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3D Sketching and Collaborative Design with *Napkin Sketch*

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "3D Sketching and Collaborative Design with *Napkin Sketch* " submitted by Min Xin in partial fulfilment of the requirements of the degree of Master of Science.

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Abstract

Computer-supported 3D design tools have become increasingly popular and abundant because they offer easy editing, efficient content management, extensive sharing, and rich rendering capabilities. However, many of these tools are focused on generating high quality, visually appealing, and detailed models of baked ideas but often seem to fail in effectively supporting the intricate process and environment which help to create and nurture these ideas in the early design stages.

Inspired by the simple yet rich interactions afforded by traditional design tools such as pencil, paper, or napkin in supporting the creative process of the early design stages, this thesis attempts to capture their essential qualities like portability, flexibility, fluidity, expressiveness, ambiguity, and sociability in *Napkin Sketch*, a computer-supported tool which enables 3D sketching and collaborative design. Concepts such as tangible interaction and freeform interaction are explored and applied to create a sketching experience which leverages users' innate ability to physically interact with tools, media, and collaborators and provides freedom to suggest ideas and invite changes without having to commit prematurely.

The contributions of the thesis are centered around *Napkin Sketch* which include a hardware platform that enables users to tangibly explore the 3D design space and manipulate the sketching media, a complementary software platform that facilitates the creation of 3D sketches while maintaining the familiar paradigm of sketching on a flat physical surface, a collaborative sketching environment that supports ad hoc co-located collaboration via multiple instances of the system, and three design critiques that provide preliminary assessment of the potential effectiveness of *Napkin Sketch* as a useful tool for supporting creativity in the early design stages.

Publications

Some of the materials, ideas, and figures in this thesis have previously appeared in the following publication.

M. Xin, E. Sharlin, and M.C. Sousa. *Napkin Sketch*-Handheld Mixed Reality 3D Sketching. In VRST '08: Proceedings of the ACM Symposium on Virtual Reality Software and Technology, Bordeaux, France, 2008. ACM Press.

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Chapter One: Introduction

Coffee Cup Scenario

An architect sits with his colleague in a trendy coffee shop. He casually sips his coffee as he scans the room. His eyes settle on a curious looking coffee cup on the counter. "What an elegant shape!" he gasps as he grabs his colleague and directs her gaze toward his new discovery. She considers it but seems uninterested. He takes out his pen and says, "I'll show you how this may fit with our project." He hastily grabs a clean napkin and starts to sketch out the shape of the coffee cup while modifying it slightly in the form of a building. As he renders some rough strokes on the napkin, he realizes the design he originally thought of has a major flaw. He takes another napkin, copies the parts of the old design he wishes to keep, and sketches an alternative design which solves the problem. He passes the napkin to his colleague, and she scrutinizes it.

She says, "There is no way this will work!" She returns the napkin to him and starts to work on some mathematical diagrams, detailing the problem with his design. "Unless," she suddenly stops sketching on her napkin, asks for his napkin back, copies parts of his design on a new napkin, and sketches her own input to the design. "How about this?" she asks, presenting him with her idea.

"How does this solve the problem?" he protests while looking annoyed.

"Here," she says, "I'll show you." She places the napkin with her design next to the napkin with his design and points out the problem areas on his and the corresponding solutions on hers. He reluctantly acknowledges her suggestions, but points out places in her design that can be made more elegant. He quickly sketches over his design with thicker strokes to indicate the changes and shows it to her. He also sketches some gardens for the surroundings of the building on another napkin and places it next to the modified design to compose a more complete scene. "Those are great ideas!" she exclaims, "I think this may work wonderfully for our project. Let's go with this!" She then takes a new napkin and carefully copies his modified design along with the added gardens and puts it in her purse. They discard the rest of the napkins and head back to the office to elaborate on the design.

Figure 1.1: Sketching as a catalyst for creativity

Sketching is a ubiquitous activity frequently performed in the early stages of creative tasks (Buxton, 2007). The importance of sketching may be overlooked because the produced sketches are often temporary, fragmentary, and easily disposed. However, the value of sketching transcends the mere byproduct of sketches themselves. As illustrated in the Coffee Cup Scenario the process of sketching involves and empowers an extensive ecology of physical settings, social environments, and interpersonal collaboration (Figure 1.1). Sketches can be used not only to record preconceived ideas but also act as stimuli for generating new proposals. They can be easily exchanged, compared, assembled, and used as props for demonstration. The flexibility and freeform nature of sketching are essential in providing an effective medium for visual exploration and communication.

In the early Renaissance artist-engineer, Mariano di Jacobi detto Taccola, used hundreds of rough sketches to explore ideas for his technological treatise, *De Machinis* (Buxton, 2007). In one section of his notebook, three alternative designs of attack boats with different weapons were shown, possibly indicating his use of sketching as an aid to thought and a tool for working through designs. Now, sketching is recognized as an essential process of cognition (Gross and Do, 1996) and has become a staple in the early stages of design and ideation for various creative fields such as architecture and engineering. The importance of sketching is reflected in the vast amount of research aimed at developing more advanced interfaces for performing this seemingly simple activity.

For centuries, the canonical pencil and paper have dominated as the tool and medium of choice for sketching. Their popularity has persisted even with the present widespread adoption of computer-aided design. Despite the saturation of technology, computer-supported tools are rarely used during early conceptual design, where ideas are generated, juxtaposed, and critically examined (Hennessey, 1999; Tovey, 1992; Fish and Scrivener, 1990; Coyne and Snodgrass, 1993). For example, sketching with pencil and paper is even preferred in the automotive industry, which employs an abundance of advanced technological tools for producing complex 3D models and highly realistic renderings of ideas that have been refined and solidified (Tovey, 1992).

If pencil and paper are so well-accepted, what exactly do they offer that other more advanced interfaces miss? Stapper and Henessey (1999a; 1999b) noted that pencil and paper are expressive, easy to use, and readily available. In contrast, various studies (Coyne and Snodgrass, 1993; Gross and Do, 1996; Kolli et al. 1993; Tovey, 1992) have identified the disadvantages of current computer-supported tools as being rigid, distracting to use, and sometimes difficult to access. Some may ask, “Do we really need to taint or replace pencil and paper with technology, or can pencil and paper actually be augmented by technology?” Theoretically, the question has been answered by Doug Engelbart in the sixties (Ruggles, 1997). He demonstrated that technology can “disaugment” the pencil by attaching a brick to a pencil and asking people to write with it. As a result, the pencil’s ease of expression was compromised. The argument was: if the pencil can be handicapped by attaching an obstacle, then it’s also feasible to augment it by removing obstacles. Following Engelbart’s argument, the question becomes which obstacles still exist for pencil and paper, and how can technology help to remove these obstacles while steering clear of introducing new ones? Ishii (1998) fears that the "technical efficiency-ism" of the digital world may trim away traces of human emotion captured by traditional media such as his example of hand-written poems. Therefore, what are the essences of sketching that must be maintained as the traditional tools that are capable of capturing varying facets of human expression become digitized?

Computer-supported tools certainly offer advantages over pencil and paper such as easy editing, efficient information management, extensive sharing capabilities, and powerful 3D depiction (Coyne and Snodgrass, 1993; Kolli et al. 1993; Tovey, 1992). However, it is not enough for such tools to simply produce an end result which looks like a sketch. Effective tools must also support the process of sketching itself. After all, the importance of sketching is also in the activity and not merely in the artifacts generated.

In this thesis, the emphasis is placed on developing a computer-supported sketching tool that attempts to augment and complement the skills and work practices of potential users in the ideation phase of early design.

1.1 Motivation

With the information processing and rendering capabilities of computer systems, there are a number of ways to augment traditional tools and media. For example, one of the possibilities suggested for the augmentation of pencil and paper in the architectural design process is the ability to actively explore 3D visualizations of design concepts. Although other conventional tools such as cardboard, clay, wire, and rubber cement and various modeling software can be used to produce 3D designs, they are not as ubiquitous, low-fidelity, and easy to use as pencil and paper (Piccolotto, 1998).

Traditionally, sketches are just 2D representations of 3D ideas. This characteristic allows them to be created quickly at the early design stages, but users must mentally and physically recompose the 2D sketches into 3D representations at later design stages. The process of transferring from 2D to 3D is not only cumbersome but also redundant since users are already evaluating their designs in 3D when creating 2D sketches, as can be seen with sketching practices such as creating multiple sketches from different points of view or sketching in perspective.

Sketching directly in 3D not only streamlines the design process, but also provides users with more opportunities for visual feedback and exploration (Lim, 2003). Buxton alludes to the possibility of sketches taking on 3D or sculptural form, and research (Igarashi et al., 2006; Eggli et al., 1997; Piccolotto, 1998) have investigated the spectrum of design activities in between conventional 2D sketching and 3D modeling.

Therefore, the main focus of this thesis in terms of augmenting pencil and paper is to support the creation of 3D sketches, but the challenge is to do so while retaining the essential qualities of the traditional tools and media in supporting the development and discussion of creative ideas. Interestingly, this challenge also forms the basis of the research goals presented in the next section.

1.2 Goals

The research goals of this thesis relate directly to the rich interactive experience provided by traditional tools such as pencil and paper. Reflecting back to the Coffee Cup Scenario, six important characteristics of conventional sketching practices are identified, and each characteristic is associated with a goal of the research. These goals serve to motivate and inform the design of a computer-supported system for 3D sketching and collaborative design, and they are described in the following list:

1. ***Portability*: The system should be able to be used in a variety of environments and should be always on hand to allow for spontaneous creativity and ad hoc collaboration with peers.**
2. ***Flexibility*: The system should support different ways of sketching and design and allow users to easily switch between them.**
3. ***Fluidity*: The system should strive to reduce the cognitive load of users in trying to use the interface to assist them in their creative process.**
4. ***Expressiveness*: The system should capture the subtle but rich information expressed in sketches from over sketched lines to crosshatched strokes to random scribbles.**

5. ***Ambiguity*: The system should use appropriate visual representations to accurately reflect the intended maturity of ideas and support the process of iterative design, where ambiguous concepts are refined and solidified over time.**
6. ***Sociability*: The system should support co-located collaboration with peers and allow sketches to be easily exchanged, compared, assembled, and used as props for demonstration.**

In Chapter Two, a more in-depth discussion of sketching and design is presented which provides further motivation for focusing on these research goals.

1.3 Approach

In order to achieve the aforementioned research goals, *Napkin Sketch*, a computer-supported system for 3D sketching and collaborative design is devised and implemented. First, a portable hardware interface is designed, involving the use of a tablet PC as the sketchpad for sketching and physical paper as napkins to be sketched on (Figure 1.2). One of the important approaches to achieving *Napkin Sketch*'s design goals is the concept of mixed reality (Milgram and Kishino, 1994), which describes the merging of the virtual and real worlds to create new visualizations and interactive experiences where elements of both worlds coexist. This is often achieved by overlaying video of the real world with computer-generated graphics that are referenced to real world objects. For example, interaction techniques associated with mixed reality are used to allow users to create virtual 3D sketches that appear anchored on top of physical napkins and to visualize the sketches on the tablet PC sketchpad as if looking through a magic lens (Figure 1.2). This allows users to intuitively move around the design space or manipulate the sketches by tangibly moving the tablet PC sketchpad or the physical napkins.

Figure 1.2: *Napkin Sketch*: creating a 3D sketch using sketchpad and napkin

Leveraging the tangible manipulations of the sketches and navigation of the design space, *Napkin Sketch*'s approach to 3D sketching is based on the projective 3D sketching technique (Dorsey et al., 2007; Kallio, 2005; Piccolotto, 1998), which requires frequent exploration of the design space. With projective 3D sketching, users sketch on the 2D surface of the tablet PC sketchpad, and the strokes are projected onto predefined 3D surfaces in the design space. In order to reduce the overhead of creating these surfaces, *Napkin Sketch* also uses a novel surface creation technique to define and position the surface often with only one stroke.

Because *Napkin Sketch* can create and manipulate virtual sketches in the real world, co-located collaboration, mediated through the physical embodiment of napkins, is also explored. The approach is to leverage the tangible manipulations of the napkins to facilitate the sharing, organizing, and assembling of sketches while providing awareness through these physical actions. *Napkin Sketch* also tries to capitalize on the users' innate abilities to interact in the real world by using the physical proximity of sketches to provide relevant functionalities for collaboration such as copying or privacy control. In Chapter Four, the Bridge Scenario provides a more complete overview of how *Napkin Sketch* is envisioned to be used in the real world and provides an analogue to the Coffee Cup Scenario to show how the research goals of this thesis can be achieved. For a more interactive demonstration and overview of the working prototype, Appendix B includes the thesis presentation video which shows the overall interaction experience of Napkin Sketch along with the details of important system features.

