Simulating Transparency and Cutaway to Visualize 3D Internal Information for Tangible UIs

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Abstract

It is recognized that tangible user interfaces (TUIs), defined and scoped by Ishii, provide more intuitive experience for manipulating and reviewing 3D digital information than conventional graphical user interfaces (GUIs). Although current TUIs for CAD enable users to intuitively manipulate and directly perceive 3D digital information via physical objects, they limit users to obtain only external and surface information. The outer 3D physical bounding shape occludes valuable layered and hierarchical internal information. Only when removing and deforming the external 3D physical volumes can users define a section-cut surface to inspect internal information. We propose a TUI system that enables users to visually inspect 3D internal information without modifying its physical outer shell. We implement two popular illustration techniques, namely transparent and cutaway drawings. Using direct touch, hand gestures and tangible tools, users are capable of specifying the transparency and section cut plane intuitively. The system used a combination of projection mapping and perspective correction techniques. After running a preliminary observation for 50 users, we collect valuable feedback including the advantages and technical issues of our system.
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Chapter 1

Introduction

1.1 TUIs for CAD Systems

Developing intuitive user interface for computer-aided design (CAD) systems has a long history. Aish proposed the first concept of building-block system (BBS) using three-dimensional (3D) physical objects as inputs 15 years ago [1]. Although graphical-user interfaces (GUIs), consisting of window, icon, menu, and pointing device (WIMP), have been the dominant human-computer interaction (HCI) paradigm for the past decades, researchers continue to develop new interaction techniques to address shortcomings of GUIs. Tangible-user interfaces (TUIs), as defined and scoped by Ishii [11], is one of the most popular and expending fields to date.

In CAD systems, one of the significant insufficiencies of GUIs is that it is difficult to review and manipulate 3D objects by using two-dimensional (2D) display and a two degree-of-freedom (2 DOF) pointing device. When navigating 3D virtual space, users need to make rapid mental conversions between the 3D orientations of digital contents and 2D navigation commands. TUIs enable users to leverage the experience of interacting with physical objects, providing both perceived and physical affordances [19] to control 3D digital information. Offloading the cognitive burdens from 2D GUI to 3D TUI helps users concentrate on the review task.

1.2 From Coupling to Merging

Coupling physical objects with their digital representations on the screen accordingly is the early approach (Figure 1-1). Researchers invent physical objects that are sensible to each other and readable for both users and computers [1][2][3][9][13][32]. Users modify the configuration of physical object at hand to change their 3D digital representations on the screen. Although this setting provides instant visual and tactile feedbacks synchronously, it still causes the eye-hand coordination issue, making users frequently shift attention between the screen and physical objects to correlate the 3D digital representation with its physical embodiment.
Under the concepts of IO Bulb [30] and Shader Lamp [23], 3D digital data are brought from 2D display to the real world and seamlessly collocated with their 3D physical representations [15][16][21][24][31] (Figure 1-2). While IO Bulb projects 2D simulated shadows on the plane surface, Shader Lamp maps 3D digital textures on 3D physical building models. The approach of using light projectors to render digital information in the real world addresses the fix focal length problem of head-attached displays. Its device-free capability also maintains users' two-handed interactions with tangibles.

1.3 Motivation

Although TUIs enable users to intuitively manipulate and directly perceive 3D digital information via physical objects, they limit users to obtain only external and surface information. The outer
3D physical bounding shape occludes valuable layered and hierarchical internal 3D information (Figure 1-3).

Figure 1-3: Internal information is hidden in the physical bounding shape

Only when removing and deforming the external 3D physical volumes [21][24] can users define a section-cut surface to inspect internal information (Figure 1-4). Even so, the information that the section-cut surface shows is internal surface information containing no-depth information.

Figure 1-4: Removing the external shape to reveal the internal information.

What if a TUI system is capable of letting users inspect internal 3D information before physically removing and deforming the outer shell (Figure 1-5)? In this research, we would like to develop a TUI system that enables users to see inside physical objects in order to do as follows:

1. Cross-reference the physical outer shape with visual inner information.
2. Get a clear understanding about the hierarchical relationships of hidden components.
1.4 Thesis Goal and Outlines

Our goal is to develop a TUI system equipped with two popular design representation techniques, in which transparent and cutaway drawings are applied. With its tangible tools, this system enables users to specify transparency and section-cut intuitively.

