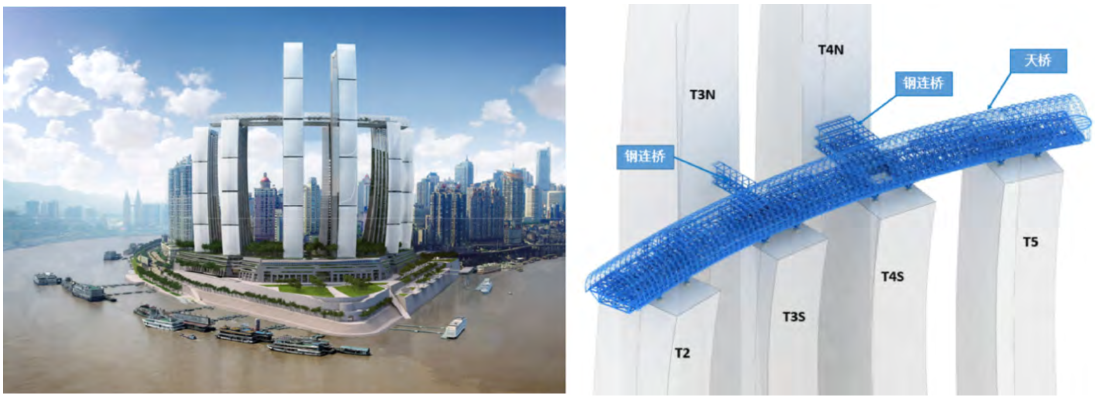
ABSTRACT: *This study proposes a method which can enhance the degree of visualization of high-rise air corridor construction and minimize the closure tolerance. High-rise air corridor is a new kind of building structure which gradually become landmark buildings in some cities. However, unique architectural form, complex lodging condition and other uncertain factors make this construction laborious and time-consuming. Moreover, the closure tolerance between two parts of the corridor are difficult to control by workers. To tackle the limitations of the current method, virtual trial assembly(VTA) of corridor is developed in this study. First, scan data and digital models with respect to air corridor are acquired. Geometric information of welding control points is derived based on BIM. Then,* closure tolerance threshold and optimal attitude of corridor are ascertained*. Finally, VTA is applied for the corridor in Chongqing Raffle City to verify the effectiveness of this method.* From the result, the tolerance threshold is identified (26mm) through *finite element analysis of the structure, which ascertains that one welding point needs to be adjusted before physical assembly, indicating the proposed method has a potential to be applied to high-rise corridor construction.*

KEYWORDS: virtual trial assembly, TLS, BIM, finite element analysis, optimal attitude adjustment,

1. Introduction

The high-rise air corridor is a new kind of complex steel structure which gradually become landmark buildings in some cities such as the high-rise air corridor in Chongqing Raffles City which is about 300 meters in length, 30 meters in width and 250 meters away from the ground, being the largest air corridor in Asia at present. The location and configuration of this coordinator and 3D BIM model are shown in Fig.1 and Fig.2. The traditional physical assembly of high-rise air corridor is pretty fussy, and hoisting, lifting and closing bring plenty of difficulties to the construction. Moreover, the closure tolerance between two parts of the air corridor are difficult to control by workers because of many factors such as machinery for assembly, manpower, suitable places for the construction, transportation of the building elements to the assembly place and some other implicit factors. Furthermore, sometimes the physical assembly of the whole structure cannot be realized due, primarily, to the size of the work.

For these reasons, generalized procrustes analysis techniques to realize a trial assembly for complex steel structure in a virtual environment (virtual trial assembly) have been recently developed (Case 2014). This was demonstrated in a number of studies that the employment of the virtual reality for many engineering applications are available (Kadir 2011). However, the previous techniques based on the geometry of steel structure and stress state analysis of structure are not discussed, which is normally not available for high-rise air corridor construction. More specifically, the stress of the corridor must satisfy the design value after finishing assembly, which can ensure that high-rise air corridor structure is safe and reliable. Therefore, it is not dispensable to discuss finite element analysis of corridor in this research.



Figue.1. Location of the high-rise air corridor

To tackle the limitations of previous techniques, the method that virtual trial assembly (VTA) based on Building Information Modeling (BIM) and Terrestrial Laser Scanning (TLS) is proposed in this paper. Building Information Modeling (BIM) has recently attained widespread attention in the construction industry (Lu 2010). Several excellent reviews describing its applications. This relatively new technology is defined as a digital representation of physical and functional characteristics of a facility (Smith 2010). Terrestrial Laser Scanning (TLS) become more and more significant in construction with the development of Building Information Modeling, which also stimulates to the emerge of new construction approaches. (Amann 2001, Song 2007).

