Combined Digital & Physical Modeling with Vision-Based Tangible User Interfaces : Opportunities and Challenges

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Abstract. Designers in architectural studios, both in education and practice, have worked to integrate digital and physical media ever since they began to utilize digital tools in the design process [1]. There are benefits of working in the digital domain as well as benefits of working physically; confronting, or seeming to confront, architects with a difficult choice. Emerging strategies for human-computer interaction such as tangible user interfaces and computer vision techniques present new possibilities for manipulating architectural designs. These technologies can help bridge between the digital and physical worlds. In this paper we discuss some of these technologies, analyze several current design challenges and present a prototype that illustrates ways in which a broader approach to human computer interaction might resolve the problems. The ultimate goal of breaking down the boundary between the digital and physical design platforms is to create a unified domain of "continuous thought" for all design activities.

1. Introduction

Architectural design is a challenging cognitive activity, involving tactile, spatial, and auditory perception and "wicked problems" [2]. Buildings are almost invariably unique, inappropriate on another site, in another climate, or with other functionality and requirements. Architects must often address conflicting goals using limited information, and seeking a solution that harmonizes the parts in a process sometimes referred to as "puzzle making" [3]. The process is complex and iterative, and requires concentration, making it prone to disruption by external events, as well as internal ones. Because of these facts, architects are often more comfortable with physical tools instead of digital one in the very early design phases.

Since most later design and documentation work is now done on computers using CAD and modeling software, transitions between physical design platforms and digital CAD systems become necessary. These transitions often straddle important decision points, forcing repeated conversions and interrupting continuous thinking process in a designer’s mental model. Since we cannot totally abandon the physical tools during the early design process due to the benefits that physical textures and materials provide, we should bring the digital powers to physical worlds in order to assist designers to make design decisions. Further, the typical "direct manipulation" human computer interface [4] provides limited freedom for designers to study their designs. Although some new programs aim to solve the digital 3D sketching and modeling problems [5], they still require training time, and are difficult to edit on a 2D screen [6].

In this paper, we present a prototype system that can assist architects to generate a digital model by building their regular cardboard models. Since the prototype requires users to attach unique fiducial markers on every piece of cardboard in order to track their geometry, we can also apply preset building information and parametric constraint to both digital and physical geometry. The embedded building information can help other designers in the team understand his/her original design intention. The information also enables construction of a complete model suitable for certain kinds of simulation. After we built this prototype, we asked several students in an architectural studio to test it. The results are described and discussed below. Finally, we discuss some challenges and possible futures that would come up after the physical objects could be associated with digital information.

2. Related work

In the architectural design community and others, researchers devote their energy to making computer power more accessible in the physical world. In 1997, Hiroshi Ishii proposed Tangible User Interfaces (TUIs) as a new way to bridge between "Bits and Atoms" [7]. He argued that information "bits" would come into the real physical world through everyday physical objects and environments (atoms) [7]. By making digital information tangible, he thought the boundary between cyberspace and physical environments could be bridged.

During design, spatial cognition plays a crucial role helping us understand complex relationships and manipulate abstract concepts. Interruptions can disrupt continuity of thought and complex GUIs frequently present command-selection interruptions. However, Tangible User Interfaces may enable us to better employ our intelligence during the design process. There have been several previous efforts to create tangible interfaces for design processes. In "URP", Underkoffler and Ishii address the issue in the context of urban planning by combing tangible models and projected simulation data [8]. The simulation images help designers to make decisions and prevent design mistakes.

There is other research that addresses the relationship between the physical and digital geometries by using smart materials. Construction kits, such as LEGO™ Technic, are easy to use [9]. Anderson et al. made a project that combines building blocks and a scanning system to achieve the goal of modeling and reducing the inaccessibility of the traditional sketch modeling system. "FlexM" is another project that uses two kinds of construction kits to build and develop a 3D digital model [10]. Researchers developing "Posey" utilize embedded sensors to make construction kits more complex and adaptable to design [4]. Both FlexM and Posey not only try to help the designer establish a system that can generate 3D models, but also construct the relationship of geometry. However, in these systems, the digital geometries have to be pre-built and registered to the particular physical objects, which is not desirable for designers in the midst of the design process.

