Sketching in 3D

Towards a fluid space for mind and body

by

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SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ARCHITECTURE STUDIES

AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2013

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ABSTRACT

This thesis explores a new type of computer-aided sketching tool for 3-dimensional designs. Sketching, as a process, has been used as an effective way to explore and develop ideas in the design process. However, when designers deal with volumetric designs in 3-dimensional space, current sketching means, including traditional free-hand sketching and contemporary computer-aided design (CAD) modeling have limitations such as dimensional inconsistency, and non-intuitive interactions. By observing the roles of sketching in the design process and reviewing the history of design tools, this thesis investigates and proposes new digital methods of 3-dimensional sketching that take advantage of motion detecting and computer-vision technology that is widely available today. In this thesis, two prototype tools were developed and compared. The first prototype uses a motion detecting sensor, projection screen, and gesture tracking software. The movement of the user's hands becomes the intuitive interface to shape 3-dimensional objects in the virtual space. The second prototype, developed in collaboration with Nagakura, uses a hand-held tablet computer with marker-based augmented reality technique. The hand-held device displays the virtual object from desired angles and works as a virtual tool like a chisel, plane, drill, and glue gun to shape virtual objects in 3-dimensional space. Testing these two prototypes for use, and comparing the resulting objects and user responses revealed the strengths and weaknesses of these different 3-dimensional sketching environments. The proposed systems provide a possible foundation for novel computer-aided sketching application that takes advantages of both the physical and virtual worlds.

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Acknowledgment

First of all, I would like to thank my thesis advisor, Professor Takehiko Nagakura, for all of your support and inspirations. Without your help, this thesis would not have been possible.

I would like to thanks to George Stiny for joining my committee as a reader and giving me wonderful insights into design and computation.

Thank you Terry Knight and Larry Sass. Your advice and comments have always encouraged me.

I would also like to thank all of our colleagues in the Design and Computation Group. You guys are always my best inspirations and motivations.

Thank you to Yoonseok. You have taken care of my days. I could not have endured all those days without your emotional support.

And last but not least, I love you my grandmom. I know you are always with me, by my side.

Table of Contents

1. Introduction

This thesis explores new computer-aided sketching systems that facilitate design explorations of 3-dimensional ideas. The term 'sketch' can be used in many ways depending on the focus of interest. A sketch as a noun, is often used to mean the visual product of a design exploration such as a traditional free-hand drawing on paper. Whereas the term sketch has a focus on physicality, this thesis focuses on the process of 'sketching.' In this thesis, sketching is defined as a behavioral and cognitive process where designers explore, develop, and externalize ideas with visuospatial elements.

Many researchers have argued that sketching plays an important role in the creative design process; creative design involves exploring diverse design options and solutions, and the sketching process supports this exploration by allowing designers to interpret and reinterpret their designs in unexpected ways with its unstructured, ambiguous nature.

According to Goel's (1995) identification, two types of reasoning transformation occur in the sketching process, the lateral transformation and the vertical transformation. In the lateral transformation, designers shift to slightly different ideas from the original idea, rather than to a more detailed version of the same idea. In contrast, vertical transformation occurs when designers move from one idea to a more detailed version of the same idea. Goel believes that the ambiguous nature of the free-hand sketch facilitates the lateral transformation and prevents early fixations.

The initial motivation of this thesis arose from the question, Do current sketching means adequately support such creative design explorations for 3-dimensional design ideas?

The history of design tools reveals that not only designer's needs but also socioeconomic changes have affected the development of design tools. In ancient times, the needs of systematizing, documenting, and representing design ideas motivated the development of design tools. Thus, design tools, such as documentation materials, drawing instruments, and visual representation methodologies, were devised. Since the Industrial Revolution, socioeconomic changes have prioritized industrial qualities such as productivity, reproduction, and standardization. Consequently, design tools have been developed in a way that primarily supplements limited accuracy and productivity of human hands. In addition, design tools have been devised to provide ubiquitous environments to overcome time and space restraints. Meanwhile, less effort has been given to develop creativity support tools.

In similar fashion, the recent development of computer-aided design (CAD) tools has made it possible for designers to attain pinpoint precision and high productivity. This ability also implies that, regarding sketching, vertical transformation has been greatly aided by those improvements that CAD tools provide. However, it seems that very few tools have been developed to facilitate lateral transformation where the exploratory nature of design is emphasized. Moreover, when designers deal with 3-dimensional ideas, current sketching means, including traditional free-hand sketching and contemporary CAD modeling, have limitations such as a dimensional inconsistency, non-intuitive interactions, and insufficient support for design ambiguity.

Based on these understandings and observations of sketching, I argue that current sketching means do not sufficiently support a design exploration of 3-dimensional ideas, and great potential exists to develop intuitive sketching systems that can support such an exploration.

Within this context, I propose two sketching systems to explore 3-dimensional ideas. Si3D-Hands, the first version of 3-dimensional sketching systems, which uses human hands as the main input interface and provides a 3-dimensional sketching environment that does not require any prosthetic equipment. From the self-trials using Si3D-Hands, several positive aspects as well as deficiencies were observed. Based on these findings, a second version of 3-dimensional sketching systems, Si3D-Mobile, was developed to explore alternative ways to supplement the issues found in Si3D-Hands and to compare the two systems. Instead of using bare hands, Si3D-Mobile uses a hand-held mobile device as an input method, which allows flexible navigation in the sketching environment and precise detection of the input device.

From the development of the two systems and user-trials, the strengths and weaknesses of the 3-dimensional sketching systems proposed in this thesis were identified. Intuitive interface and interactions and non-hierarchical geometric representations of the proposed sketching systems supported effortless and impulsive sketching operations. In contrast, difficulties in perceiving spatial depth from a 2-dimensional screen and unstable gesture tracking had to be improved. In addition, user-trials also provide meaningful insights into how people would approach sketching design ideas with the two sketching systems.

Because this thesis does not account for every aspect of the computer-aided sketching process, the validity of the 3-dimensional sketching systems proposed is not fully confirmed at this point. However, findings from and evaluation of the development and trials of this thesis contribute to envisaging a new computer-aided sketching system by providing viable proof of rich and creativity-centered design interactions.

1.1 Chapter summary

In this chapter, I provide a general overview of this thesis. The second chapter describes the theoretical background of the thesis. The first section of this chapter illustrates the role of sketching in the design process. The second section briefly reviews the history of design tools and its relationship to the sketching practice. The final section introduces related works that categorize their approaches in the frame of integrating a sketching interface into CAD systems.

In the third chapter, I introduce the first version of the 3-dimensional sketching systems, Si3D-Hands. The sections in this chapter contain detailed discussions of the hardware devices and techniques used in the development of Si3D-

Hands, as well as technological constraints faced during the development of this system. Self-trials and findings are also discussed in the final section.

In the fourth chapter, Si3D-Mobile, the second version of spatial sketching systems, is introduced. This chapter focuses on explaining the motivations for the second version and the different techniques used in Si3D-Mobile. The final section of this chapter illustrates different user experiences observed during self-trials.

User-trials, performed with Si3D-Hands and Si3D-Mobile, are described in the fifth chapter. This chapter also presents the design outputs and feedback received from participants.

The sixth chapter presents the analysis of this thesis project. The sketching systems developed in this thesis are evaluated and limitations are discussed. In the final chapter, I conclude the thesis by summarizing contributions and proposing open questions and directions for future development.

2. Background

This background chapter consists of five sections. The first section elaborates on the role of sketching in the design process. The following section observes the history of design tools and its relationship to the design practice and sketching. The third section proposes the criteria for a new 3-dimensional sketching system, which guides the development process of this thesis. The fourth section discusses related work that focuses on integrating sketching into computer-aided design tools. The approach taken in this thesis toward integrating sketching and computer-aided design (CAD) tools is also described in the forth section.

2.1 Sketching in the design process

As human beings, we have left our traces using various types of media, such as orally transmitted literatures, written manual scripts, and paintings. Most among all such media, visual representation has been used as an effective way of expressing and communicating ideas due to its spontaneity and expressiveness.

In the design context, as a visual representation, a sketch is very familiar to designers. In academia, many researchers have emphasized that sketches (or drawings) play an important role in the design process. Arnheim (1993: 16) described the role of sketches in the design process as the "primary nucleus". According to Goldschmidt (2006), sketches are “imaginative universals” that facilitate creativity. She also insists that sketching is the most effective medium for creating mental models of tangible objects. Other researchers such as Masaki Suwa and Barbara Tversky (1997), and Vinod Goel (1992) have conducted analytical and empirical studies in order to articulate how designers draw sketches and what they obtain from sketches.

The term 'sketch' can be used in many ways depending on the focus of interest. We may use 'sketch', as a noun, to mean the visual product of an exploration, such as a traditional free-hand drawing on paper. As a visual medium, a sketch is an externalization of ideas, which serves to record transient, ephemeral ideas and concepts. Tversky states that "Although written language plays the same role, sketches have the advantage of conveying visuospatial ideas directly, using elements and spatial relations on paper to convey elements and spatial relations in the world". Even when expressing abstract ideas, the visuospatial quality of sketches makes it easier to grasp and fully comprehend them (Tversky 2002). Sketches are also means of communication. By making physical representations of ideas, designers share and exchange them with others. The *prescriptive sketch* and the *talking sketch,* identified by Ferguson(1992) illustrate typical cases where sketches are used as means of communication in design practice. According to his classification, the prescriptive sketch is made by a designer to communicate with a draftsman to make a finished drawing, and the talking sketch is produced in order to clarify complex and confusing parts of a drawing.

While the term 'sketch' put its focus on physicality, this thesis focuses on the process of 'sketching'. In this thesis, 'sketching' is defined as a behavioral and cognitive process where designers iteratively explore, develop and externalize ideas with visuospatial elements. Thus, sketching may include a variety of developmental design processes, such as traditional free-hand sketching, creating clay prototypes and modeling with 3D CAD tools.

Goel (1995) identified two types of reasoning transformation occurring between the successive sketching processes: the lateral transformation and the vertical transformation. In the lateral transformation, a designer examines various design solutions moving from one idea to a slightly different ideas, rather than develops a more detailed version of the same idea. In contrast, the vertical transformation occurs when a designer develops one idea into a more detailed version of the same idea. Figure 1-1 illustrates these two different transformations.

In the context of lateral transformation, sketching contributes to creative design that involves exploration and development of design alternatives (Cross 1997). In

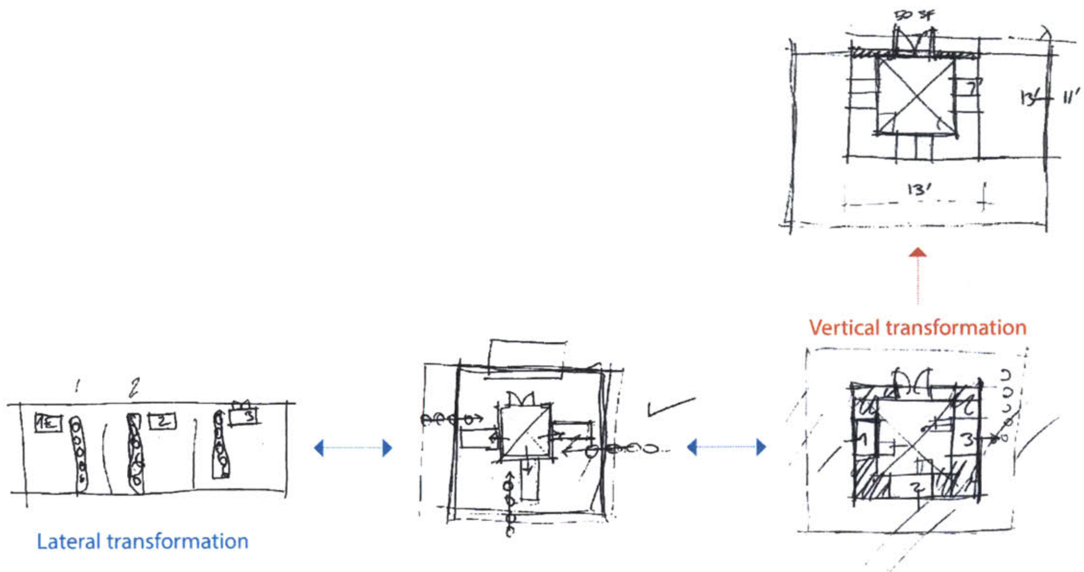


Figure 1-4: Reasoning transformations in the sketch process: lateral transformations and vertical transformations.
(Source: Goel, 1995)

the sketching process, designers constantly leave marks of thoughts, look at them, and potentially discover new possibilities, having a reflective conversation with design materials (Schön 1992). Since the flexible structure of sketching supports multiple interpretations and reinterpretations through continuous reflection, designers can quickly visualize their ideas without much effort (Schön 1983). Goel (1995) also states that since freehand sketches in the early design process are 'dense' and 'ambiguous', they work well for exploring different design ideas.

The initial motivation of this thesis arose from the question: do current sketching methodologies adequately support creative design explorations for 3-dimensional design ideas? Thus, in proposing a new 3-dimensional sketching system, this thesis gives major attention to the role of the sketching process in the frame of the lateral transformation In addition, this thesis distinguishes sketches from diagrams, which have primitive elements and schematic structure, although they may be combined in practice. This thesis mainly focuses on proposing a sketching system for non-diagrammatic sketches, since the hosting systems for those two may require different characteristics.

2.2 The History of Design Tools

This section briefly reviews the history of design tools and examines these tools in terms of the sketching process.

Design tools are the physical means by which we realize our conceptual design ideas. Since the beginning of civilization, there have been ceaseless endeavors to formulate one's design system and record one's design traces. However, in ancient times, designers (or artisans) could hardly systematize their design conventions and knowledge because of the lack of design tools. This deficiency of tools also made it difficult to document and transmit their design legacies by any means other than the materialized designs of their time. Thus, they had no choice but to leave schematized design representations on clay tablets, parchments, and walls (Figure 1-2).

Figure 1-2: Architect's drawing of the ground plan of the palace of Nur Adad in Larsa. 1865-1850BC. (Source: http://architecturedcblog.com)

As paper and xylography became common in the 15th century, designers actively started to produce detailed visual representations of their designs (Figure 1-3). However, because the design tools and manufacturing systems for documentation and reproduction were still very limited, design products were still custom-made objects, and designers did not often produce accurate drawings with sophisticated tools. This limitation led designers to rely on alternative ways of formulating their design systems and strategies, such as canons of proportion, systems of order, and stylish ornaments that could be written or orally passed between generations (Decker 2007).

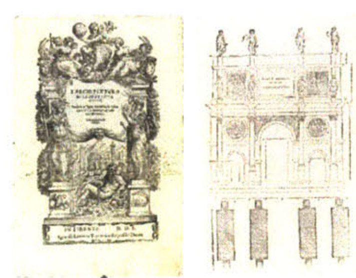


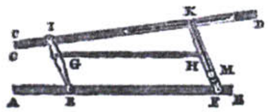
Figure 1-3: A drawing of Leon Battista Alberti in L'Architettura. Image (Source: http://www.christies.com)

As the Industrial Revolution made possible the mass-production of commercial goods and industrial parts, designers and draftsmen were requested to produce elaborated drawings to reproduce standardized design products. A pencil and tracing paper allowed designers to reproduce and propagate their designs more widely. Moreover, as the separation between different design players (e.g., designer, engineer, and manufacturer) became greater, the necessity of standardized means of drawing shapes and forms increased. Thus, other drafting instruments aimed at drawing certain type of lines or curves, such as Set squares and French curves, were actively invented during this period.

Figure 1-4: The history of design tools. The diagram was produced based on the information in "Tools of the imagination"

All images taken from Wikipedia except volute compass from http://diomedia.asia , Ellipsograph from http://www.sciencemuseum.org.uk, Helicograph from http://507movements.com, technicap pen from http://www.flickr.com/photos/patlejch/3315277805, AutoCAD 80 from http://www.fourmilab.ch, AutoCAD10 from http://www.jrrio.com.br and 3D printing of 3D System from http://www.3ders.org.