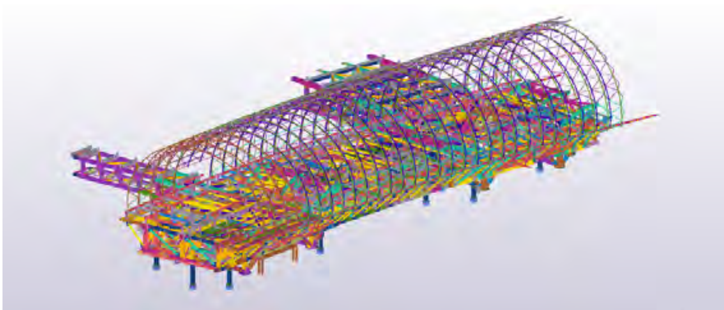


Fig.2. 3D Tekla model of the high-rise air corridor

Virtual trial assembly (VTA) (Case 2014) is defined as the process that simulates, in a virtual reality, the physical digital trial assembly of a high-rise corridor with the aim of optimizing the geometrical configuration obtained by a survey of key composing elements and minimizing the assembling tolerances, which can be used to guide physical assembly in construction.

2. Research Methods

In the first step, the points cloud data and digital models with real geometric information of high-rise corridor are derived using reality capture technology such as terrestrial laser scanning, industrial photogrammetry system, total station scanning. Then, point cloud data are processed using DBSCAN algorithm and fixed filtering algorithm, which makes point cloud data more reliable and explicit for the following research steps. Next, BIM models of welding control points are reconstructed using some point cloud reconstructed algorithm (Rusinkiewicz 2001) and geometric dimensions of these control points are extracted from BIM structure. Configuration of welding control points is shown in fig.3.

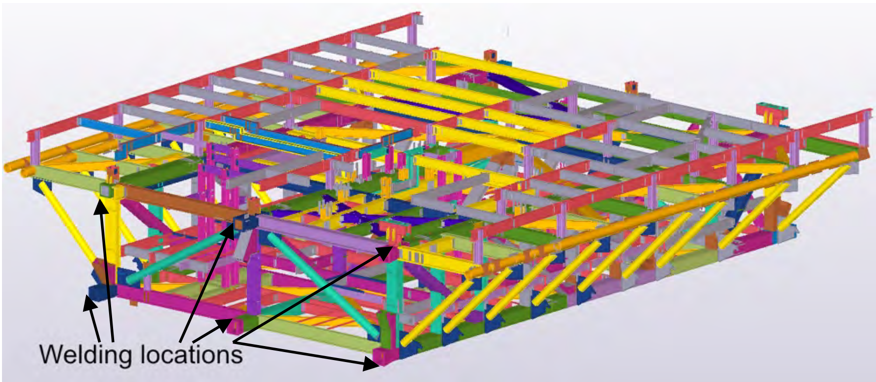


Fig.3. Configuration of welding control points

Finally, according to the closure tolerance threshold identification through finite element analysis, the optimal attitude is estimated by solving a nonlinear minimization problem based on optimized Procrustes Analysis.

3. Analysis of Virtual Trial Assembly

The procedure that virtual trial assembly of a complex steel structure by generalized procrustes analysis techniques is as explained by (Beinat 2014). The practical purpose is to verify the correspondence between two data sets – design and as-built, both extract from the BIM structure – in such a way to guarantee that, despite the inevitable minimal defects, the structure can be effectively built, satisfying the assembling tolerances admitted by the design, and avoiding or forecasting any change of the built elements during the final construction.

The procedure of VTA of high-rise air corridor includes the following steps. First, reality capture technology is adopted to acquire the digital model with respect to high-rise air corridor. Then, the essential geometric information is derived from BIM structure, as described in Section 3.1. Next, a new method that optimal attitude control for air corridor is proposed by solving nonlinear optimization problems based on Procrustes analysis, using Matlab programming, as presented in section 3.2.

3.1 Reality Capture Technology

3.1.1 Digital model acquisition with respect to corridor

To obtain the digital model reflecting the real geometric characteristics of this corridor, terrestrial laser scanning(TLS) is applied for this program. The principle of TLS is shown in section 1. The procedure of laser scanning includes the following steps: (1) The scan components of high-rise air corridor are identified, and three-dimensional laser scanner is used to scan the different azimuth stations of these components under the condition of constant temperature. When there are multiple connection sections, it is necessary to ensure that at least two stations are scanned for each section to ensure the measurement accuracy and the density of the point cloud. (2) Point cloud obtainable from different scan stations are put together in Faro software thereby acquiring a integrated digital model with respect to the high-rise air corridor.

3.1.2 Data processing and geometric information extraction of corridor

After obtaining point cloud digital models with respect to the corridor, the proposed technique first removes noise data of the digital model using DBSCAN algorithm or mixed filtering algorithm (Kim 2015), which enables point cloud data to be more reliable and explicit. Next, BIM models of significant components of corridor are built using point cloud digital models. At the same time, geometric information of these control points is extracted from BIM models.