3. The Prototype – Tangible user interface for model building and analyses (TiMBA)

3.1. Descriptions and scenario

Cardboard models are commonly used by architects in studying the form of a building. The designer can trim or replace parts in order to study alternative shapes, and the model may be used as the focus of face-to-face conversations with clients who might have difficulty interpreting architectural drawings and digital models. In order to fulfill our vision on both digital and physical platforms, the software system has to know the shape, the location and the orientation of the pieces of cardboard. There are several possible ways to find the whereabouts of physical objects for the system, such as embedding radio frequency ID tags in every piece of cardboard, building a model with multiple 6 degree-of-freedom sensors, or detecting the related position of every piece by knowing which are attached. However, these all restrict the range of formal expression available to the designer. In the end, we adopted a computer vision strategy in order to work with almost any cardboard, permit re-shaping of pieces, and minimize instrumentation costs (as compared to processing time) while producing a practical system. We divided the model-building process into two steps. The first step employs an edge detection algorithm to discover the shape of each cardboard piece as the designer works. The second step uses the marker-tracking library from ARToolKit [11] assemble the virtual model based on the location of each piece in the physical model.

Since cardboard pieces are usually cut flat in the first place, we provide a black cutting mat with an overhead camera for a better edge detection process. After cutting, each piece is given a fiducial marker. The camera acquires an orthogonal, or "true-view" of the piece and links it to the marker ID and location. After users combine the individual cardboard pieces in step two, the composite digital model can be computed using the positions of the markers relative to a marker set on the foundation board (Figure 1) for the model and the individual piece geometry. Thus, a digital model can be constructed from the physical model. If designers want to resize a piece, they need only remove it from the model and adjust the size on the cutting mat before re-inserting it in the composition.

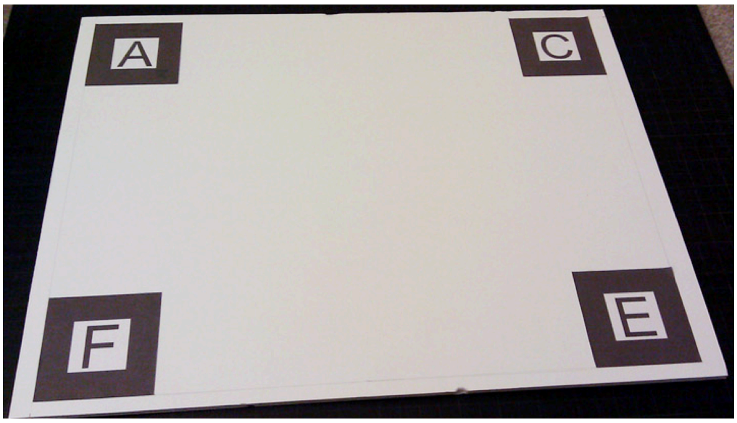

Fig. 1. Foundation board for users to build a model on it.

While building their models, the designer can also use the digital model to conduct analyses such as shading, sun-penetration, or hold a discussion around the physical model with their colleagues, etc. Using digital projectors, analysis results can even be projected onto the surfaces of the physical model. In this way, TiMBA seeks to give designers more flexibility to build and study their models in the environment with the greater affordances, fitting into the existing design process with minimal disruption and maximum benefit.

3.2. System overview

In this prototype, we modified ARToolKit 2.7 (ARTK) to address both vision tasks, and utilized an API for the widely available commercial modeling program, Google SketchUp to build the host-modeling environment. ARTK is designed for use in Augmented Reality applications. The TiMBA system utilizes the ARTK edge-detection algorithm and the ability to register the location and orientation of fiducial markers. Three applications based on ARTK were created to complete the steps identified above. Step 1 is carried out by the "Shape Scanning Application" (SSA). Step 2 is completed by the "Location Detector Application" (LDA). After these applications analyze frames from their respective camera inputs, they transfer data to a custom script running in SketchUp. The SketchUp add-on, "SketchUp Ruby Helper" (SRH), receives the data provided from the two ARTK applications and uses it to control the shape, location, and orientation of the geometry in SketchUp. Basically, as shown in Figure 2, the Shape Scanning Application and the Ruby Helper comprise step 1, which lets the user scan a piece of cardboard into SketchUp. As shown in Figure 3, the Location Detector Application and the Ruby Helper comprise step 2. Here are some more details.

