Tangible-Tango: Designing and Fabricating Tangibles with Tangibles

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Abstract

We present Tangible-Tango, a system which enables users to fabricate new tangibles and their equivalent 3D virtual models. Thus the cognitive load required to understand and interact with virtual models is reduced. Users build new models by iteratively creating and assembling physical models. Each physical model has an associated virtual model. The new models, both virtual and tangible, can be iteratively re-used in the system. This iterative fabrication of tangibles and their virtual partners is the key contribution of Tangible-Tango. Our user study found that all participants efficiently produced the desired results, regardless of their background. This indicates the system is easy to learn and takes us one step closer to melding tangible and virtual 3D representations.

Keywords: tangible user interface, TUI, tangible interaction, fabrication.

1 Introduction

Viewing and manipulating objects in the real-world is a familiar experience and is more direct than viewing and interacting with their virtual counterparts using a display and mouse and keyboard. Physical objects have been converted to virtual models and manipulated on computers for years. However usually this is a one way process and once converted the physical objects are abandoned and interaction is entirely with the virtual model which is more cognitively demanding than interacting with the tangible models (Price and Marshall, 2013). Furthermore, interaction in the virtual space reduces our ability to perceive the relationship between objects created by their layout (Schubert *et al.*, 2012). Architects and interior designers, as designers of 3D spaces, have always understood the need to make physical models and still routinely do so today even when most modeling is done in the virtual space. Indeed one of our user study participants who is an architect summed up his experience at the end of the study with the statement

"God this is the future".

It is known that computer-based 3D modeling is a difficult task. This is partly because many current 3D modeling tools are extremely complex and take a long time to learn. This restricts their use to experts or people who have spent some time learning the systems. Also, people who do not regularly work with 3D modeling tend to have difficulty visualizing 3D representations, particularly in remembering how the different points relate to each other spatially and the result of transformations on the 3D object (Parslow and Wyvill, 2008).

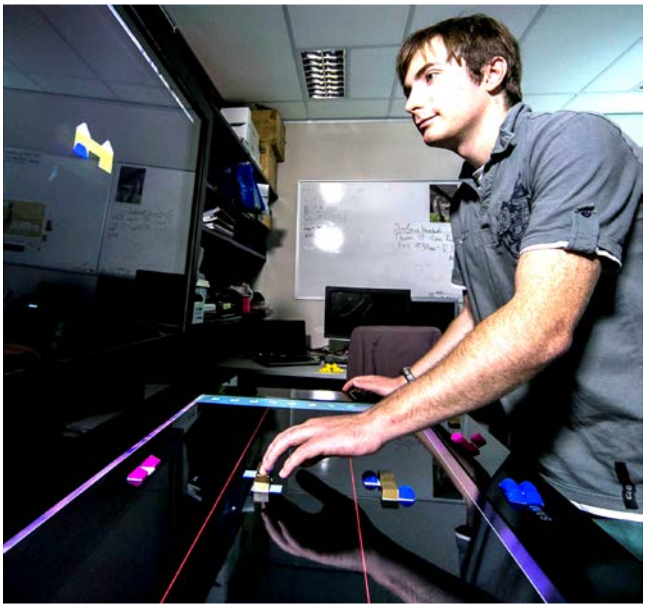

Fig 1 3D design using tangibles

In contrast manipulating physical 3D objects is a familiar interaction experience and allows us to maintain a level of spatial awareness that is not possible in the virtual world. We live in a 3D world and interact with 3D objects from the moment we are born. Many early childhood toys are miniature models of real objects for example racing tracks with cars and playhouses.

Many adults resort to physical models when undertaking tasks such as kitchen design. Most kitchens are assembled from a number of fixed sized units (fridge, cupboards, etc) with one or two bespoke units to fill the space. Many people cut out 2D models of the components and move them around the floor space. Our system could be used to plan in 3D, easing the transition between physical and virtual modeling and improving users' comprehension of the spatial relationships.

The ease, familiarity, and spatial understanding typical of this type of modeling makes it a desirable approach to replicate and extend to the virtual world. It is for these reasons that tangible models may be a useful addition to difficult 3D modeling environments (Fig 1).