1.4 Contributions

Based on the motivations, approaches, and goals outlined, this thesis has three main contributions:

1. ***A portable hardware device and supplementary physical props which allows users to tangibly explore the 3D design space and manipulate the sketching media***
2. ***An enhanced projective 3D sketching software interface that incorporates gestures and other effective techniques to reduce the complexities of 3D sketching to better support creative thinking***

3. ***A collaborative sketching environment which makes use of the hardware and software to support and extend the social activities of sketching***

Another important contribution of this thesis are the three design critiques conducted which provide insight for future directions of the research and served to iteratively refine the design of the *Napkin Sketch* prototype.

1.5 Thesis Overview

In the remaining chapters of this thesis, the motivations, approaches, and contributions of this research are described in more detail. In Chapter Two, a high level review of relevant works and theories relating to sketching and design are explored, followed by a more comprehensive investigation of approaches taken by other research on supporting 3D sketching and collaborative design. The opening of Chapter Four presents the Bridge Scenario which illustrates a realistic vision of the ways that *Napkin Sketch* can be used in the real world. This scenario grounds the discussion of design concepts in the rest of the chapter with interaction examples that are motivated by them. In Chapters Five and Six, the hardware and software components of *Napkin Sketch* are outlined, and in Chapter Seven, the features and concepts relating to the collaborative aspects of *Napkin Sketch* are explained. Chapter Eight presents the findings of three brief preliminary evaluation efforts, and Chapter Nine concludes the thesis while also providing a discussions of future work.

Chapter Two: Understanding Sketching and Design

Before tackling the challenge of augmenting the existing tools and practices of sketching, this chapter provides insight for the actual sketching process, the larger context within which sketching is employed, and the characteristics of the produced sketches. This knowledge helps to establish the foundation and the motivation for the design of *Napkin Sketch* which is elaborated on in Chapter Four.

2.1 Sketching and the Design Process

Numerous studies have investigated the elements of sketching in various design applications (Plimmer and Apperley, 2002; Do and Gross, 1997; Tovey et al., 2003). A good starting point for gaining insight into how sketching fits into real world work practices is the field of architecture, in which sketching plays an important role, and the creative process is well studied (Suwa and Tversky, 1996; Suwa and Tversky, 1997; Aliakseyeu, 2003). There are also many examples of computer supported tools (SketchUp, 2010; AutoCAD, 2010) used for architectural design as well as established work practices around their use. In the following, the relationships of sketching, design, and the current role of computer-aided design (CAD) software are considered by examining various elements of the architectural design process.

As in many creative tasks, this process involves progressing from an abstract ill-defined problem to a solution (Goel, 1995). Four major design stages are identified (Aliaskseyeu, 2003), and each stage is characterized by the artifacts produced for design and the corresponding tools which produced them (Table 2.1).

Table 2.1: Four stages of architectural design (Aliaskseyeu, 2003)

Sketch design stage	Conceptual and sketch drawings
Preliminary design stage	More detailed sketch drawings
Definitive design stage	Detailed drawings
Final (shop) design stage	Working drawings

Rough and abstract sketches (Figure 2.1 left) are usually used in the sketch design stage mainly for conveying the most important ideas (Do, 1998). They tend to contain only simple elements such as lines, ovals, and rectangles (Do, 1998) which allow thoughts to be quickly downloaded from short-term memory (Plimmer, 2002). The preliminary design stage is similar but involves more precise drawings with added detail. Together, these first two design stages can be considered as the early design stages, where architects produce many drawings (Brown and Norton, 1992) to continuously observe, analyze, and critique their own work. Commitments are rarely made as ideas are “played” around with, and quick design iterations occur, while sketches are rapidly constructed, refined, and disposed. As reflected in the Coffee Cup Scenario, the process of sketching helps architects to uncover hidden relationships and unexpected discoveries as they engage in a cycling process amongst the brain, hands, sketch, and eyes (Laseau, 1989).

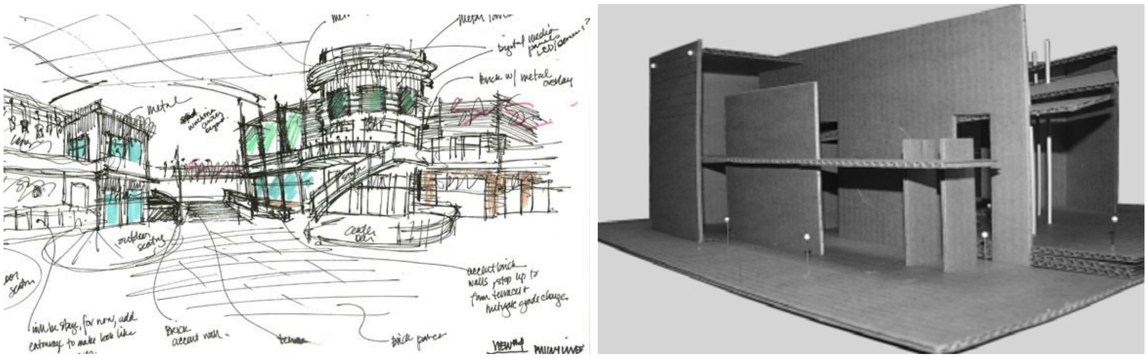


Figure 2.1: Early design sketch (left) (from http://www.arnoldimaging.com/blog/wp-content/uploads/2008/02/sketch0blog-02.jpg) and cardboard model (right) (Piccoloto, 1998)

The main purpose of the early design stages are to define basic ideas for construction which can be elaborated on at later design stages. On top of sketching, 3D mock-ups of the design may also be created with materials like clay and cardboard (Figure 2.1 right) to study the exterior form of the building and its relationship with the surrounding space. This shows the need for tools beyond pencil and paper to explore ideas and suggests possibilities for computer-supported augmentation.

The definitive design stage brings about commitments to particular design solutions. Architects use detailed drawings to elaborate on refined ideas and determine specifications such as dimensions, materials, and connections (Aliaskseyeu, 2003). Large-scale working drawings (Figure 2.2 left) are used in the final design stage which is more precise and communicates detailed information to contractors. These last two design stages allow less flexibility and deal with more concrete information. Their main purpose is to evolve already committed ideas, resulting in a deepening rather than a widening of the problem space (Goel, 1995). Unlike the early designs stages, where hand-drawn sketches are often used and valued for their expressiveness, drawings and 3D models (Figure 2.2 right) in the later design stages are mostly created with CAD software which provides precise depictions of the design and works well with standardized components.

From the description of the various architectural design stages, a few important insights should be noted. First, the early design stages tend to be more creative and flexible than the later design stages. This can be seen when comparing the corresponding activities, tools, and resulting artifacts. The sketch design stage and the preliminary design stage mostly involve exploration and experimentation, whereas the definitive design stage and the final design stage are more concerned with confirmation and presentation. Design decisions made in the early design stages have more impact than ones made later on (Aliaskseyeu, 2003). Therefore, the importance of the early design stages cannot be overlooked.

Figure 2.2: Working drawing (left) (from http://www.believeallthings.com/wp-content/uploads/2010/02/Kirtland_Temple_architectural_drawing.gif) and 3D model rendering (right) (from http://3detc.com/wp-content/uploads/2009/08/volkovo2.jpg)

It is also evident that sketching plays an important role in the architectural early design stages. In fact, Brown and Norton's study on the *Le Corbusier* Ronchamp drawings (Brown and Norton, 1992) showed a significant amount of activity in the sketch design and preliminary design stages especially for creating conceptual and sketch drawings. This reflects the exploratory nature of the early design stages and the various creative tasks supported by sketching. Although sketching is used in all stages of architectural design, this thesis focuses on designing a computer-supported sketching tool for the types of tasks and interactions involved in the early design stages.

2.2 Computer-supported and Traditional Design Tools

In architectural design, it is apparent that a mix of computer-supported and traditional design tools are used. Their strengths and weaknesses reflect their appropriateness for supporting various design stages and provide insight for designing future tools that will complement the users' existing work practices and needs.

Computer-supported tools help users with physical and geometrical calculations, 3D modeling and rendering, routine and meticulous tasks, and easy information access. Judging from the various architectural design stages, the advantages offered by CAD software appear more suited for tasks and interactions that occur later rather than earlier in the design process. Although CAD software may be used in early design, they are often high fidelity and targeted toward the later design stages (Suwa and Tversky, 1997), where the focus is on carefully recording the finalized plans of end products rather than exploration. Some use CAD software throughout the entire design process, but this practice tends to limit creativity in the early design stages and encourage poor design solutions (Lawson, 1999).

In contrast to computer-supported tools, traditional tools such as pencil and paper, cardboard, clay, wire, and rubber cement are more pliant, flexible, forgiving, and less committing. They encourage exploration and are more suitable for the early design stages. Traditional tools can be used to repeatedly create and reform ideas because they are low fidelity and easy to use. However, their representational capabilities are limited by the physical restrictions of the media. For example, pencil and paper can only be used to create 2D drawings, and cardboard, clay, wire, and rubber cement are dedicated for building 3D models with specific styles and levels of detail. Therefore, a wide range of tools and skills are required to accomplish various tasks and meet the needs of users. Perhaps, the most versatile, popular, and ubiquitous traditional tool is pencil and paper. It is a staple in the early design stages because it embodies the essential properties of sketching such as portability, flexibility, and fluidity in supporting the exploration of ideas. In attempting to introduce computer-supported tools to early design, much research (Gross and Do, 1996; Piccolotto, 1998; Dorsey et al., 2007) have targeted pencil and paper as the model for interaction design. In particular, interaction examples with napkins similar to those reflected in the Coffee Cup Scenario are often cited as motivation. In fact, Stappers and Hennessey (1999) provide an analysis of the differences between interacting with computer-supported tools and napkins in the early design stages to highlight the shortcomings of current computer-supported tools and hint at how they may be improved (Table 2.2). The research in this thesis is also inspired by pencil, paper, and napkins as the ideal interactive tools for the early design stages and attempts to integrate their characteristics in the design of *Napkin Sketch* along with the added capabilities of 3D sketching, light weight editing, and other advantages of computer-supported tools.

Table 2.2: Comparison of computer tools with conventional media (Stappers and Hennessey, 1999)

Computer-supported tools	**Sketching on napkins**
• Need to learn the syntax of actions, operate through an interface of menus, naming conventions, coordinate systems, transformations and units before starting	• Very easy to start to use • Only requires a pen and moderate drawing skills
• Interact with the representation, a hidden mathematical model, by moving a pointer over derived visual representation and choosing appropriate actions from a menu or toolbar • Menus or toolbars must be manipulated before seeing all parts of the visual representation	• Interact directly with the sketch • Focus attention by physically lifting it or move it
• Must be used in specific physical settings where the tools are	• Can start sketching right away • Do not have to travel to where the tool is situated • Can be transported easily
• Allow no vagueness • Must precisely indicate the weight and curvature of every line	• Can employ controlled vagueness
• Lack expressiveness • Shows only bare and "dead" geometry	• Sketches carry much more information than mere geometrical shapes
• Cumbersome to manage multiple drawings which disturbs the continuity of the work-flow	• Can easily lay out separate sketches and rearrange them spatially

2.3 What are sketches?

In the previous sections, the essences of traditional tools and media are made evident by studying the process of design, but further understanding of sketching practices can be gained by examining the actual sketches themselves, which also provide valuable insight for *Napkin Sketch*. Buxton (2007) offers an in-depth look at sketches by outlining a list of their properties (Table 2.3).

Table 2.3: Important characteristics of sketches (Buxton, 2007)

Quick	A sketch is quick to make, or at least gives that impression.
Timely	A sketch can be provided when needed.
Inexpensive	A sketch is cheap. Cost must not inhibit the ability to explore a concept, especially early in the design process.
Disposable	If you can’t afford to throw it away when done, it is probably not a sketch. The investment with a sketch is the concept, not the execution.
Plentiful	Sketches tend not to exist in isolation. Their meaning or relevance is generally in the context of a collection or series, not as an isolated rendering.
Clear vocabulary	The style in which a sketch is rendered follows certain conventions that distinguish it from other types of renderings. The style, or form, signals that it is a sketch. The way that lines extend through endpoints is an example of such a convention, or style.
Distinct gesture	There is a fluidity to sketches that gives them a sense of openness and freedom. They are not tight and precise.

Minimal detail	Include only what is required to render the intended purpose or concept. Superfluous detail is almost always distracting, at best, no matter how attractive or well rendered. Going beyond “good enough” is a negative, not a positive.
Appropriate degree of refinement	By its resolution of style, a sketch should not suggest a level of refinement beyond that of the project being depicted.
Suggest and explore rather than confirm	Sketches don’t “tell,” they “suggest.” Their value lies not in the artifact of the sketch itself, but in its ability to provide a catalyst to the desired and appropriate behaviours, conversations, and interactions.
Ambiguity	Sketches are intentionally ambiguous, and much of their value derives from their being able to be interpreted in different ways, and new relationships seen within them, even by the person who drew them.

From Buxton's summary of sketches and the practices of sketching in early design described in previous sections, it is clear how the tools and processes relate to the characteristics of these artifacts of sketching. Properties such as quick, timely, inexpensive, and disposable point to the transitory nature of sketching, indicating that sketches are mostly used to reflect on and stimulate creative thought rather than serve as representations of ideas. The notion of exploration is also reiterated which is expressed in characteristics such as distinct gesture, minimal detail, and ambiguity, suggesting that sketches must have conceptual holes that can be filled in through iterative refinement.