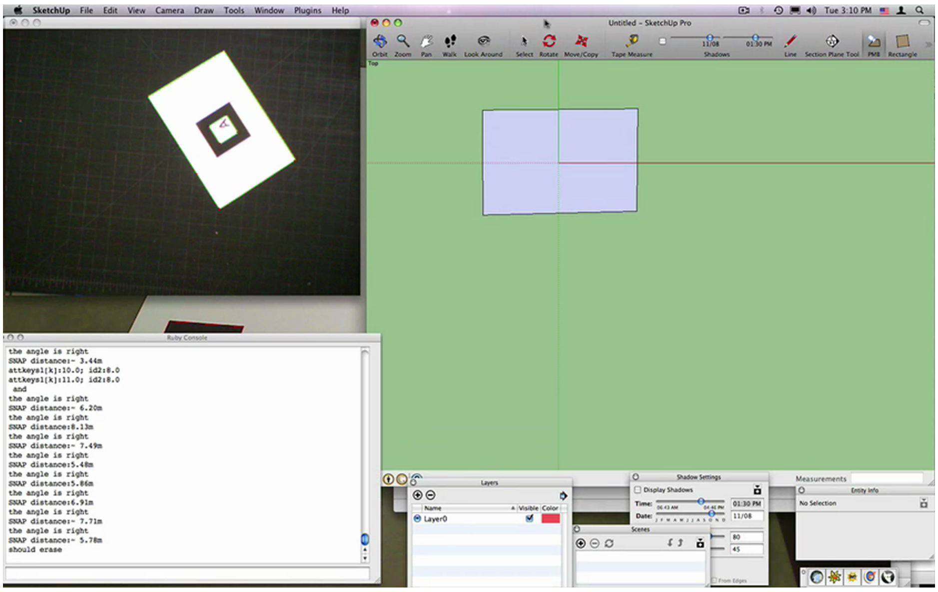

Fig. 2. The Shape Scanner, showing model piece (left) with fiducial marker, and model geometry (right).

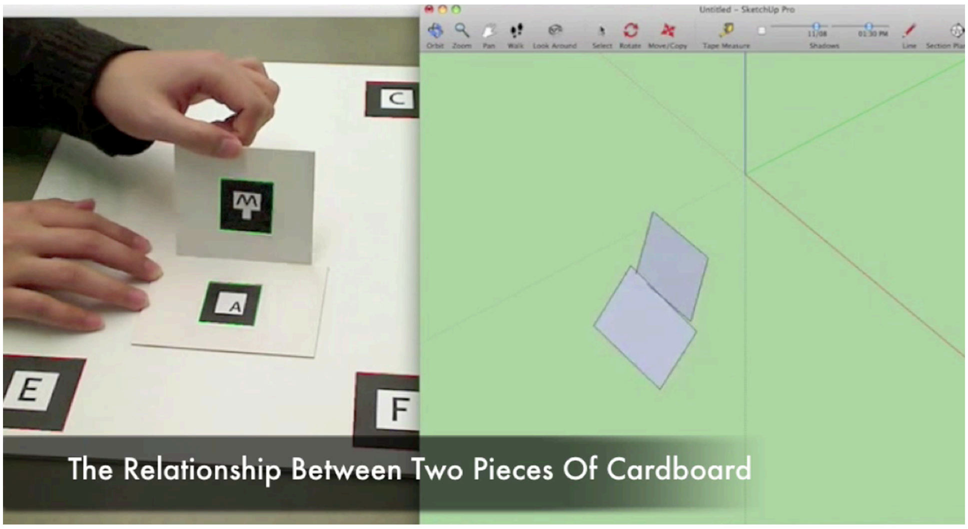

Fig. 3. The Location Detector showing physical model and resulting digital model.