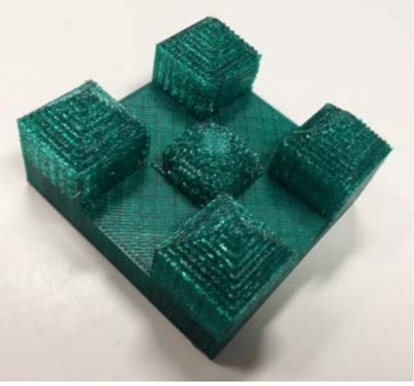

Fig 2 A tangible created with Tangible-Tango

Tangible tools have demonstrated advantages over traditional mouse and keyboard input and touch based interaction. Interacting with physical objects is a more natural interaction than using a mouse and keyboard. The mouse and keyboard "point and click" approach has little relation to how we interact with the rest of the world (Ishii *et al.*, 2012), and visually seeing information only displayed on a screen interferes with our ability to accurately perceive the relations between objects. The use of tangibles and touch compared to purely touch-based interaction has also been shown to improve interaction with interface objects as tangibles are easier to manipulate, acquire and control (Tuddenham *et al.*, 2010).

Tangibles lower the level of interaction abstraction allowing users to apply their natural tool based skillset to the digital environment as they would the physical. For example, studies have shown that the use of tangibles increases the spatial awareness of users constructing a 3D scene, whereas with the traditional graphical user interface (GUI) users are more focused on the individual items (Kim and Maher, 2008). Tangible user interfaces (TUIs) work towards solving this problem by representing some of the underlying data in a physical form, allowing for more natural interaction which can speed up the working process (e.g. moving something by physically picking it up), and improving the user's perception of how objects are arranged in relation to each other (Price and Marshall, 2013).

Many design tasks are iterative. In some cases the designer starts with the overall vision and iteratively defines the detail – for example an architect may start with a building exterior before planning the interior. In other cases arranging of relatively fixed components comes first – for example when designing a kitchen it is probable there will be a refrigerator, oven, sink and so on. Regardless of the design strategy, seeing the physical model being built along the way helps cognitively comprehend the model and thus improve the design process.

What is missing in TUI research is the ability to quickly fabricate tangibles from virtual models. Our tool aims to provide an environment that can be used with minimal training to iteratively construct complex virtual and tangible models. With Tangible-Tango users can iteratively fabricate models such as that shown in Fig 2. The main contribution of this work is the iterative nature of tangible fabrication – we know of no other work that supports this.

2 Related Work

Given the aforementioned advantages physicality brings, TUI's offer a promising approach for generating 3D models. An early project used tangibles that contained electronics and communicated between each other and the computer to generate the desired model (Kitamura *et al.*, 2001). Others (Anderson *et al.*, 2000; Ichida *et al.*, 2004; Jota and Benko, 2011) use blocks that work in a similar manner to the popular children's Lego toys. The blocks can be snapped together to form a basic representation of the model, that is then interpreted by the system. The system then generates the model according to its best guess or to the user's earlier specification (Anderson *et al.*, 2000; Ichida *et al.*, 2004). Lumino blocks (Baudisch *et al.*, 2010) allow tangibles to be connected, stacked and detected on a tabletop without the need for added electronics. Tangible detection is achieved by building blocks containing glass fiber bundles that reflect light and allow fiduciary markers from vertically stacked blocks to be read by a camera-based tabletop. Lumino uses two tangible shapes: a cube and cylinder. The position and orientation of the upper blocks is not detectable.

Our work differs from these approaches in several ways. We provide more flexibility in the shapes that can be used to construct the 3D models. The user can quickly develop new shapes for use in the system; whereas, for other approaches you would typically have to build specialist tangible equipment. In addition, with other systems the modeling is done mostly in the physical space, therefore there are limited contact points available for attaching tangible pieces together. Our system is partly modeled in the virtual space which provides more freedom as to where the tangibles can be attached to each other.

The ease of use and spatial awareness afforded by tangibles makes them an attractive tool for design work. Recent work by Follmer and Ishii (2012) demonstrates the use of tangibles to allow children to design and ultimately fabricate new tangible objects using 3D printing technology. They use a deForm gel mat as the input interface claiming that children can relate to it due to its similarities to clay and play dough. This system allows children to stamp their existing toys on the mat to add the imprint to the working model. The children can then manipulate the stamped model by using tangible eraser and pen tools, and a multi-touch interface allows for scaling, rotation and translation. The end result is a 3D model constructed from the 2.5D input, which can then be exported to the 3D printing software to create a new tangible toy. Because of the stamping nature of this approach the full 3D model cannot be obtained, only 2.5D is possible. It is also limited to a mirror image of the imprint therefore it would be unable to produce an asymmetric model along the axis of the plane of the mat. These issues are addressed by our system.