Buxton (2007) also states that sketches are social things. Not only are they useful for intrapersonal communication in terms of externalizing ideas and exploring new concepts, sketches also serve as the medium for collaboration. As demonstrated by the Coffee Cup Scenario, sketches can be shared, juxtaposed, assembled, critiqued, and used for interpersonal communication. Sketches encourage discussion and modification because they are rough and incomplete. In an example describing the visual representations used in the design of Lance Armstrong's bike, Buxton (2007) notes that visual cues such as lines that continue past their natural end points indicate the suggestive and tentative nature of sketches. Their purpose is to invite criticisms and changes from others. Furthermore, with traditional media like paper or napkins, sketches can be easily passed around, pinned up in public spaces, and spread out on a table for multiple collaborators to interact with. This alludes to the various physical environments and social settings that sketches may be involved in. Buxton (2007) advocates that cultivating the practice of sharing which defines the culture of design is more important than simply enabling it with technology. Therefore, an effective tool for the early design stages must also take into account the greater social and environmental context of the practice of sketching.

2.4 Summary

From the above sections, the relationships between the process of design, the tools used for design, and the artifacts of design provide both motivation and insightful design guidelines for *Napkin Sketch*. Currently, computer-supported tools are not well suited for the early design stages, and there is a gap between working with traditional media in the early design stages and having to convert their products into concrete digital representations in later design stages. It appears that computer-supported tools have distinct advantages such as 3D support that may benefit users, but often these advantages are offset by their shortcomings in supporting the creative process of the early design stages. These shortcomings are highlighted by looking at the characteristics of sketches, their affordances, and the interactions they enable. From the in-depth exploration of sketching and design, several key aspects of tradition tools and media emerge as critical guidelines that drive the design and implementation of *Napkin Sketch* and also serve as the goals of this research:

1. ***Portability*: The system should be able to be used in a variety of environments and should be always on hand to allow for spontaneous creativity and ad hoc collaboration with peers.**
2. ***Flexibility*: The system should support different ways of sketching and design and allow users to easily switch between them.**
3. ***Fluidity*: The system should strive to reduce the cognitive load of users in trying to use the interface to assist them in their creative process.**
4. ***Expressiveness*: The system should capture the subtle but rich information expressed in sketches from over sketched lines to crosshatched strokes to random scribbles.**
5. ***Ambiguity*: The system should use appropriate visual representations to accurately reflect the intended maturity of ideas and support the process of iterative design, where ambiguous concepts are refined and solidified over time.**
6. ***Sociability*: The system should support co-located collaboration with peers and allow sketches to be easily exchanged, compared, assembled, and used as props for demonstration.**

These guidelines and goals are reflected upon in the rest of the thesis as the design and implementation of *Napkin Sketch* are outlined.

Chapter Three: Beyond Pencil and Paper

Having gained a deeper understanding about the fundamental interactions related to sketching and design in Chapter Two, this chapter provides an overview of a wide range of related works that attempt to extend the interactive capabilities of traditional tools and media. First, different approaches to 3D sketching and design are discussed, which grounds *Napkin Sketch* in a rich history of 3D interfaces for modeling and informs its design as a sketch-based 3D modeling tool. Second, the concepts and relevant works of co-located collaboration are explored to support *Napkin Sketch*'s goal of not only enabling 3D sketching but also defining a new framework for collaborative sketching that is sensitive to its social nuances.

3.1 3D interfaces for sketching and design

One of the important ways *Napkin Sketch* tries to improve upon pencil and paper is by providing the ability to sketch and design in 3D. Because of the advanced visualization capabilities of digital systems, computer-supported sketching and 3D design is a broad and well researched area. There are a wide range of approaches that are aimed at creating intuitive 3D design experiences using computer-supported tools. The approach taken by *Napkin Sketch* draws inspiration from the types of approaches described in the following subsections.

3.1.1 Commercial 3D design software

Because of the popularity of 3D computer graphics in architecture and the entertainment industry, various commercial software products are available to create high quality 3D content. AutoCAD, Maya, and 3ds Max (AutoDesk, 2011) are frequently used by professional architects, designers, and artists to model buildings, scenes, and characters.

Although there are a few recent developments to incorporate hand-drawn sketches from early design stages into these software products, their main focus is on delivering precise and polished production quality content that may be animated and dynamically manipulated (i.e. games) or used as blue prints.

Despite being able to support stylus input, mouse and keyboard interfaces are often preferred by users of AutoCAD, Maya, and 3ds Max (AutoDesk, 2011) because of their precision. Typically, users create geometry by building on top of simple primitives using geometric operations such as union or intersection. They are also able to refine their designs by manipulating controls points or even individual vertices of the geometry. In order to provide such fine-grained control for modeling, these software products make use of explicit complex data structures to support various features that modify and transform the content in different ways. For example, in Maya, users can directly modify the node graph used to define the relationships of geometries in a scene. This allows detailed control of the lighting and animation of the geometries.

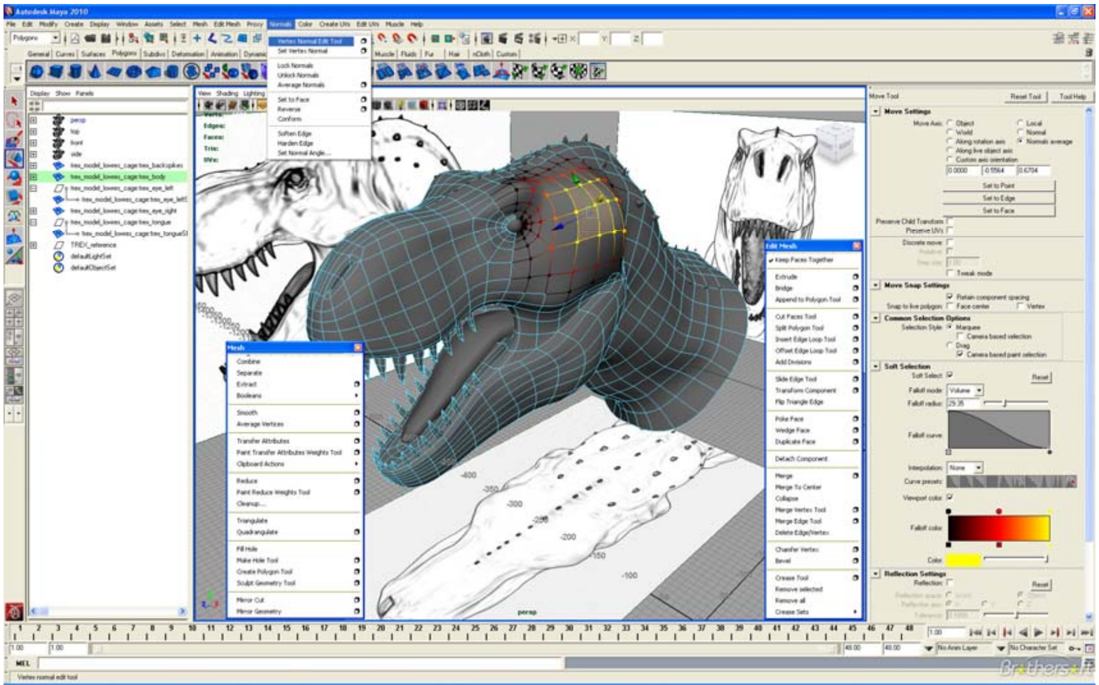


Figure 3.1: AutoDesk Maya 2010 (from http://img.brothersoft.com/screenshots/softimage/a/autodesk_maya_2010-339835-1265876404.jpeg)

Because the aforementioned commercial products are full-featured, their graphical user interfaces are packed with functionality (Figure 3.1) and often require extensive training before becoming proficient in their use. SketchUp (Google, 2011) is a commercial software which tries to simplify 3D modeling for casual use by the general public. Its focus is on providing intuitive and easy to use tools that are optimized for designing more geometric rather than organic models for architecture, civil engineering, and mechanical engineering.

Users typically create geometry in SketchUp by drawing 2D geometric primitives such as lines, curves, circles, and rectangles onto different surfaces. The program provides drawing aids based on the assumption that users are trying to create regular geometric shapes. For example, lines drawn will snap to existing end points, edges, principle axes, and positions that maintain parallel or perpendicular relationships with existing geometry. Although SketchUp has a pencil tool and its name is reminiscent of sketching with pencil and paper, the program actually does not allow freeform sketching. The pencil tool is simply a line tool that creates straight lines by defining two end points. With 2D primitives like lines, curves, circles, and rectangles, SketchUp allows users to use a push or pull technique to extrude them into surfaces. For example, a circle can be pulled into a cylinder, or it can be pushed into a hole. Using these basic operations along with the drawing guides, users can quickly construct complex geometric shapes (Figure 3.2).

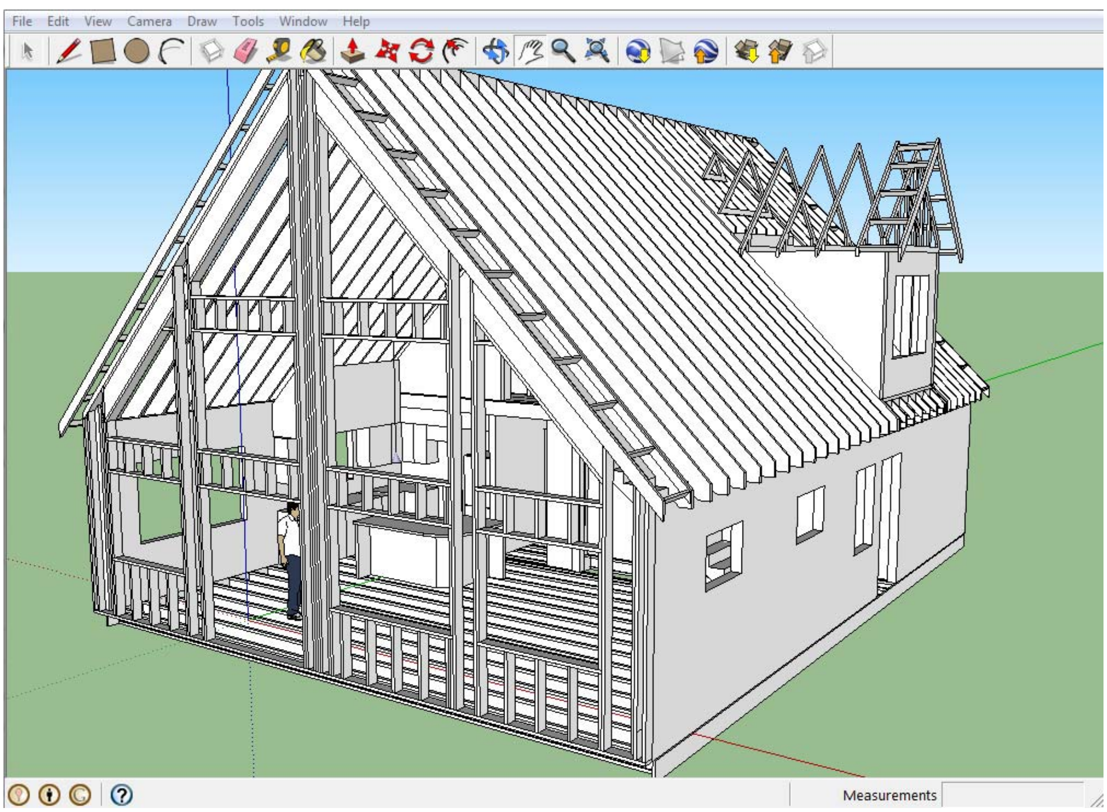


Figure 3.2: Google SketchUp 7.1

SketchUp's design view is most often a perspective view of the scene, and drawing guides such as snapping are dependent on the user's current view of the model. The program infers desired operations and provides the corresponding guides for them based on its interpretations of whether certain operations are more natural to perform in certain views. Therefore, changing the view of the scene is a common and necessary task. SketchUp currently distinguishes between modeling and view manipulations with the mouse by using explicit rotation, pan, and zoom modes activated by either keyboard shortcuts or toolbar buttons.

Because commercial 3D design software must appeal to the public where ubiquitous mouse and keyboard interfaces still dominate, their interface design options are limited. Furthermore, most commercial software are made for later stages of the design process where precision and the quality of the 3D content are more important than the process of producing them. In contrast, the goal of *Napkin Sketch* is not to allow users to create visually polished 3D content and therefore does not focus on precision and fine grained control, but rather it explores how some of the key 3D modeling and design space navigation techniques of commercial software can be adapted to work with new inputs devices that afford more fluid and expressive interactions.