1800 **1900** **2000**



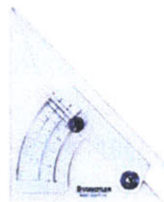
1814
Centrolinead

1840
Tracing paper becomes common

1853
Set squares (Triangles)

1860
French curve

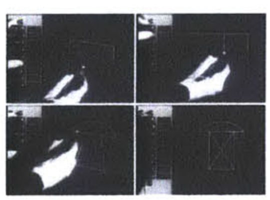
1880
Blueprinting becomes available



1920
Adjustable triangle

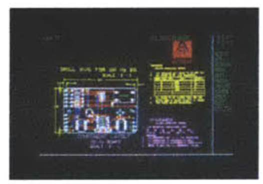
1932
Technical pen

1960
Quick-set compass with wing arc or horizontal screw



1963
Ivan Sutherland develops Sketchpad.

1980s
Pen plotter

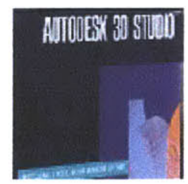


1982
The first release of Auto-CAD 80

1984
The first release of MicroStation by Bentley Systems

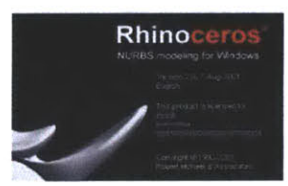
1987
The first release of AutoCAD10 with 3D capability

1988
3D Systems introduces 3D printing



1990
The first release of 3D studio of Autodesk

1997
Irwin Jungreis and Leonid Raiz develop Revit



1998
The first release of Rhino V1

2000
The first release of SketchUP

Since Ivan Sutherland showed the potential of CAD tools with a graphical user interface, CAD systems have radically evolved over the past a few decades. The development of digital technologies and CAD tools drastically changed how designers created, visualized, and communicated their designs. Having passed the time where designers produced designs by making drawings with a pen and paper in physical space, they now are creating designs in 3-dimensional virtual spaces with a mouse and keyboard. Analogue strokes on paper are also replaced by computational geometries that are mathematically represented inside the computer with extremely high precision, which allows designers to manage complex forms. These changes facilitate the exchange of design information between different design players and assist design schemas with pinpoint accuracy.

In sum, in ancient times, the needs of systematizing, documenting, and representing design ideas motivated the development of drawing materials and instruments, as well as the creation of visual representation methodologies. Since the Industrial Revolution, socioeconomic changes prioritized qualities such as productivity, reproduction, and standardization; therefore, design tools in modern times, including CAD systems, were been developed to supplement the limited accuracy of human hands and to provide ubiquitous environments to overcome time and space restraints.

From the standpoint of sketching, the vertical transformation in the sketching process has been greatly empowered by many design tools that offer designers precision and productivity. However, it seems that very few tools have been developed to facilitate lateral transformation where the exploratory nature of design is emphasized. Perhaps it could be said that contemporary computer-aided design tools, such as 3D modeling and simulation tools, have greatly improved the sketching process by supporting designers to develop prescribed design ideas more precisely and efficiently. However, the question still remains, Do we have corresponding computer-aided design tools that assist designers' ill-structured, open-ended design explorations in the sketching process?

2.3 Sketching 3-dimensional designs

Designers have a variety of options in selecting a sketching medium, and each medium has its own merits and demerits. This section reviews two representative sketching media that designers utilize for sketching 3-dimensional ideas: free-hand sketching and computer-aided modeling. Based on this analysis, criteria for a new 3-dimensional sketching system are introduced.

- **Free-hand sketching**

  In general, traditional free-hand sketching has several strengths that facilitate design explorations. When performing free-hand sketching, designers usually do not need special equipment or environments. A pen and paper have been best mates of sketchers for a long time, and they require little prior knowledge to be operated. Good affordance and intuitiveness of the traditional free-hand sketching environment are great advantages, which allow designers to quickly express ideas.

  Moreover, by giving multi-feedback, Free-hand sketching allows designers to better understand and represent their ideas. When designers perform free-hand sketching with two-dimensional design ideas on paper, they see how their designs are visually represented on the surface, and feel how their designs are shaped in the space through the continuous movements of hands. In addition, the tactile feedback from the physical sketching materials, such as friction, has a variable quality, which can effectively guide or constrain sketching operations. In the free-hand sketching process, designers simultaneously incorporate feedback from these multi-sensory modalities.

  In addition, ambiguous representation of free-hand sketches facilitates creative designs, where exploration and development of possible design alternatives is highly emphasized (Cross 1997). Stiny (2008) explains how designers use the visuospatial ambiguity to extract embedded shapes from what we already draw using shape grammar. He states that, by performing visuospatial calculations with those extracted shape elements, designers explore diverse design options. Free-hand sketching also supports a similar cognitive process for creative design reasoning. The ambiguous nature of the freehand sketching facilitates lateral transformations by "preventing early fixation or crystallization of the design" (Goel 1995). Suwa and Tversky (1997) also indicate that unexpected design ideas are often obtained by reinterpreting visual parts or elements during the sketching process.

However, when it comes to 3-dimensional design ideas, traditional free-hand sketching has several limitations caused by different dimensionality. Firstly, designers need to have a good amount of drawing skills in order to properly represent their 3-dimensional ideas onto two-dimensional space. Since designers are constantly required to convert their designs between two different dimensionality, a lack of proper drawing skills often interrupts quick and smooth sketching processes.

Secondly, since 3-dimensional shapes and properties should be schematized and projected onto a two-dimensional space, a designer cannot have holistic shape-based object construction and recognition; when a designer draws 3-dimensional shapes on paper, he only obtains two-dimensional physical experiences when he draws and sees his designs, which do not coincide with the actual form of his designs.

Lastly, two-dimensional sketches can represent design objects from only one angle at a time. Repetitively drawing the same objects from different angles is sometimes laborious, and poorly drawn successive sketches can cause perceptual inconsistency.

- **Sketching with CAD tools**

Even as recently as a few decades ago, free-hand sketching was indispensable to designers, especially during the conceptual design phase. However, it is now observable that designers sometimes start directly with CAD tools without drawing a line on paper because CAD tools provide several advantages over free-hand sketching when dealing with 3-dimensional ideas.

CAD systems provide a 3-dimensional virtual space where designers can build their design with 3-dimensional perception. In this virtual space, designers can see the design objects from multiple angles by navigating the virtual modeling space. Moreover, CAD systems considerably help designers develop more detailed designs by allowing them to control their designs precisely with discrete controls. In addition, CAD systems provide quantitative methods to evaluate prepared designs, such as a digital simulation and optimization.

Despite the advantages discussed above, CAD systems possess shortcomings that impede creative design explorations. First, conventional CAD tools require users to have a good amount of knowledge in their operation. Moreover, although sophisticated commands and highly precise dimensioning systems are advantageous, designers often find them burdensome when they want to examine design possibilities quickly. Paynter, Shillito, Wall, and Wright (2002) contend that CAD software does not provide appropriate support in the "germinal phase" of the design process where designers rapidly externalize different design options and concepts. They believe that characteristics of contemporary CAD software, such as the complex interface, demand for high precision, and complex coordinate systems, distract designers from the creative design process. In contrast, they argue that physical model-making and freehand drawing (e.g., sketching tools) allows designers to explore multiple ideas rapidly and expressively.

Second, conventional CAD tools do not adequately support flexible interpretation and reinterpretation of visuospatial design elements. In CAD systems, the data structures of geometries are highly structured and hierarchical. Moreover, their representations are very deterministic in that there is no room for designers to discover unexpected possibilities. Even though this property of CAD systems is very powerful when designers develop and standardize their designs in detail, it often impedes designers' imaginative explorations.

In addition, sketching processes using CAD tools also lack the shape-based object recognition described earlier. In detail, geometry using most CAD tools is controlled by sub elements. For instance, 3-dimensional mesh structures are discretely controlled by vertices and edges that belong to its sub dimensions. Thus, designers do not have continuous and body-inclusive sensations of the shape of their designs while creating them.

Based on the historical review in the previous section and the observations on the current means of scketching 3-dimensional ideas, I argue that current sketching means do not sufficiently support a creative design exploration of 3-dimensional ideas, and great potential exists to develop intuitive sketching systems that can support such an exploration. In addition, from the obervation above, the criteria for the development of a new 3-dimensional computer-aided sketching system are established as below.

- **Readiness**

  Good readiness and affordance of sketching systems allow users to easily perform sketching without unnecessary distractions. The criterion 'readiness' includes an intuitive interface and interaction mechanism that can accommodate impulsive and imprecise sketching operations of users, not demanding extensive prior knowledge.

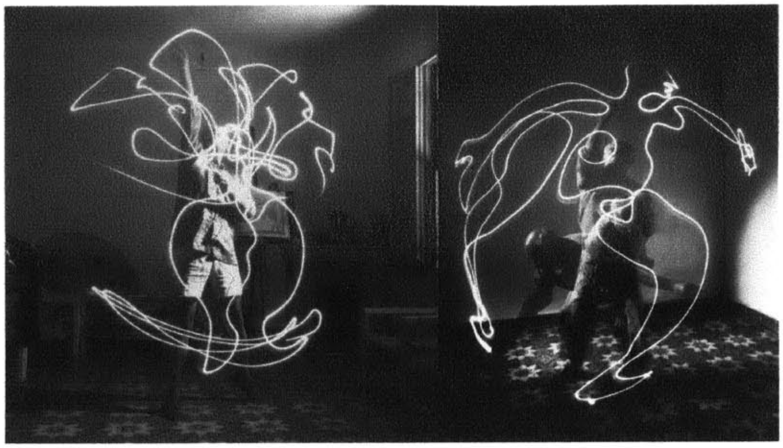


Figure 1-5: Light Painting Photography. Pablo Picasso and Gjon Mili 1949.
(Source: http://lightpaintingphotography.com)

- **Multi-Feedback system**

  During the sketching process, designers receive various stimuli that help them perceive and understand their designs. In a 3-dimensional sketching system, a user should be able to obtain sufficient feedback while he interacts with his designs in 3-dimensional space.

- **Support for perceptual ambiguity**

  Visual ambiguity plays an important role in the early phase of design, by allowing designers to discover unexpected possibilities. A sketching system that facilitates creative design explorations should be able to accommodate designer's flexible interpretation and reinterpretation of design externalizations.

2.4 Related Work

In this section, a survey of sketch systems that explore 3-dimensional sketching is presented. A series of impressive artworks, which were produced by Pablo Picasso and Gjon Mili in 1949, could be considered as one of the earliest explorations into the spatiality of the sketching process. By capturing the physicality of Picasso's sketching process with long-exposure photographs, this series of visual artworks reveals interesting 3-dimensional spatiality pro-

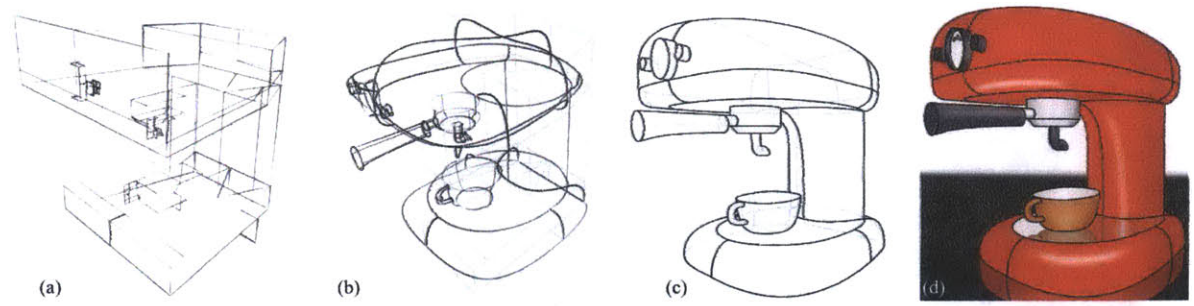


Figure 1-6: Analytic Drawing of 3D Scaffolds
(Source: Schmidt et al. 2009)

nounced by continuous human gestures.

With the development of digital technology, there has been a significant number of studies on integration of sketching interface and computer-aided design systems. These studies can be categorized into two: implementing the two-dimensional sketching interface, and enabling 3-dimensional gesture-based interactions within CAD systems.

The first group mainly focuses on inferring 3-dimensional shape from 2D drawing. Schmidt et al. (2009) proposed an analytic drawing interface which supports both single- and multi-view incremental construction of complex scaffolds and curve networks. In their system, two-dimensional curves are evaluated based on the 3D scaffolds as they are drawn on the screen, and appropriate 3D shapes are inferred in real time. They argue that since two-dimensional drawing is more intuitive than traditional 3D modeling systems, they could benefit from introducing sketch interpretation, making a 3D CAD system more efficient and expressive.

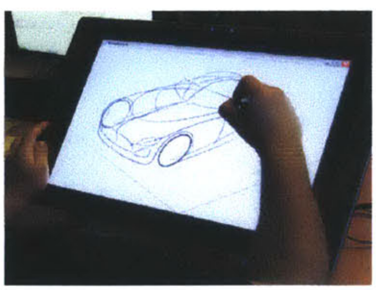


Figure 1-7: ILoveSketch
(Source: Bae et al. 2008)

ILoveSketch (Bae et al. 2008) provides a similar interactive approach that interprets sketch strokes as they are drawn. In the ILoveSketch system, instead of creating 3D scaffolds, users are required to specify drawing mode or manipulate the camera for the interpretation of each curve. In the commercial market, *CATIA V6* developed by Dassault Systems adopted a similar pen-based 2D sketching interface named *Natural Sketch* (2011). By integrating a 2D sketching interface into their widely-used CAD software, they aimed to provide designers with a seamless work-flow from ideation to refinement.

The 3-Draw system pioneered another stream, which strives to incorporate 3-dimensional sketching input into virtual CAD systems (Sachs et al. 1991). In 3-Draw, a user is provided with pen and palette input devices, where six-degree-of-freedom sensors are embedded on each prop. By utilizing these input devices, a user can create curves directly in 3-dimensional space, and adjust the orientation of their drawings. *CavePainting* (Keefe et al. 2001) also explored a direct sketch system based on 3D input interface in the field of art. Using specially designed drawing props with embedded trackers, a user draws a flattened thin stroke or a tube with a circular cross section in the virtual space.

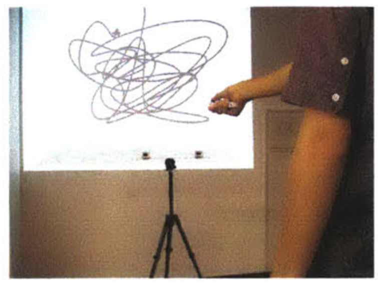


Figure 1-8: Spatial Sketch
(Source: Willis, et al. 2010)

Spatial Sketch aims to produce a physical object based on embodied sketching interaction (Willis et al. 2010). A user is provided with an infrared pen light with a button for toggling on and off. A simple stereo-vision 3D input system consisting of two infrared cameras is positioned in front of the user and tracks the movement of the user. The user's gestures in the space are represented as a continuous curve geometry. Once the sketch has been drawn, the curve is automatically transformed into an appropriate 3-dimensional shape forming a convex hull. This shape is then converted to series of slices for digital fabrication using planar material.

Figure 1-9: Turn
(Source: Cho, et al. 2012)

The *Turn* project demonstrates integration of real-world gestures and a digital modeling system, using a tangible interface and real-world metaphor (Cho et al. 2012). In this system, a user can perform a sculpting operation in the 3D virtual space projected on a 2D screen by physically rotating a wooden wheel with one hand and moving the other one over the wheel. This research shows a very similar approach with the first prototype developed in this thesis, in that it adopts volumetric manipulation of a virtual object and utilizes body gestures without additional equipment.

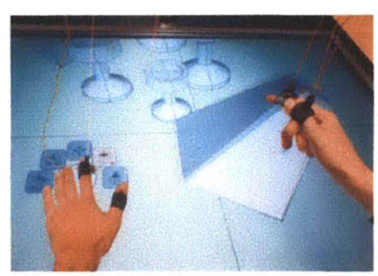


Figure 1-10: Mockup Builder
(Source: Araujo, Casiez, and Jorge 2012)

The *Mockup Builder* project uses both 3-dimensional gestures and a conventional graphical user interface for a spatial modeling process (Araujo, Casiez, and Jorge 2012). This system utilizes a stereoscopic multi-touch display, 3-dimensional position tracker, and depth camera in order to visualize a sketching scene, implement graphical user interface (GUI), and track human gestures. Sketch recognition and beautification are used to recognize and adjust the shapes drawn by a user. Using 3-dimensional gestures and a GUI interface on the screen, users can manipulate design elements with modeling commands, which are similar to those of conventional CAD systems, such as split and extrude. Mockup Builder seems to have positioned itself in the middle between a 3-dimensional sketching tool and modeling tool, in that it utilizes an intuitive gestural interface, but employs hierarchical system for geometric representation and manipulation.

While these works clearly provide the potential to integrate a sketching interface into computer-aided design systems in various ways, many require a good amount of operating skills, time to learn how they work, and sometimes demand specially designed instruments. In addition, apart from their high level of technological achievement, some systems do not pay attention to the design process that is affected by their systems because their main interests are not in design explorations, rather in human-computer interactions.

In choosing the approach of integrating sketching with a CAD system, the first approach, to implement the 2-dimensional sketching interface into the CAD system, did not satisfy the second criterion described in the previous section, lacking support for empirical shape-based object recognition.