The use of gestures to create 3D objects has also been explored (Willis *et al.*, 2010; Weichel *et al.*, 2014). MixFab (Weichel *et al.*, 2014) is an immersive augmented reality environment where users can create objects using gesture recognition and existing tangible objects. Spatial Sketch (Willis *et al.*, 2010) allows users to create 3D sketches via gestures made in mid-air using the Nintendo Wii controller. After some post-processing, the 3D sketches can be fabricated using various materials with a laser cutter. User studies showed that users had some difficulties in making models in terms of producing the intended result. LaserOrigami (Mueller *et al.*, 2013) is another recent fabrication tool. It supports creation of a tangible by cutting and bending pliant material such as Perspex. However these fabrication projects focus on one-way, one-time fabrication. GaussBricks (Liang *et al.*, 2014) takes a different approach with single format bricks joined by magnets which are used to detect the position of the bricks: no fabrication of bricks is supported and there is no apparent way to have different types of bricks.

3 Tangible-Tango

Given the exploratory nature of the project we have focused on end-to-end iteration. Users start by making tangible components from a virtual 3D model. This initial virtual model could already exist (there are numerous online libraries of 3D models) or be created by the user in a tool such as Google SketchUp (http://www.sketchup.com/). An alternative starting point is to scan a physical object – again this functionality already exists. The physical models can then be arranged on the tabletop, joined and 3D printed to make increasingly complex models.

For demonstration purposes we use three primitives; a cuboid, a pyramid and a dome (Fig 3). Depending on the context these can be replaced with representative models, for example, refrigerator, oven, cupboards and so on for kitchen design or conveyor belts, grading machines and packing machines for fruit processing. These tangible blocks are placed on the tabletop (Microsoft PixelSense (Microsoft Corporation)) with a tagged side facing downwards.

When a tangible is detected the virtual 3D model matching the tangible is displayed under the tangible on a vertical display behind the table (Fig 1)

A design is constructed by placing many of these tangibles on a tabletop display. To stack tangibles we adopt the approach architects use and show each level in a different section of the table. To enable accurate placement the outline of a tangible is shown on the next level up (Fig 4).

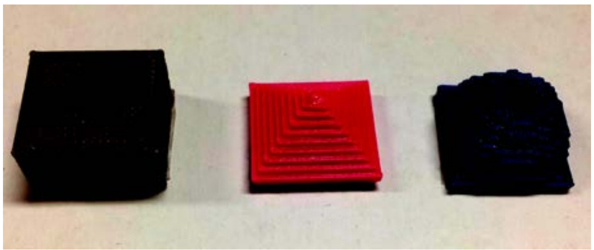

Fig 3 Basic tangible blocks, cuboid (2x2x1cm), pyramid and dome

The virtual 3D model of the construction is computed in real time and displayed on a vertical display placed behind the tabletop (Fig 5). This visualization complements the bird's eye view users already have of the physical model by providing a convenient side view. This view of the virtual model can be manipulated using buttons on the tabletop i.e. users can zoom and rotate to examine the model from different perspectives if they wish.

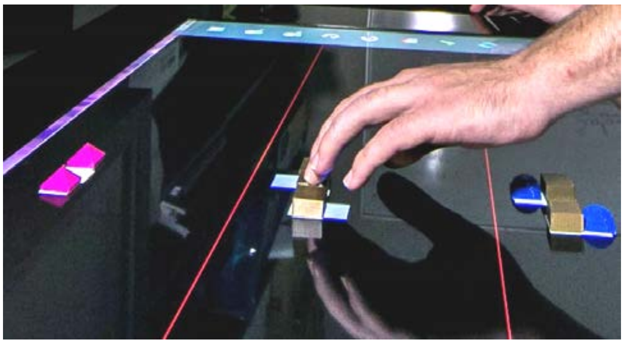

Fig 4 Basic Tangible blocks on tabletop with visualizations under each and outline showing on the next level up. Levels borders are indicated by red lines

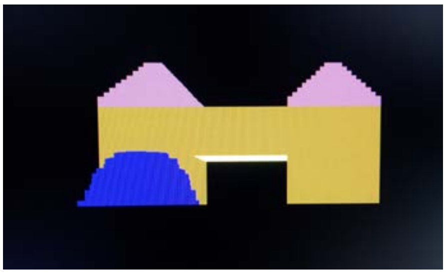

Fig 5 A 3D model of the Fig 4 construction is generated in real time and shown in the vertical screen behind the tabletop

Once a desirable result has been reached, the pieces are joined together into one virtual model. Additional blocks can still be added using more physical pieces and the virtual model rejoined. The virtual model is then saved and fabricated with a 3D Printer [7] controlled by the Cura software [8] (Fig 6 & Fig 7). Printing time depends on the size of the model and fidelity of the print, as an indication, using our low-end printer all the models shown in this paper print in under an hour.