3.2 Optimal attitude adjustment of air corridor based on Procrustes analysis

Considering the characteristics of high-rise air corridor and construction method, the approach that optimal attitude control of air corridor is proposed based on previous study (Case 2014). In order to estimate and identify the optimal hoisting, lifting and closing attitude of high-rise air corridor, the optimal attitude control (OAC) process, is described as follows: (1) The significant components of corridor are estimated and identified. (2) Geometric information of these components is distilled from BIM models and the 3D coordinates have been stored in a set of $n{\times}4$ matrices (where n is the variable number of points belonging to a single structural element). (4) Optimal rotation and translation matrices by solving the nonlinear minimization problem of OAC, as shown in the following equations, respectively. The rotational and translational moves are expressed collectively as

$$\boldsymbol{R_{xyz}} = \boldsymbol{R_\alpha R_\beta R_\gamma T_{xyz}}$$

Where, the three rotation matrices and a translation matrix, $R_\alpha, R_\beta, R_\gamma, T$ are defined as follows:

$$\boldsymbol{R_\alpha} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos_\alpha & -sin_\alpha & 0 \\ 0 & sin_\alpha & cos_\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \boldsymbol{R_\beta} = \begin{bmatrix} cos_\beta & 0 & sin_\beta & 0 \\ 0 & 1 & 0 & 0 \\ -sin_\beta & 0 & cos_\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{R_\gamma} = \begin{bmatrix} cos_\gamma & -sin_\gamma & 0 & 0 \\ sin_\gamma & cos_\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \boldsymbol{T_{xyz}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ x & y & z & 1 \end{bmatrix}$$

Where, α, β, γ are the angles of X axis, Y axis and Z axis rotation of the corridor to be hoisted , x, y, z are the translation distance between the corridor along the X axis, Y axis and Z axis.

The coordinates matrix of the fixed part of the corridor on the tower is $\boldsymbol{A}$ and the coordinates matrix of the part of the view bridge is $\boldsymbol{B}$. The nonlinear error function is defined as follows:

$$f(\alpha, \beta, \gamma, x, y, z) = \sum_{i=1}^{n} \sqrt{\left(a_{i,1} - b_{i,1}\right)^2 + \left(a_{i,2} - b_{i,2}\right)^2 + \left(a_{i,3} - b_{i,3}\right)^2}$$

where, $a_{i,j}$ is a element of matrix $\boldsymbol{A'}(\boldsymbol{A'} = \boldsymbol{B}{\times}\boldsymbol{R}_{xyz})$, and $b_{i,j}$ is a element of matrix $\boldsymbol{B}$, $i \in [1, n], j \in [1,3]$

The aim is that find optimal $\alpha, \beta, \gamma, x, y, z$ to minimize the value of this nonlinear function by assigning initial values to these variables and iterate several times.

4. VTA application for high-rise air corridor in Chongqing Raffle City

The construction of high-rise air corridor in Chongqing Raffle City is a very complex process, using Synchronous lifting technology for super large hydraulic components. Fig.4 shows the lifting and hoisting construction procedure. In the past construction experience of the corridor, workers usually hoist the view bridge vertically on the ground to a height of 250 meters with six slings, and then close the lifted corridor with the fixed corridor on the top of the tower. There are six steel pipes with 50 cm length which regarded as welding control points on each side of the connecting corridor. When closing the coordinators, workers need to observe welding control points on both sides, and then adjust the position of these slings to make these control points as possible as integrated, so that it is convenient for welding. However, this assembly procedure is pretty time-consuming and laborious and joining positions are not identical on account of many uncertain factors in the process of hoisting and closing.

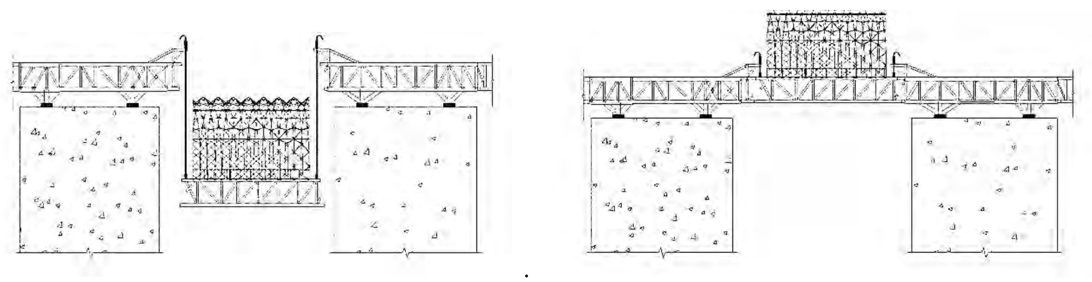


Fig.4. Lifting and hoisting construction procedure of corridor.