The sketching systems proposed in this thesis aimed to integrating 3-dimensional sketching interactions into CAD systems, and thus, to exploit the advantages of both the physical and virtual worlds. At the same time, it was intended to make these computer-aided sketching systems as accessible as possible by designing an intuitive interface without heavy technical requirements. The criteria set in the previous section for the new sketching systems also served as the basis of the development of this thesis project.

3. The First Experiment: Sketching in 3D with Hands (Si3D-Hands)

In the previous chapters, I illustrated the background of this thesis with a general overview of sketching activities in the design process, historical observations in the development of design tools, and related work.

In this section, I introduce Sketching in 3D with Hands (Si3D-Hands), the first software prototype developed to explore a gesture-based sketching system for 3-dimensional design ideas. The basic concept of Si3D-Hands is to use the human body as a computational interface and enable computer-aided sketching activities in physical space with virtual material. While many related works focus on integrating traditional 2-dimensional sketching environments into 3-dimensional CAD modeling systems using specially designed input devices, such as an infrared pen light, Si3D-Hands aims to establish a 3-dimensional sketching environment where a user can draw, sculpt, and erase virtual material without prosthetic instruments.

In the sketching system of Si3D-Hands, the user situates an interaction space near his body space where he can perform sketching operations with virtual material. His hands are the main source of the input interface, and hand gestures are tracked by a motion sensor. By moving the hands within the interactive space, the user can add or subtract the virtual material using prepared computational tools. Using Si3D-Hands, the user can perform sketching activities in a few different interaction modes. These modes include emulation of real-world sketching circumstances such as pottery making and computationally augmented environments where the sketching material autonomously morphs or heals itself. As the user sketches, he receives sound and visual feedback of his manipulations. A real-time view of the sketching scene provides visual feedback on the display to help the user navigate his way through the physical space.

Figure 3-1 :The Kinect sensor by Microsoft.
(Source: http://research.microsoft.com)

The hardware and software used for Si3D-Hands and the detailed implementation of Si3D are introduced in this chapter. Additionally, the evaluation of self-trials is described in the final section of this chapter.

3.1 Hardware

A. Motion Detecting Sensor

To capture gestures of users, Si3D-Hands uses the Kinect motion-detecting sensor, which Microsoft originally commercialized for video gaming (Figure 3-X). The Kinect sensor consists of paired CMOS infrared and color cameras, an infrared-structured light projector, and a microphone for voice input. Raw data obtained from the Kinect sensor includes an RGB video stream, depth data of captured scenes, and sound data recorded from embedded microphones. To obtain the depth data of the space, the infrared projector of the Kinect emits a structured light pattern into the space (Figure 3-2). Objects reflect this pattern back into the Kinect, which captures the pattern using the infrared sensor. Because the pattern is distorted when it is reflected, the depth data of the scene can be generated by comparing the difference between the original and captured patterns. The software implementation of the Kinect Software Development Kit (SDK) contains logic to decode depth data and recognize elements that have characteristic human shapes. The Kinect SDK contains a wide range of body shapes; therefore, it can identify and track human figures and gestures from the captured depth data. Figure 3-3 shows the 48 skeleton points on a human body that can be tracked by the Kinect. By concatenating captured skeleton data of each frame, gestures of a human figure can be tracked in real time.

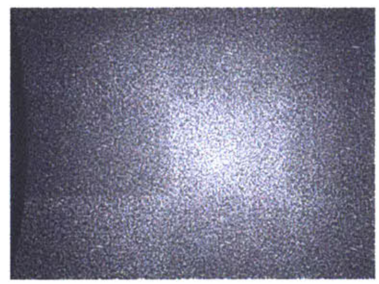


Figure 3-2:The structured pattern emitted by the infrared projector of the Kinect.
(Source: Draelos 2012)

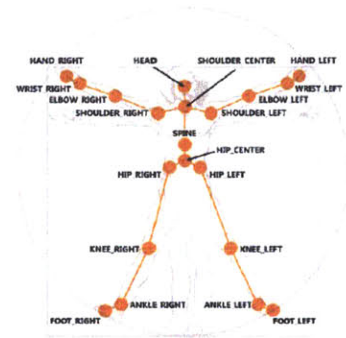


Figure 3-3: Trackable Joint information of the human body using the Kinect
(Source: http://research.microsoft.com)

3.2 Software

A. Development Environment

The first prototype for Si3D-Hands was written using the Processing framework, which is based on the JAVA language and widely used among designers to create interactive applications. However, because the Marching Cube algorithm (used for geometric representation) required significant computing power for real-time calculations in 60 FPS, this first application had severe delays between each frame, and it was hardly possible for users to make real-time interactions. During an examination of this issue, the researcher found that this delay was mainly caused by the time required to access large blocks of memory that contained the Marching Cubes data. Given this experience, successive versions of the applications were written in the C++ programming language using the Cinder framework, which is an open-source C++ library for creative coding. Because the C++ language allows programmers to access memory locations directly by allocating memory pointers, it greatly improved the performance of the application.

3.3 Implementations

A. System Configuration

To capture user gestures, the Kinect sensor is placed in front of a user. A user is situated with virtual material that he can interact with in a 3-dimensional space. During sketching operations, his hands are tracked by the Kinect sensor and their positions in the Kinect's coordination frame are calculated in real time. Figure 3-4 illustrates the schematic configuration of the Si3D-Hands sketching system. Further, a user can assign different virtual tools to his hands and use them simultaneously. The simultaneous use of two hands takes advantage of complicated modeling operations in the physical world, such as excavating and stuffing volumes at the same time with both hands. Because

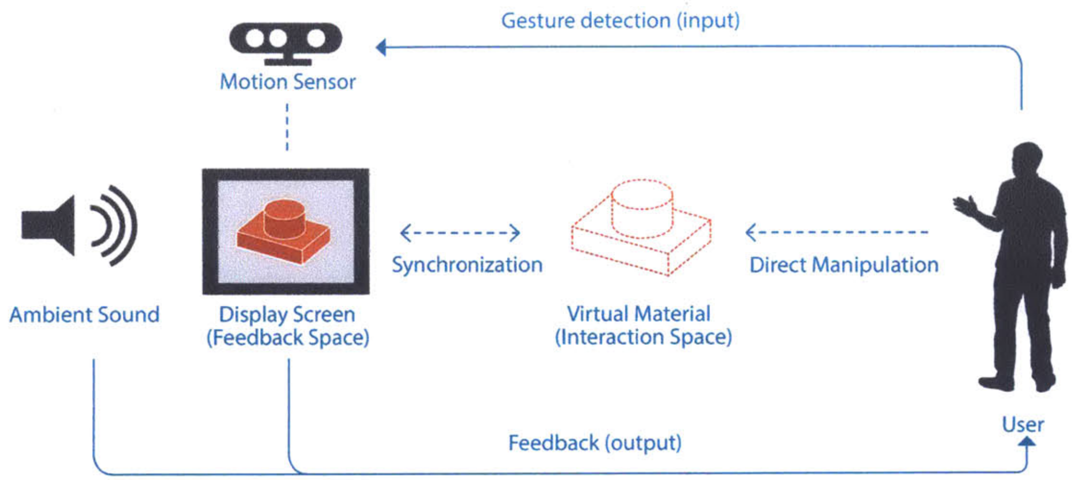


Figure 3-4 : The system configuration of Si3D-Hands

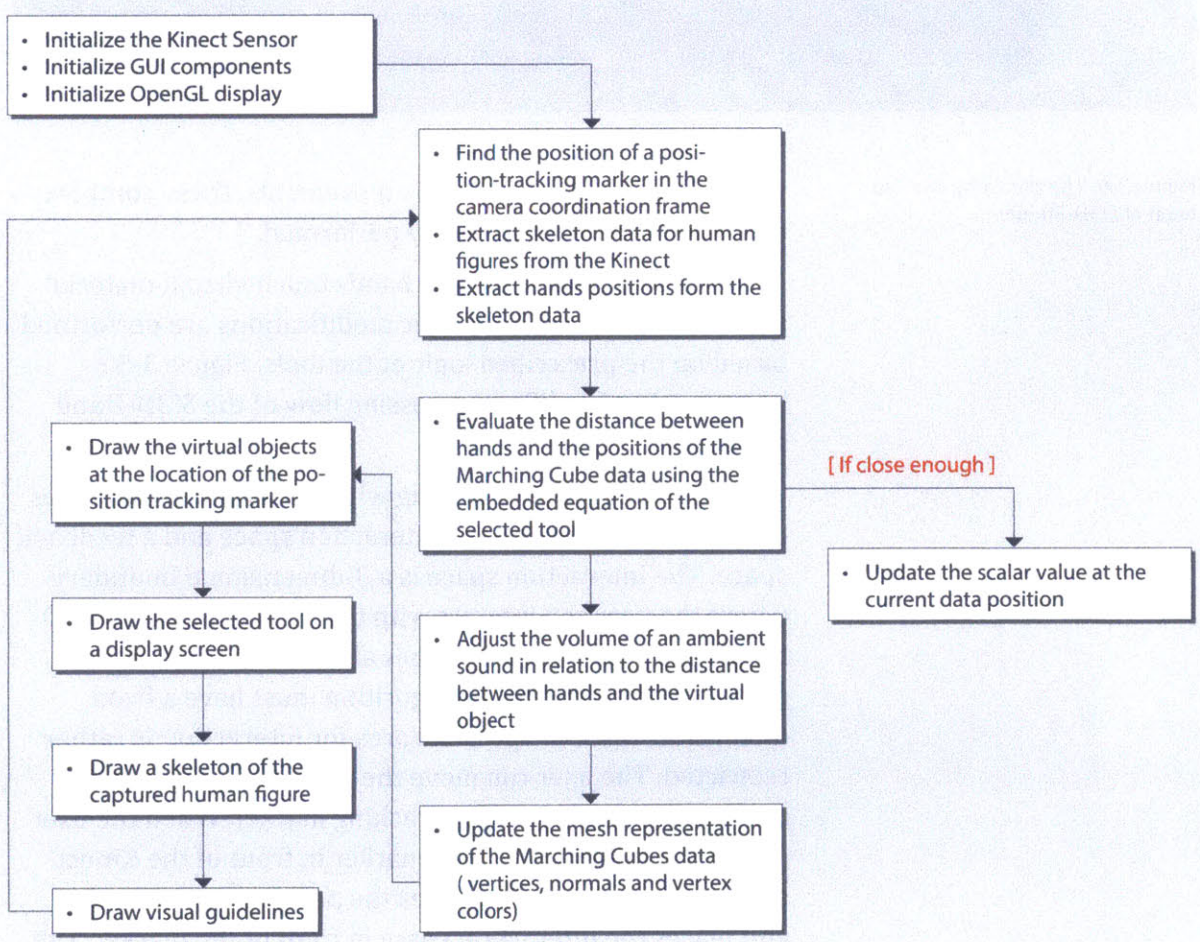


Figure 3-5: The diagram of the core process of the Si3D-hands

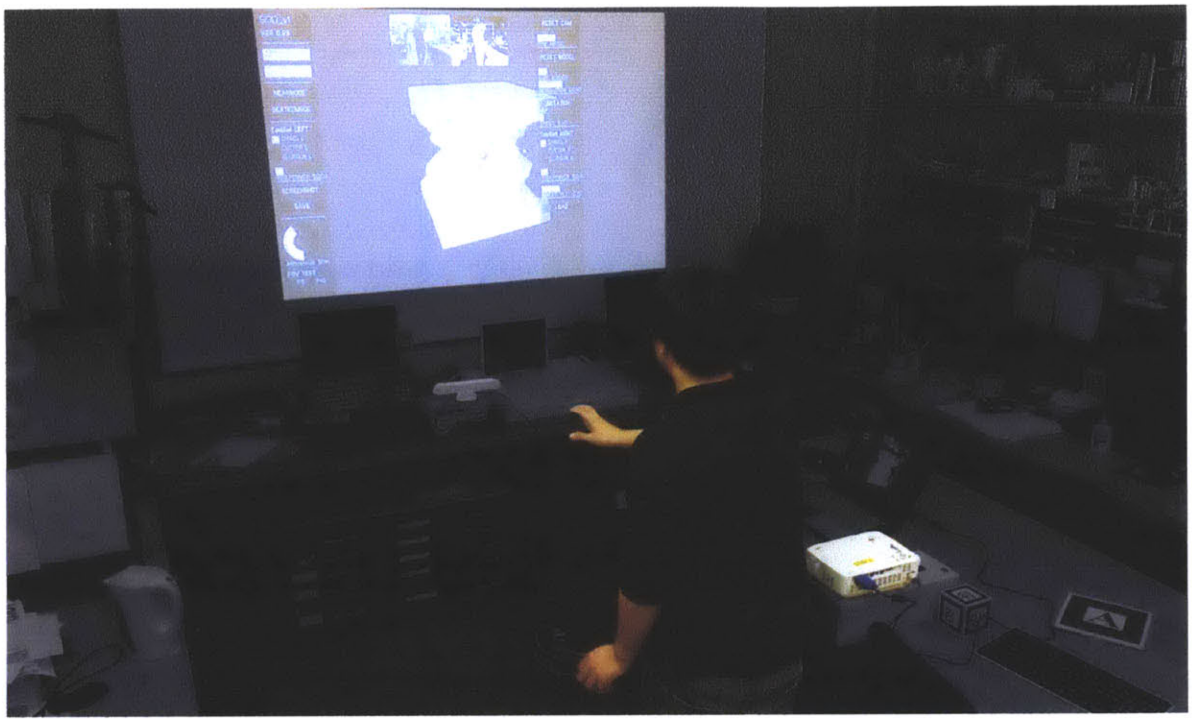


Figure 3-6: The sketching environment of Si3D-Mobile.

we have full control over body movements, these complex operations are spontaneously performed.

If the tools that are in the hands touch virtual material in the virtual space, geometric modifications are performed based on the prescribed logic of the tools. Figure 3-5 illustrates the simplified processing flow of the Si3D-Hand software.

In the experimental setting with Si3D-Hands, two types of spaces are identified: an interaction space and a feedback space. The interaction space is a 3-dimensional boundary where the user can interact with the virtual material. Si3D-Hands uses the Marching Cubes algorithm to represent geometries; therefore, the algorithm must have a fixed dimension, thus, the possible area for interaction is rather restricted. The user can move the position of the interaction space using a position-tracking marker. When the user places the position-tracking marker in front of the Kinect sensor, Si3D-Hands recognizes the position of the marker and places the interaction space in front of the marker. The user can also adjust the size and resolution of the interaction space using the graphical user interface of Si3D-Hands.

The feedback space allows the user to obtain feedback on his sketching activity. The main source of feedback is a 2-dimensional screen that displays a schematized figure of the user with a representation of the virtual material. In experiments, a video projector was used to display a computer screen on a wall. Once a user sets the position of the interaction space, a virtual camera is set behind the user and streams the sketching scene. On the screen, visual cues are provided to help the user better recognize the distance between his hands and the virtual material. An ambient sound is also provided as an additional reference to the virtual object.

B. Geometric Representation System

While developing the applications, two types of geometric representation systems were explored: a conventional mesh representation system (Figure 3-7) and the standard Marching Cubes algorithm (Figure 3-8). The data structure of a conventional mesh-boundary representation contains information on the positions of vertices, their connectivity, and their connecting orders. This information represents the boundaries of the object, and changing these values results in deformation of an object's shape. In contrast, the Marching Cubes algorithm uses on a 3-dimensional scalar field and dynamically generates the boundary polygonal mesh of an isosurface. Lorensen and Cline (1987) first proposed this algorithm was first proposed during the SIGGRAPH proceedings, and it has been used to reconstruct a surface from medical volumetric datasets such as CT and MRI scan data images, or to visualize a 3-dimensional contour of a mathematical scalar field.

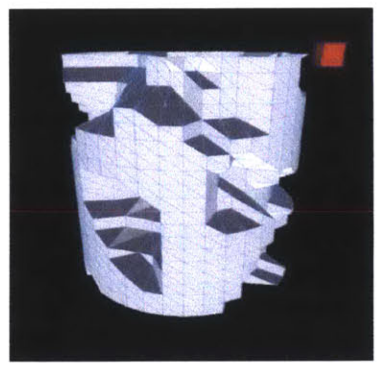


Figure 3-7: Mesh structure with a fixed number of vertices.