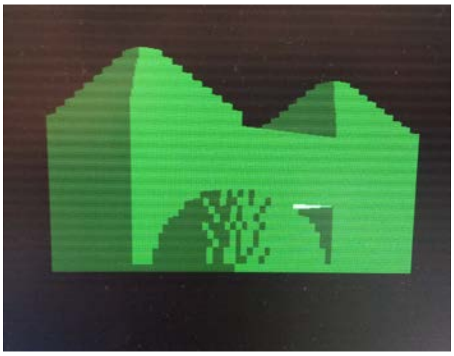

Fig 6 A 3D model of Fig 5 Joined ready for printing

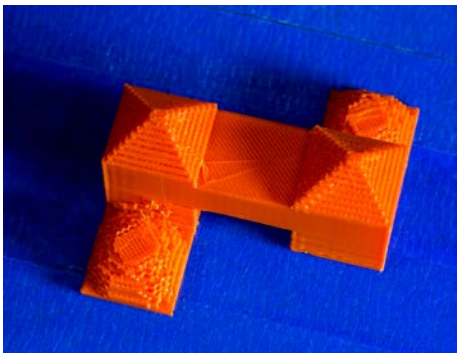

Fig 7 Fabricated tangible from model in Fig 6

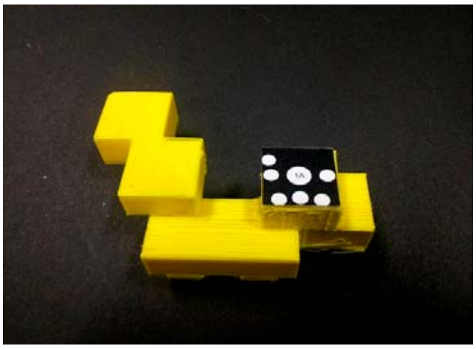

Fig 8 Tagged tangible.

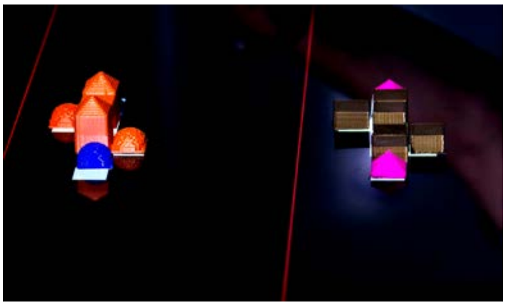

Fig 9 Using a fabricated tangible to make a new one by basic blocks being added below and beside the fabricated tangible.

Fig 10 Profile view of joined virtual model of tangibles in Fig 9

Once fabricated and tagged (Fig 8), the new tangible can be placed on the tabletop and can be used in the system the same as any of the basic tangibles. It has the same capabilities as the basic blocks and can be added to using basic blocks or other fabricated tangibles (Fig 9).

Fig 11 Tangible created from model constructed in Fig 9 & Fig 10

There is no limit to the number of times users can iterate around this process of making tangibles by combining basic blocks and other tangibles that have already been constructed. This end-to-end process closes the production and design loop. Tangible-Tango creates an environment where users can iteratively design and fabricate tangible representations, while maintaining the advantages of a virtual environment. This prototype presents a new way to approach 3D modeling.

4 System Requirements and Implementation

Our goal is to create an iterative design process for 3D modeling using tangibles as both physical representations of the model and as interactive components of the blended physical and virtual environment. The requirements of the system are as follows. A tabletop with infrared sensing is used as an interactive surface and it provides the ‘ground’. We use a variety of atomic 3D components as both physical and virtual models. To connect the physical and virtual models the physical models must be accurately tracked on the tabletop. We also want to view the virtual model in various orientations. To create the new model the virtual representations of the individual tangibles must be joined together to create a new virtual model for printing. Finally load, save and other basic interaction functionality is required.