3.2.1. The Shape Scanning Application (SSA)

The first step of this application uses a utility process from ARTK to accumulate the dark area, and gives the same area a flag. In the original ARTK process, these areas will be recognized whether they are a four-vertex shape or not. However, in our modified version, the new code grabs the area information of reversed color to recognize the number of vertices around the contour of the area and which pixels these vertices are when the previous frame contains a fiducial marker. In order to get more accurate vertex information, TiMBA combines information from a number of video frames.

In addition to the vertex information, SRH needs to know the size of the shape, the ID of the marker, and the transformation matrix of the marker. These data, combined with the vertex data will comprise an entry in the complete data stream. A Unix "pipe" is used to communicate between SSA and SRH. Each cardboard piece is represented as a record similar to the following :

Tab. 1 : Sample record of data transferred from SSA to SRH

-1	2	383.7	340.1	170.2	277.7	164.5	197.9	268.8	187.6	283.2	264.1
a	b	c	d	e	f	g	h	i	j	k	l

In Tab. 1, the meanings of these numbers are as follows : (a) beginning of data flag, (b) the marker id, (c) marker center X, (d) marker center Y, (e) to (l) the coordinates of the four vertices of the marker on the XY plane of the piece of cardboard.

3.2.2. The Location Detector Application (LDA)

The concept of this application is simply to compare the location data of the cardboard markers to the coordinate system provided by a "base" marker set on the foundation board (Figure 1). When it gets appropriate data, it will transfer to the SketchUp Ruby Helper. In order to improve the speed when multiple markers are encountered in the same scene, the system tries to compare the location data of the markers to the previous frame. If markers have not moved too much, it will not send the new geometry information for this marker, but send the next moving marker in the current loop instead.

3.2.3. The SketchUp Ruby Helper (SRH)

This program has to analyze the data from both LDA and SSA. Then, it transforms them into the coordinate system of SketchUp and displays the geometry for users. There are three main tasks to deal with in this application : 1) creating a 2D shape, 2) moving the 2D geometry to the appropriate 3D location, and 3) trying to glue the adjacent shapes together. The first two tasks simply take the data from the other two applications and analyze them to verify a reasonable shape and location. The goal of the third task is trying to decide whether it needs to assemble the cardboard pieces as one model or not. The reason for doing this is to avoid the situation where the camera for the LDA cannot see a marker at the rear of the model but the user can.

4. Experiment

After we built the prototype we asked several graduate students from our architecture school to test it. While TiMBA uses a general model-building approach intended to fit every designer’s habits, there are still some features that bother users. For example, the prototype requires users to scan each piece of cardboard before assembling them, which annoyed subjects who are used to gluing two pieces of cardboard together right after cutting them. Users must pay attention to which side of the cardboard they affix the AR marker to, because the program needs to see the marker to locate the geometry. The experiment was designed to help us find out how these features impact users.

4.1. Experiment design

One of the hypotheses is that TiMBA can leverage the digital model by providing more information during the early design stages. We believe that the user will be inspired by the availability of more information and avoid errors. In addition, based on the information, s/he can make immediate adjustments to the model. Another hypothesis posits that the prototype will not significantly slow down the speed of building both the physical and virtual models, because it employs the traditional model-building materials and techniques. In addition, TiMBA should save time by automating the production of the digital model. In order to simulate this, we developed an experiment in which we provided subjects a drawing set of a simple building and asked them to build both digital and physical models with these drawings. We also gave them tasks that utilized affordances of both digital and physical models. At the final part of the experiment, in order to get the perceptual data from subjects, we asked several assessment questions.

At the beginning of the tests, the participants were given a short set of instructions. Before the experiments started, each subject had a 5 minute "learning phase" so that they could familiarize themselves with the prototype system. We provided the same tools and materials for each participant to complete both a digital and a physical model using TiMBA. After finishing the learning phase, they were given two tasks, including the building of digital and physical models, and were asked to resolve two related questions. For these tasks, the subjects were asked to consider a particular design of an element for this building. We avoided discrete, binary, yes/no style answers for tasks, which might encourage guessing. Subjects were told they were being timed on the experiment and to "complete each task as quickly as possible". After building the models, they were asked to save the digital model and kept the physical one for the experiment result, and then moved on to the next experimental condition. Finally, they were given a post-experiment questionnaire.