3.1.2 Direct 3D Input

One of the challenges with 3D design using standard mouse and keyboard interfaces is the limited degrees of freedom of such input devices. A normal mouse or stylus typically only offers input intended to manipulate objects on a 2D plane such as windows on a virtual desktop. This maps well to 2D drawing applications that mimic pencil and paper, where the application simply records the 2D raw input from the mouse or stylus and outputs the data as 2D strokes. As presented in the previous subsection, 3D design applications are more complex because they must extend the 2D raw input of the mouse and stylus by combining it with key presses on the keyboard or explicit functions in the graphical user interface such as the push and pull function of SketchUp (Google, 2011). This relates to Beaudoin-Lafon's (2000) degrees of integration which is described as the ratio between the number of degrees of freedom provided by the logical part of the activity and the number of degrees of freedom captured by the input device. Interfaces that have a ratio of one tend to be more efficient because they do not have to incur the activation costs of having to deal with the extra complexities of the interactions required.

One approach to improving the 3D design experience and avoiding the complexity of conventional 2D interfaces for 3D design is to use 3D input devices and interaction techniques. Instead of the mouse or stylus only being able to provide 2D raw input, 3D input devices often offer full six degrees of freedom tracking which allows the input to directly map to the geometry that it is attempting to create. Several systems enable users to directly create and manipulate sketches and geometry in 3D with the help of various 3D tracking technologies such as magnetic sensors. The 3-Draw system (Sachs et al., 1991) introduced the concept of “design directly in 3D" which makes use of a pair of handheld six degrees of freedom 3D trackers. One tracker is attached to a clipboard while the other is attached to a stylus. The 3-Draw 3D design environment is anchored to the clipboard and can be adjusted by moving it with one hand, while the other hand can directly create and manipulate 3D curves within this design space by moving the stylus (Figure 3.3). This technique leverages people's innate sense to judge the relative spatial relationships of objects in both hands to make interaction within the virtual design space easier.

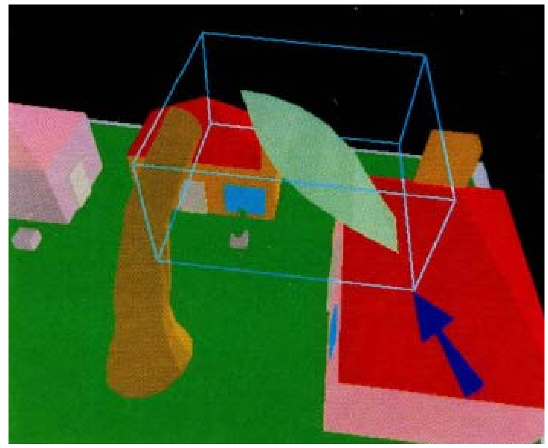


Figure 3.3: 3-Draw (left) (Sachs et al., 1991) and 3DM (right) (Butterworth et al., 1992)

Unlike the 3-Draw system (Sachs et al., 1991) where the 3D design space is visualized on a monitor, the 3DM system (Butterworth et al., 1992) uses a tracked head-mounted display to simplify the problem of 3D model manipulation and understanding by immersing users within a virtual 3D design space. It supports a handheld pointing device to allow users to build 3D geometry from within the virtual design space. Users can move around the design space by simply moving their head since the tracker maps physical movements into corresponding movements in the virtual space. Similarly, HoloSketch (Deering, 1995) uses head-tracked stereo shutter glasses, a desktop CRT display configuration, and a 3D wand manipulator to create virtual objects directly in front of the user (Figure 3.4). A stereoscopic view of the design space can be seen through the glasses, and the movement of the wand leaves behind trails of the current selected modeling primitive (i.e. spheres, points). The system also focuses on tracking accuracy and can allow users to precisely measure virtual objects with physical rulers.

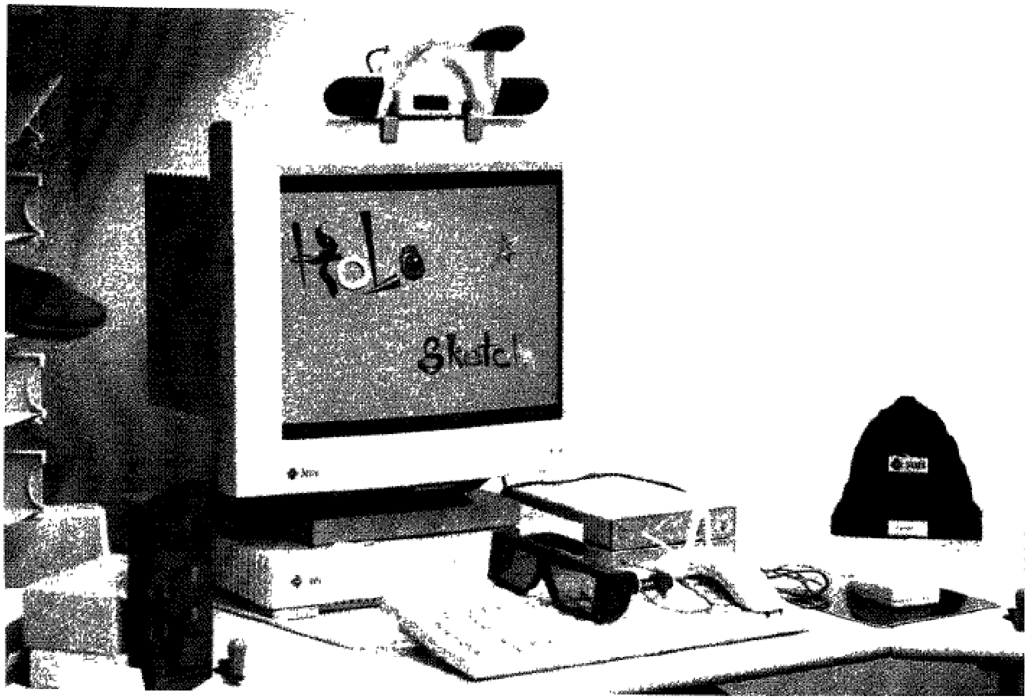


Figure 3.4: HoloSketch desktop virtual reality display system with head-tracked stereo glasses and 3D mouse/wand (Deering, 1995)

While most of the aforementioned systems used stylus-based sketching paradigms for modeling, others took advantage of richer interactive tools such as hands to shape and mould 3D geometry. Cheok et al. (2002) created an inexpensive curve and surface modeling system based on mixed reality visualization and the tangible manipulation of mesh control points with hand gestures. Users wore gloves that are tagged with markers and can see the virtual design space displayed on top of another set of markers through their camera equipped head-mounted displays. The tagged glove can be tracked by the camera and its movements can be interpreted as gestures to trigger functionality such as adding new control points or modifying existing ones. Another example is Surface Drawing (Schkolne et al., 2001) which allows users to create freeform surfaces in 3D space with hand gestures, where the shape of the hand becomes the primitive that leaves a trail in the design space to define a surface. This system also leverages mixed reality visualization and interesting tangible tools such as tongs to perform operations like scaling (Figure 3.5).

Figure 3.5: Surface Drawing (Schkolne et al., 2001)

Whereas most of the earlier works were designed to be used in stationary desktop or tabletop settings, Piekarski and Thomas (2003) explored the idea of design in situ. They presented a mobile outdoor mixed reality system that allows users to model and compose 3D geometry directly in the physical environment while also being able to walk around in it (Figure 3.6). Similar to Cheok et al.'s (2002) work, a pair of marker-tracked pinch gloves is used for modeling and user interface control, and a head-mounted display is used for mixed reality visualization (Figure 3.6). With a GPS tracking device, this system enables users to model in the Earth's coordinate space and place virtual 3D objects next to real world objects such as buildings and cars. Being able to design anywhere and within the context of the target physical design space provides opportunities for users to be inspired and influenced by their surroundings. This system capitalizes on such opportunities with features like the ability to quickly capture textures from the physical design space and reused them for creating new content.

Figure 3.6: Outdoor Mixed Reality modeling (Piekarski and Thomas, 2003)

All of the works presented in this subsection support direct manipulation because they all map 3D input directly to 3D modeling operations and 3D visual output in order to achieve a straightforward correspondence between them. Many of the systems' fundamental interaction techniques are simple in concept and allow unconstrained creation and exploration within the 3D design space. However, the setup of the technologies which enable such experiences can often be heavy weight and expensive even for mobile systems. Some of the shortcomings identified in these work include the lack of a clear design medium, the insufficient spatial understanding of the 3D design space, and the lack of haptic feedback. For example, users of the 3DM system (Butterworth et al., 1992) reported difficulties with wanting to sketch parallel lines. Unlike these works which attempt to provide a new design in space experience, *Napkin*

Sketch sticks to the basics of pencil and paper interaction, which provides the tangible affordance of a physical surface for sketching. However, *Napkin Sketch* does draw from the simplicity of direct manipulation using 3D input for the intuitive navigation of the 3D design space, and does so with a lighter weight and more portable solution.

3.1.3 Gesture-based 3D Sketching

Although 3D input devices are able to provide an intuitive where-you-sketch-is-what-you-get user experience, having to move the stylus through the air to sketch within a vacant 3D design space seems unnatural compared to traditional pencil and paper sketching, where the input is 2D, and the medium is almost always a flat physical surface. Whereas the use of 3D input devices tries to simplify 3D sketching for users through direct manipulation techniques, another approach described as gesture-based 3D sketching attempts to maintain the interaction paradigm of 2D sketching on a flat surface while inferring 3D geometry based on the sketched strokes.

With gesture-based 3D sketching techniques, a stroke on a 2D surface can be considered a gesture that triggers a 3D modeling operation based on that stroke. The Teddy system by Igarashi et al. (1999) makes use of a set of basic sketch-enabled modeling operations like shape inflation, extrusion, and cutting. For example, when the user sketches an isolated closed 2D stroke, the system automatically inflates the 2D shape into a 3D shape by making wider areas of the stroke fatter and narrow areas thinner (Figure 3.7). For more complex modeling operations such as extruding features, the system uses multiple strokes or gestures in sequence and leverages the context of where they are sketched. To create an extruded feature such as a horn, the user first sketches a closed shape on an existing surface to establish the base, then the user sketches a profile curve that extends from the base to form the shape of the feature (Figure 3.7).

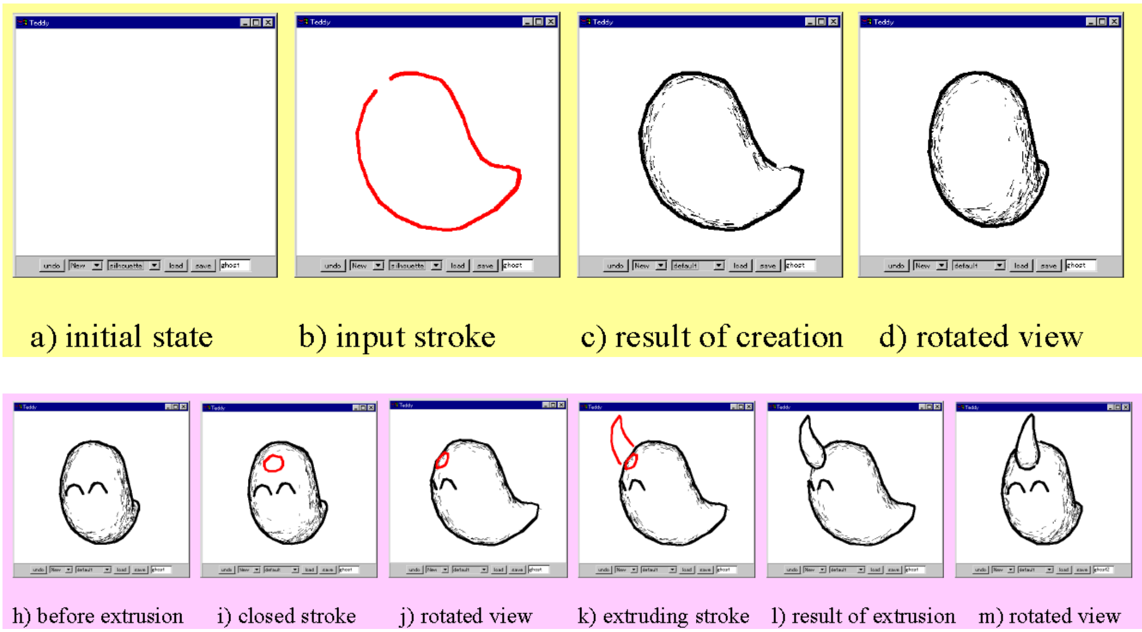


Figure 3.7: Gesture-base modeling operations of Teddy (Igarashi et al., 1999)

Similar to Teddy (Igarashi et al., 1999), Cherlin et al. (2005) also uses a shape inflation technique that requires user to first sketch two profile curves, then the system automatically fills in the space between the curves with circular disks of varying diameter and orientation based on the space in between the two curves (Figure 3.8). Non-circular 3D shapes can also be created but requires users to sketch an extra profile curve that is used to inflate the space between the first two profile curves instead of circular disks (Figure 3.8). The system also provides an editing mode that allows already sketched 3D shapes to be deformed based on a sketched deformation stroke (Figure 3.8).