4.1 Atomic Models

We start with a 3D virtual model in Collada file format (Mueller *et al.*, 2013). These can be made in numerous 3D modeling packages such as SketchUp (http://www.sketchup.com/) and are compatible with the Ultimaker 3D printer (Ultimaking ltd) used for this project. Tangible versions of the models are fabricated on the 3D printer. When required the virtual model is loaded into memory using OMI for XNA run time loader (Bottoni *et al.*).

4.2 Connecting tangibles to touch screen

In order to detect the position of a tangible on the table we attach the byte tags natively recognized by the Microsoft PixelSense (Microsoft Corporation) to the bottom of the tangibles. This allows us to retrieve the x and y location and orientation of the tangible on the table space, and also the ID of the tag. Each tag detected on the tabletop prompts the corresponding virtual model to load and the ID of the tangible and its position is added to the current virtual world. Any movement of the tangible is then used to update the position of the corresponding model.

As different areas of the screen represent different levels, the virtual world space has a different coordinate system to the table space. We need to adjust any change in the x/y coordinates of the tangible position in table space to the x/y/z position of the model in virtual world space. To do this we initially transform the table space coordinates of the tangible to a common area, at this time we set the z coordinate of the model according to where the tangible is on the table. The x/y position in the common area is then translated into the x/y/z world space for the virtual modeling.

4.3 Visualization

The user interface of the tabletop is shown in Fig 12. A set of touch controls are displayed down the right-hand side and the remainder of the tabletop is used for the creation area. The different levels in the creation area are separated by red lines. This view uses an orthographic perspective to make it similar to viewing a building layout plan. Each tangible on the screen has a visualization shown underneath it and also shadowed on the level above.

In order to view the models as they look in the world space we use a second display which displays the 3D rendering of the world space (Fig 5). This view is controlled using the touch controls on the tabletop screen. Standard zooming and rotation operations are provided.

4.4 Snapping

To assist the user in attaching the model pieces together basic snapping functionality is provided. It uses the bounding boxes of the primitives to check for proximity and as join points for the snapping. For the larger models made with the system, the bounding boxes of a model's primitives are stored as a part of the complex model and these are used for snapping purposes.

Fig 12 Tabletop user interface

4.5 Joining to form a complex model

Snapping provides temporary joining of the models in the system, however each piece of the model is still individually defined. In order to print a single physical model we must join the virtual models together into a single virtual model. Once the user has constructed the desired model the pieces are joined together by combining the voxelization data according to the positions of the bounding boxes.

It is nontrivial to join 3D models with the XNA library; there are no standard routines and writing one's own is a significant task. Furthermore it is computationally expensive to join detailed models. However joining models is essential for our system. To simplify the task we convert the model to a voxelized model using an algorithm derived from (Voorhies, 1992), (Anonymous) & (Rosen). The voxelized model is saved for further reference and printing. In addition, bounding box information and other metadata such as the PixelSense tag is held in another file.

The new complex model is generated from this data. This model is then loaded into the Cura (Braam) software and fabricated using an Ultimaker 3D Printer (Ultimaking ltd). Once fabricated, the tag is attached to the physical model and the tangible is now able to be recognized on the tabletop for further use within the system.

5 Evaluation

To evaluate whether the software produces the models users expect (both physical and virtual) and is usable by a general audience, we conducted a task based user study. Participants were asked to complete four tasks. To control variability and time, although the system supports users constructing their own primitives, we gave the participants the primitive tangible components shown in Fig 3. The first two tasks asked them to create virtual models that matched the physical models shown in Fig 13. The purpose of these tasks was two-fold – to test the usability of the system in a controlled manner and also to further familiarize the participants with the system before the third task. The third task was a free design task – they could design anything that was within the printer's capability. When they were happy with their design, it was printed. The final task was for them to use their new tangible to interact with the system. Information was gathered from observation and a questionnaire. In this section, we first describe the details of the study methodology and then the results.

5.1 Methodology

The ten participants (9 M, 1 F) aged between 19 and 40 had varied backgrounds including: computer science students (6), architects (2) and others (2). We gathered information on their existing experience with tangible interfaces and 3D modeling software. One had frequently used tangible interfaces, 3 had a couple of times and the remainder had on one occasion (2) or never (4). Two were frequent users of 3D modeling software (the architects), of the others 2 were occasional users, 5 had a couple of times, and 1 never. Each participant undertook the study individually and we captured the screen activity for later review.