In this thesis, we first review the development of TUI for CAD systems, the coupling-to-merging process of the physical and visual representation of TUIs, existing projects of inspecting 3D internal information, and the reason for choosing a projection based approach for our system in Chapter 2. We then propose our design of a visually transparent and cutaway TUI system in Chapter 3. The implementations of our system in terms of system overview, hardware, and software are delineated in Chapter 4, Chapter 5, and Chapter 6. We demonstrate two applications that are Cube and Building in Chapter 7. In Chapter 8, we conduct a preliminary observation and list our findings. Lastly, we summarize the lessons we learned and propose potential scenarios for merging our system with other TUI systems in Chapter 9.
Chapter 2

Related Work

2.1 Early TUI for CAD Systems

Ivan Sutherland invented and demonstrated the Sketchpad in 1963 and initiated the research of both HCI and CAD [27]. With a light pen and CRT monitor mimicking pen and paper, users were able to generate and manipulate line drawings by hand (Figure 2-1). Users could refine and confine the line drawings by applying the computationally defined constraints. Sketchpad and the following drawing system, Light Handles [18], combined users’ existing drawing experiences of pen with computational functions. They exploited the potential of extending human’s physical abilities through computation embedded physical tools.

Figure 2-1: Sketchpad 1963
In addition to taking advantage of the directness of the pen and paper metaphor, Douglas Engelbart invented a computer mouse from scratch to remotely control the on-screen information [8] (Figure 2-2). Along with GUI, the computer mouse became the most dominating physical device since the introduction of the computer. Using a computer mouse as a pointing device to manipulate window, icon, and menu became a standard HCI paradigm.

![Image of the first mouse 1963](image)

Figure 2-2: The first mouse 1963

Although it is effective in dealing with 2D graphical information, the combination of mouse and GUI has issues with 3D spatial and volumetric information. One of the more common insufficiencies is its frequent conversion between 3D information to 2D actions, which generates many cognitive loads and requires plenty of practice. Even for an experienced user, some errors and disorientations still occur.

According to experiments on and observations of real architects, Aish concluded that physical models allowed both expert and non-expert designers to generate design solutions more efficiently and effectively than graphical CAD systems [1]. He proposed a building block system (BBS) in which physical models are readable for both computers and humans (Figure 2-3). The change of the states of physical models by hand updated the states of the digital ones accordingly. This approach could potentially solve the problems of conventional GUI.
2.2 Coupling

Aish’s proposal of BBS was later made manifest in the geometry-defining processors (GDPs) system [2]. A GDP was a physical cube with a microprocessor inside. It had optical transmitters on each side of the cube to communicate with other GDPs when connected. The shapes constructed by GDPs were interpreted as 3D digital meshes by the software and displayed on screen. Manual reconfiguration of GDPs updated the 3D digital interpretation (Figure 2-4). The 3D digital meshes were used for further computational simulation. Later projects such as Triangles [9], Computational Building Blocks [3], ActiveCube [13] and Posey [32] developed different shapes of physical building blocks for diverse applications.
Instead of stacking physical objects with fixed and predefined shapes to specify a collected geometry, another approach is creating a sensible physical object to deform its on-screen representation. CUBIK replaced a fixed physical building block with a stretchable mechanical structure [17]. By stretching the physical cube along its axis, the on-screen digital model was deformed accordingly (Figure 2-5). The iSphere [14] replaced the mechanical mechanism of CUBIK with capacitive sensors to let users employ both on-object touches and mid-air gestures to modify the coupled 3D digital models (Figure 2-6).
The coupling approach enables users to manipulate 3D digital information through the direct manipulation of the physical objects. It provides a better spatial sense of shapes and orientations than on-screen 3D information. However, manipulating physical objects with hands and perceiving visual feedback from the screen leads to the eye-hand coordination problem. Users always need to shift their attention between the screen and physical objects frequently to correlate the information from both places.