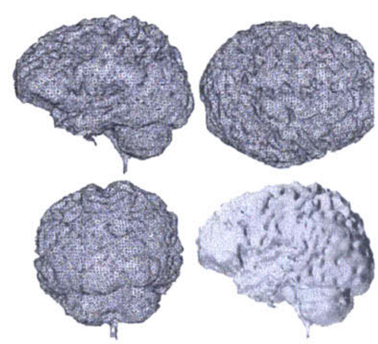


Figure 3-8: The 3D model of a human brain from MRI scanning data using the Marching Cube algorithm. (Source: http://paulbourke.net)

A dataset of the Marching Cube algorithm has a scalar value positioning at each lattice point of a rectilinear lattice in 3D space, and the algorithm processes the value data by taking eight adjacent data points(Cube) at a time. Figure 3-9 illustrates the 4x4x4 Marching Cubes value data. If the value at a given data location exceeds the threshold, the point is considered an inner point, and vice versa. Based on the distribution of an inner and outer scalar value in a cube,

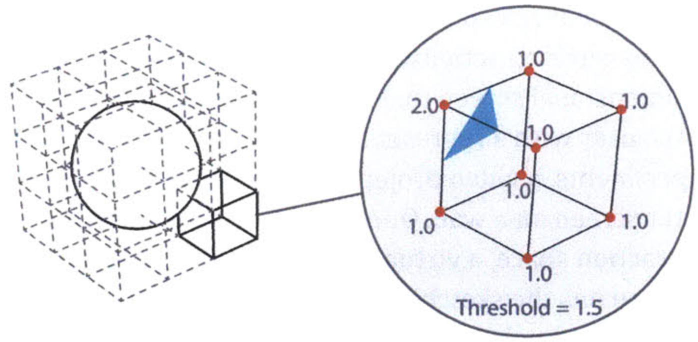


Figure 3-9: Example of the 4x4x4 Marching Cube data.

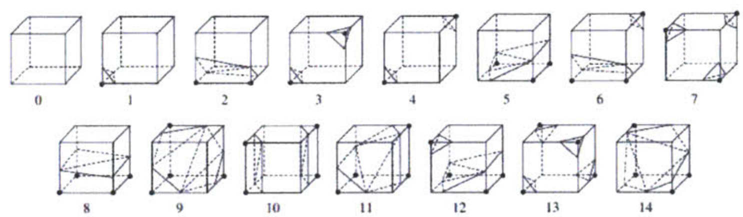


Figure 3-10: The 15 basic intersection topologies after exploiting rotated, reflected, mirrored symmetry. (Source: Newman 2006)

the topology of an individual cube's mesh faces is determined. Because a cube contains eight points, there are 256 possible polygon configurations within each cube (28=256). By exploiting all possible symmetries, 15 basic intersection mesh topologies within the cube result. In the Marching Cube implementation of Si3D-Hands, all 256 possible topologies are pre-calculated in an index table of an array of 256 possible polygon configurations; by searching through this index table, the operation of finding the appropriate mesh topology is accelerated. Finally, each vertex of the polygon is placed on the edge of the cube by linearly interpolating the two scalar values that lie on the two ends of that edge.

Based on the experiments, a strength of the Marching Cubes for modeling purposes was that topological transitions in the modeling process could be easily implemented. Because the boundary mesh representation of Marching Cubes data is algorithmically regenerated with the change of values of the scalar field, complex geometries were easily visualized with a set of scalar values, and without performing special geometric calculations. For example, transforming a sphere (Euler characteristic 0) to a torus (Euler characteristic 1) could be implemented easily using the Marching Cubes algorithm compared to the conventional mesh structure because it was only necessary to change the values within the penetrating area below a threshold. Conversely, a conventional mesh structure usually involves Boolean operations or manual vertex-level manipulations.

C. Natural User Interface

Si3D-Hands uses hand gestures as a main input method. Therefore, by moving the hands close to the virtual material, the user can manipulate that material. However, one issue in using body gestures as a main interface in Si3D-Hands is the limited number of recognizable gestures when using the Microsoft Kinect SDK while there are quite a lot of controllable parameters within the sketching environment. This was mainly caused by the fact that, although the official Microsoft SDK package provides functionality to track skeleton data of human figures, it is not capable of recognizing human gestures. This means that Si3D-Hands could not recognize sophisticated gestures such as drawing certain shapes in the air or waving the hands over a head. Although many ongoing studies on gesture recognition systems use the Kinect sensor, they could not be explored in this thesis project due to time constraints. In the final version of Si3D-Hands, a few simple gestures could be recognized by measuring the distance between joint positions from the skeleton data; these recognizable gestures were used to execute additional commands. For example, a user could iterate different tools by touching his shoulders with his hands, and reset the position of a virtual camera by touching his head (Figure 3-11).

D. Display Screen and Graphical User Interface (GUI)

Using a video projector, a 2-dimensional screen is projected onto a wall displaying a sketching scene (Figure 3-X). The user is represented as a stick figure, and the selected tools are visualized as simple geometries (a sphere for the Chisel, Glue-gun, and Plane tools, and a line for the Cutter tool). The screen also displays additional parameters of the sketching environment such as the rotation speed of the

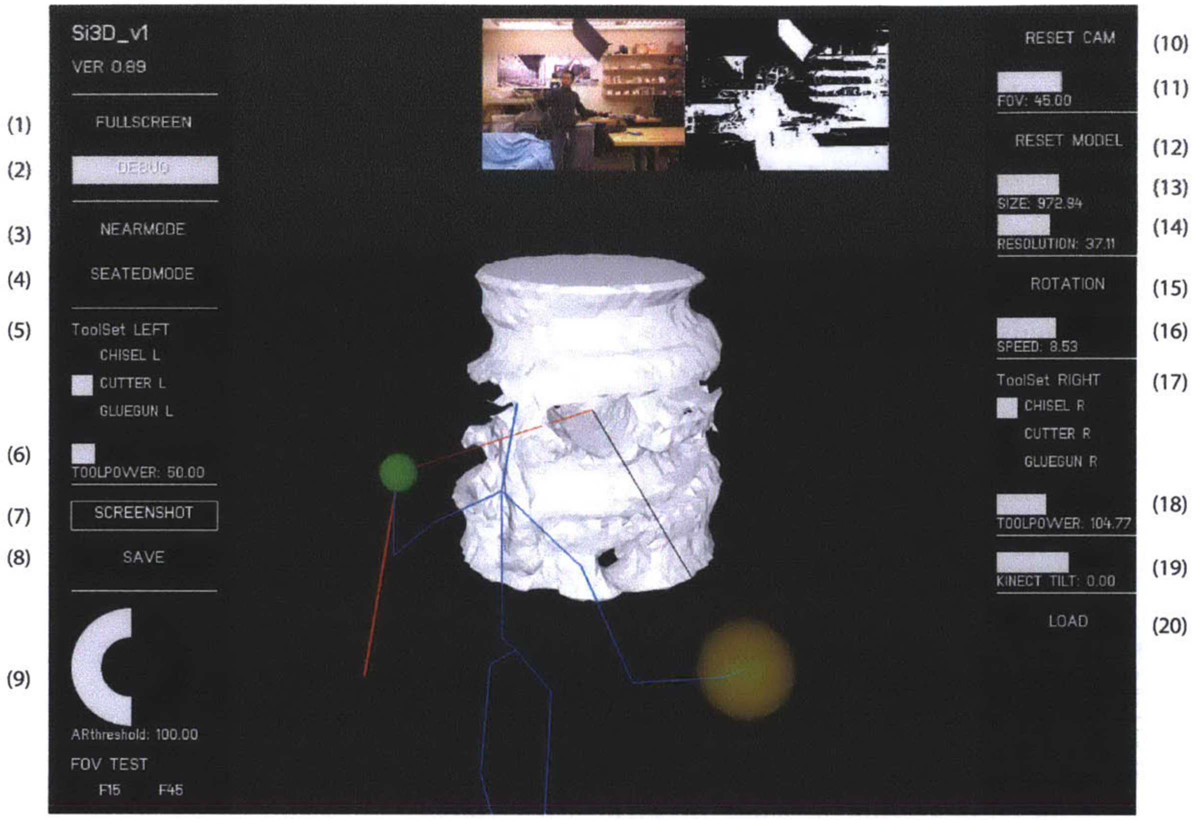


Figure 3-11: The GUI and display screen of the Si3D-hands system.

pottery-making mode and the size of the virtual material. Controllable parameters within the display screen are listed below:

(1) Full-screen toggle: Enable/disable full-screen.
(2) Debug screen toggle: Show/hide binary image converted from a video image to detect visual markers.
(3) Near mode toggle: Enable/disable the near mode of the Kinect.
(4) Seat mode toggle: Enable/disable the seated mode of the Kinect.
(5) Tool selection button: Change the current tool of the left hand to a desired tool.
(6) Tool power slider: Change an effective threshold of a left-handed tool.
(7) Screens-hot button: Save screenshot as a PNG.
(8) Save button: Save the current Marching Cubes data, and export the model as a OBJ file format.
(9) Marker detection threshold slider: Change the threshold to detect a visual marker from the binary

image.

(10) Rest camera button: Adjust the position of a virtual camera based on an interaction space.

(11) FOV button: Change the field of view of a virtual camera.

(12) Reset model button: Reset the Marching Cubes data.

(13) Size slider: Change the size of the interaction space.

(14) Resolution slider: Change the resolution of the interaction space.

(15) Pottery-Making mode toggle: Enable/disable the Pottery-Making mode.

(16) Rotation speed slider: Change the rotation speed of the Pottery Making mode.

(17) Tool selection button: Change the current tool in the right hand to a desired tool.

(18) Tool power slider: Change the effective threshold of a right-handed tool.

(19) Tilt slider: Adjust the tilting angle of the Kinect sensor.

(20) Load button: Load the latest Marching Cubes data.

As described earlier, because the number of recognizable human gestures was very limited in this thesis project, the parameters above cannot be fully controlled using body gestures. Thus, a GUI, such as a button and slider, was designed to control most of the parameters; the user is provided with a wireless mouse to access the GUI.

E. Tracking-Markers

The early version of Si3D set the interaction space near the user's chest once it detected the human figure in front of the Kinect. After this initialization, the position of the interaction space was fixed. However, in practice, during experiments, the user found it difficult to estimate the position of the virtual interaction space. This became more problematic as the user continued manipulating the virtual material because he inevitably moved his body around the virtual material to interact with it, which made it difficult to remember the fixed position of the interaction space. To

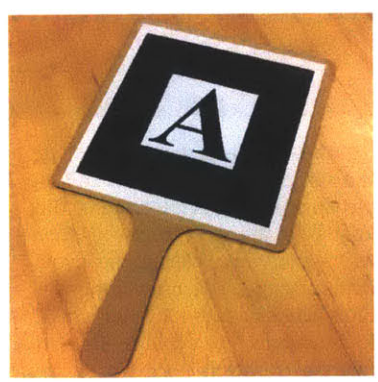


Figure 3-13: The tracking marker used to orient an interaction space.

deal with this issue, a marker tracking system was employed.

The Si3D-Hands uses two types of tracking markers: positioning-tracking marker and rotation-tracking marker. By moving the position-tracking marker, the user can freely move the position of the interaction space around his body anytime during the modeling process. The user can also use the positioning marker as a physical reference of the interaction space by dropping it onto the floor after setting the position of the interaction space.

The rotation-tracking marker was introduced to make up for the limited number of command-inputs. By facing the rotation-tracking marker toward the camera, the user can rotate the virtual model by enabling or disabling the Potter-Making mode. This marker tracking system is widely used in many Augmented Reality applications. The basic concept of this system is to detect the position of specially designed makers in relation to the camera's coordination frame via an image-processing algorithm. Details on the marker tracking technique are further described in the next chapter.

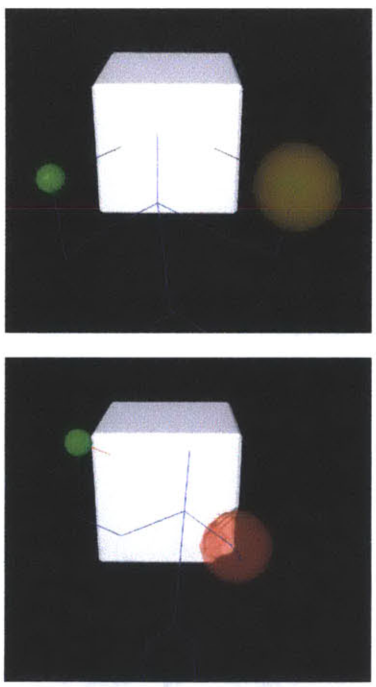


Figure 3-14: Visual cues to estimate the distance between hands and the virtual object. Thin lines connecting hands and the object turn red when user's hands approach to the virtual material (top). The visualizations of tools also turn into red color when tools actually interact with the virtual material (bottom).

F. Audio and Visual Feedback

From the experiments using the early version of Si3D-Hand, it was recognized that the user felt challenged in estimating the distance between the position of his hands and the position of the virtual material. Specifically, because user interactions and sketching scenes were displayed on a 2-dimensional screen while the user performed sketching operations in 3-dimensional space, it was difficult for a user to approximate the spatial distance between his hands and the virtual object. To supplement this problem, two visual cues and an ambient sound feedback system were implemented in the final version of Si3D-Hands.

The first visual cue is a black line that connects the hands and virtual objects, and is displayed on the screen. Si3D-Hands calculates the bounding box of a virtual object and, if user's hands are close enough to the virtual object, it changes the color of the lines to red. The second visual cue is the color and size of the sketching tool representations. Sketching tools are attached to the user's hands and represented as either lines or spheres; their size indicates the thresholds (or power) of the current tool. When users' hands touch the virtual object and start to interact with the virtual material, the color of the tool representation turns red.

In addition to the visual cues above, the user also receives feedback on the distance between his hands and the virtual material from an ambient sound. The ambient sound used in Si3D-Hands is a subtle, but audible, soundtrack of a raindrop, the closer the distance between the hands and virtual object, the louder the sound. After having tested many soundtracks from drums to music, the raindrop sound was selected because it was the least intrusive, and allowed the user to focus on the sketching process without paying too much attention to the sound. The use of an ambient sound was inspired by the ambientROOM project from the Tangible Media Lab at MIT (Ishi 1998).

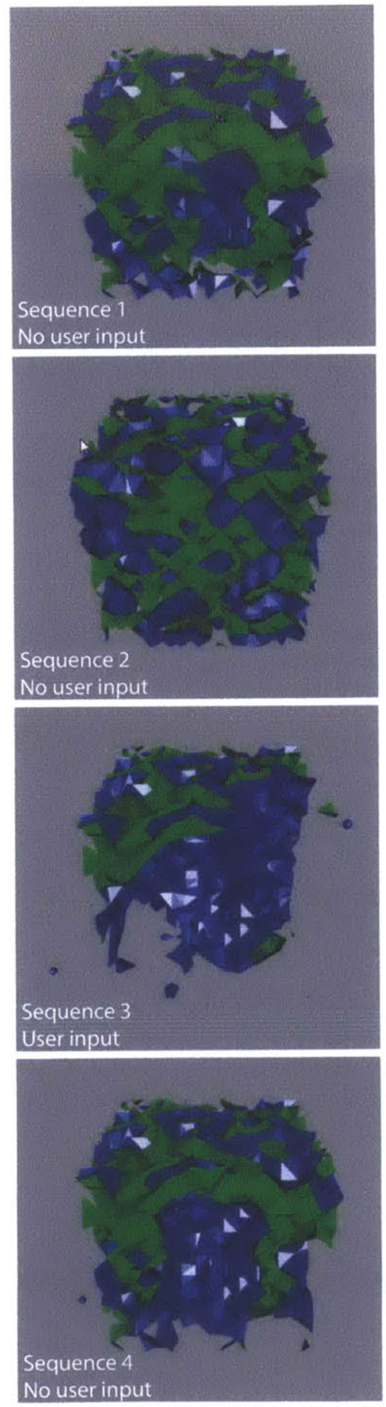


Figure 3-15: The morphing virtual material in the living-creature interaction mode. User's inputs interfere in its morphing status and produce unexpected results.

G. Interaction Modes and Tools

Si3D-Hands provides users with three interaction modes and four sketching tools. Two interaction modes emulate real-world sketching circumstances, such as pottery making, and they aim to provide the user with familiar interaction environments where he can use real-world knowledge in a computer-aided sketching environment. The other interaction mode simulates a sketching environment that cannot be experienced in the real world.