4.2. Experiment design

A total of 6 architecture students with at least one-year architectural study from the University of Washington College of Built Environments participated in the experiment. One of the students was at the doctoral level in the college; 5 of them were Master of Architecture students. All the participants were male. All participants were right-handed. All the participants had a certain level of physical modeling skill. On a scale of (none) 1-5(significant), one of the participants has full SketchUp modeling skill while three of them have four, two of them have three, and one of them has two. They all use SketchUp as an architectural modeling program. Two of them even use it for brief design study or evaluation.

4.3. Experimental measures and the results

We employ two different measures: performance measures and subjective perceptual measures. In performance measures, we recorded a) time (the number of minutes to complete the task) and b) the accuracy of the results. In the "accuracy of the result" part, the result is the answers of the questions that come with the tasks. For example, the first task is "at 12:00 pm, June 21, which walls would receive direct sunshine (east, west, south, north) ?". The subject has to build accurate digital and physical models, and then use the digital models to simulate the shadow patterns on the site. An alternative question is "which orientation of the building is the best one in terms of avoiding the shadows from the other building near the site for the garden near the building (east, west, south, north) ?". In this case, the subject could rotate the digital model until they achieved a satisfactory answer. The results are convincing. All of our subjects arrived at correct answers in a relativly short time when constructing both of the digital and physical models.

The perceptual measures were recorded in the form of a subjective post-experiment questionnaire. Participants were presented with a number of statements concerning the experiment and instructed to rank their level of agreement or disagreement with the statement on a scale between 1 and 9. For example, Statement 1 reads :

"Building the model by using the prototype is easy and intuitive".
1 2 3 4 5 6 7 8 9
Completely Disagree Completely Agree

Figure 4 shows the list of questions and the results of the post questions. In general, the subjects did not think "sticking the marker" on the pieces distracted them from building the physical model. They also believed that the assistance from the computer made it easy for them to judge the answer of the task. However, they think the prototype could be more intuitive. According to the observation, the separation between the working platform and the monitor could cause the intuitive issue with which the subjects encountered. Although they thought they could build a better digital model with mouse and keyboard, some of them indicated that it depends on the complexity of model. For instance, some complicated models require advanced digital modeling skill. On the physical side, however, we only need our hands to bend materials or place them at the specific location. Overall, they think this is a fun and effective way to build a digital model.

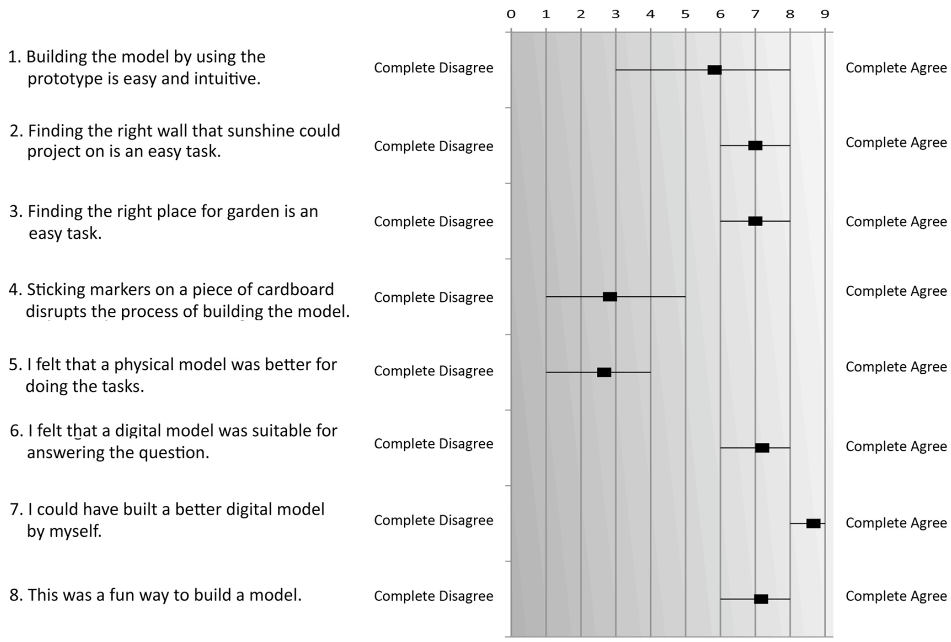

Fig. 4. List of the Assessment Questions and the Results.