### 2.3 Merging

Under the vision of TUI defined and scoped by Ishii in 1997 [11], the IO Bulb, originally aimed to seamlessly augment digital information on every surface of our physical environment, potentially solving the eye-hand coordination problem [30]. By directly projecting digital information on the physical objects, users get both visual and tactile feedbacks from the same location. One of the examples of IO Bulb, Urps [31], perfectly combined physical models with digital shadow simulations (Figure 2-7). The states of physical models were synchronized with their simulated shadows. The physical models and virtual simulations were tightly stitched, and no more visual references from the screen were required.

The early IO Bulb examples projected 2D information on 2D plane surface. With advanced computer graphic and projector calibration algorithms, Shader Lamp went beyond to merge 3D information on 3D physical objects [23]. For example, a physical building model of Taj Mahal could be augmented with realistic textures and 3D simulated shadows (Figure 2-8).

![Figure 2-7: Urp 1999](image)
In addition to static and discrete physical objects, Illuminant Clay projected information on malleable clay to assist in landscape design [21]. Users’ direct modification on clay were captured by a 3D-scanning system to conduct real-time simulation (Figure 2-9). Simulation results were updated on the clay to provide instant visual feedback for users. SandScape replaced clay with glass beads to allow free manipulation of shapes [24]. Relief merged 3D digital information with active 2.5D shape display to create collocated bidirectional interactions [15] (Figure 2-10). Sublimate adopted the half-silvered mirror technique, instead of a projection-based one, to attach not only on-object information but also mid-air information [16].
Based on the above-mentioned trajectory of TUI development, we can see that it is a continuous process of bringing digital information from a 2D screen to the 3D real world. By seamlessly merging 3D visual information with its 3D physical embodiment, users have access to more intuitive and direct perception and manipulation.

### 2.4 Internal 3D Inspection

Reviewing the internal information of 3D model and volumetric data on the 2D screen with a 2 DOF pointing device is even more problematic. For selection, users need to use three 2D projective viewports, e.g., top, front, and left, to specify the 3D location of a single point. For manipulation, users have to mentally convert the 3D orientation to 2D mouse manipulations and keyboard events such as roll, pitch, and yaw.

As proven by previous projects, TUI is a promising solution. During the early coupling approach, Hinkley enabled users to hold a prop of skull in one hand and a prop of section cut in the other [20]. By using an optical tracking system that tracked the markers attached on the props, neurosurgeons could specify an arbitrary plane section cut and retrieve the section cut information from the screen (Figure 2-11). Qi and Martens replaced the skull prop with a generic cube to make it applicable for diverse applications [22] (Figure 2-12). Their preliminary study revealed that, for specifying and reviewing on-screen section cut information, TUI gathered more positive feedbacks than a computer mouse. Handsaw replaced the marker-based tracking system.
with a depth-sensing technique that allowed users to use their hands to directly define the section cut plane on real objects and bodies [6] (Figure 2-13).

Figure 2-11: Props as tangible tools for digital sectional information by Hinkley etc. 1994

Figure 2-12: Generic tangible tools for manipulating 3D volumetric data by Qi etc. 2005
In the merging category, PHOXEL-SPACE implemented another brain MRI viewing application [24]. By removing and adding clay or glass beads to create the physical terrain, users could define an arbitrary cross-section surface to view the MRI information (Figure 2-14). Sublimate also had a similar MRI viewing application in which users could push and pull the actuated pins to specify the cross-section surface [16]. Different from PHOXEL-SPACE, Sublimate adopted the half-silvered mirror technique to augment the visual information (Figure 2-15). Specifying a cross-section plane/surface via TUIs is much more direct and intuitive than using GUIs.
Figure 2-15: Sublimate 2013

However, these applications that helped users inspect internal 3D information still has two main insufficiencies, which are what we are going to improve in this research.

1. The internal information is occluded by the external physical bounding shell. Only when removing the physical parts can users see the internal information.
2. The internal information available for inspecting is only the surface information of the section cut. There is no inner-depth information.

2.5 Why projection based spatial augmented reality?

In the augmented reality (AR) field there are many techniques that can achieve the goal of augmenting 3D digital information on a real-world environment [5]. The popular techniques are shown in Figure 22, including retinal display, head-mounted display, hand-held display, spatial optical see-through display, and projector (Figure 2-16). Different approaches have their pros and cons. We set up three criteria to determine the projection based AR to be the means for our project.
**Hands Free**

The advantage of TUI is that it enables users’ direct manipulation of physical objects, so keeping users two hands free is required. In regard to this criterion, the hand-held display approaches are not suitable and excluded.