Using four virtual sketching tools implemented in Si3D-Hands, the user can manipulate virtual material in different ways. When the user's hands approach the virtual material, the distances between the hands and the positions of each Marching Cubes data entity are calculated. If the distance between hands and the position at a given Marching Cubes data point is less than the threshold (represented by a tool power), the scalar value at the give data location is either increased or decreased to regenerate the boundary isosurface of the virtual material. These tools use symbols of

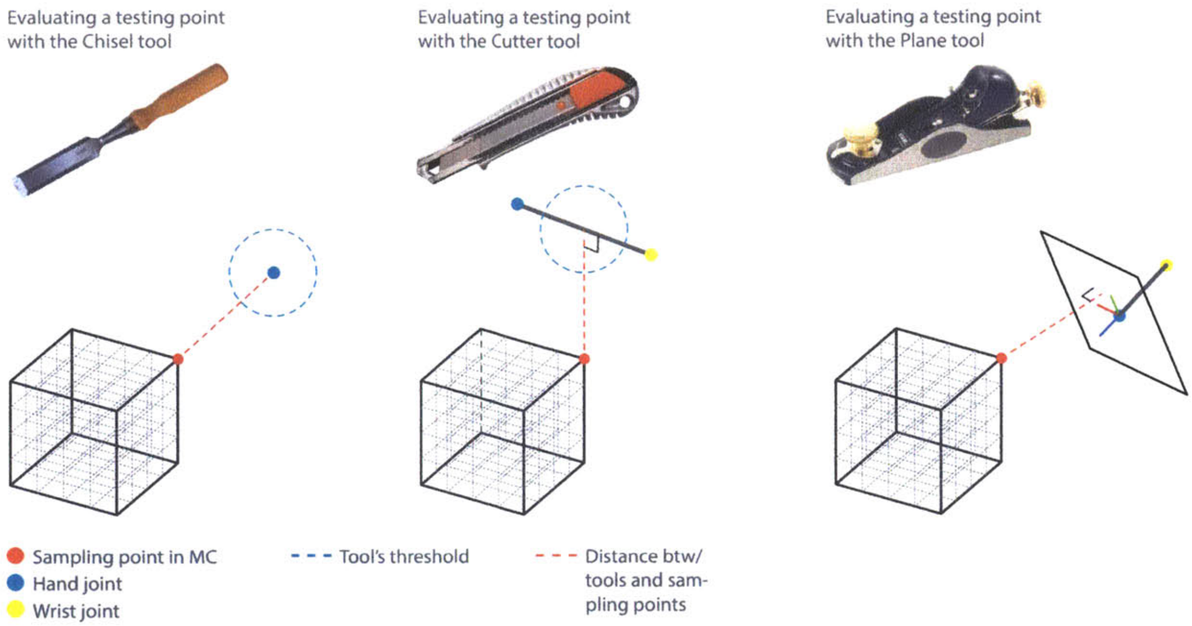


Figure 3-16: Evaluation processes of the Marching Cube data with different tools.

familiar real-world metaphors such as a cutter and a plane so the users can easily understand the functions of the tools. Detailed implementations of the interaction modes and virtual sketching tools are described below:

- Interaction Modes

- **Static mode**

  In this mode, the position and orientation of a virtual material is fixed once a user locates the interaction space using a position-tracking marker. This mode is set by default.

- **Pottery-Making mode**

  The Pottery-Making mode emulates the traditional pottery-making environment where the user can interact with a constantly rotating material. By moving the hands around the rotating material, the user can add or subtract volumes to the virtual material. Users can enable/disable this mode using a rotation-tracking marker

- **Living-Creature mode**

In the Living-Creature mode, a simple cellular automata logic is embedded into the virtual material so it can autonomously change its form over time. The user can interfere in its morphing process, which will bring about unexpected results. Because the other two interaction modes emulate real-world sketching conditions, this mode was developed to propose a novel interaction mode that can hardly be made in real-world circumstances.

- Tool-set

- **Chisel**

The Chisel Tool is the simplest tool that removes volume from the virtual material. The distance between a testing point and hand joints are first calculated and, if the distance is less than the tool's threshold, the scalar value of the testing point is decreased. In the display screen, the Chisel tool is visualized by a sphere attached to the user's hands.

- **Cutter**

A user can cut the virtual material using the Cutter tool, which removes volumes of the virtual material along its edge. The Cutter tool is internally represented by a line segment in 3D space. When a projected point of a testing point to the line segment is within the line segment and, if the shortest distance between the testing point and the line segment is less than the threshold, the scalar value at the testing point is decreased. This calculation is processed as follows:

The Cutter tool is mathematically represented by a line segment using a parametric equation

$$S(t) = P + t\mathbf{v}$$

where P is the starting point of the line segment, and **v** is a vector from the starting point to the ending point of the line segment. In this case, the line segment is represented by the convex combination of a starting and ending point, $0 \leq t \leq 1$; therefore, to find the projected point of a testing point, **Q**, onto the line segment, parameter **t** can be calculated as

$$t = \frac{w \cdot v}{v \cdot v}$$

where w is a vector from the starting point of the line segment to testing point **Q**. Because v·v is always positive, we can simply check **w·v < 0** or **w·v > v·v** to determine whether the projected point of testing point, **Q**, is ahead of the starting point **(t<0)** or behind the ending point **(t>1)** of the line segment. If parameter, t, is within the domain **[0, 1]**, and the distance between **Q** and **Q'** is less than the tool's threshold, the testing point is considered to be within the effective area of the Cutter tool. The cutter tool is represented by a red line that extends from a hand joint to an elbow joint.

- **Plane**

Using the Plane tool, a user can evenly sand the virtual material. Internally, the Plane tool is represented with a mathematical equation of a plane. If a testing point is in front of the plane and the shortest distance between the testing point and plane is less than the threshold, the scalar value of the testing point is decreased. The calculation is processed as follows:

The Plane tool is represented by the generalized plane equation

$$0 = ax + by + cz - (ax_0 + by_0 + cz_0)$$

where **a**, **b**, and **c** are respectively **x**, **y**, and **z** coordinates of the normal vector of a given plane, and **x0**, **y0**, **z0** is the origin point of the plane. When **x**, **y**, and **z** are replaced by the coordinates of a testing point, the absolute value of the equation above returns the distance between the testing point and given plane,; its sign indicates whether the point is located on the negative or positive side of the plane. If the shortest distance between the point and plane is less than the tool's threshold and the point is located on the positive side of the plane, the testing point is considered to be within the effective area of the Plane tool. The Plane tool is represented on the screen with a quadrangular polygon.

- **Glue-gun**

  Using the Glue-gun tool, the user can add volume to the virtual material. This tool uses the same evaluation logic as the Chisel tool, but increases the scalar value of a testing point.

3.4 Self-trials and evaluation

After the development of the final version of Si3D-Hands, the author conducted self-trial to examine the capabilities of Si3D-Hands. The author freely performed 3-dimensional sketching without rigorous guidelines or requirements. Figure 3-17 shows design samples made from these self-trials. Several positive aspects and deficiencies of Si3D-Hands were observed from the self-trial sessions as discussed below:

-Intuitive and engaging sketching experience

Using Si3D-Hands, a user can easily create organic or complicated forms in an intuitive fashion. Because the tools and environments of Si3D-Hand use real-world metaphors and provide similar interactive environments, they allow the user to apply real-world knowledge. At the same time, sketching operations performed in the virtual space gives the user unique experiences that could not be obtained from real-world sketching environments, such as hanging volumes in the air and sculpting with living materials.

- Flexible shape recognition

The traditional 2-dimensional free-hand sketch-

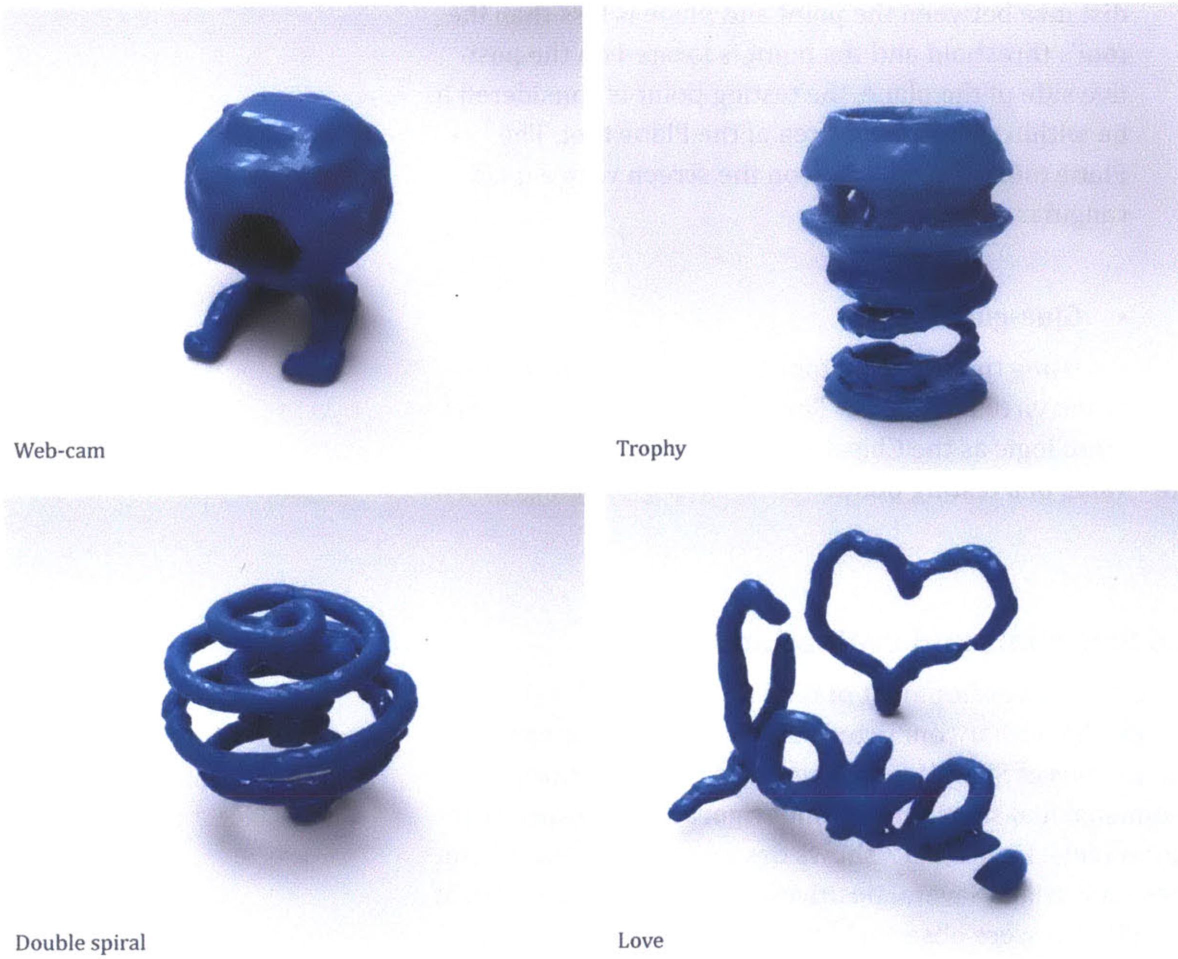


Figure 3-17: Design samples made with Si3D-Hands.

ing process has a strength in that it allows designers to reinterpret their drawings as they progress due to its visual ambiguity. Similarly, it was observed that Si3D-Hands supported a similar type of flexible shape recognition.

In most contemporary 3-dimensional modeling systems, geometries in different dimensions, such as a point and curve, have different internal data structures and visual representations. Each of these entities are discretely controlled by sub entities that belong to lower dimensions. For example, when the user manipulates a curved geometric shape in Rhino software, he transforms the shape of the curve by moving the control points that define that curve. While this discrete

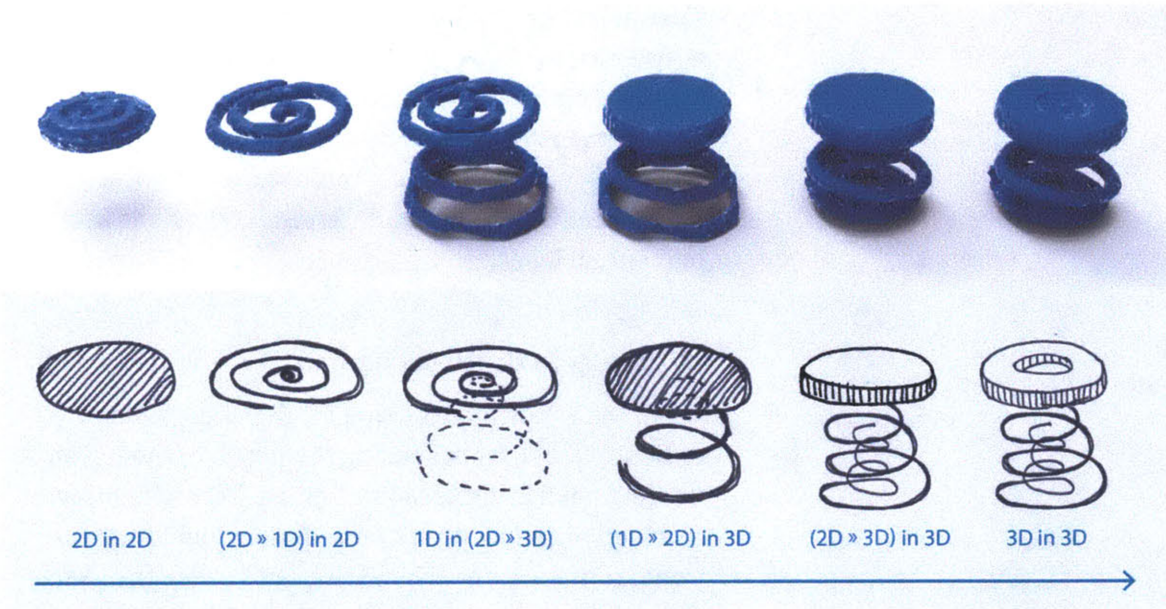


Figure 3-18: Development of a table design using Si3D-Hands.

control and hierarchical geometric system gives users great capability to control shapes precisely, it does not support flexible shape recognition that allows users to perceive shapes from different dimensions.

On the contrary, Si3D-Hands has an opposite nature. Because Si3D-Hands uses the Marching Cubes algorithm for geometric representation, there is no distinction or hierarchy between entities in different dimensions; rather, they are all visualized by volumetric representations within the scalar field and sub entities do not define them. Because of this reason, once shapes are drawn into the space, they cannot be precisely adjusted by discrete controls. However, as a benefit, Si3D-Hands provided users with greater flexibility in perceiving shapes in different dimensions. In the trials, depending on in which dimension the user perceived shapes, he could easily reinterpret shapes and convert them into entities in different dimensions just by adding or subtracting volume.

Figure 3-18 illustrates the development of a table design observed during a trial session. In this design process, the user constantly reinterpreted his shapes by changing the perceptional dimension in which he saw them. For instance, after he drew a spiral curve with 1-dimensional perception and readily perceived it as a 2-dimensional circle. He then easily converted the 2-dimensional circle into a 3-dimensional cylinder by adding volume. This example shows that the user could freely move across different dimensions at a perceptual level.

- *Difficulty in depth perception*

In the experiments using Si3D-Hands, a major difficulty arose from sensing the depth of the physical world from a 2-dimensional screen. When the user received visual feedback on 3-dimensional interactions from a 2-dimensional display screen, the user did not clearly recognize the spatial depth of the real world. This issue is directly related to binocular vision. In the real world, our eyes create two slightly different images of a scene because of their different positions on the head. These differences are called binocular disparity, which is a major means that the brain uses to perceive depth from a visual scene. However, in the Si3D-Hands system, the user has to perceive depth of the physical world from a 2-dimensional screen, and his eyes do not have enough binocular disparity from the visual elements displayed on the screen to do so effectively. Therefore, it was very difficult for a user to estimate the distance between his hands and the virtual material on the screen, and the depth of the virtual material. Even though this issue was complemented by multi-sensory feedback, such as visual cues and ambient sound, having precise sensation of spatial depth from a 2-dimensional screen was still challenging.

- *Separation of an interaction space and feedback space*

In real world sketching environments, such as freehand drawing or clay modeling, there is no distinction between the feedback and interaction spaces (Figure

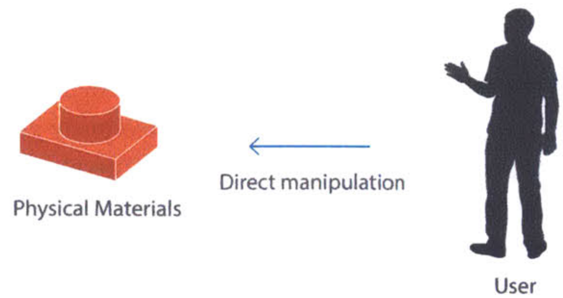


Figure 3-19 : Spatial configurations of traditional sketching environments e.g. freehand drawing or physical sculpting.