The hardware used was a Samsung PixelSense SUR40 with a second vertical display directly behind the tabletop (see Fig 1). The computer was running our prototype system and the users had available 6 cuboid, 6 pyramid and 6 dome tangibles, each of which had a standard byte tag attached to the bottom and was registered in the system.

The study started with the facilitator showing the participant the features of the software and creating a simple model with the participant. For the initial part of the study, the participants were then asked to reproduce the models in Fig 13. The first simpler model has two levels, the bottom is a 4 unit square and the top has two pyramids and two domes with each pair set on the diagonal. The second is more complex with three levels and a suspended midsection. For the third task they could design anything that would print on our printer. To keep the printing time reasonable we allowed them to use up to 6 cuboids and a combination of 6 pyramids and/or domes. They could take as long as they liked designing their third model. When they were satisfied with the model we printed and tagged it. As printing takes approximately 45 mins they could either wait or come back. For the final task they then took the printed model and placed it on the surface. This retrieves their virtual model. They could then add on to their model using any of the basic blocks, thus making a new virtual model.

After the third task was completed the participants filled in a qualitative questionnaire and described the best and worst things about the experience. After the final task they answered a further two questions on the tangible they had created and had the opportunity to provide comments.

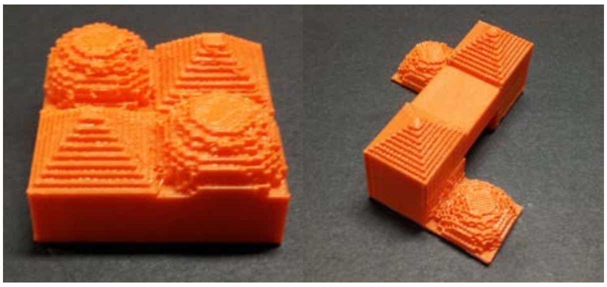

Fig 13 Models made in tasks 1 and 2

5.2 Results

Fig 14 shows the printed models created by the participants. The summary of the quantitative questionnaire responses is shown in Table 1. The enjoyment of the task was high with all users scoring 4 or 5 with a mean of 4.6. This was reflected in the comments both written and verbal. One participant commented

"It was a cool way to create virtual models, it was a good combination. It felt intuitive but at the same time it wasn't trivial (i.e. it was fun to use, wasn't boring, kinda like a fun puzzle)."

Task understanding was similarly high with no one having problems comprehending what was required or how to do it. The tangibles as interaction tools were seen as making the task completion and creating the model easy by most participants, they scored these questions agree or strongly agree. Discussion with the two participants who were neutral for task completion suggested that occasional problems with tag detection on the tabletop reduced their rating – these problems would not occur with higher definition 3D printing and a higher fidelity tabletop. Seven participants agreed that viewing the virtual model was easy. The final question in this section on whether they would like to use this method of interaction in the future was on average positive, but not strongly so. The comments around this pertained to problems with tag sensing and precision. Of note is that attitudes were much more positive after the next phase.

Participant	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**M**	**SD**
Pre-Questions												
I have used tangible controls on a computer	3	5	2	1	1	1	3	1	2	3	**2.2**	1.32
I have used 3D modeling software on a computer	4	3	3	3	1	3	4	5	3	5	**3.4**	1.17
Post-Task 3												
This exercise was enjoyable	5	4	5	5	5	4	4	5	4	5	**4.6**	0.52
I understand the task	5	3	5	5	5	4	5	5	4	5	**4.6**	0.70
The interaction tools helped with my task completion	5	5	5	5	5	3	4	4	4	3	**4.3**	0.82
Creating the model was easy	5	4	4	5	4	5	4	4	4	5	**4.4**	0.52
Viewing the model was easy	4	3	4	3	4	2	5	4	4	4	**3.7**	0.82
I would like to use this method of interaction in the future	4	3	4	4	4	3	3	4	4	3	**3.6**	0.52
Post-Fabrication												
The printed model is what I expected	4	4	5	4	4	5	4	5	5	5	**4.5**	0.53
The 3D model shown on the screen is what I expected	5	4	5	4	4	5	5	5	5	5	**4.7**	0.48

Table 1: Questionnaire responses. Participants responded on a 5 point scale. For the pre-questions where 5 was frequently and 1 was never. For the remainder of the questions the 5 represents strongly agree, 3 neutral and 1 strongly disagree.