**High Resolution**

One of the parameters of realistic merging is the resolution. The resolution of rendered images should be close to that of the human visual system to prevent the visual inharmony. According to this, most of the head-attached solutions providing limited display resolution are excluded.

**Identical Focal Length**

Another parameter of realistic merging is focal length. The head-attached techniques had the fix focal length problem. Because the image plane worn on the head of the user is away from the projected objects, users need to shift their focus between the image plane and the objects. This made the visual information attached to the physical object unrealistic.

![Figure 2-16 Displays for augmented reality](image-url)
Chapter 3

Simulating Transparency and Cutaway

We sought techniques of inspecting 3D internal information and found there were two in the design field: transparent and cutaway drawings. The transparent drawing is employed to make the shell component transparent. The cutaway one is to slice outer objects into parts and remove the parts that block the inner target components.

3.1 Transparency

The transparent illustration has been widely adopted in the design process. By turning shell components that are originally solid and opaque transparent, designers are able to show internal occluded information. For example, an architectural illustration turns the facade of a building transparent to show internal structures (Figure 3-1). A car illustration makes the body shell transparent to expose inner mechanical systems (Figure 3-2). An illustration of product design, such as a camera, turns its housing transparent to demonstrate precision optical components (Figure 3-3). The transparent components still remains visible in outlines for users to inspect the relationship between the outer bounding shell and the inner structures.

Figure 3-1: Transparent illustration of building
(http://media.economist.com/images/20080607/2308TQ22.jpg)
Figure 3-2: Transparent illustration of car
(http://www.automotiveillustrations.com/carimages/nissan-300z-chassis-magazine.jpg)

Figure 3-3: Transparent illustration of camera
(http://www.kenrockwell.com/nikon/d700/d700-xray-768.jpg)
This transparent strategy also applies to physical models. A model with transparent outer shell enables viewers to flip around and walk around to inspect information from arbitrary viewing angles (Figure 3-4). A transparent model provides users 6-DOF manipulation to view internal information that is better than viewing a static plane illustration with a fixed view angle. Products with transparent outer shells sometimes serve aesthetic purposes (Figures 3-5, 3-6).

![Figure 3-4: Transparent model of building](http://www.showroomworkstation.org.uk/sketchesoffrankgehry)

Figure 3-4: Transparent model of building

![Figure 3-5: A real car with transparent shell](http://www.showroomworkstation.org.uk/sketchesoffrankgehry)

Figure 3-5: A real car with transparent shell
3.2 Cutaway

The cutaway illustration is another strategy to show internal information. Designers define a section cut plane to slice objects into parts. The parts that block the inner targets are removed. Architects use cutaway drawings to show the inner relationships between the spaces of building (Figure 3-7). Such a technique can also be used to inspect interior lighting conditions and structural details. Car designers use it to review the spatial ordering between different mechanical systems (Figure 3-8). Camera cutaway drawings illustrate how lenses guide the light (Figure 3-9). While transparent illustrations emphasize on the inner and outer relations, cutaway drawings reveal the layered and intersystem relationships.
Figure 3-7: Cutaway drawing of building

Figure 3-8: Cutaway drawing of car
(http://evnewsreport.com/model-s-and-x-service-and-warranty-ceo-musks-four-points/4398/)
Designers also make cutaway models to create better review experiences. Cutaway models not only visually show hierarchical information of the object but also enable users to physically touch the inner components and experience the interior space (Figures 3-10, 3-11, 3-12).
Figures 3-11: Cutaway model of car
(http://www.advancedvehicle.com/show-car-capability.html)

Figure 3-12: Cutaway model of camera
3.3 System Specification

Our goal is to develop a TUI system with transparent and cutaway functions to enable users to view internal 3D information. This system provides several interaction modalities for users to navigate content and specify functions.