5. Discussion and challenges

The prototype does help users make a digital model with a physical model. It can reflect the movement, shape, and position of a piece of cardboard in the physical world and give some responses back to the user. It also takes one step forward from systems with preset geometry, such as construction kits, to editable geometry. However, the real benefits of this system are the ability to leverage the digital model, using it to provide the designer with more information and better represented information than the physical model alone can provide. Thus, we believe that this prototype system is just a beginning, and there are still many more possibilities to explore.

5.1. More elegant ways for presenting simulation information

One of the distractions that the subjects mentioned during the experiments is the separation between digital and physical platforms. Because of this, we thought that projecting simulation results from the host computer could be a more appropriate way in providing simulation information. The simulation results could be presented as 2D or 3D images, such as shading, sun penetration, thermal diagrams, and visibility data. These images could be projected on 3D objects to illustrate the real-time situation in the current model. For example, shadows can appear on the ground as well as on walls, windows and roofs. Projecting information onto 3D objects may benefit designers more than just presenting simulation results on the X-Y plane because these environment factors can affect the comfort of the residents in the building (not just on the ground).

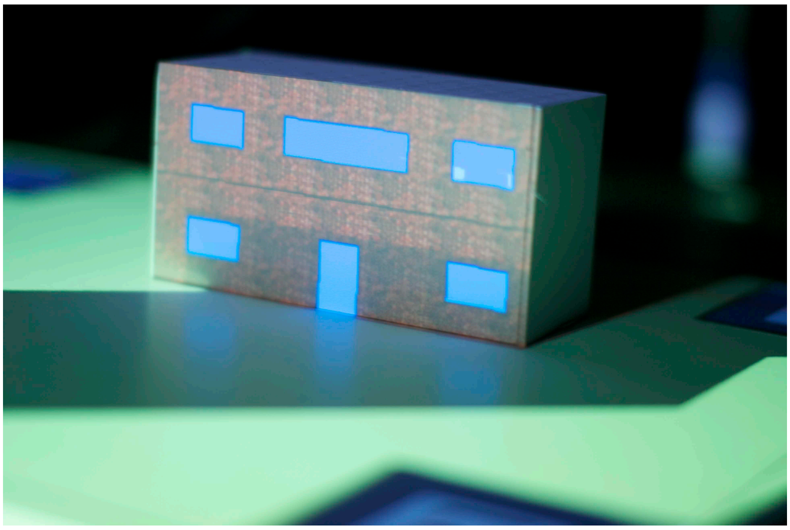

Fig. 5. Real-time tracking a cardboard model with projected (brick) textures and projecting a simulated shadow on a it (The marker is on the back of the box)

Figure 5 is a preliminary example of applying these concepts. We projected results of a simple shadow simulation onto a building to study how the surrounding environment impacts the proposal. We also experimented with use of fiducial markers as tangible controllers for users to adjust parameters for the simulation tools, such as modify the time, modes, and editing the basic materials. Using these techniques, architects no longer need to check the simulation results on monitors and study their design on the physical objects. Two architects could discuss their design in a more comfortable environment, and do not need to compete for control of the mouse and keyboard in order to make changes. In addition, because they can focus on the real physical model, they can engage more on the real issues instead of being interrupted by switching between two platforms. Non-professionals may also understand the design more easily than through viewing a computer screen since designers can present the simulation results in an intuitive way.

5.2. Getting rid of the markers

While TiMBA uses a general model-building approach intended to fit every designer's habits, we had to add fiducial marker placement and scanning to the workflow. In our preliminary observations, the subjects did not think "sticking the marker" on the pieces distracted them from building the physical model. However, one additional concern did bother users. They must pay attention to which side of the cardboard they affix the AR marker, because the program needs to see the marker to locate the geometry. If we could utilize a 3D depth camera in the second step, we can avoid this additional action during model building. With 3D depth camera, the computer program could recognize each piece of cardboard in the view field by matching the size and shape with the scanned one in the step 1. Though, we still need to sort out the way for associating different type of building elements if there is no marker to indicate it.