To address these issues, VTA is applied for this project, as presented the following steps: (1) The scan cloud point data of high-rise air corridor are acquired using a 3D laser scanner, and removal of noise data are undertaken using DBSCAN and mixed filtering algorithm. (2) 3D BIM models of welding control points are reconstructed using some cloud point reconstructed algorithm such as ICP algorithm (Rusinkiewicz 2001). (3) Key dimensional features, welding control points geometric information are extracted from BIM models. (4) Finite element models of this coordinator are established based on BIM models, to analyze the stresses of welding control points thereby identifying welding tolerance threshold. (5) Nonlinear error function considering welding tolerance threshold, is solved using unique algorithm, consequently optimal attitude of corridor and welding points which need to be adjusted are ascertained

4.1 Scan data acquisition and processing

4.1.1 Scan data acquisition

Fig.5 shows the Criteria for optimal selection of a laser scanner (Kim 2015). The 3D laser scanner *Faro X330* was adopted for this construction to obtain points cloud data with regard to the corridor, as shown in fig.6. Several scanning stations were assigned and these points cloud data obtainable from these stations were put together. This method was chosen because it allowed the integrity and accuracy of point cloud data.

4.1.2 Data preprocessing

This step aims to remove noise data from raw scan data of corridor and align the coordinates of the scan data with respect to the local coordinates of the high-rise air corridor. Scan data usually consist of data from two categories: valid points and noise points including mixed pixels and background points. Both mixed pixels and background points are considered noise data and need to be removed.

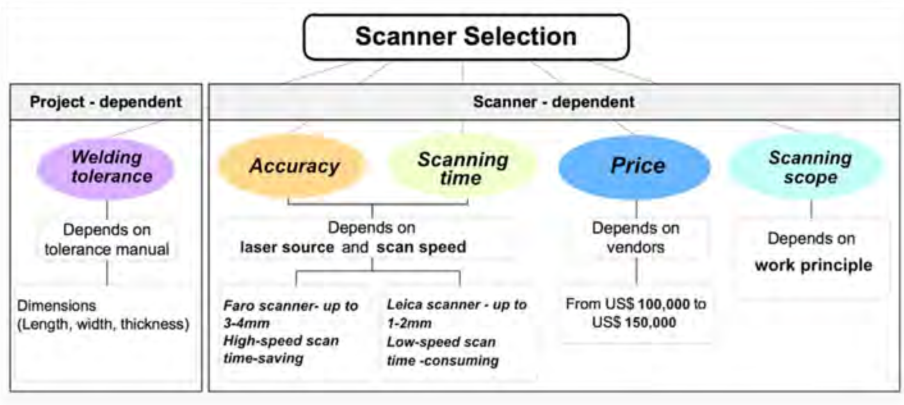


Fig.5. Criteria for optimal selection of a scanner for corridor assembly

(a) (b) (c)

Fig.6. Scan data acquisition and information extraction: (a)the procedure of data acquisition and information extraction; (b) (c)point cloud data acquisition using Faro laser scanning

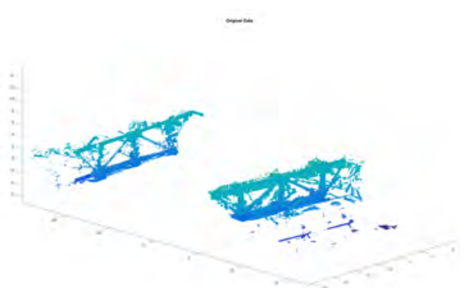


Fig.7. Original scan point cloud digital model

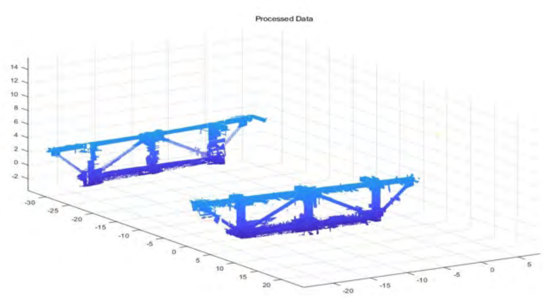


Fig.8. Processed point cloud digital model

The DBSCAN-based data classification algorithm developed by (Kim 2015) is hence applied for data classification. This DBSCAN-based algorithm performs classification based on spatial densities such that mixed pixels are classified as noise data due to their low density while the valid points and the background points form two clusters. The valid points are then distinguished from the background points as the valid points have shorter distances to the 3D laser scanner than the background points have. Most noisy data are removed using the DBSCAN-based algorithm, as shown in fig.7 and fig8.

The point cloud digital models reflecting the real geometry of corridor was acquired by point cloud digital splicing using *Faro software*, and BIM models of welding locations were reconstructed, as shown in fig.9.