Model Navigation

Through inspecting the transparent and cutaway physical models, the system enables users to freely navigate both surface and internal information of a 3D digital model in the real world. Users can move their bodies and heads to view the tangible information (the 3D digital information seamlessly merged with its physical outer shell). They can also rotate and relocate the tangible information manually.

Transparency Modification

The system enables users to modify the transparency of the outer shell of tangible information with intuitive touch. By detecting the touch event on physical outer shells, transparency decreases according to the touch duration (optical sensing) or touch force (force sensing).

Cross-Section Specification

The system has two ways for users to specify the cross section plane. One is to use a tangible wand of section cut. The other is for users to use their hands to specify the position of the section cut plane.

Light Source Manipulation

We also provide users a tangible wand of light source to adjust the lighting condition in the 3D digital model. Manipulating the position of the light source by TUI provides for more intuitive control than by using GUI.
Chapter 4

System Design

The system has a pipeline consisting of five hardware and software components. These components are input, localization, digital model manipulation, perspective correction, and output.

Details of input and output components are described in Chapter 5: Hardware Setup, while implementations of localization, digital content manipulation, and perspective correction modules are explained in Chapter 6: Software Implementation.

In this chapter, instead of going deep into details, we explain the system pipeline generally (Figure 4-1).

4.1 Pipeline Overview

Input module

We adopt an IR camera to capture images of users’ heads and tangible tools. We use a pressure sensor pad to detect physical models, as well as finger touch and hand touch.

Localization module

The detected signals of previous stage are interpreted into 3D locations and orientations of the user’s head, hand, tools, and light source in the virtual world.

Content manipulation module

The interpreted 3D locations and orientations are used to register related digital content, such as target models, section cut model, light source, and virtual cameras.
**Perspective correction module**

We develop projective texture technique to display the viewport images with accurate perspectives for the viewer.

**Output module**

By projecting the rendered images back to the physical models from a projector, the system enables users to perceive the physical models with perspective-corrected digital information.

![Figure 4-1: System pipeline](image)

**4.2 Signal Flow**

We take the scenario of free hand section cut described in Chapter 3, for example, to show how the signals flow through the hardware and software components (Figure 4-2).
(a) A user places a physical model on the pressure sensor pad. The pressure sensor pad detects the signals generated by the physical model. These signals are sent to the pressure-based localization module and interpreted into ID, X-Y position, and orientation.

(b) The user makes his hand into a handsaw shape and places it on the pressure sensor pad. The signal is detected and sent to the pressure-based localization module and interpreted into the X-Y position and orientation of the handsaw shape.

(c) The user’s head is captured by camera and sent to the optical based localization module. The module recognizes the head from the camera image and converts into an X-Y-Z position and orientation in the virtual world.

(d) The interpreted ID, X-Y position and orientation of the physical model are sent to the cutaway module to register a corresponding digital target model. The digital model is pre-made with the same shape and size as the physical one and stored in the database.

(e) The X-Y position and orientation of the handsaw shape are also sent to the cutaway module to register a section-cut model.

(f) The X-Y-Z head position is sent to the cutaway module to register a virtual camera representing a virtual head.

(g) The cutaway module conducts a Boolean operation to subtract the section cut model from the target model. The new target model is then sent to the projective texture module.

(h) The virtual head is passed to the projective texture module.

(i) If the cutaway module does not receive any information of light source from the previous step, it will automatically register a light source with a predefined X-Y-Z position. The light source is then sent to the projective texture module.

(j) The projective texture module has a pre-calibrated virtual camera representing a virtual projector. The virtual projector renders a projective texture image according the virtual head, target model, and light source information and passes the rendered viewport image to the physical projector, projecting the image on the physical model.
Figure 4-2: Detail signal flow of system pipeline
Chapter 5

Hardware Setup

5.1 Input

The system has two input sources, one is an IR camera (g) and the other is a pressure sensor pad (b).

We use the Kinect’s IR module as our IR camera. With an IR lamp, we can filter out the visible light of the environment and the projector. The IR camera captures the images of the scene containing the section cut tool (d), light source tool (e) and user’s head (f), all that have AR markers attached. The image is later sent to the optical based localization module to localize the above-mentioned components.