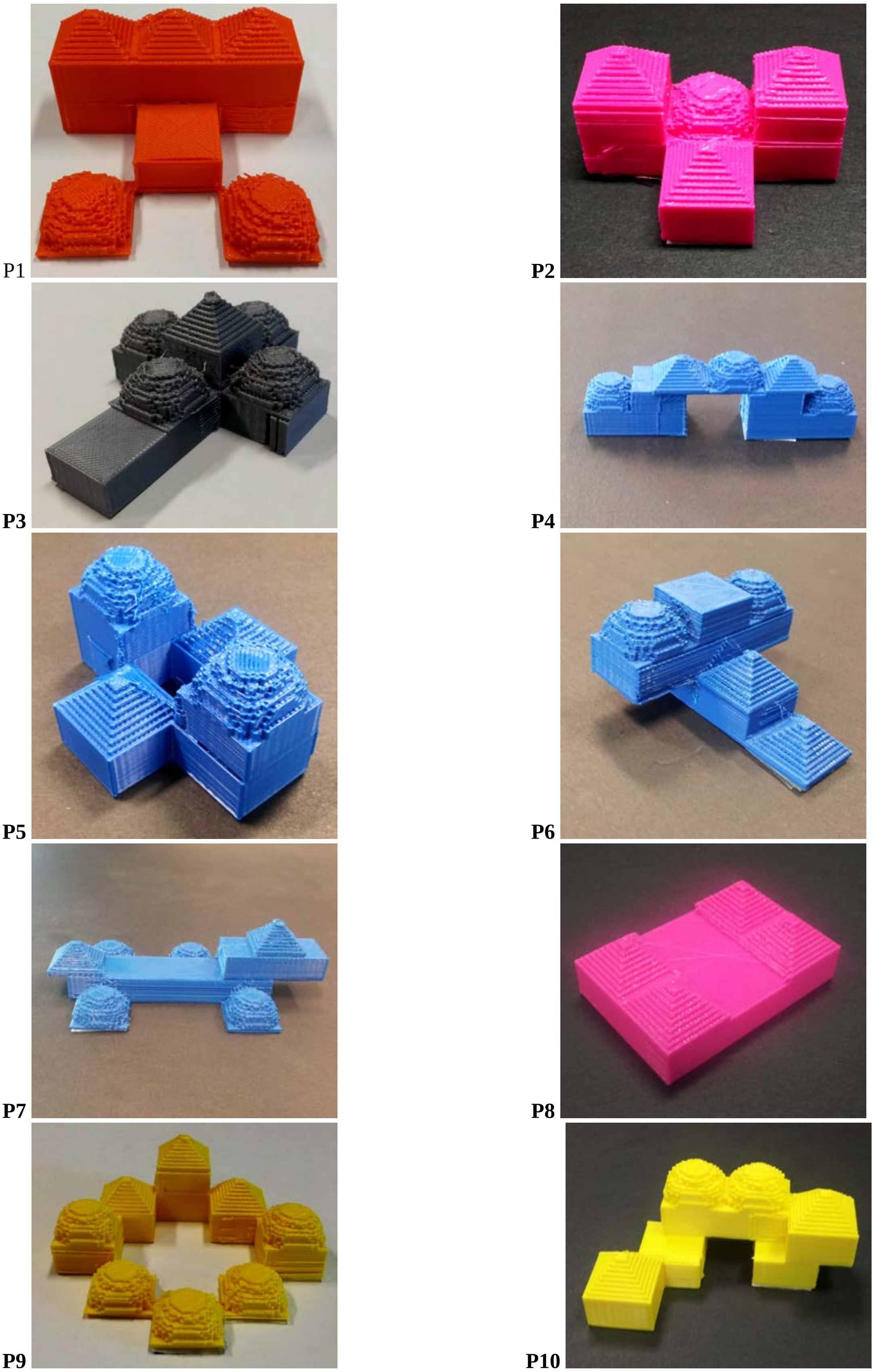

Fig 14 Tangibles created by the participants

After the 3D model was printed and the participants had used it in the system the participants answered the final two questions. All agreed that the physical and virtual models were as they expected. At this point they also filled in the final section of the questionnaire. There were two distinct types of responses in this section: architects versus non-architects. The non-architects focused mostly on technical issues. However the architects saw possibilities for various application areas in particular town planning and communicating with clients.