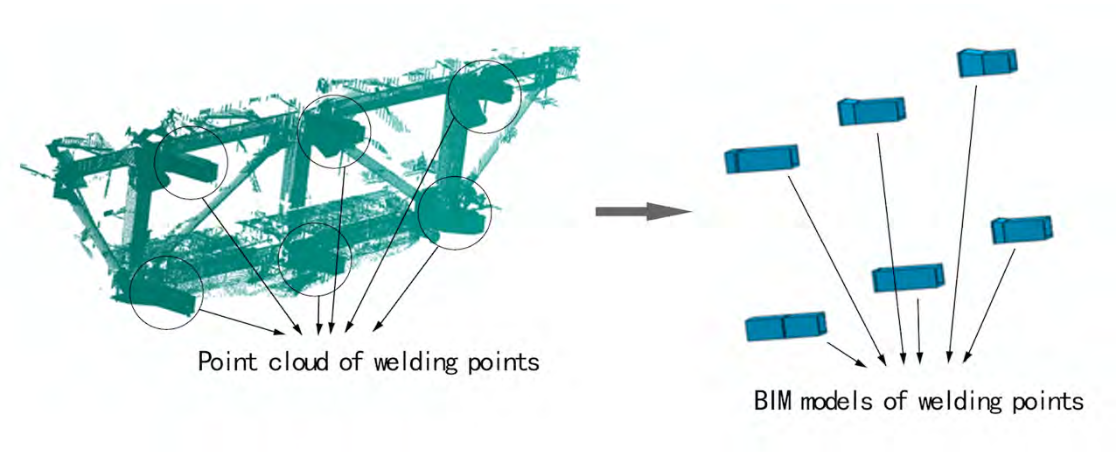


Fig.9. Point cloud and BIM models of welding control points

The 3D coordinates of welding control points have been stored in matrix $\boldsymbol{A}$ and matrix $\boldsymbol{B}$.

$$\boldsymbol{A}=\begin{bmatrix} -0.2862 & 0.2388 & -2.4653 & 1 \\ -0.2346 & 0.2481 & 2.3935 & 1 \\ -0.6015 & -17.8943 & -2.1110 & 1 \\ -0.6462 & -17.9030 & 2.0967 & 1 \\ -0.2899 & -9.2389 & 2.0653 & 1 \\ -0.2807 & -9.2080 & 2.0968 & 1 \\ -29.4412 & 0.2130 & -2.1031 & 1 \\ -29.3219 & -0.4762 & 2.1037 & 1 \end{bmatrix} \qquad \boldsymbol{B}=\begin{bmatrix} -0.2525 & 0.2749 & -202.4721 & 1 \\ -0.2519 & 0.2482 & -197..5864 & 1 \\ -0.5931 & -17.8616 & -202.1503 & 1 \\ -0.5396 & -17.8578 & -197.8516 & 1 \\ -0.2320 & -9.1771 & -202.1455 & 1 \\ -0.2885 & -9.1651 & -197.8713 & 1 \\ -29.4889 & 0.1906 & -202.1611 & 1 \\ -29.9903 & -0.3739 & -197.8656 & 1 \end{bmatrix}$$

Where, $\boldsymbol{A}$ is the coordinate matrix of welding points of fixed part on the tower, $\boldsymbol{B}$ is the coordinate matrix of welding points of hoisting part on the ground.

4.2 Welding points stress state analysis and tolerance threshold identification

It can be concluded that coordinates of the X direction have little impact on physical assembly, consequently coordinates of the X direction are not discussed in this program. Besides, the welding tolerance in Z direction has more essential influence on stress state of welding locations through the knowledge of structural mechanics and finite element analysis, compared to that of Y direction, and the analysis method of Y direction and Z direction is similar. Therefore, so as to improve the operation efficiency of the program, the welding tolerance in Z direction is regarded as main variable in finite element analysis.

To ensure the stress of the corridor under design stress, the finite element model of this corridor is established based on BIM models, as shown in fig.10.

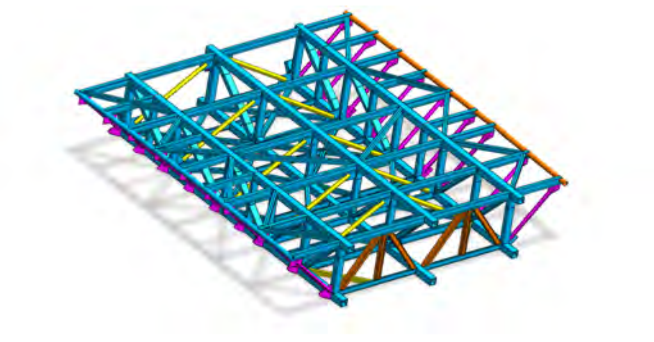
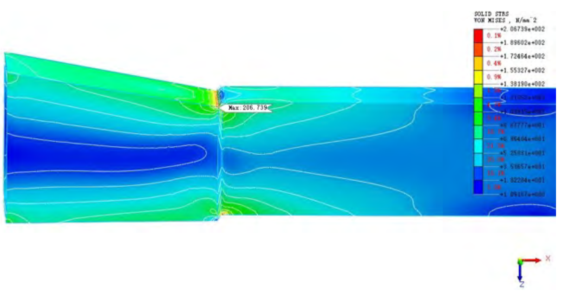
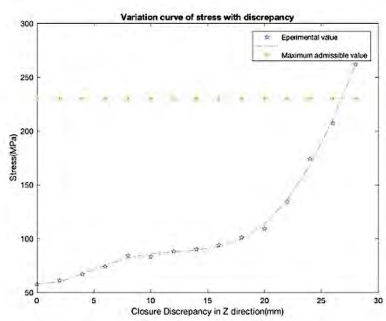