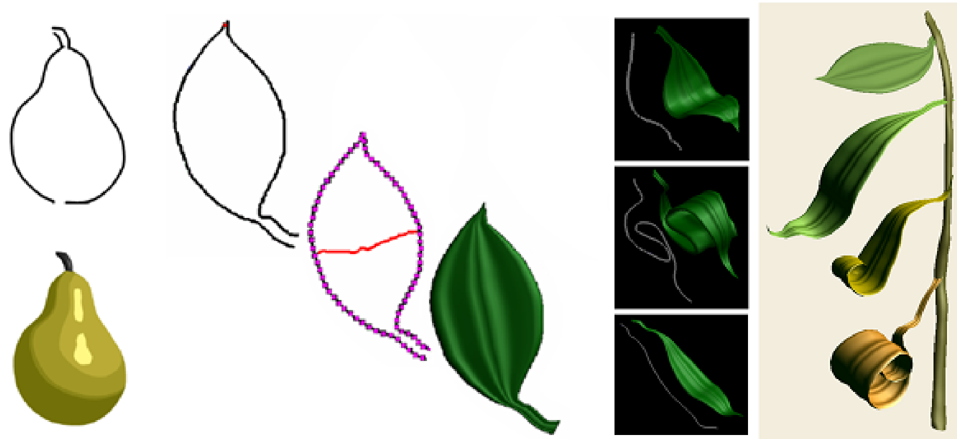


Figure 3.8: 3D modeling based on the inflation of profile curves (Cherlin et al., 2005)

One of the characteristics of gesture-based 3D sketching techniques is that the complexity of the modeling gestures required often scales proportionally with the complexity of the modeling operation because the ambiguity of converting from 2D to 3D increases. Some works (Eggli et al., 1997; Michalik et al., 2002) deal with this issue by applying geometric constraints like curve continuity to resolve modeling ambiguities, while others (Zeleznik et al., 1996; Do, 2001) deal with this issue by distilling strokes into a modeling grammar that must be composed in a particular sequence to create the desired outcome. For example, Anastacio et al.'s (2006) work on plant modeling allows users to sketch and modify a set of structured construction lines to influence the automatic growth of simulated plant models. Users sketch curves in a grid-like fashion, where the vertical curves define the boundaries of the plant and the shape of the stem, and the horizontal curves define the shape and orientation of branches (Figure 3.9). This technique gives users high level control over the general shape of the plant, and the details are filled in based on the established high level parameters and phyllotactic patterns.

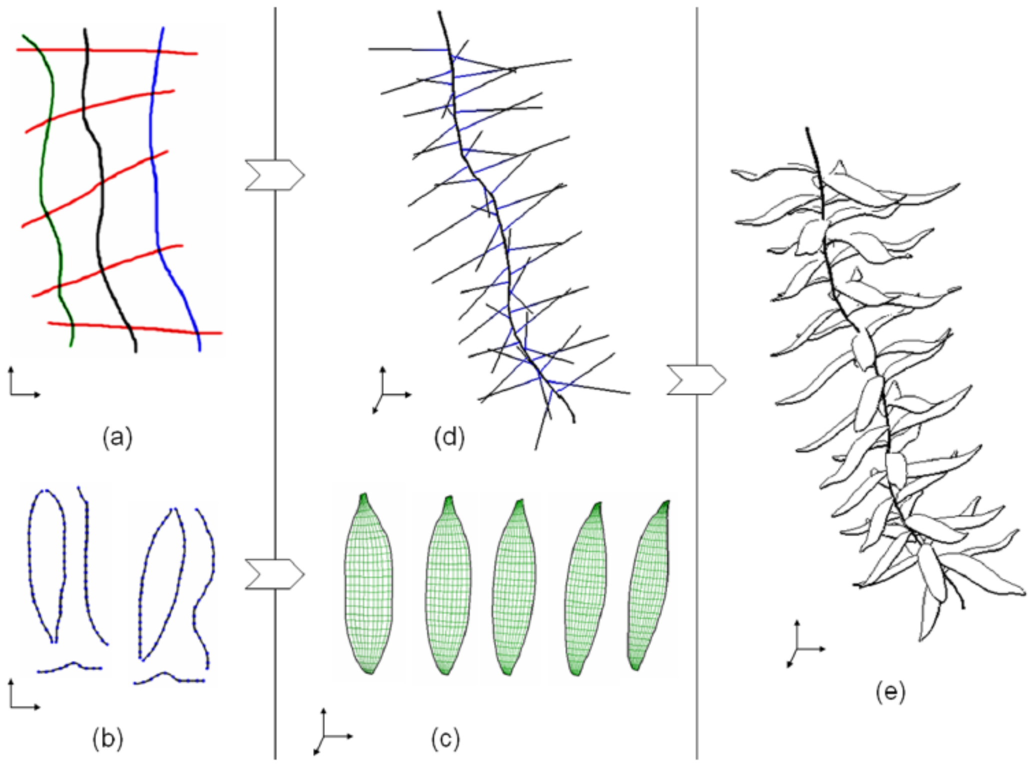


Figure 3.9: 3D plant modeling based on sketched structures and phyllotactic patterns (Anastacio et al., 2006)

Gesture-based 3D sketching techniques can be viewed on a spectrum based on the level of autonomy provided by the system in assisting modeling operations. Sketch recognition can be seen as one extreme which attempts to map a single gesture or sketch representation to a modeling operation or target 3D model (Severn et al., 2006). This is essentially a sketch-based method for triggering various functionalities and is therefore often used for simple editing commands like deleting or copying content. More complex gesture-based techniques allow more customization of the created content but requires more steps to complete. Although gesture-based techniques can help to simplify the process of sketching 3D content, the output may not always be what is desired by the user because the system tries to make logical inferences based on limited user input to disambiguate the intention of the user. Gesture-based techniques also tend to throw away or transform too much of the important information that is captured in sketches, and since one of the goals of *Napkin Sketch* is to support expressiveness and ambiguity in the design process, gesture-based techniques are not appropriate to use as the main interaction paradigm for 3D sketching. However, *Napkin Sketch* does explore the use of gesture-based techniques as efficient ways to establish relevant sketching guides to aid the sketching process and improve the fluidity of the interaction.

3.1.4 Projective 3D Sketching

Another approach for creating 3D sketches while maintaining the familiar 2D sketching interaction paradigms of traditional pencil and paper is described as projective 3D sketching. This approach allows users to first intuitively sketch on a 2D surface, but the sketched 2D strokes are then projected from that surface into the 3D design space and onto 3D surfaces that are placed in it. Unlike gesture-based techniques where strokes sketched are immediately transformed and interpreted by the system, projective 3D sketching comes even closer to familiar pencil and paper sketching by providing a what-you-see-is-what-you-sketched experience that preserves the appearance of the original sketched strokes.

Sketchpad+ (Piccolotto, 1998) allows users to sketch 2D strokes with a stylus on the surface of a large tilted digital design table which result in the creation of 3D sketches through the process of projection (Figure 3.10). The process is analogous to picking up a sheet of paper, holding it up in a certain orientation in the 3D design space, and sketching on it. In this sense, a 3D sketch can be described as the combination of various strokes sketched on different sheets of paper or surfaces in the design space. In Sketchpad+, these virtual surfaces for sketch projection can be moved and rotated anywhere in the virtual design space using the stylus and typical object handles for 3D manipulation. The system also enables users to model explicit surfaces framed by sketched strokes to create a more solid representation of the design.

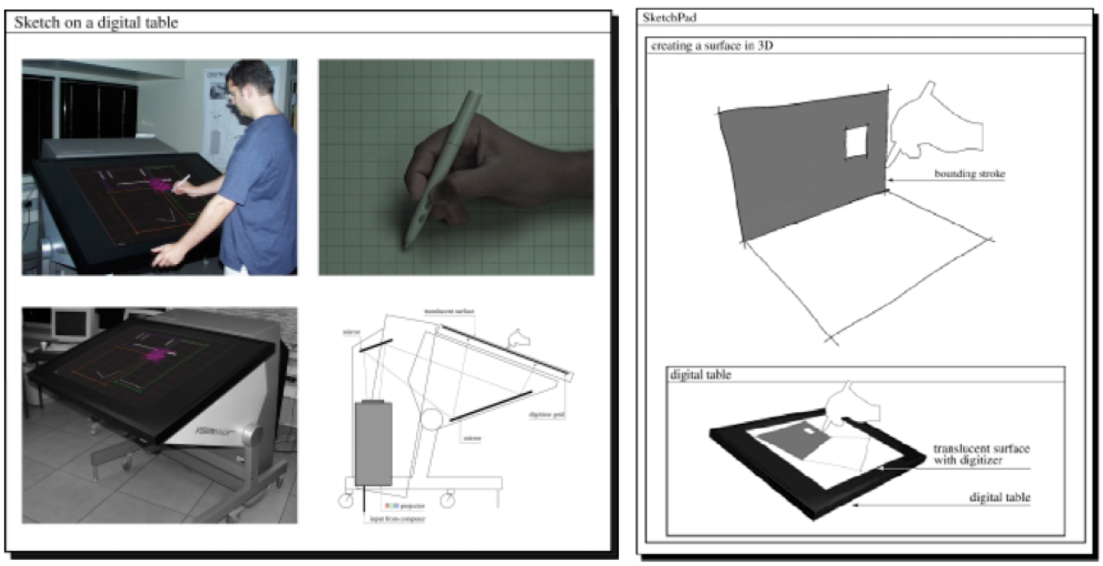


Figure 3.10: SketchPad+ (Piccolotto, 1998)

3D6B (Kallio, 2005) is similar to Sketchpad+ (Piccolotto, 1998) in its use of the projective sketching approach. Its goal is to produce sketches which can be incomplete and ambiguous in nature. Therefore, it does not support surface generation through interpretation. Users can transform grid planes for sketch projection in 6 degrees of freedom and manipulate them using keyboard commands while they sketch with the mouse or stylus at the same time. Using bimanual interaction to move the sketching surface while sketching allows complex non-planar curves to be created.

Tsang et al. (2004) devised a system which makes use of existing 2D images as guides for sketching 3D wire frame models. 3D models are created by sketching 2D profile curves on construction planes from top, side, and front viewpoints. Construction planes can also be moved to allow users to sketch curves in different locations, and non-planar curves are supported by projecting 2D strokes onto non-planar surfaces. The system also employs many suggestive techniques by using the 2D image as a guide to interpret the context of the sketches.

Another approach to projective 3D sketching is explored in the work on the Mental Canvas (Dorsey et al., 2007). This system is designed to allow architects to organize concept drawings in 3D and compose a 3D sketch from multiple 2D sketches created from different points of view. Similar to other projective 3D sketching systems, users can build a 3D sketch by first defining and positioning planar sketching surfaces called canvases in the design space (Figure 3.11). This is achieved using typical 3D interface controls to position, rotate, and scale the canvas on three coordinate axes. Users can then either sketch directly onto different surfaces which requires them to switch canvases as they sketch, or they can lock the view of the scene to a certain perspective and produce a static 2D sketch registered to that specific point of view. The system allows users to quickly go back to these registered view points to review their sketch and also to select strokes within the sketch to push or project onto existing canvases. This technique provides an alternative work flow, allowing users to first make several regular 2D sketches and later fuse them together to create the 3D sketch (Figure 3.11). Unlike Sketchpad+ (Piccolotto, 1998) where surfaces can be explicitly modeled as meshes, the Mental Canvas facilitates the suggestion of surfaces by allowing users to paint parts of a canvas opaque with a 2D binary texture map to hide the strokes shown behind it. This maintains the system's support of ambiguous intentions since surfaces are only perceive but not explicitly modeled.

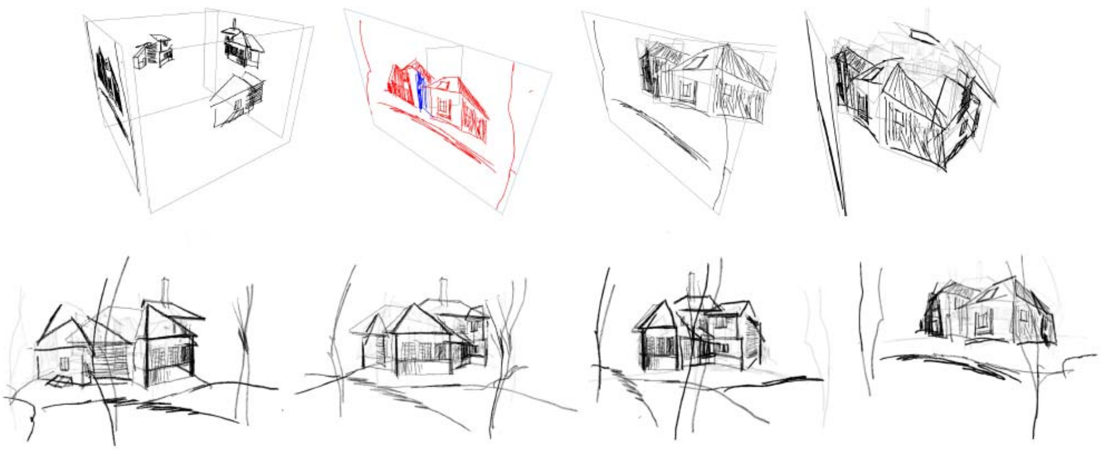


Figure 3.11: A 3D sketch created by combining 2D sketches from different perspectives (Dorsey et al., 2007)

Because projective 3D sketching provides the closest sketching experience to pencil and paper, it is the approach used by *Napkin Sketch* as the main interaction paradigm for 3D sketching. However, it requires the extra overhead of having to define projection surfaces. A bottleneck of this approach is the efficient placement of these surfaces in the design space. The systems described in this subsection make use of typical 3D manipulation operations to position and orient the sketching surfaces. These operations can be slow and non-trivial because they may require several extra steps to complete, potentially disrupting the users' creative process. *Napkin Sketch* attempts to improve upon this problem with a novel gesture-based one stroke technique for efficiently creating and positioning planes in the design space to allow users to quickly continue sketching as they switch between sketching surfaces.