3-19). Here, the user receives feedback on his sketching interactions from what he sees with eyes and feels from his gestural movements. This multi-sensory feedback works simultaneously and allows the user to gain a solid spatial perception of the body and sketching medium. However, in the Si3D-Hands sketching environment, the interaction and feedback spaces are separated from each other (Figure 3-4); the interaction space is positioned near the user's body space and the feedback space is projected onto a wall. Moreover, the visual feedback obtained from the projected screen is a 2-dimensional image that lacks binocular disparity. These differences caused the issues discussed below.

First, because the interaction and feedback spaces are separated, the user has to choose where to focus. Depending on which space the user focuses on, sketching behaviors and results may differ. When the user focuses on the screen (the feedback space) and using visual feedback, he experiences cognitive dissonance because of the different dimensionalities of the two spaces. For example, when a user tries to move his hand along the perpendicular edge of a virtual object while paying attention to the screen, he tends to move his hand at an angle. This is because, on the 2-dimensional feedback screen, the edge is visualized at an angle because of the perspective effect while standing at a right angle in 3-dimensional space. Lowering the field of view of a virtual camera alleviates this perceptual disparity to a certain degree, but, in turn, the lower field of view makes it difficult to estimate the distance between the hands and virtual material due to a lack of the perspective effect. In contrast, when the user focuses on his hands in the 3-dimensional interaction space, he can produce more fluid forms without cognitive dissonance. However, because body gestures in the space do not leave any recognizable mark or trajectory, the user could not identify the forms that he drew, thus, he was not able to know whether his sketches were properly aligned.

Secondly, the fixed position of the feedback space, which is a screen projected onto a wall, limits the user's movement. Because the position of the screen is fixed on a wall, the user can only move his body to the extent that he can see the screen, and his head always has to face the screen. This limitation on body movements causes great inconvenience and interrupts smooth sketching operations of a user.

- Erratic hand tracking

The Kinect sensor produces the best skeleton data when the body is facing it and when body parts are not overlapping each other. Thus, the tracking data of the hands was sometimes very erratic, especially when the user's hands overlapped with the body, or the user did not stand facing straight at the Kinect. Because users tend to freely take their places during the 3-dimensional sketching process without paying much attention to the position of their hands and body, this instability in tracking hands often causes inconsistent and inaccurate sketching operations and interrupts a smooth sketching experience.

- Inability to detect detailed orientations of the hands

In real world sketching circumstances, we can engage in sophisticated manipulations just by moving the fingers or rotating the palms. However, in the Si3D sketching environment, such a subtle movement of the hands cannot be detected because the Kinect only tracks joint positions of the human figure. In addition to erratic hand tracking of the Kinect, this inability to detect subtle movements further limits sophisticated and precise sketching functions.

-Limited number of gestural commands

As described earlier, Si3D-Hands had a limited number of recognizable gestures. Thus, detailed parameters of the sketching environment, such as the position of a virtual camera and the threshold of a tool, has to be controlled by GUIs, which are accessible using a wireless mouse. Thus, users have to change these parameters frequently during the sketching process. Reports following the testing phase indicated that users feel it is inconvenient to swap between GUIs and the gestural interface. In addition, Si3D-hands uses continuous body gestures as the main input method without any additional prop and it is difficult to implement functions to distinguish meaningful gestural commands, such as triggering the Glue-gun, from continuous sketching gestures. During the trials, this drawback did not bother the user when he was using subtracting tools; however, it was inconvenient when using the Glue-gun tool because it added volume when the user made a gestures without a drawing intention.

4. The Second Experiment: Sketching in 3D with a Mobile Device (Si3D-Mobile)

From the development and trials with Si3D-Hands, positive aspects of the 3-dimensional sketching environment, such as intuitive interactions and body-inclusive sketching experience, were observed. However, several shortcomings of the Si3D-Hands sketching system were also found. It was deemed that some of these shortcomings were inherent qualities in spatial sketching systems while others were caused by the specific hardware and sketching configurations of Si3D-Hands. This experience prompted the exploration of alternative spatial sketching systems that could address the issues found in the Si3D-Hands system.

The next version, *Sketching in 3D with a Mobile Device* (Si3D-Mobile), uses a hand-held mobile device as the main interface instead of the hands. Here, the mobile device serves as a medium that mediates human gestures and computational sketching operations. In the Si3D-Mobile sketching environment, the user performs sketching with a hand-held mobile device. Using an image-based AR recognition technique (ARtoolkit), the built-in camera of the mobile device tracks the position of a specially designed visual marker and places the interaction space on top of that marker. The video stream captured by the camera is augmented with the virtual sketching environment and displayed on the screen of the mobile device.

Si3D-Mobile was deliberately designed to have properties that are different from those of Si3D-Hands so that the two sketching systems could be compared. The major differences of Si3D-Hands and Si3D-Mobile are as follows.

First, the interaction and feedback spaces are close together. In the experiments using Si3D-Hands, the most apparent issue was that a user experienced difficulty in perceiving the 3-dimensional sketching environment from the 2-dimensional feedback screen. As described in the previous chapter, this issue was related to several reasons including a lack of binocular disparity and the separation of the interaction and feedback spaces. In Si3D-Mobile, by moving the interaction and feedback spaces closer, the researcher could examine whether user had better depth perception from cross-referencing how he moves in the 3-dimensional space and how his interactions are visualized on the 2-dimensional screen.

Secondly, Si3D-Mobile uses a mobile device as an intermediate medium of sketching interactions to enhance the detecting precision of an input medium. Because the marker tracking technique can calculate the accurate orientation of a mobile device, Si3D-Mobile was expected to have more precise tracking capability.

In this chapter, different techniques used for the development of Si3D-Mobile and its sketching environment are described. The findings from the self-trials are also discussed in the final section of this chapter.

4.1 Hardware

A. Hand-held Mobile Device

Si3D-Mobile uses the Surface Pro table manufactured by Microsoft (Figure 4-1). Because the Surface Pro has a fast CPU compared to other mobile devices (e.g., iPad or Android tablets), it best fit the Si3D-Mobile, which required good computing power to perform real-time Marching Cubes calculation.

Figure 4-1: A Surface Pro table by Microsoft
(Source: http://www.microsoft.com/surface/en-us/surface-with-windows-8-pro)

4.2 Software

A. Developing Environment.

Si3D-Mobile was written in the C++ language with the Cinder framework. For more information, refer to the section 3-2-A.

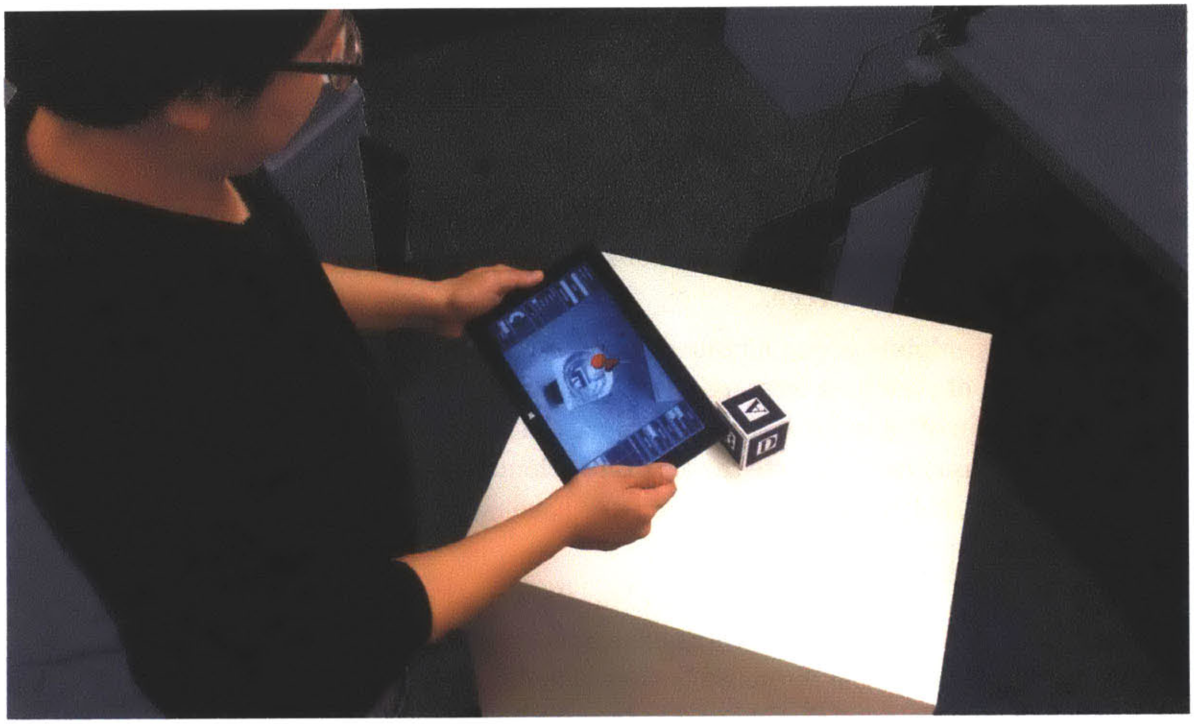


Figure 4-2: The sketching environment of Si3D-Mobile.

4.3 Implementation

A. System Configuration

In the sketching environment of Si3D-Mobile, the user is given a mobile device with a specially designed marker. When the user views a visual marker with the mobile device, Si3D-Mobile captures a real-time video stream from the built-in camera of the mobile device and calculates the orientation of the device in relation to the visual marker. Based on this information, Si3D-Mobile places a virtual material on the visual marker. Finally, the virtual material is visually augmented on the sketching scene as captured by the camera.

As with Si3D-Hands, Si3D-Mobile provides the same sketching tools (Chisel, Cutter, Plane, and Glue-gun). These tools are placed in the virtual space near the mobile device and are displayed on the screen of the device. Because their spatial positions are fixed in relation to the mobile device, the device itself serves as a physical reference for these

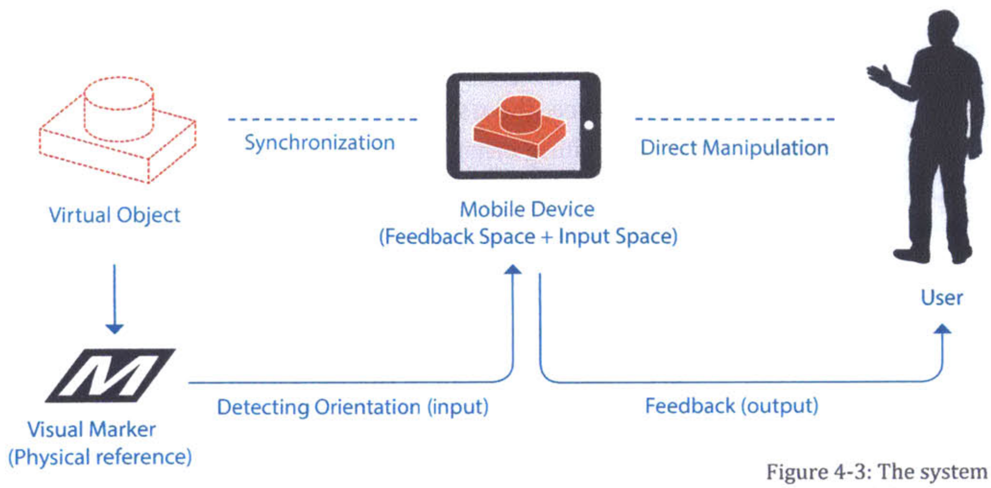


Figure 4-3: The system configuration of Si3D-Mobile

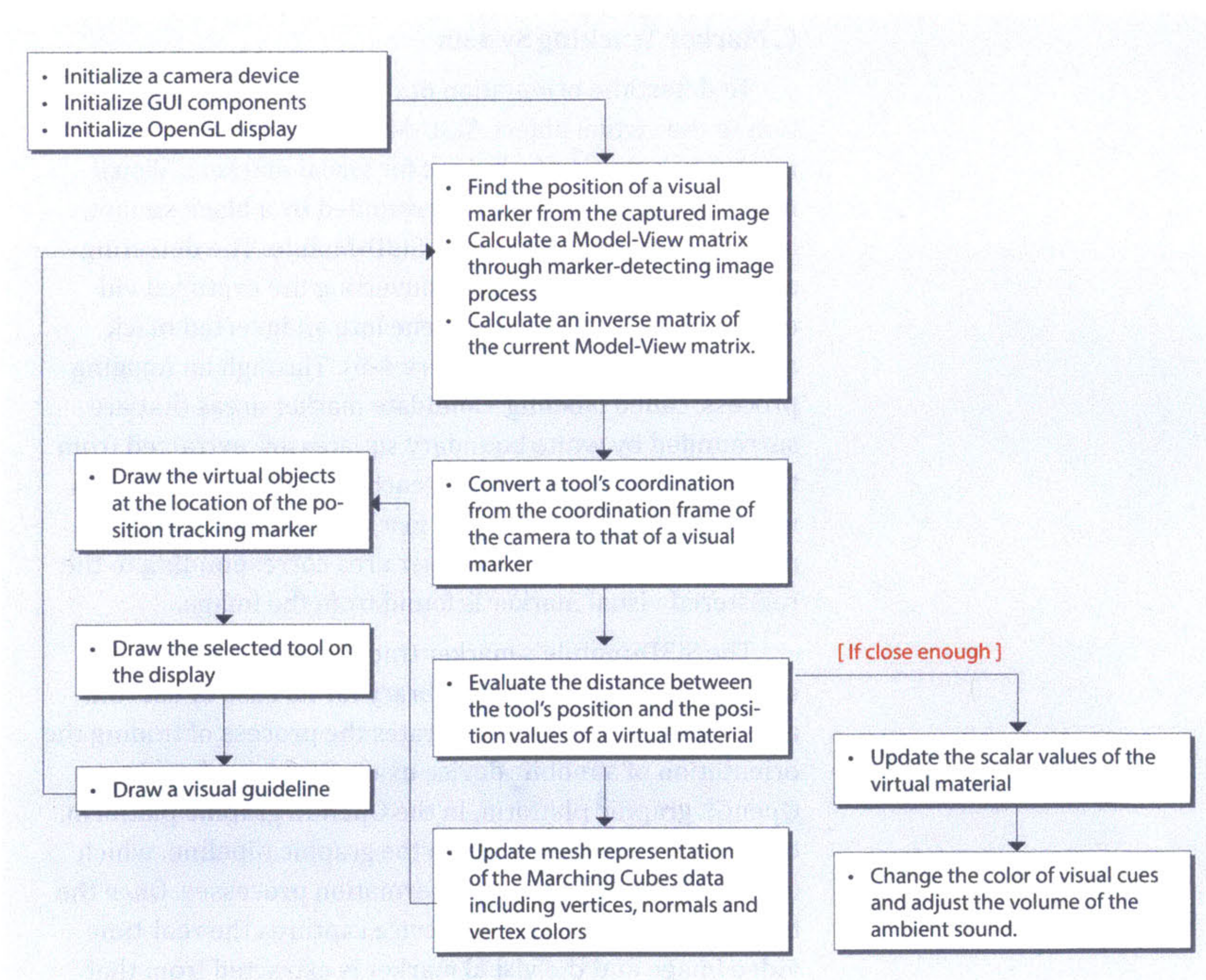


Figure 4-4: The diagram of the core process of Si3D-Mobile.

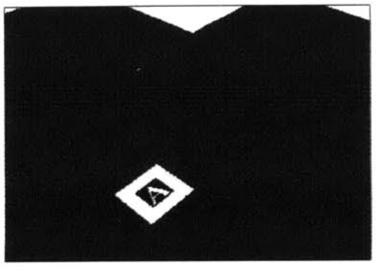


Figure 4-5: A binary Image converted from a RGB video stream.

tools. By moving the mobile device around the marker, the user can interact with the virtual material on the screen. Through the graphical user interfaces on the screen of the mobile device, the user can also adjust detailed parameters of the sketching environment, such as the power of tools and the positions of the virtual tools in relation to the mobile device

B. Geometric Representation System

Si3D-Mobile also uses the Marching Cube algorithm as a geometric representation system. For more information, refer to the section 2-2-B.

C. Marker Tracking System

To detect the orientation of the mobile device in relation to the virtual object, Si3D-Mobile uses an image-based marker recognition technique for visual markers. Visual markers can be any shape surrounded by a black square, and they are preregistered to Si3D-Mobile. The detecting algorithm proceeds first by converting the captured video stream of the sketching scene into an inverted black and white binary image (Figure 4-6). Through an imaging process, called labeling, candidate marker areas that are surrounded by white boundary squares are extracted from the image. Finally, comparing each candidate marker area with the preregistered visual markers using the template matching technique, the marker area corresponding to the registered visual marker is found from the image.