We adopt the Tactonic Sensor pad [28] developed by Tactonic Technologies as our pressure-sensing device (Figure 5-1). The pressure sensor pad can detect pressures applied on it and generate a pressure image with 100*100 dpi resolution. After sending the image to our pressure-based localization module, we can recognize and localize the physical models (a), finger touch on models, and hand touch on the pad (c) in the virtual world.

![Figure 5-1: Tactonic pressure sensor pad](image)
5.2 Output

There is only one output device for the system, a projector. The projector project 3D digital information including both surface and internal information on physical models with accurate perspective.

Figure 5-2: Schematic of system hardware setup
Chapter 6

Software Implementation

6.1 Projection Mapping

Our system is based on the projection-mapping technique. There are two steps in projection mapping. First, a virtual camera renders its viewport image containing the 3D digital model (Figure 6-1). Second, the viewport image is sent to the physical projector to project on the physical model (Figure 6-2).

The key for successful projection mapping is that the position, orientation, and parameters of virtual camera should be the same as that of the physical projector, so that the virtual viewport perfectly matches the real scene. How to localize the physical camera in a virtual world is the first task of our research (Figure 6-3).

Figure 6-1: A virtual camera renders the digital model in a viewport
Figure 6-2: The viewport image is projected back to the physical model

Figure 6-3: Localization of the projector in the virtual world is the first task for projection mapping related applications
There are many ways to achieve this objective. Developers manually measure the position and orientation of physical projector to place the virtual camera in the virtual world. Alternatively, in an automatic way, a depth camera captures the physical scene and reconstructs the whole scene digitally from depth information [26][29]. While the manual approach is time consuming because of tedious measurements, the automatic way has problems with accuracy of reconstruction because of limited image resolution and stability.

The way we implement is a popular semiautomatic way. First, the projector projects a blank image on the physical model (Figure 6-4). Users then locate the mouse cursor at the corner points of the physical model. While clicking on the corners of the physical model, users actually specify their 2D projected coordinates on the projector viewport (Figure 6-5). Because the physical model has a pre-defined digital representation, with the known 3D corner points of digital model and the 2D projected corner points on the viewport, the system can calculate the 3D position, orientation, and parameters of the virtual camera (Figure 6-6).

![Figure 6-4: The projector projects a blank image on the physical model](image)
Figure 6-5: Specifying 2D coordinates of corner points on the projector viewport by clicking the 3D locations of corner points on the physical model

Figure 6-6: Using 6 3D points and 6 2D viewport points to calculate the virtual camera position
6.2 Localization

To realize the designed tangible interaction, we have to localize not only the physical models and tools but also the user's hand and touch. We also need to locate the user's head to generate a perspective corrected image (described in 6.4). We developed two localization modules, an optical-based module handling images from the IR camera and a pressure-based module dealing with signals from pressure sensor pad.

Optical based

To localize head and tools positions, we adopted the popular AR Toolkit [10] as our solution (Figure 6-7). We attach AR markers on a user's head (c) and tangible tools (b) to track 3D positions and orientations in the camera coordinate. Then, we use another AR marker representing the origin of the 3D virtual world coordinate to calibrate other markers (a).

![Figure 6-7: Localization by attaching AR markers on user’s head (c), tools (b) and the origin point (a).]

Pressure-based

The idea of pressure-based localization is to convert the 2D coordinate of pressure images generated by the Tactonic Sensor pad to the 3D coordinate of the virtual world. First, we use the origin of the pressure image as the origin of 3D virtual world. Then we calculate the scale factor
by dividing the actual size of the sensor pad by its resolution. With this scale factor, the signals on
the pressure sensor pad are converted to the 3D virtual world coordinate. Once the locations of
physical models are changed, their digital ones are updated accordingly for rendering the
viewport image for projection (Figure 6-8).

![Diagram](image)

Figure 6-8: Update the position of the digital model by the location of the physical model to
update the viewport image for the projector

Further, we design pressure markers to encode the information of ID, center position, and
orientation (Figure 6-9). As shown in Figure 6-10, the three touch points at the corner form a
perpendicular triangle. The system uses this triangle to find the center position and orientation of
an object. The fourth touch point outside the triangle shape is for encoding the object ID.
According to the current stability and resolution, we can encode 20 IDs on a 5 cm by 5 cm
marker.
Once users touch on the objects, the pressure of the touch points increases. This change of pressure is interpreted as a touch event (Figure 6-11).
Figure 6-11: The change of the pressure of the marker is recognized as a touch event

A user's hand acting like a handsaw generates a blob shape on the pressure image. With the blob-detecting algorithm of openCV [12], the center position and orientation are interpreted (Figure 6-12).