3.1.5 Hybrid Approaches to 3D Sketching

In an effort to improve upon the shortcomings of various 3D sketching approaches, there are a couple of systems that combine the aforementioned techniques in interesting ways. The 3D Tractus (Lapides et al., 2006) is a system that makes use of a novel 3D input device to provide a tangible way of defining surfaces for projective 3D sketching. It uses a tablet PC placed on top of a mechanical table which can be moved up and down to record the third dimension (Figure 3.10). By moving the table and drawing with the stylus on the tablet simultaneously, complex non-planar curves can be generated much like 3D6B (Kallio, 2005). This setup also solves the problem of haptic feedback common for 3D input devices because users are always sketching on the flat surface of the tablet PC. However, since its design space can only be explored through axis-aligned vertical volume slices, the 3D Tractus (Lapides et al., 2006) is not suitable for sketching arbitrary 3D geometry.

Figure 3.12: The 3D Tractus (Lapides et al., 2006)

ILoveSketch (Bae et al., 2008) is a curve sketching system that also strives to capture the affordances of pencil and paper for professional designers. It integrates and improves upon a variety of design space navigation and 3D sketching techniques such as projective 3D sketching to provide a fluid sketching experience. While the system supports basic navigation techniques such as panning, zooming, and 3D rotation and five different 3D sketching techniques including projective 3D sketching, it also introduces the concept of sketchability which is used to implicitly and automatically adjust system parameters to increase a user's throughput. Sketchability is a view dependent scalar measure that helps determine how good a given viewing angle is for 3D sketching, and base on this measure, the system applies auto-orientation to the design space to achieve a more comfortable sketching experience. For example, when a new planar surface is created for projective sketching, the system adjusts the view of the design space to optimize sketching on that surface. ILoveSketch (Bae et al., 2008) also makes heavy use of a small gesture set to trigger various functionalities offered by the system. One example is a small lasso gesture on a sketched curve which activates an axis widget that allows users to select a 3D sketching technique by crossing over different axes.

Similar to the two systems described in this subsection, the design of the *Napkin Sketch* 3D sketching experience is also a hybrid of the aforementioned techniques. Unlike the 3D Tractus (Lapides et al., 2006), *Napkin Sketch* stays true to the pencil and paper interaction experience and does not focus on the simultaneous bimanual manipulation of the sketching surface and the stylus to create 3D strokes. Instead, the 3D sketching experience in *Napkin Sketch* focuses on the projective 3D sketching technique while attempting to improve upon it with the use of mixed reality, a 3D input device, and gestures. Unlike ILoveSketch (Bae et al., 2008) where the system automatically optimizes the sketching experience for users to increase their efficiency, *Napkin Sketch* integrates 3D input hardware with complementary software to capitalize on users' innate ability to physically navigate around the design space. The exploration with *Napkin Sketch* also goes beyond just 3D sketching and attempts to creates a collaborative environment that is essential to the early design stages. The works which inspired the latter part of this exploration are discussed in the following section.

3.2 Collaborative Design

The area of computer supported collaborative work is well-studied in the field of human-computer interaction. It addresses how collaborative activities and their coordination can be supported by means of computer systems (Carstensen and Schmidt, 1999). As seen in the Coffee Cup Scenario and also highlighted in the previous chapter, collaboration is an important aspect of sketching, and cultivating the practice of sharing which defines the culture of sketching is more important than simply enabling it with technology (Buxton, 2007). The sociability of the sketching experience is one of the important research goals of this thesis, and the works that motivated the design approaches of *Napkin Sketch* are discussed in the following subsections.

3.2.1 Collaboration in Augmented Environments

In order to more effectively support collaborative work as information becomes increasingly digital, the focus on computer-augmented environments is gaining popularity as a way to relate abstract digital information to real world environments and to capitalize on real world interactive techniques that are innate and familiar to users. This approach also attempts to address the challenge that collaborative systems may be resisted if they interfere with the subtle and complex social dynamics that are common to group work (Grudin, 1994). Such social subtleties can be difficult to integrate and support in computer systems. Therefore, the concept of augmented environments is to mimic the interaction settings and techniques of the real world to create more effective computer supported collaborative environments.

Ishii et al. (1994) advocated the concept of seamlessness in computer-supported collaborative technologies. Their design goals are to maintain continuity with existing work practices and facilitate the smooth transition between different functional spaces such as individual and shared workspaces. Their work on the TeamWorkStation-2 (Ishii et al., 1994) enabled remote collaborators to share a virtual workspace by providing each collaborator video of individual workspaces translucently overlaid on top of each other (Figure 3.13). Each collaborator can work in their individual workspace, but video of their work along with their hand movements are captured and visually augmented with the work and hand movements of other collaborators. This technique not only allows work to be shared, but it also provides awareness of the collaborators through the movements of their hands so that the dynamic process of the work can be shared as well. Videos of the faces of collaborators are also captured and displayed in a separate window to enhance the sense of presence of remote collaborators (Figure 3.13).

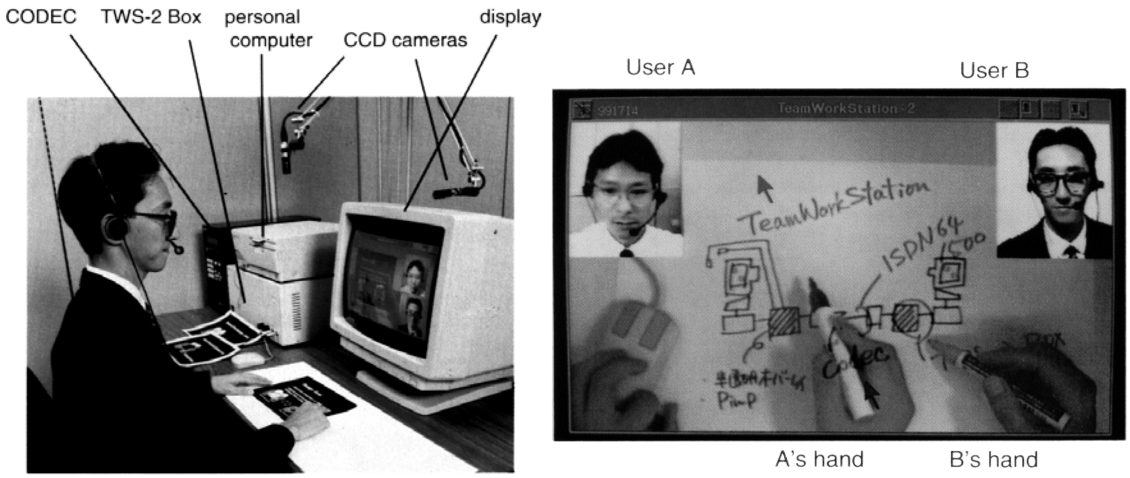


Figure 3.13: TeamWorkStation-2 (Ishii et al., 1994)

In their follow up work on ClearBoard 2 (Ishii et al., 1994), mirrored drafting tables are used to capture the face, hands, and annotations made by each remote collaborator and overlaid onto the table surfaces of other collaborators. This provided an experience similar to talking through and drawing on a big transparent glass board. With this setup eye contact and gaze awareness are better supported, increasing the feeling of intimacy and copresence of the collaborators. A new shared drawing application called TeamPaint is also used to digitally capture the drawing of collaborators which enables more advanced editing capabilities of the shared work.

Similar to Ishii et al.'s (1994) work, Billinghurst and Kato (1999) wanted to reduce the functional and cognitive seams in collaborative interfaces by supporting face-to-face conversion through mixed reality. They advocated for the benefit of relating virtual objects to the physical environment of the user and the utility of being able to seamlessly transition between interacting within the virtual space and the physical space. The WearCom project explores the use of wearable computers to facilitate remote collaboration (Billinghurst and Kato, 1999). The user is equipped with a head-mounted display to deliver video of the augmented physical environment, and head tracking is used to provide a body-stabilized display of remote collaborators, visualized as a virtual cylinder of visual and auditory information surrounding the user (Figure 3.14). By placing virtual remote collaborators in the physical space around the user, the system allows the user to use natural head motions to attend to different collaborators simultaneously while maintaining awareness of the physical environment and other conversations in the communication space.

Figure 3.14: WearCom system for mixed reality remote collaboration (Billinghurst and Kato, 1999)

Another work on mixed reality collaboration studied the concept of Shared Space (Billinghurst et al. 1998) which allows multiple users to work together in both the real and virtual world through head-mounted displays. The focus of this work is to evaluate the benefits of being able to collaborate in a mixed physical and virtual environment instead of being fully immersed in the digital world and isolated from the real world. This new approach for three-dimensional computer-supported collaborative work attempts to maintain continuity with the users' existing physical workspace. In order to explore the differences in task performance between collaboration in immersive virtual reality and the mixed reality Shared Space, a two player game is created, where players have to arrange different coloured virtual shapes in a target configuration. Players play the game in both an immersive virtual reality setting and a Shared Space setting, and the results show that players performed better when they can see the real world and each other while communicating using body cues and perceived that they performed better under such conditions. This is because increased communications bandwidth facilitated by seeing the real world and real people aid task performance when body cues are used (Billinghurst et al. 1998).

Recognizing the advantages of grounding collaboration with digital content in the physical environment, Xiangyu et al. (2008) developed a mixed reality tabletop system for enabling face-to-face collaborative design review. Their goal is to investigate the effectiveness of mixed reality tools for design reviews compared with paper-based methods. They noted that 2D or even 3D design drawings are often difficult for users to interpret in 3D, and spatial cognition is critical to ensuring successful face-to-face design reviews. The system consists of a tabletop decorated with a sparse distribution of markers (Figure 3.15). Collaborators are seated across from each other while wearing head-mounted displays each fitted with a front-facing camera (Figure 3.15). Through the head-mounted display, each collaborator is able to visualize the shared 3D design subject from a unique point of view. Interaction with the 3D design subject is supported with the use of tangible cubes covered with markers (Figure 3.15). Results of the experimental studies indicate that collaborators using the mixed reality system completed tasks faster than collaborators using only paper-based methods because the mixed reality system helped to offload some mental processing necessary for spatial cognition.

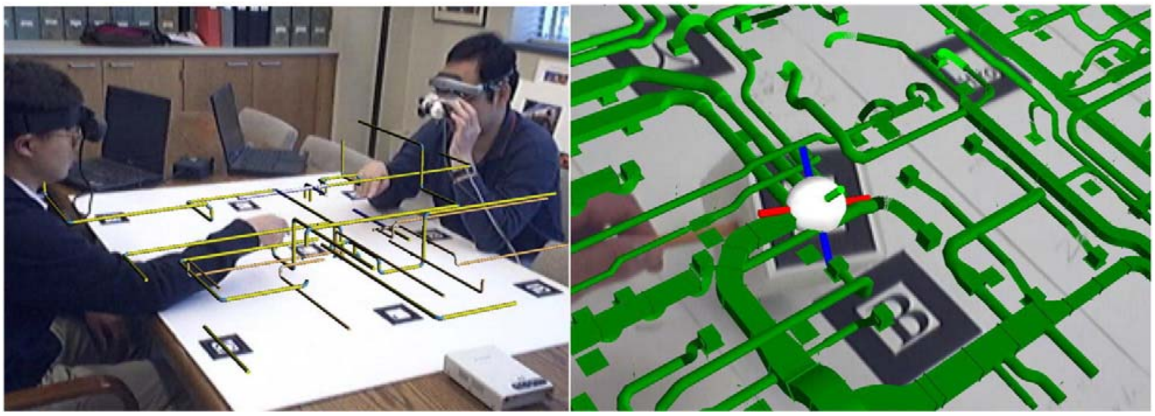


Figure 3.15: Mixed reality system for face-to-face collaborative design review (Xiangyu et al., Year)

Seichter's (2003) Sketchand+ also explored mixed reality interaction on a tabletop surface but focused on the use of physical props to easily annotate, share, and compose different virtual sketched content. Users of the system are equipped with head-mounted displays and can create virtual 3D sketches by sketching directly on top of a magnetic digitizer while visualizing the augmented output through the head-mounted display (Figure 3.16). Special storing slots implemented as markers can then be used to transfer the current sketch from the digitizer to the storing slot, allowing users to create new sketches. The intent to store sketched content is inferred by placing a storing slot close to the digitizer, and once stored, the content in the storing slot is distributed to all collaborators so they can view the shared content. Users can also attach text messages and audio to the content in the storing slots as metadata to help collaborators better understand design intentions. The attached metadata can be revealed by placing a designated marker close to the storing slot.