The Si3D-mobile's marker tracking implementations uses an ARToolkit software library for its ease of use and accessibility. Figure 4-6 illustrates the process of finding the orientation of a mobile device using visual markers in the OpenGL graphic platform. In the OpenGL graphic platform, objects are displayed through the graphic pipeline, which is a continuation of the transformation processes. Once the built-in camera of a mobile device captures the real-time video image and the visual marker is extracted from that image, $\mathbf{M}_{\mathbf{marker}}$, the transformation matrix from the mark-

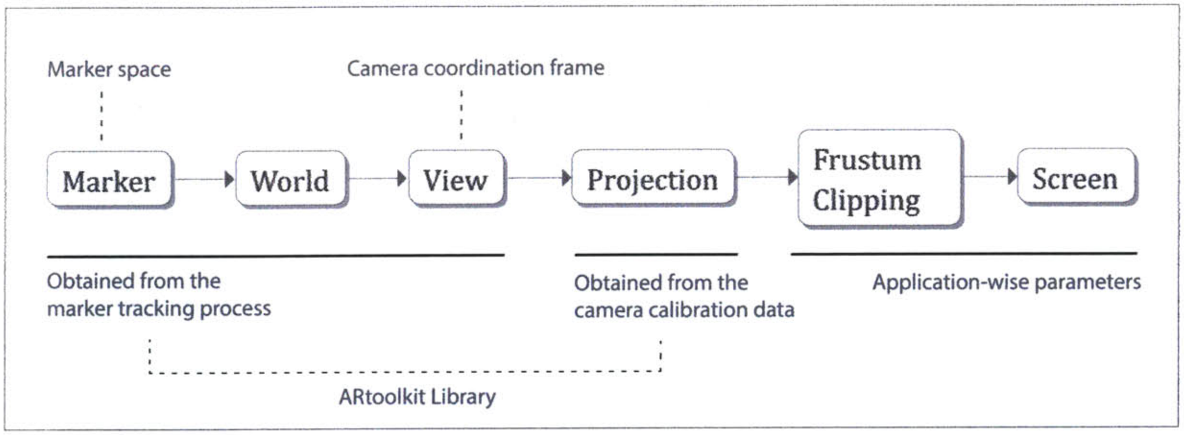


Figure 4-6: The role of the ARtoolkit library in the OpenGL graphic pipeline.

er's coordination frame to the camera coordination frame is calculated using the imaging process described above. Here, **M_{marker}** is a 16-dimensional matrix that contains a 3x3 rotation matrix and a 3x1 translation matrix. Using this matrix, positions and orientations between the two coordination frames are easily calculated as described below:

$$P_{cam} = M_{marker} \# P_{marker}$$

where **P_{marker}** is a position in the marker coordination frame and **P_{cam}** is a transformed position of the given position in the camera (or device) coordination frame.

The advantage of using the marker tracking technique is that, because it only requires video image to be processed, there is no requirement for special sensors or hardware. In addition, because the position of the embedded camera is fixed to a mobile device, the precise orientation of an input device (mobile device) can be obtained easily, which was a challenge in Si3D-Hands.

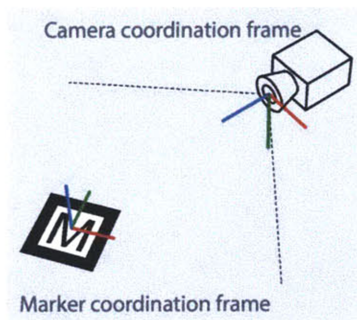


Figure 4-7: Camera and marker coordination frames.

D. Display Screen and Graphical User Interface (GUI)

The graphical user interface of Si3D-Mobile provides the user with detailed control over the modeling environment (Figure 4-8) that are displayed on the screen of a mobile device. Because a user performs sketching operations with the mobile device in his hands, he can easily access GUIs with his fingers.

(1) Full-screen toggle: Enable/disable full-screen.

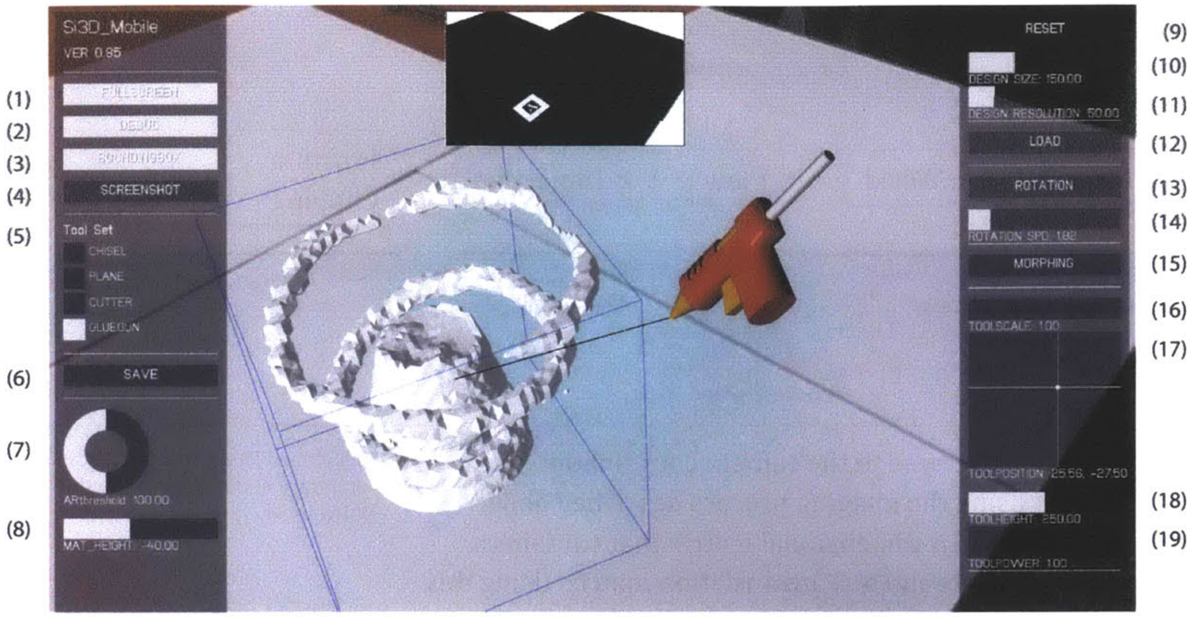


Figure 4-8: The GUI and display screen of the Si3D-Mobile system.

(2) Debug screen toggle: Show/hide a binary image converted from a captured video stream.

(3) Bounding box toggle: Show/hide a bounding box of the interaction space. The box drawn in blue represents the maximum extent where the user can interact with the virtual material

(4) Screen-shot button: Save the current screen-shot as a PNG image.

(5) Tool selection button: Change the current tool to a desired tool.

(6) Save button: Save the current Marching Cubes data and export the model in OBJ file format.

(7) Marker detection threshold slider: Change the threshold for detecting a visual marker from the binary image.

(8) Model positioning slider: Change the vertical placement position of a virtual material in relation to a visual marker.

(9) Reset model button: Reset the Marching Cubes data.

(10) Size slider: Change the size of the interaction space.

(11) Resolution slider: Change the resolution of the interaction space.

(12) Load button: Load the latest Marching Cubes data.

(13) Pottery Making mode toggle: Enable/disable the Pottery-Making mode.

(14) Rotation speed slider: Change the rotation speed of the Pottery-Making mode.

(15) Living Creature mode toggle: Enable/disable the Living-Creature mode.

(16) Tool scale slider: Change the displaying scale of a tool. When the tool representation covers the screen area too much, the a user can adjust the displayed scale of a tool with this slider.

(17) Tool positioning pad: Change the position of tool. Using this button, the user can move a tool parallel to the rear-face of the mobile device.

(18) Tool positioning slider: Adjust a tool's perpendicular position from the camera. This slider changes the vertical position of a tool in the virtual space.

(19) Tool power slider: Change the effective threshold of a tool.

While Si3D-Hands represent tools with primitive geometries (sphere and line), Si3D-Mobile has more realistic tool representations (Figure 4-9).

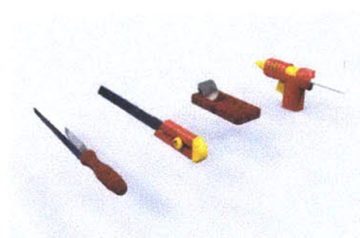


Figure 4-9: Graphical representations of sketching tools in Si3D-Mobile.

E. Audio and Visual Feedback

Si3D-Mobile uses the same sound and visual feedback systems as Si3D-Hands. For more information, refer to the section 3-3-F.

F. Interaction Modes and Tools

Si3D-mobile provides the same interaction modes and tool set as Si3D-Hands as below:

- Interaction Modes

- **Static mode**
- **Pottery-Making mode**
- **Living-Creature mode**

- Tool-set

- **Chisel**
- **Cutter**
- **Plane**
- **Glue-gun**

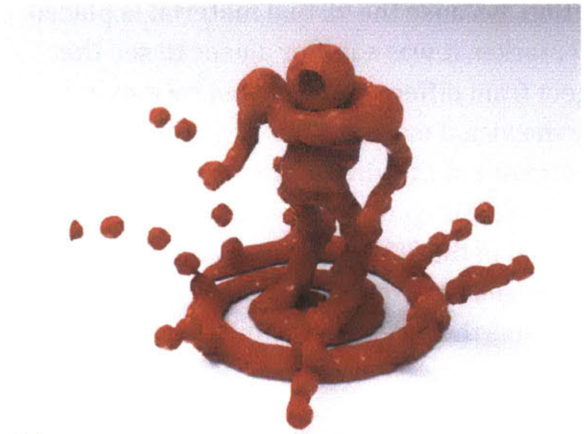
For more information about these features, refer to the section 3-3-G.

4.4 Self-trials and evaluation

As in the previous experiments with Si3D-Hands, the author performed self-trials to obtain hands-on experiences with the Si3D-Mobile sketching system (Figure 4-10). While basic qualities found in Si3D-Hands, such as intuitive sketching interactions and flexible shape recognition, remained the same, several differences of Si3D-Mobile were identified from the self-trial sessions.

Better perception of spatial depth

When using Si3D-Mobile, the user could have a better sense of spatial depth than when using Si3D-Hands. In the Si3D-Hands sketching environment, the user could not check an interaction and feedback space at the same time. In the Si3D-Mobile environment, he can simultaneously cross-reference where the mobile device in his hands is positioned in the interaction space, and where the mobile device (or a sketching tool) is visualized in relation to the virtual object from the feedback screen. This ability greatly helps the user in estimating the actual distance between his hands in physical space and the virtual material in the virtual space. However, despite this improvement, it does not fully address the difficulty of navigating the 3-dimensional space without binocular disparity and tactile feedback.



Cyborg

Lamp

Rabbit

Tree

Figure 4-10: Design samples produced using Si3D-Mobile

Ease of navigating the sketching space

In Si3D-Mobile, the feedback space is displayed on the screen of a mobile device, which is held in the user's hands. Thus, the user's body movements automatically update the viewing position and angle, thus, not requiring additional adjustment. This feature enables the user to navigate the sketching space easily by moving his body around the interaction space while holding the mobile device in his hands. In the Si3D-Hands sketching environment, this freedom of navigation was not allowed because the position of the feedback space was fixed onto a wall and the user had to adjust the position of the virtual camera manually to see the sketching scene from different angles.

In addition, because the virtual material is placed on a visual marker, it was easy for a user to see the virtual object from different angles just by moving or rotating the visual marker, thus, regarding it as a physical reference of the virtual object. Overall, the navigation of the sketching space and viewing the virtual material in the Si3D-Mobile environment were more intuitive and easy than in the Si3D-Hands environment because they were very similar to that of the real world.

Smooth integration of GUI and gestural interface

Because GUIs, which were used to control detailed parameters of the sketching environment, were displayed on the screen of the mobile device in the user's hands, the user could easily control those parameters with his fingers. In the Si3D-Hands experiments, the user felt that it was inconvenient to switch between the GUIs and a gestural interface because he had to stop making gestures and grab a wireless mouse to access the GUIs. However, when using Si3D-Mobile, the user only has to move his fingers to access the GUIs as these components are placed near his hands. This integration of GUIs and gestural interface allow the user to perform more dynamic sketching operations (e.g., changing tool powers and adjusting positions of sketching tools while drawing a line). This accessibility to additional controls partly addressed the issue of executing additional commands in Si3D-Hands, which was caused by a limited number of recognizable gestures.

Precise detection of the orientation of the input device

The marker-tracking technique used in Si3D-Mobile successfully tracked the orientation of the mobile device. Thus, the user could freely position and orient the input device (mobile device) at the desired angles.

Less body-inclusive interactions

Even though the both sketching systems, Si3D-Hands and Si3D-Mobile, use body gestures as an input method, Si3D-Mobile provides less body-inclusive experiences because body gestures are mediated by the mobile device and the user always has to hold the device with both hands. While the user could make very natural gestures using his hands in Si3D-Hands, these gestures in Si3D-Mobile are limited, to a certain degree, by the mobile device held in the hands.

Limitation in tracking a visual marker

Despite its advantages of convenience, the image-based marker-tracking system also has limitations. First, because the video images captured by the camera of the mobile device inevitably contained noise that varied in each frame, the position data of the mobile data extracted from these images could not be perfectly stabilized even when the mobile device was stationary. Thus, the virtual object displayed on the screen of the mobile device constantly pitched and rolled at a slight degree. Second, when the visual marker is not visible to the camera of the device, the interaction space disappeared from the screen and interrupted the user's sketching operations. Because user tend not to pay much attention to the visual marker during the sketching process, the requirement that the marker always be visible to the camera was sometimes bothersome and distractive.

5. User Trials

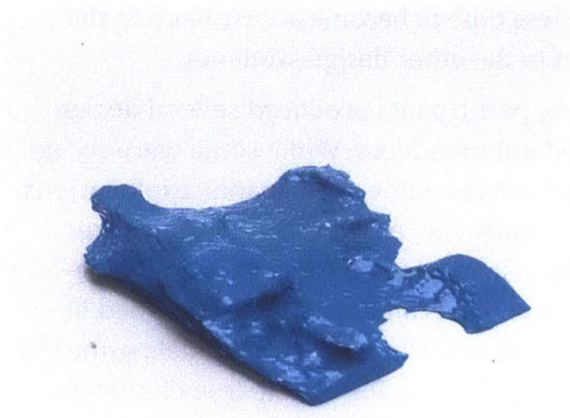
User trials were performed after the development of Si3D-Hands and Si3D-Mobile. The goal of the user trials was to observe differences and design processes in the use of the two systems, and obtain user feedback for future development. Because user trials lacked rigorous guidelines and were performed with few participants, it might not be appropriate to generalize merits and demerits of the 3-dimensional sketching systems in design practice or to comparisons between the two systems developed in this thesis project. However, these trials can serve as an informal basis to observe the design process of and reveal differences between the two systems.

5.1 Trial Setup

Three students were invited to participate by sketching 3-dimensional ideas. Participants A and B were graduate students from an architectural design program, and Participant C was from a computer science department who had little design experience.

I gave a brief demonstration of the two sketching systems with minimal explanation about GUI. Because the goal of trials was to test usability and observe the design process using the 3-dimensional sketching system, participants were asked to freely sketch whatever they wanted. Each participant had a time limit of three hours of time and one and half hours to use of each sketching system. Once the sketching processes were completed, free discussion occurred and the following questions were asked:

- What do you feel the differences were between the two systems?
- What do you feel the differences were in the design process using the 3-dimensional system compared to the other sketching media?
- What difficulties did you experience in using the two



Landscape / Participant A / Si3D-Hands

Trophy / Participant B / Si3D-Hands

Pyramid / Participant A / Si3D-Mobile

Building / Participant B / Si3D-Mobile

Figure 5-1: Design samples produced in user trials.

systems?

- What functionalities do you think need to be further implemented?

5.2 Result and Users Feedback

Because the Si3D system does provide tactile feedback or strong visual in space, it took about 20 to 30 minutes for participants to get accustomed to 3-dimensional sketching systems. During this preparation time, participants tried different tools and functionalities of the systems. Once they grasped how the systems worked, they started to sketch design ideas. Interestingly, Participant C, who had little design experience, took less time to become accustomed to the system compared to the other design students.