Figure 6-12: Hand recognition by the pressure sensor pad
6.3 Digital Content Manipulation

Transparency

In the transparent module, the system registers digital models, a light source, and a virtual camera representing the user's head. According to touch events, the system adjusts the transparency of the touched digital models according to pressures. We also implement an alternative to modify the transparency of the digital model based on the duration of touch (Figure 6-12).

Cutaway

In the cutaway module, the system obtain parameters from previous step to register digital content, including digital models, a section cut model, a light source, and a virtual camera representing the user's head. We use carveCSG [7], a c++ library dealing with Boolean operations of 3D geometries, to subtract the section-cut model from the digital models (Figure 6-13).
6.4 Perspective Correction

Projective Texture

So far, we can project the cutaway and transparent 3D information on physical objects. However, users may only view the internal information with accurate perspective from the position of the projector. To enable users to view internal information from arbitrary positions and view angles, we have to dynamically generate perspective corrected images of viewport for the projector. We implement the solution by integrating the projective texture technique to conventional projection mapping system.

First, the system renders a viewport image from the virtual camera of user’s head (Figure 6-15). Second, the rendered image is projected back to the 3D virtual model as its surface textures (Figure 6-16). Third, the system renders a viewport image from the virtual camera of projector (Figure 6-17). Lastly, the projector projects the viewport image of the virtual projector on the physical model (Figure 6-18).
Figure 6-14: The virtual head renders a viewport image
Figure 6-16: The rendered viewport is projected back to the digital model as its surface textures.

Figure 6-16: The virtual camera renders a viewport image.
Figure 6-17: The rendered image is projected back to the physical model
Chapter 7

Applications

The following two applications demonstrate the potential of visually transparent and cutaway tangibles. The Cube application allows users to use their bare hands to define section-cut planes and direct touch the physical model to change the transparency. The Building application provides users a cutaway tool and a light source to inspect internal spatial relationship and lighting conditions.

7.1 Cube

Free Manipulation

When inspecting physical models, direct manipulation accompanied by users’ head movements is the most intuitive way to select the desired view. Users could rotate and relocate the cube with their hands (Figure 7-1).

Figure 7-1: Free manipulation
**Touch to Change Transparency**

In addition to cutting the outer shape to see inside one, users may simply touch on the cube to change the transparency directly. The force a user applies on the physical cube would map to its transparency degree of digital model (Figure 7-2).

![Figure 7-2: Changing the transparency](image)

**Section Cut by Hand**

We hide a small red cube inside a big outer white cube. The system enables users to use their hands in a handsaw shape by placing them on the touch sensor pad to define the position and orientation of the section cut plane (Figure 7-3).
To show the potential ability of internal inspection, we implement a structural simulation using a finite element method to merge with the physical cube. By direct touching the cube, users deform the virtual simulation (Figure 7-4).

Figure 7-4: Structural simulation
Touch to Inspect Internal Force

We also implement the force distribution application to allow users to see how forces propagate inside the cube. Again, by direct touch, the actual pressure applied on the cube could be sensed and triggers the simulation (Figure 7-5).

![Internal force propagation](image)

Figure 7-5: Internal force propagation

7.2 Buildings

Spatial Arrangement Review

We design an architecture site containing two buildings. These two buildings have irregular outer shapes. The inside arrangements containing tunnels, basements, floors and atrium spaces are also complicated. For people without an architecture background, it is not easy to review it by 2D drawing and 3D CAD systems. With our system providing tangible section-cut tools, users can remove the outer bounding shell easily to inspect the internal arrangements (Figure 7-6, 7-7).
Figure 7-6: Buildings with 3D surface texture

Figure 7-7: Use section cut to inspect internal spatial arrangement
Lighting Quality Inspection

Users could further use the tangible light source to specify the position of the sun in the space. The tangible light source position would activate the simulation to cast shadow or light up the internal space. Users could eventually dynamically inspect the lighting quality of the interior (Figure 7-8).