Fig.10. Finite element model of the hoisting part

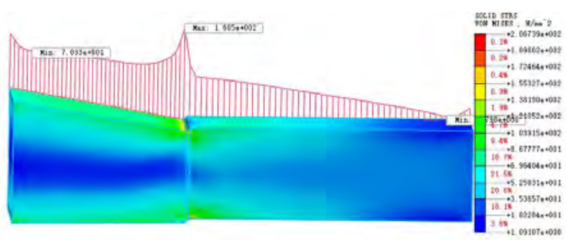
Obviously, the most significant parts which need to be concerned are welding positions, respectively. Due to the complexity of this corridor structure and uncertainty of welding procedure, welding residual stress of these control points is not discussed in this study. To obtain the welding tolerance threshold of this corridor in VTA, the finite element analysis of welding control points is processed, as shown in fig.11. Consequently, the welding tolerance threshold of Z direction is determined (26mm), according to variation curve of stress with closure tolerance and the allowable stress (230MPa) at the control points.



(a)



(c)



(c)

Tolerance (mm)	Stress(MPa)
0	58
4	67
8	88
12	90
16	101
20	109
24	174
26	207
28	262

(d)

Fig.11. Finite element analysis of welding point: (a) (b) Stress analysis (26mm tolerance); (c)(d) Variation of stress with closure tolerance

4.3 Optimal attitude adjustment(OAA)

Optimal attitude adjustment (OAA) of corridor is defined that the corridor is adjusted to achieve its optimal assembly attitude in the virtual environment and the tolerance satisfy welding closure tolerance, as described in section 4.2, thereby guiding physical construction. To solve the nonlinear error function, it is not dispensable to establish optimization algorithm to minimize tolerance as much as possible based on Matlab optimization functions, as shown in the following steps. First, nonlinear transformation of B matrix is implemented, as presented in section 3.1 and section 3.2. after obtaining the coordinate matrices $\boldsymbol{A}$ and $\boldsymbol{B}$. Then, the nonlinear error function $\mathrm{f}(\alpha, \beta, \gamma, \mathrm{x}, \mathrm{y}, \mathrm{z})$ with respect to variables $\alpha, \beta, \gamma, \mathrm{x}, \mathrm{y}, \mathrm{z}$ is acquired. The optimization algorithm is established through Matlab programming. After several iterations, the local optimal solution of the error function can be derived. The values of these variables $\alpha, \beta, \gamma, \mathrm{x}, \mathrm{y}, \mathrm{z}$ are brought back to the program, consequently the coordinate matrix $\boldsymbol{A'}$ $(\boldsymbol{A'} = \boldsymbol{B} \times \boldsymbol{R}_{xyz})$ of the welding control points of the hoisting part can be obtained, The tolerance matrix in VTA can be described as $\boldsymbol{D} = \boldsymbol{A} - \boldsymbol{A'}$.

Fig.12 shows welding closure tolerance of VTA. It can be concluded that number 3 welding point whose tolerance more than 26mm must be modified before physical assembly to ensure stress under design value.

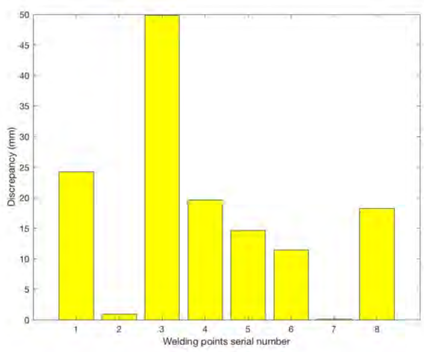


Fig.12.Welding closure tolerance of VTA

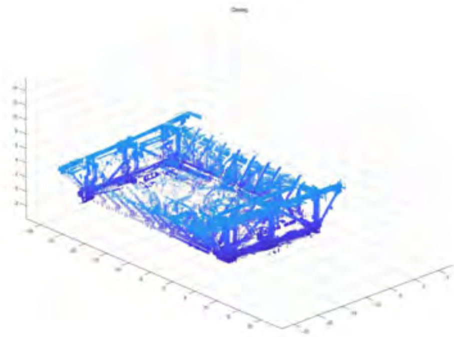


Fig.13. Integrated high-rise air corridor

To verify effectiveness of this method, the closure tolerance of physical assembly in the early stage is derived. Table 1 shows closure tolerance in VTA and physical assembly (PA) in the early stage of construction. There are main two observations from the results: (1) The average closure tolerance of VTA, 17.4mm in Z direction, is less than that of PA. (2) Only one welding point (VTA) needs to be adjusted (tolerance more than 26mm), compared to four welding points (PA).