From the trials, participants produced several design models and tested different ideas. While some were recognizable, others did not resemble participants' explanations. Figures 5-1 and 5-2 present recognizable design figures produced from the user trials. Some design models produced during the user trials and self trials (described in earlier chapters) were made into physical models using the Zcorp 3D printer (Figure 5-3). During the free discussion sessions, participants shared their experiences and suggested the following valuable ideas:

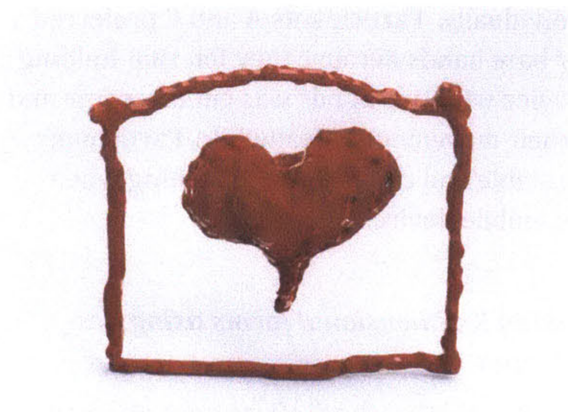
Impulsive sketching

Participants said that, because the Si3D systems solely relied on continuous gestural input and did not have a hierarchical geometric structure, they could quickly try their ideas without clear images or even intentions. Participant A stated,

> *"Whenever I try creating 3D designs using CAD tools, I always have to preconceive proper commands and geometric structures, which are not actually related to designs themselves. But when I tried the Si3D systems to create certain forms, I could just start from stirring my hands in the air, without spending any time thinking about the right procedures or command. Then more specific design ideas emerged as I processed the sketching."*

Difficulties in perceiving depth

In using Si3D systems, all participants reported difficulties in estimating the hand positions from the 2-dimensional screen. They found it more difficult in the Si3D-Hand sketching environment because they mainly relied on the visual feedback from the screen. Thus, they preferred sketching using the Pottery-Making mode because they needed to move their hands


Prisoned Heart / Participant B / Si3D-Mobile


Wine Glass / Participant C / Si3D-Mobile


Cyborg / Participant C / Si3D-Mobile


Nuclear Bomb / Participant C / Si3D-Mobile

Figure 5-2: Design samples produced in user trials.

less when virtual materials were rotating. Meanwhile, participants noted had better depth perception when using Si3D-Mobile because they could better estimate the position of the virtual material that was referring to the visual marker as a physical reference. Moreover, as described in the previous chapter, because participants' hands were within the sight when using Si3D-Mobile, they also had a better sense of spatial interactions by seeing how much their hands moved.

Preferences on different input methods

All participants responded that experiences in the Si3D-Hands system were more 'natural' than in the Si3D-Mobile; however, preferred input methods differed individually. Participants A and C preferred to use their bare hands because they felt that holding a mobile device with two hands was cumbersome and restricted their movements. Meanwhile, Participant B felt more stable and comfortable sketching when holding the mobile device.

Ease of making 3-dimensional forms using gesture-based input

Participants said that the Si3D systems allowed them to create certain forms easily. Specifically, Participant B explained that those forms can be easily conceived in the mind, but are difficult to model using conventional CAD tools. For example, he said, the building model with a spiral ramp inside (Figure 5-1) would need laborious procedures to be modeled in CAD tools, but he was able to shape it easily in the Si3D systems with physical gestures.

Lack of discrete controls and primitive geometries

Participant A responded that the lack of supporting discrete controls and predefined primitive geometries often caused inconveniences. Because the input of the Si3D systems was based on continuous body gestures, he felt that it was physically tiring to constantly move his hands or hold them stationary in the air. Moreover, the lack of discrete controls also made it difficult for participants to precisely manipulate sketched objects.

Participants also requested support for primitive geometries. When they wanted to use primitive shapes, such as a box or cylinder, they had to construct those shape manually, which they said was laborious. In addition, because Participants A and B were very familiar with CAD tools, they suggested incorporating some common geometric manipulation functions into the Si3D systems, such as scale, mirror, and copy.

Figure 5-3: 3D printed design samples.

Virtual simulations of unreal design circumstances

Participants expressed great interest in the Living-Creature mode, where virtual material autonomously changes its form. Because this interaction mode was implemented for testing purposes, thus, did not have meaningful interaction logic, participants could not produce recognizable designs. However, they noted that interacting with such a unreal material was very interesting. They anticipated that there is more potential for integrating intuitive gesture-based interfaces and virtual simulations, such as designing with fluid materials in a real-time simulation, or dynamic daylight simulations of buildings that could be deformed easily with hands.

6 Analysis

Developing the Si3D systems and conducting a series of trials, I was able observe several strengths and weaknesses of the 3-dimensional sketching systems developed in this thesis. In the first section, I summarize the findings obtained from a series of user trials and evaluated the Si3D systems. The limitations of this thesis are also described in the following section.

6-1. Evaluation of the Si3D sketching systems

Support for an impulsive, intuitive sketching experience.

The intuitive gesture-based interface and non-hierarchical geometric structures supported designers' quick and effortless sketching processes. Many CAD modeling systems require that users have a good amount of knowledge of geometric systems and modeling commands. These requirements often cause unnecessary distractions and interrupt the quick and effortless examination of ideas. However, the sketching systems developed in thesis do not required any prior knowledge of operations or geometric structures, thus, allowing designers to express their ideas quickly in 3-dimensional space. For example, during the user trials, after spending less than an hour getting accustomed to the system, participants, including a non-design professional, were able to produce meaningful 3-dimensional designs.

Body-inclusive sketching interactions for creative designs.

The intuitive interface and body-inclusive interaction mechanisms, which were implemented in this thesis project, helped users to externalize their 3-dimensional designs easily. For example, although complex and organic forms produced in the user trials can be conceived in the designers' mind easily, those forms often require that laborious and sophisticated modeling operations be constructed with contemporary CAD tools. In contrast, the 3-dimensional sketching systems developed in this thesis allowed designers to represent those forms easily in space by allowing them to construct 3-dimensionality with body gestures.

I speculate that the ease of externalizing 3-dimensional designs, which is aided by an intuitive gestural interface and body-inclusive interactions, facilitates 'reflection-in-action' as in Schön's frame (1983). In the sketching process, designers constantly have reflective conversations with their externalized ideas in fast rate. When it comes to 3-dimensional designs, the current means of sketching do not provide enough support for such conversations. For example, 3D CAD modeling tools delay reflection-in-action by demanding unnecessary precision and modeling procedures. Further, when performing 2-dimensional free-hand sketching, users cannot construct the full dimensionality of their 3-dimensional ideas. However, it seems that the Si3D systems support reflection-in-action at a fast rate by allowing users to test 3-dimensional ideas easily. For example, in the user trials, it was observed that participants quickly developed meaningful designs, even if they did not have clear images or intentions in the beginning.

Flexible shape recognition

The non-hierarchical geometric structure and representation of the Si3D systems allowed users to convert dimensionality of their design elements easily, which permitted users to reinterpret their drawn sketches in different ways. Due to the primitive nature of the Marching Cube representation system, there is no distinction between elements in different dimensions; all geometries are represented as volumes.

Ironically, this feature gave users more flexibility in reinterpreting their drawn elements by supporting visual ambiguity. For instance, even if the user drew a solid circle, it could then be interpreted as a cylinder. Moreover, he could easily convert it into a circular curve just by subtracting inner volume.

Potential of Integrating gestural interface and virtual interaction

The Si3D systems can provide rich sketching interactions where the designer can use physical knowledge and digital augmentation. For example, users could have original experiences that could hardly be obtained in real-world circumstances; such as sculpting a virtual wine glass that is half the size of the body, or drawing with living materials. Although this thesis demonstrated only a few possible cases, it seems that integrating a 3-dimensional gesture-based interface into computer-aided sketching systems has great potential to take advantage of the physical and virtual worlds.

Difficulties in constructing immersive 3-dimensional sketching environments.

The most apparent issue during the trials was that users perceived spatial depth and the 3-dimensionality of the virtual sketching space. In Si3D applications, various feedback systems, including visual cues and ambient sounds, were implemented to supplement difficulties in perceiving spatial depth from 2-dimensional feedback displays. However, users still found it difficult to perceive 3-dimensionality from 2-dimensional visual images without tactile feedback.

Moreover, in the case of Si3D-Hands, the inability to change viewing angles according to the body position caused a great inconvenience. Si3D-Mobile provided a better environment and allowed users to move the viewing angle with a body; however, they still reported inconvenience because the screen of a mobile device was rather small and it moved according to hand movements, not head movements. Therefore, a more effective feedback system to construct an immersive 3-dimensional sketching space needs to be developed.

The Lack of non-distracting controls over sketching environments.

When using the Si3D systems, users frequently changed several parameters of a sketching environment, such as intensities of tools and orientations of their sketch elements. In the case of Si3D-Hands, in which the uses' bare hands were the input devices, users experienced inconvenience when they had to switch between GUIs and a gesture interface. Moreover, a limited number of recognizable gestures could be used for additional commands. Meanwhile, when using Si3D-Mobile, users could easily access GUIs near their hands during the sketching operations; however, the sketching experiences were less body-inclusive and controlling GUIs with the fingers was still distracting to a certain degree. In reality, we can easily use different sketching tools, such as a pen, chisel, and eraser, and control them by slightly changing holding pressure, orientation, etc. To accommodate this type of spontaneous and natural control, more versatile input methods and intelligent gesture recognition systems should be investigated.

The lack of support for discrete controls and design primitives

Although the Marching Cube's geometric representation system provided several advantages as described above, it did not support functionalities as well as conventional CAD tools. It was observed that continuous gesture-based interactions of the Si3D systems could be laborious when users want to create primitive shapes. Moreover, because the Si3D systems basically provide only two geometric operations, adding and subtracting volumes, users can not modify or manipulate their design forms, especially when they were trying to further develop drawn sketches. Last, because the Marching Cube's geometric representation system was based on a scalar field, there was a limitation in implementing basic object-based manipulations such as copy, move, and scale.

Technical difficulties in tracking body gestures.

To accommodate a smooth body-inclusive sketching experience, a stable and accurate gesture tracking system is essential. This thesis used the Kinect motion-detecting sensor and marker-tracking technique to detect gestures. However, the erratic results of tracking hands (Si3D-Hands) and the loss of a visual marker from the a camera (Si3D-Mobile) frequently interrupted smooth sketching operations. Thus, more stable and unconstrained methods for gesture tracking need to be developed.

6-2. Limitations of the Study

The initial motivation of this thesis sought to determine whether it could be confirmed that the sketching systems developed in this thesis actually facilitate the design explorations of 3-dimensional ideas. Even though several positive aspects and drawbacks of spatial sketching systems can be identified through the development of this thesis, I must admit that this thesis has several limitations to answer this question.

First, this thesis focused on a partial area of the sketching process—making 3-dimensional volumetric forms using continuous body gestures. However, in practice, designers combine several types of sketches from a representation of design shapes to diagrammatic sketches with a schematized structure. Therefore, to confirm the validity of spatial sketching systems in real circumstances, those that can accommodate more types of sketches should be developed and examined.

Second, although this thesis explored original sketching experiences that lay on the border between the physical and virtual world, it did not fully investigate possibilities within the digital domain. Throughout the development of this thesis, it was observed that gesture-based computer-aided sketching systems are able to absorb the strengths of the advantages of physical and traditional sketching media and exploit advantages of the digital world, such as real-time simulations and intelligent design suggestions. Thus, extensive research on these possibilities needs to be implemented and tested.

Last, the user trials in this thesis do not adequately reflect real-world design circumstances. While designers explore and develop their ideas with specific constraints and goals, the participants of the current user trials did not have any of those and performed unconstrained design processes as the trials focused on observing usability. In this respect, merits and demerits of the 3-dimensional sketching systems observed during the user trials cannot be generalized within the real-world design context. In addition, the user trials in this thesis were not performed in a rigorous experimental setting with analytical methodologies, thus, a large portion of their interpretations does not achieve objectivity.

In sum, due to the limited scope of this thesis work and the lack of rigorous user experiments, the validity of 3-dimensional sketching systems in the general design context cannot be fully confirmed at this point. However, the observations and evaluations of this thesis do show great potential of 3-dimensional sketching systems, and set the foundations for further development.

7. Conclusion

In previous chapters, I illustrated the detailed implementations of the two versions of sketching systems, findings from a series of trials, and the overall evaluation of the Si3D systems. In this chapter, I summarize contributions of this thesis and introduce directions for future development.

7.1 Contributions

In this thesis, I have provided the theoretical background for the study of integrating a sketching interface with computer-aided design tools. By observing the history of design tools and comparing currently-available sketching media, I argued that the current means for sketching 3-dimensional ideas have several drawbacks. From this observation, I presented the criteria for a spatial sketching system that can facilitate creative design explorations. I then introduced related research projects exploring the integration of a sketching interface and computer-aided design tools, as well as clarifying different approaches that they have taken.

In order to propose a new 3-dimensional sketching system, I developed two versions of computer-aided sketching system: Si3D-Hands and Si3D-Mobile. By introducing detailed implementations and technologies used for the two, I demonstrated an integration of contemporary technologies, such as motion detecting and augmented reality technologies, into the sketching environments in the design context. By conducting a series of trials, I identified the strengths and weaknesses of the 3-dimensional sketching systems developed in this thesis.

In spite of difficulties immanent in implementing 3-dimensional sketching interactions in a virtual space, numerous indications exist that the recent technological advancements will soon change the way of interacting with computers. Researchers in the fields of computer vision, sensor technologies, and artificial intelligence are now trying to build computers that can understand us, as humans, and merge the physical and digital worlds. From the design perspective, a major questions should be, How could we exploit the advantages of this digital stream to facilitate the creative nature of design? As Sutherland stated, we were once writing letters to computers, and we are now conferring our ideas with computers. Perhaps, in the near future, we will be asking ourselves better questions with the support of computers that can unleash our inherent creativity.

This thesis project presents one possible way of using computer-aided sketching systems by integrating spatial gestures with virtual interactions. Therefore, the Si3D systems do not suggest a decisive proposition to a future sketching system that can aid designers' creative explorations of 3-dimensional ideas. However, findings from and evaluation of the Si3D systems contribute to envisaging a new computer-aided sketching system by providing viable proof of rich and creativity-centered design interactions that lay on the border between the physical and virtual worlds.

Throughout the development of this thesis, several underlying questions have been raised, including (1) How do different geometric representation systems support 3-dimensional design ambiguity? (2) How is our imagination related to our body knowledge? and (3) Can we conceive 3-dimensional designs that cannot be physically externalized? Further development of the Si3D systems will be continued not only to improve the current technical deficiencies, but also to answer these questions.

7.2 Future work

Throughout the development and user trials of Si3D-Hands and Si3D-Mobile, a number of potential applications and improvements emerged. This section outlines the next steps for future development of Si3D-Hands and Si3D-Mobile.

Gesture recognition

The capability to recognize diverse human gestures seems to have great potential in 3-dimensional sketching environments. If a sketching system can recognize unique gestures of individuals and allow users to assign different functionalities to their gestures, it would lead to a more customizable and user-centered sketching system.

Virtual interactions

During the trials, it was observed that users had a great interest in experiencing interaction modes that could not be implemented in the real world. Even though this thesis project implemented a few such interaction modes, a variety of possibilities could exploit advantages of the digital domain, such as sketching with fluid materials, interacting in spaces with different gravity fields, and sketching ideas with real-time simulations.

Improved Marching Cubes algorithms

The standard Marching Cubes algorithm used in this thesis has several limitations when used in the real-time sketching environment such as a demand for high computing power and coarse visual representations. However, the Marching Cubes algorithm has been extended in a number of ways to address such limitations. In future developments, improved versions of the Marching Cubes algorithm, such as adaptive Marching Cubes algorithm that use multi-resolution data, could be used.

Support for design ambiguities

Even though the geometric representation system used in this thesis project supported visual ambiguities, to a certain degree, there seems to be numerous ways to facilitate design ambiguities. For example, point-based representation systems could be experimented with to visualize geometry. Because human perception has a great capacity to extract diverse shapes from ambiguous silhouettes or boundary representations, this option could give users more flexibility in interpreting and reinterpreting their designs. In addition, because body gestures are inseparable from the passage of time, time-based synthesis of one's sketching traces could be also experimented with to allow users to reinterpret their designs in reference to time.

Support for the vertical transformation

The sketching systems developed in this thesis focused primarily on expanding the lateral transformations of the design process. However, it is also possible to improve these platforms so they accommodate vertical transformations seamlessly. For example, it may be possible to implement functionalities that extract primitive geometries, such as a sphere, box and cylinder, from the Marching Cubes data, so users can further develop their designs with standardized geometries in other CAD platforms.

Support for diagram sketches

A gesture-based interface seems to have great strength in sketching operations where spontaneous interactions are needed more so than are precise manipulations. Thus, if the systems developed in this thesis provide predefined geometries and convenient ways to embed semantic information into sketching elements, they could be efficiently used to create diagrammatic sketches that usually require tedious and repetitive processes when created by free-hand drawings or conventional CAD tools.

8. Bibliography

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9. List of Figures