Figure 7-8: Use tangible light tool to review the internal natural light quality
Chapter 8

Preliminary Usage Observations

To collect suggestions for future development and improvement, we demonstrated this system in the 2014 Spring Member’s Week of MIT Media Lab. More than 50 users experienced the system. We collected their opinions and listed significant pros and cons.

8.1 Pros

Free Head Navigation

Moving the body and head to view the physical model with 3D digital information freely was recognized as a natural way to navigate our system. No more mouse and keyboard events are needed to prevent mental conversion generating cognitive load.

Easy Manipulation

In addition to moving the head to navigate, a user manipulates the physical model to inspect information. With the current setting, the physical model affords X-Y movement and rotation, which enables users to view information on five sides of a cube. The bottom side should stay on the pressure sensor pad and could not be seen.

Intuitive Specification

Using a tangible section-cut tool to specify a section-cut plane was also recognized as an intuitive interaction of the system. Users with design background felt that it is much better than current CAD functions requiring tedious steps to achieve the similar aims. Touching to change the transparency also got positive feedbacks. The mapping between pressure and transparency was simple enough.

Internal Surprise
Users are familiar with projecting information on physical objects. However, when the system showed the internal information, most of the users were surprised. They were even more surprised with the function of moving their heads to view internal information from different angles.

8.2 Cons

Single User

The current system can only generate and project perspective corrected image for one user. It means the system cannot afford multi-user collaboration, which is one of the most popular advantages of TUI. However, this is the limitation of our implementation not the technology. By using a high frequency projector accompanying with multiple shutter glasses, this system could achieve multiuser scenario [4].

Limited View Area

The current system uses only one camera to track AR marker on a user’s head. This setting limits a user’s head movement within the visible area of the camera. It also adopts only one projector to project information. This setting only covers the surfaces of physical models that face the projector. It might random cast shadows according to the shape of the physical models. By incorporating multiple cameras and projectors, the system could enlarge the navigation area.

Constrained On-plane Object Movement

The system uses the pressure sensor pad to track the positions of physical models. This setting limits users to manipulate physical models on the 2D surface. Lifting up the physical models to viewing in the mid-air is not supported. Replacing the pressure sensor pad with depth cameras for tracking could enable mid-air manipulation.

Single Transparent Layer

The system enables users to specify the transparency of the outer shell by touch. When the digital information has more than two layers, the inner object could not be seen.
**Plane Cutaway**

In the current system, we implement plane cutaway to remove the unwanted part of the models. However, in some of the cutaway drawings, components are selectively removed to form a random cutaway shape. Some computer graphic researches have also developed algorithms to smartly remove the blocked components [25].

**Latency**

When users changed their viewing position and angle, or when they moved the physical models, the projected digital information has a bit lately which creates unnatural scene motion and degrade the perceptual experiences.
Chapter 9

Conclusion and Future Work

9.1 Conclusion

We developed a visually transparent and cutaway TUI system for intuitively inspecting internal information. We focus on the seamless integration of physical and digital representations by combining perspective corrected and projection mapping techniques. Adopting projection-mapping technique to attach internal 3D digital information on physical objects has not been done by previous TUI researches.

After preliminary study inviting approximately 50 users to experience our system, we showed that this system not only enables users to intuitively navigate and inspect the 3D internal digital information merged with its physical bounding shell model but also showed the potential of visually transparent and cutaway techniques. There are also many insufficiencies to address, but most of them may be solved by technical improvements, such as adding more cameras and projectors to enlarge the active area, using depth camera to track physical model movement in the mid-air, developing more intuitive interactions for layered transparency, and enabling free-form cutaway shapes.

9.2 Future Study

Our system is not designed as an independent system but a system that could be further integrated with other existing TUI systems. It can help address the current insufficiency of being unable to view internal information and simulation. Modularizing our system to make it easily integrated with existing systems is going to have to be our next task. Conducting systematical user tests to study how visually transparent and cutaway tangibles could help the inspection of internal 3D digital information is also the next step.
Bibliography