Figure 3.16: Sketchand+ makes use of physical props to store various design for collaborative design (Seichter, 2003)

The works presented in this subsection demonstrate various ways digital systems can support collaborative work but also identify potential interaction problems with certain approaches. The design of *Napkin Sketch* attempts to follow Ishii et al.'s (1994) goals of maintaining continuity with existing work practices and facilitating the smooth transition between different functional spaces. *Napkin Sketch* tries to achieve these goals by extending various mixed reality techniques that are discussed such as the use of physical props and inferring user intention through proximity. To improve on the heavy weight nature of typical mixed reality systems, the use of mobile devices for collaboration are examined in the next subsection.

3.2.2 Collaboration with Mobile Devices

As mobile devices are becoming increasingly ubiquitous and powerful, they are perfect platforms for achieving *Napkin Sketch*'s goal of portability and being able to support spontaneous collaboration in almost any environment. One of the drawbacks of many mixed reality systems is the cumbersome hardware users are required to wear such as head-mount displays and tracking-enabled gloves, but mixed reality systems can also be implemented using mobile devices which offer a less immersive but simpler setup. Rekimoto (1996) developed a hand-held mixed reality system for collaborative design. His system allowed two or more collaborators to hold palmtop see-through displays to visualize shared virtual objects relative to a shared physical space (Figure 3.17). Collaborators can select and move objects using their palmtop displays by aiming the display at a virtual object in the physical space, picking it up using a button on the display, and manipulating it with physical movements of the display. A virtual beam is rendered in the direction pointed at with the display, and selection can be triggered by the button once the beam is close to a virtual object. Only one collaborator can manipulate a virtual object at a time, and ownership of virtual objects is implicitly determined through selection. A study of the system found that overlaying virtual objects in the physical space was effective in helping users understand the location and size of virtual objects and externalizing interaction with virtual objects through physical movements helped to increase the collaborators' awareness of each other's actions. Collaborators can use body gestures to engage in natural communication because their interactions with virtual objects are made visible to other collaborators through physical movements.

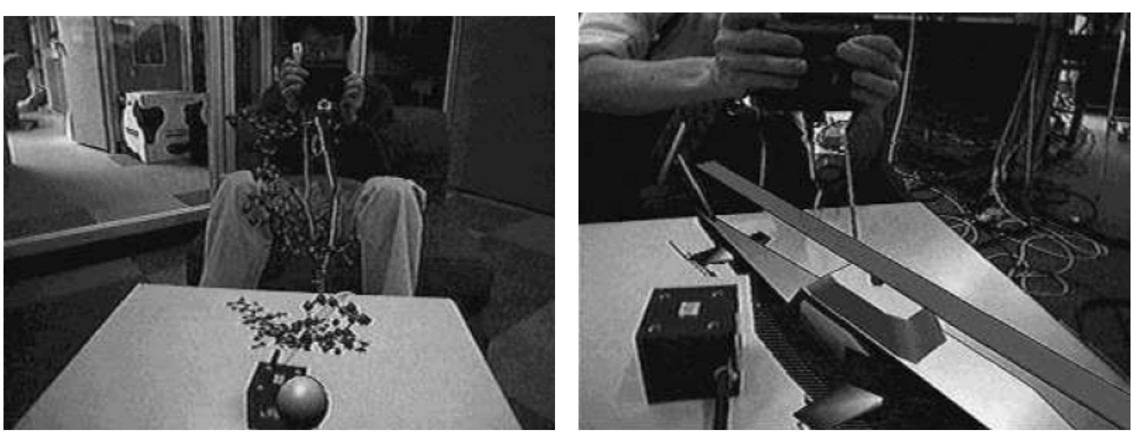


Figure 3.17: Handheld augmented reality collaboration (Rekimoto, 1996)

One of the advantages of mobile systems is that users can use them to engage in ad hoc collaboration because these tools are always at hand. Cao et al.’s (2007) work on multi-user interaction using handheld projectors shares *Napkin Sketch*'s goal of supporting seamless co-located collaboration with mobile devices in a variety of environments. Their system enables each collaborator to operate a small handheld projector that projects information from the personal device onto any surface (Figure 3.18). The interaction makes use of a flash light metaphor for projecting and revealing digital content in the physical environment, where multiple users can share and exchange digital content through overlapping projections using drag and drop with a projected cursor (Figure 3.18). Because the position of each projector is also tracked, the system can infer the spatial context of the interaction within the physical space. For example, if a collaborator is reading a private document and another collaborator approaches, then the projection of the document becomes automatically blurred, or when two collaborators start to explore the same object such as a calendar, the view of the calendar switches from showing an individual schedule to a shared schedule (Figure 3.18).

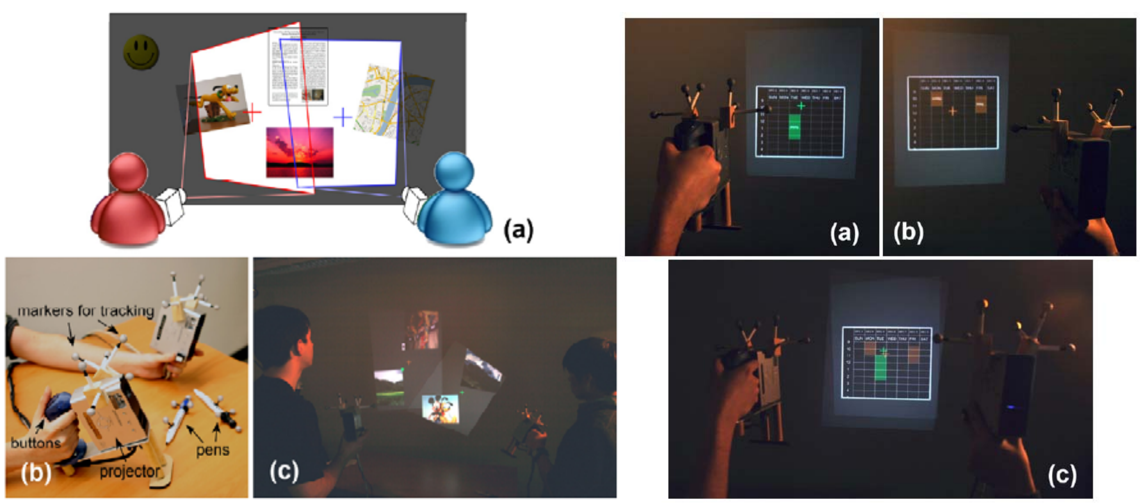


Figure 3.18: Handheld projector collaboration (Cao et al., 2007)

The works presented in this subsection provide an interesting perspective on co-located collaboration because it is supported using personal mobile devices instead of stationary public devices such as interactive tables. This approach provides opportunities to further explore the social nuances of co-located collaboration because collaborators have both a personalized and shared view of the interaction space. Following Rekimoto and Cao et al.'s work, *Napkin Sketch* explores co-located collaborative sketching along with concepts such as ownership of content and privacy control by using a handheld mixed reality sketchpad supplemented with physical napkins.

3.3 Summary

In this chapter, several past efforts attempting to use technology to create interfaces that reach beyond the functionalities of pencil and paper are presented. From 3D sketches to collaborative design with rich media, it is evident that there is great potential in exploring the interaction possibilities of computer-supported sketching and design. However, the drawbacks of novel interaction techniques identified in these works must be carefully considered. Despite the variety of approaches discussed, one central theme seems to be that new technologies should attempt to support existing practices while cautiously layering on extra functionality. The design of *Napkin Sketch* follows these concepts by exploring novel techniques that are grounded in the pencil and paper sketching experience. For example, projective 3D sketching is chosen as the main interaction paradigm for sketching which allows users to engage in 2D perspective sketching on a flat surface, and a collaborative tabletop environment is created with mobile devices to support ad hoc co-located collaboration. In the next chapter, the design motivations and principles of *Napkin Sketch* are elaborated.

Chapter Four: Design Motivations and Concepts

Bridge Scenario

Two architects are hunched over a picnic table located at a popular observation stop overlooking a scenic valley between two mountains. They had been commissioned to design a visually pleasing bridge that will span the valley and connect two busy sections of the highway. It is a beautiful day, and the architects had decided to take a field trip to enjoy a picnic while they worked onsite to get a better sense of the project. They brought along a variety of snacks and drinks as well as a stack of paper napkins and a tablecloth, each decorated in peculiar black and white patterns. After finishing their lunch, they set aside the leftover food, and each pulled out a compact tablet computer to work on the design of the bridge.

One architect suggests, "I'll start by creating a rough sketch of the setting." After receiving confirmation from his colleague, he takes a napkin and places it in front of him on the tabletop covered by the tablecloth. While holding a stylus in his right hand and the tablet in his left, he points the camera on the backside of his tablet toward his napkin and starts to sketch on the tablet. In the meantime, his colleague had also taken a napkin and placed it on her side of the table and started to sketch some ideas for the bridge on her tablet. As she sketches, she constantly moves and rotates her napkin and even shifts her body while occasionally turning her head to glance at the valley. An intrigued tourist looks over her shoulder and sees that she is actually looking at the napkin placed in front of her through the display and the camera of her tablet, except her napkin is no longer covered in black and white patterns but instead is showing a 3D visualization of her sketch.

After a while, she stops sketching, looks up at her colleague, and says, "Here, have a look at what I have so far." She then takes her napkin, rotates it 180 degrees, and places it in front of her colleague on the tabletop. He acknowledges her and quickly points his tablet at her napkin to see what she has created. He carefully examines the sketch through his tablet while rotating the napkin with his right hand in order to see the design from different angles. He notices that the base of her bridge is faintly sketched as a row of uniform circular arches. "What do you think of the base? The concept is floating *bubbles lifting up the bridge.", she says, as she notices the perplexed expression on his face.*

"It's intriguing, but it looks like you still need to elaborate on it.", he responds, indicating the incompleteness of the design suggested by her faint strokes. She quickly mentions that she is not so sure that others will perceive the circles as bubbles. "Hmmm, I have an idea!", he says. He then reaches over to grab another napkin from the stack, places it next to her napkin, and instantly copies her design with the click of a button onto the new napkin. Using his tablet, he starts to sketch circles of different sizes directly over her original design in a darker color. After he is satisfied with his modifications, he moves both her napkin and the new napkin he worked on to her side of the table and orients them to face her. She aims her tablet at the two napkins to see his suggested changes compared side by side with her original design.

"Wow! That's much better.", she says, "I like the variation in size. The bubbles look much more dynamic now." After effortlessly copying his design onto a new napkin, she immediately begins to elaborate on the design by adding more details to the copied version of the sketch. When she is satisfied with her changes, she suggests, "Let's put our sketches together and see how it fits." Her colleague then takes the napkin that he is sketching the setting on and places it in the centre of the table, on the tablecloth. He fiddles with the orientation a bit and copies the sketch from his napkin to the surface of the tablecloth. When his colleague see this, she takes the napkin that has the latest design of her bridge and places it at approximately the same location where the sketch of the setting was copied. After aligning her bridge to his sketch of the valley, she proceeds to instantaneously copy her design to the tablecloth to compose a merged sketch of the bridge and the valley. Afterward, both of them start to review the sketch from various points of view by aiming their tablets at the centre of the table and the tablecloth while engaging in discussions about their design......

Figure 4.1: Collaborative design and 3D sketching using *Napkin Sketch*

The fundamental goal of *Napkin Sketch* is to create a collaborative design and 3D sketching experience (Figure 4.1) similar to the experience described in the Coffee Cup Scenario using traditional tools and media. The challenge is to augment the functionality of pencil and paper with 3D design capabilities, advanced collaboration support, and various benefits of computer –supported tools, while retaining the essential qualities of conventional sketching activities. The Bridge Scenario provides a glimpse of how a hypothetical *Napkin Sketch* system may be used in the real world and demonstrates several examples of similarities with the Coffee Cup Scenario. These similarities capture the essential of the conventional practice of sketching on napkins and are explored and discuss in this chapter.

As suggested in Chapter Two, there are several key aspects of conventional sketching to consider which relate directly to the design goals of *Napkin Sketch* stated in Chapter One. These include: portability, ease of use, flexibility, fluidity, expressiveness, intentional ambiguity, and collaboration. In this chapter, four critical design principles in *Napkin Sketch* that reflect upon these aspects of conventional sketching are discussed. They motivate the interaction examples presented in the Bridge Scenario and serve as a prelude to the discussion of the prototype *Napkin Sketch* system in Chapters Five, Six, and Seven.