6 Discussion

This paper has presented a system for the design and fabrication of 3D tangibles using a tangible controlled, tabletop 3D modeling environment. We have provided core technology to handle an end-to-end process from virtual-to- tangible-to-virtual-to-tangible.

As this is the first prototype of the system there are a number of limitations. Currently, Tangible-Tango is purely additive, we cannot remove pieces from a defined tangible. The system does keep track of where the primitives are in each model therefore the system could easily be made subtractive by removing those blocks from the model. Additionally we could add the ability to modify the virtual models using standard CAD editing approaches. A solution to this while maintaining the core interaction metaphor would be to support fabrication of modified primitives.

For simplicity we placed only 1 tag on each tangible for the user study, however the system can support multiple tags on each tangible thus allowing the tangibles to be placed with different surfaces on the table. Also currently there is no sensing above the tabletop. This prevents us from being able to stack the tangibles on top of each other; however our virtual layers have the advantage of supporting construction of objects that cannot easily be physically stacked such as those constructed by participants 4, 6, 7 & 10 (Fig 14). While one user commented that they would prefer stackable tangibles, we observed that participants quickly understood the virtual layers.

Accurate sensing of tangibles off a surface either stacked or in the air, is an ongoing challenge for the community. It has been addressed partially in other research such as Lumino Blocks (Baudisch *et al.*, 2010), but orientation and position information is not available. While (Willis *et al.*, 2012) has explored 3D printing of objects with embedded optical elements which may allow the approach used with Lumino Blocks to be easily manufactured using a 3D printer, an essential part of our iterative environment. A common approach has been to use external depth cameras to detect stacked objects. There are two issues with depth cameras: users' hands occlude the tangibles and an environment with both stacking and virtual levels would probably be confusing. A more promising direction is to incorporate sensors for near-field and orientation sensing. Further research is needed to find an elegant solution to this issue without effecting the easy to manufacture aspect of the tangibles.

Currently the point of entry for new components is from a virtual 3D model developed using traditional 3D modelling packages. Future work could incorporate ways to import physical 3D objects into the system by, for example converting photographs to 3D models (Nguyen *et al.*, 2013).

Despite these limitations we received highly positive reactions to the end result of the process. The tangibles accurately reflected the users' intentions and they were impressed that they could hold and use a physical representation of the model they had built. Most of the participants chose to take their created tangible home with them, indicating the real sense of ownership that tangibles can invoke. One user was excited by the possibilities, saying that

"it shows that tangible objects can evolve from something super simple to something unbelievably complex."

The system has the capability to support realistic components that are much more compelling representations of their real-world equivalents than, say, a 'red' lego block masquerading as a refrigerator.

Tangible-Tango provides a novel proof-of-concept iterative 3D model and tangible fabrication environment. There are a number of contexts of use to which it could be applied immediately as people currently generate both virtual and physical models. These include town planning, architectural design and interior design layout. Each of these activities include fixed known constraints and variable components and or placements. The system could support some fixed virtual elements to work with such as terrain for town planning or floor plans for interior design with moveable and modifiable elements such as kitchen components and manufacturing plant.

In regard to town planning, one of the architects envisaged a blended physical and virtual environment where the physical models could be placed on a landscape and the virtual representation used to visualize environmental effects such as light and wind. The other architect mentioned the advantages of using such blended environments to facilitate collaboration with clients or colleagues. He thought that this type of system would allow the client to better communicate ideas through physical actions which change the model, but could also be subject to any virtual restrictions the architect deems necessary.

Our system also has potential in the realm of education. It could be used to introduce students to 3D modeling, allowing them to explore the basic concepts while being able to see the physical results. The system could be used to train them to think in 3D (Parslow and Wyvill, 2008), as any 3D modeler must learn to do. In addition, it could be adapted to cater to other educational fields for younger children such as Mathematics, Art / Design or with the right abstractions for the models, introduce them to basic programming by example. One 7 year old child, visiting our lab had an informal play with the system and within a few minutes was happily creating various models on the tabletop.

7 Conclusion

Tangible-Tango is the first system to support iterative fabrication of tangibles with tangibles. There have been numerous technical challenges solved in the duration of this project and some still to be addressed. However as a proof of concept, we and our study participants see this as the foundation for a new and exciting way to 3-Dimentionalize the interaction design space.

8 Acknowledgements

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9 References

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