Welding Points Serial Number	1	2	3	4	5	6	7	8	Average
Z Direction (PA)	6.8	20.0	39.3	51.7	20.1	31.9	18.0	30.7	27.3
Z Direction (VTA)	24.2	0.9	49.8	19.6	14.6	11.4	0.1	18.2	17.4

Table 1: Comparison of tolerance between Virtual trial assembly and Physical assembly

According to the coordinate matrix $\boldsymbol{A'}$ of the welding points for the hoisting part, the aim that VTA for this high-rise air corridor is achieved, integrated corridor shown in fig.12. From the result, it can be concluded that the VTA system based on BIM and TLS can be used to find welding points that need to be adjusted and modified before physical assembly and give optimal attitude control advice of corridor, which will increase construction efficiency and shorten time limit for this project.

5. Conclusions

A new method that VTA for high-rise air corridor is developed, which can minimize the physical assembling tolerances and enhance the degree of visualization of corridor construction. First, real geometric information of significant points is derived through point cloud data and BIM model of corridor. Next, significant structure stress state analysis is implemented to determine closure tolerance threshold. Finally, optimal attitude adjustment (OAA) program with respect to the high-rise air corridor is proposed to ascertain hoisting corridor optimal orientation and location to minimize closure tolerance. This program is processed with unique algorithm.

To examine the effectiveness of the proposed approach, VTA of the high-rise air corridor in Chongqing Raffle City is conducted. From the results of comparison between VTA and physical assembly of corridor, VTA provide more accurate assembly results, indicating that the proposed method could be effective to exploited in high-rise corridor construction. Further studies are needed to determine that closure tolerance threshold identification when considering that the influence of three direction (X,Y,Z) deviations on finite element analysis, and whether these findings could be applied to other assembly complex steel structure construction.

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COMPETENCY TRAINING THROUGH SERIOUS GAME TECHNOLOGY AT INDUSTRIALIZED CONSTRUCTION PROJECTS

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ABSTRACT: *The Malaysian Construction Industry Transformation Program (CITP) 2016-2020, was launched to nurture the development of Malaysian companies in capturing growth beyond the domestic market. Hence, there is a need to improve the competency of the local workforce for local companies to partner with international builders in joint project deliveries. With increased exposure to better technologies, workforce competency and safety awareness would establish an integral industry culture at all levels. This paper focuses on the capability training for the construction workforce, specifically on worker amenities and safety standards during on-site assembly process of selected Industrialized Building System (IBS) components. The aim of this paper is to outline the feasibility of utilizing game-based virtual environment technology for improving skills and safety aspects among the low-skilled workforce in Malaysia. In conclusion, the research outputs are expected to introduce safer and non-threatening virtual learning environment that will encourage the younger workforce to join the construction industry given the "Dangerous", "Dirty", and "Difficult" perception of the practice.*

KEYWORDS: *Virtual Training; Serious Game; Construction Safety; Construction Informatics; Industrialized Construction.*

1. BACKGROUND MOTIVATION

The Malaysian construction industry forms a significant component of Malaysia's Gross Domestic Product (GDP) which is expected to contribute 5.5 percent to GDP by 2020. According to the Department of Statistics of Malaysia in 2013, construction industry consumes a significant proportion of employees and representing 9.5 percent of the total national workforce. Malaysian construction industry representing a fourth largest employer in Malaysia for employing approximately 1.2 million registered workers. There is a need to train 756,000 general workforces at construction sites and about 444,000 building professionals in the Malaysian AEC industry (Construction Industry Development Board, 2015). In addition, the Malaysian construction industry is undergoing transformation from conventional on-site construction to Industrialized Building System (IBS). The IBS is defined as "a computer-integrated design, manufacturing and construction system using the concept of off-site or on-site prefabricated mass-production technique within a controlled environment while utilizing proper coordination and planning to transport, position and install building components with minimal in-situ works" (Rashidi and Ibrahim, 2017). The aforementioned study also found a successful IBS implementation requires extensive knowledge of design, manufacturing, and construction processes. In lieu of introducing and innovating advanced industrialized building systems to the country, the next challenge to the technology developer is, how one transfers such technology in the simplest form to the workforce involved. In addition, with more industrialized approaches dominating the future of labor landscape in the construction industry, among the developing countries, the situation has raised concern where local manpower is increasingly lagging behind in areas where advanced construction technologies are being introduced.

In this regard, the Malaysian Construction Industry Transformation Program (CITP) 2016-2020, was launched to nurture the development of Malaysian companies in capturing growth beyond the domestic market. The first Strategic Thrust of the Construction Industry Transformation Program (CITP) 2016-2020 is "Quality, Safety & Professionalism" while the third is "Productivity". Both these Thrusts are integral for the construction industry to proceed successfully in "Internationalization" of the industry. Hence, expediting skill development among low-skilled workforce is on top of the list if a country plans to embark on implementing industrialized building techniques for its prosperity (Construction Industry Development Board, 2015). Hence, there is a need to improve the competency of the local workforce for local companies to partner with international builders in joint project deliveries.