5.3. Parametric modeling

When architects use physical tools for designing, intended design variability is difficult to record and store. This issue could be resolved since we can bridge the physical and digital worlds with this prototype. In a digital environment, the design intent could be recorded as parametric modeling and annotations. In our case, we only focus on the part of parametric modeling. In the later stage of design, architects and engineers usually utilize parametric models to describe the relationship between geometries. In the concept design stage, we have found that architects start to use parametric tools such as Grasshopper or Generative Components. With these tools, architects could clearly know the purpose and settings for the target building. For example, one project from NBBJ utilizes the parametric strategy to define the seats in a stadium location in order to let viewers have the best sight-lines [12]. However, the current digital design environment still has some disadvantages such as the scale and WIMP (Window, Icon, Menu, Pointing) manipulation issues [13]. In sketching realm, Naya et al. suggest several automatic detection algorithms to build parametric drawings. Likewise, since we can turn physical object to digital geometry in a simple manner, further question becomes how can we define the relationship between different pieces of physical objects.

5.4. Design recording

Besides the design intent, architects make many decisions while they are studying the size, orientation, or form of a shape. When they decide to use a certain shape for the specific location of a model, they would attach it to the model. This is a decision they made during the process of modeling. However, they would change this piece of cardboard while they change the shape of the whole model because of the needs of adjustment. These actions could be represented as nodes in the property of digital geometry in our prototype system. In the latter design stage, designers or other disciplines could know why designers made that decision at that particular point. Further, architects can avoid revisiting unnecessary design alternatives during the design process.

5.5. Data exchange

Being able to capture the physical model as data raises the question of how best to represent the physical model data in a digital format in order to leverage the information for analysis or subsequent use. Industry Foundation Classes (IFC) offer a powerful neutral modeling language, but are quite complex. In order to shrink these large schemas into a useful and concise set, we consulted and referred to several previous Model View Definition projects (MVD), such as "Concept Design BIM 2010" [14], and "Engineering Semantic MVDs" [15]. A good MVD for data exchange is made by using a more rigorous framework and focusing on a more specific issue. The purposes of data exchange in our case are mainly for extending the data sets for later usage, doing simple simulations, and developing better cooperation environments. We are still exploring options here.

6. Conclusions

In this paper, we have presented some recent uses of Tangible User Interfaces and other digital technologies, how they are increasingly valuable in the design process, and how, by using these new technologies, we may derive certain benefits. We also described TiMBA, a prototype software system that we developed to demonstrate that the concept is useful and implementable. The most exciting "take-away" from these applications is the notion that we can treat a physical object in digital ways. This could lead to infinite possibilities when computational power can get "off the screen" and lay on our working platform.

Why do we not simply finish all the tasks in a virtual world ? Why do we need to connect the physical and virtual worlds together ? We believe that the ubiquity of computational power will let us treat computational tools as additional physical objects. These two different categories of "objects" are essentially the same thing, created and utilized by us. We seek to make available the affordances of every tool that designers wish to utilize to achieve their goals. The computational power is just the magic that can bring these objects alive and offer them the ability to interact with humans, enabling them to augment architect's intellect.

All of these new approaches make the design process less cumbersome. At the present time, users struggle to manipulate digital objects though they know how to interact smoothly with physical ones. With the widespread use of TUIs, the boundary begins to blur between digital and physical worlds. When any physical object can be instantly given a digital representation and any digital data may be made evident in the physical world, the two begin to merge. Using computer vision, all objects in the physical world, not just the ones with sensors, can become part of our digital environment. The designer, able to work in either or both, experiences "continuous thought" and produces better design.

7. Acknowledgement

We thank Daniel Belcher, Randolph Fritz, members of DMG Lab at University of Washington, Ellen Y.-L. Do and the colleagues at Georgia Tech for giving us insightful feedback and suggestions.

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