With increased exposure to better technologies, workforce competency and safety awareness would establish an integral industry culture at all levels. To improve the workforce competency on construction sites, training and education were among the main suggested recommendations (Abang Abdullah and Wern, 2010).

This paper focuses on the capability training for the construction workforce, specifically on worker amenities and safety standards during on-site assembly process of selected Industrialized Building System (IBS) components. The serious game training module could provide alternative access to real project experience. Where the real physical construction training is risky and hazardous, a virtual game-based construction training environment is a safe environment to introduce workforce trainees the early aspects about safety and site operation pertaining to a specific new technology (Ibrahim et al., 2014). The aim of this paper is to outline the feasibility of utilizing game-based virtual environment technology for improving skills and safety aspects among the low-skilled workforce in Malaysia. It employs gaming characteristics to create an engaging and immersive learning environment through replication of real-world challenges that would deliver the design of specified learning outcomes. Where the gaps are, there are opportunities in engaging the serious game approach where we believe IT/ICT applications be able to transform the method in transferring technical knowledge to the low-skilled workforce.

2. METHODOLOGY

This research study followed an experimental research method where the timber-framing serious game which is called as THE IBS FOREMAN© has been tested among novice timber practitioners. The proposed workforce competency training process is grounded on 14 design principles and instructional content. The proposed design principles merge engagement factors with effective educational design criteria pertaining to training about the jobsite skill and safety responsibilities. In addition, the developed training curriculum is designed according to the construction process of a selected industrialized timber framing system for a low-rise residential building, which features a new timber framing technology that will be used in the construction of a Semi-Detached type house on a campus site. The curriculum focuses on testing the performance of low-skilled workforces regarding safety and assembly of a construction technology. The instructional scenario for the training curriculum in this experimental study is applied to two distinguished methods of training. The experiment includes a pre-test measure, which is about the In-Person training module where the training was a scaled-model of the timber framing system. It was conducted in an indoor office environment. The second type of training module was in the form of Serious Game environment where the same house is modeled in a 3D virtual construction site (See Figure 1). Hence, the experiment concluded with a post-test measure, which is about the Serious Game training module for a single group of low-skilled construction laborers. The Serious Game training was conducted in an interactive 3D virtual construction jobsite as opposed to the In-Person training using a scaled timber house model. Therefore, the Charrette Test Method was chosen to increase reliability and validity by utilizing a comparative empirical experiment to determine whether a process performed using computer-aided instrument is effective in terms of speed and quality of processes compared to a manual process (Yee, Fischer and Kam, 2013).

Fig 1. THE IBS FOREMAN© Serious Game Training Application (Source: Rashidi, 2015)

3. RESULTS AND DISCUSSION

The results show significant (92%) improvement in the understanding of safety aspects as well as 60% lesser technical errors for the respondents while using Serious Game training mode compared to conventional In-Person training (See Table 1). Moreover, it is evident from the results that participants responded 73% for using Serious Game training for continuing their future IBS training. In contrast, only 27% of participants prefer to use the manual In-Person training as their IBS training approach.

Table 1: Comparative Accuracy Analysis for Low-skilled Workforce

Description	In-Person		Serious Game		Performance Change	
	Mistake - Mean (SD)		Mistake - Mean (SD)			
	Skill	Safety	Skill	Safety	Skill	Safety
Total	11.87 (3.94)*	25.40 (10.14)*	4.73 (1.71)*	1.93 (1.43)*	60%	92%

Note: *$\rho < 0.001$ (two-tailed t-test)

The Serious Game environment simplifies the delivery of a selected building technology training by allowing trainees to experience the required skill and safety knowledge in an almost a simulated real site situation as compared to the traditional In-Person training module. The results added to previous studies by other international scholars such as Bowman & Wingrave (2001); Schabel, M. A. & Kvan, (2002) and Lipman, & Reed (2000) where they reported affirmative improvements. In lieu of these positive results, Dawood, (2009) incorporated the promotion and consideration for Virtual Reality approach in many aspects of construction training. All the studies found the Virtual Reality (VR) environments and advanced game-based visualization could assist and enhance users' learning experience.

In conclusion, the research outputs are expected to introduce safer and non-threatening virtual learning environment that will encourage the younger workforce to join the construction industry given the "Dangerous", "Dirty", and "Difficult" perception of the practice. Due to the results of the study, it is recommended to shift the current academic-industry training platform towards Technical and Vocational Education and Training (TVET) by utilizing Mixed-Reality Serious Game training environment. Strengthening lifelong-learning for workforce skills enhancement is critical, which will in turn enable support through efficient and effective nationwide labor market. This support is vital to attract more investments into construction industry of developing countries.

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