4.1 Mobile Interfaces and Ubiquitous Computing

One of the most impressive characteristics of the conventional practice of sketching on napkins is their unrivalled ubiquity. Napkins are available in most places, and the only tool required to sketch on them is a pencil. Due to the simplicity and compactness of the tool and the disposable nature of the medium, conventional sketching is extremely portable, and this aspect of sketching is often lacking in most computer-supported design systems implemented for desktop interfaces. Weiser's (1991) vision of "tabs, pads, and boards" for ubiquitous computing took inspiration from everyday objects like whiteboards and sticky notes which captures and conveys information. In turn, his description of "pads" as "scrap computers" inspired the use of mobile computing devices in the design of *Napkin Sketch*, which is actively pursuing portability rather than being a mere port of a desktop interface. Although the decision to design *Napkin Sketch* around mobile devices appears obvious, it does come with several unique challenges that are especially difficult for applications intending to support sketching in early design.

Designing mobile interfaces can be more difficult than designing desktop interfaces mainly due to the hardware limitations of mobile devices. In order to be portable, the form factors of mobile devices are generally small, resulting in limited display space. This becomes problematic when having to represent large design spaces, since users will have to invoke many zoom, translate, and rotate operations to inspect the design subjects. Another related challenge is dealing with limited input options. Usually, mobile devices have few hardware buttons, and many lack keyboards. Most computer-supported design systems make heavy use of keyboard shortcuts for operations such as camera control, and their usability would be severely impacted if ported directly to mobile devices. Other challenges in working with mobile devices include computing power and battery life, but these constraints are less important because they are being lifted by the short term advancement of technology. However, despite these challenges, working with mobile devices is essential to achieving one of the fundamental goals of *Napkin Sketch*, and as seen in the Bridge Scenario, the design of *Napkin Sketch* also offers some novel techniques to outcome these challenges.

4.2 Tangible User Interfaces and Mixed Reality

Some of the fundamental differences between conventional tools like pencil and paper and computer-supported tools are the spaces, media, and content associated with interaction. Conventional tools operate directly in the physical environment, and the content produced by these tools exists readily in the physical spaces in which it is created. In contrast, computers mainly deal with digital content. Bits of information are usually fed through various types of displays to become visible in the physical environment. With conventional computer interfaces, interaction with digital content is separate from the physical environment. Instead of occupying the space of a physical desktop like sketches produced on a napkin, digital sketches are often materialized and stored on displays representing a virtual desktop.

Physical objects such as napkins provide rich, expressive, and intuitive interaction for users. As seen in the Coffee Cup Scenario and the Bridge Scenario, they afford various tangible manipulation techniques such as rotating the napkin to access different parts of the medium for sketching, passing the napkin to share the sketch, and placing multiple napkins close to each other to compare and assemble ideas. In order to mimic the interaction style of napkins, the use of tangible manipulations in *Napkin Sketch* is another major design focus in this thesis. This approach not only serves to narrow the gap between interacting with conventional physical tools and computer-supported tools, it also provides potential solutions to the challenges of interacting with mobile devices such as limited input and output.

Ishii and Ullmer (1997) introduced the idea of “Tangible Bits” which allows users to “grasp and manipulate” digital content. By coupling bits with everyday physical objects, the intention is to capitalize on natural physical affordances, innate spatial awareness, and intuitive manipulation. This is the essence of tangible user interfaces, where the physical world itself becomes the interface in an attempt to bridge the gap between the digital world and the physical environment. Reflecting back on the previous section, Weiser’s (1991) vision of ubiquitous computing is also related to the concept of tangible user interfaces. They both share the goals of making digital content more accessible in the everyday physical environment and enabling the use of technology in a “transparent” or “invisible” fashion. Through the availability and portability of mobile devices, digital content becomes increasingly interleaved with everyday life as it manifests itself in the physical environment via numerous small displays. However, ubiquitous computing does not directly focus on the desire to tangibly manipulate digital content in a manner similar to physical objects. On the other hand, the concept of tangible user interfaces is less concerned with the ubiquity of technology but rather concentrates on leveraging the well-learned interaction with physical objects to achieve a more seamless interaction with digital content. As demonstrated in the Bridge Scenario, being able to tangibly manipulate virtual sketches and interleave interactions in both the physical and virtual environments are key aspects of *Napkin Sketch* interaction.

The idea of merging the digital world and the physical environment is critical to the concept of tangible user interfaces because if these interaction spaces are unified, then digital content can be manipulated as physical objects. One approach to achieve this involves the technique of mixed reality, where the physical environment is augmented with digital enhancements (Milgram and Kishino, 1994). The DigitalDesk (Wellner, 1993) demonstrates this synergy of physical and digital content by projecting or superimposing computer generated images onto a real desk, allowing digital content to be manipulated with physical gestures and physical content to be recognized and processed by the computer. Mixed reality mainly focuses on creating a visual coherence of the digital world and the physical environment through tracking and video projection or video composition. Ullmer and Ishii’s (1997) MetaDesk (Figure 4.2), where physical objects are used as handles to manipulate digital content, focuses more on making abstract representations graspable. *Napkin Sketch* is designed to incorporate both mixed reality and graspable “Tangible Bits” to produce an interaction experience similar to sketching on napkins with conventional tools.

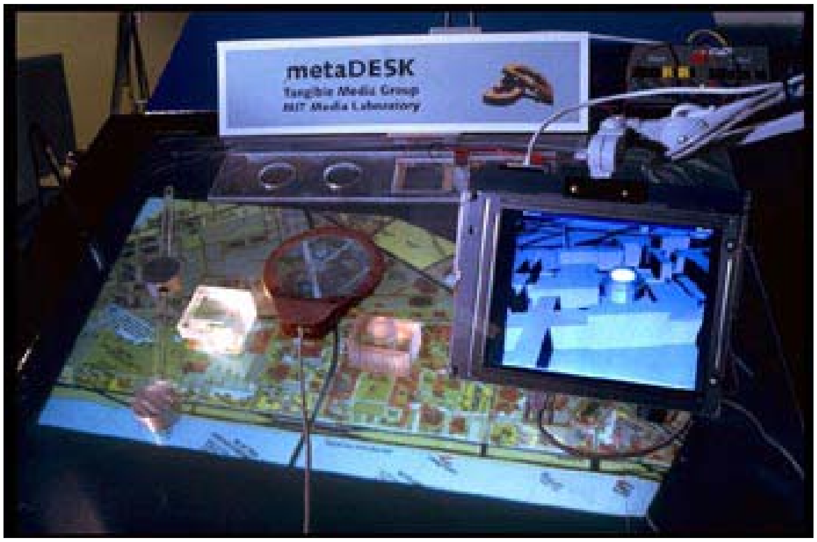


Figure 4.2: Physical objects and lenses can be used to tangibly manipulate a digital map on the MetaDesk (Ullmer and Ishii, 1997)

4.3 Freeform Interaction

One major difference between the conventional practice of sketching on napkins and the operation of most computer-supported design tools is freeform interaction. The essential qualities of sketching such as flexibility, expressiveness, and the support of ambiguity and varying levels of detail are byproducts of this fundamental principle. The concept was introduced in Moran et al.’s (1995) work on implicit structures for pen-based systems. Typically, computer systems deal with information as formalized representations. This means explicit structures are defined and maintained by the system to manage the representations. Text is an example where words are arranged in a sequential fashion and cannot appear on top of each other. Analogously, in 3D design, mesh models are formalized representations because there is an explicit structure to the way vertices, edges, and faces are organized. With formalized representations, if an element is created, modified, or deleted, other elements are affected as well. For example, if the vertex of a face is removed, the face no longer exists. Informal representations such as sketches in the traditional sense also have structure, but this structure is implicit as it exists only when perceived by the person who created it. For example, four lines forming a rectangle can be interpreted as a plane. In contrast to formal representations, when the user removes a line, none of the other lines are affected; only the interpretation of the lines may have changed. Keeping the structures of representations implicit or temporary is the essence of freeform interaction (Moran et al.'s, 1995). By taking the approach of freeform interaction in 3D sketching, *Napkin Sketch* will enable users to suggest different designs with unconstrained strokes for laying out their rough ideas and not worry about having to commit to explicit geometric structures before they are ready.

4.4 Co-located Collaboration

Reflecting back on the interaction described in the Coffee Cup Scenario which opened this thesis, collaborative activities took place frequently between the two architects, and sketches on napkins served as both the medium and stimulus for collaboration. These sketches can be used to effectively convey ideas through visual representation. They can also serve as visual aids to support and stimulate discussion while allowing different ideas to be compared, assembled, and critically evaluated by both collaborators. Because sketches on napkins are tangible objects that dwell in the physical space, they can be easily manipulated. They can provide task awareness and support intricate social interaction between collaborators through tangible, transparent, and understandable actions such as sketching, moving, and turning.

Computers are powerful vehicles for collaboration as well. With access to highly connected networks, near real-time streaming of information like text, audio, and video, they are capable of not only co-located collaboration but also remote collaboration. However, many computer-supported design tools only provide the basic functionality for collaboration such as sharing displays or transferring information between collaborators. Often, they tend to overlook areas of the interaction design which affect the social aspects of collaboration. For example, while several collaborators can huddle around a computer screen to discuss ideas, the conventional practices of co-located collaboration are hindered. With a stationary desktop interface, the tool itself becomes the focus of attention rather than the collaborators and their design ideas. Often, the display dominates the attention of the users in such settings because it must be viewed to receive the digital information being worked on. In conventional sketching practices, collaborators are usually situated facing each other, allowing them to easily engage in conversation and communicate via gestures and body posture. This social arrangement can be difficult to achieve with computer-supported tools because the users are looking at the display, and they must make an effort to reorient themselves to communicate.

Another issue is the lack of simultaneous input from multiple collaborators. In most cases, collaborators must take turns and share one input device and only work on the idea shown on the display (Kruger et al., 2003). With the conventional practice of sketching on napkins, collaborators can use many napkins and work on different ideas at the same time. Some typical solutions to this problem involve providing multiple input devices and splitting the display into individual views. This technique can be seen, for example, in various multiplayer console games such as Mario Kart (Nintendo, 2008).

However, although this approach supports separate and simultaneous work, users are missing out on the shared view which is essential for collaboration. Furthermore, research on tabletop interaction has uncovered interesting yet subtle nuances in co-located collaboration such as the three key roles of orientation in supporting comprehension, coordination, and communication (Kruger et al., 2003) and the establishment of personal, group, and storage territories within interaction areas (Scott et al., 2004). Recommended design guidelines such as support for free and lightweight rotation techniques (Kruger et al., 2003), visible and transparent actions (Scott et al., 2004), and support for casual grouping of items and tools in the workspace (Scott et al., 2004) are often not considered in desktop design applications, but as previewed in the Bridge Scenario, these guidelines will be explored in the design of the collaborative aspects of *Napkin Sketch*.

4.5 Summary

In this chapter, four critical design principles which motivate *Napkin Sketch* have been discussed. Ubiquitous computing and tangible interaction prompted the design of the hardware components of *Napkin Sketch*, leading to the implementation of the mixed reality sketchpad and napkins, hinted at in the Bridge Scenario. On the software side, the concept of freeform interaction inspired the use of projective 3D sketching techniques to allow users to design using unconstrained strokes rather than rigid surfaces. Finally, co-located collaboration was explored in the implementation of the collaborative aspects of *Napkin Sketch*, which takes into account the research on collaborative environments and computer-supported collaborative work. In Chapters Five, Six and Seven, the hardware and software design of *Napkin Sketch* as well as the collaborative aspects of the system are described in detail.

Chapter Five: *Napkin Sketch* Hardware

The metaphor of sketchpad and napkin is used to describe the core interaction experience of *Napkin Sketch*. This metaphor is carefully chosen to reflect the design decisions of using mobile devices and applying the concept of tangible user interfaces. Conventional sketchpads and napkins are portable and tangible, and the design of *Napkin Sketch* attempts to provide an interaction experience for the computer-supported tools which are similar to their counterparts. In *Napkin Sketch*, a light weight tablet PC is used both as a drawing surface and also as a lens for inspecting the 3D design space (Figure 5.1). The napkins are made of regular paper, serving as the media onto which 3D sketches are created. Users hold the tablet PC in one hand like a sketchpad and draw directly on the display of the tablet PC with the stylus using the other hand (Figure 5.1). Because the tablet PC is equipped with a front facing webcam, live video of the napkin and the physical design space is presented on the display. Strokes sketched by users on the display appear anchored to the napkin, and when the napkin or sketchpad is moved relative to each other, the view of the strokes change accordingly. In the rest of the chapter, various hardware components of *Napkin Sketch* such as the sketchpad and napkins are described in more detail.

Figure 5.1: *Napkin Sketch* interaction: tangible manipulations of the cardboard napkin and sketching with the tablet PC sketchpad

5.1 Sketchpad

The most important component of the *Napkin Sketch* hardware is the sketchpad, which serves as a hub, managing all input and output of the system. Since it is used both for sketching and exploring the design space, support is required for recognizing stylus input and displaying digital content. Various devices have these capabilities such as the iPhone, Nintendo DS, and an assortment of tablet PCs. During the design of *Napkin Sketch*, three different platforms were considered, each with its own advantages and limitations.

Following the motivation for portability, an OQO model 2.0 (Figure 5.2) Ultra-Mobile PC (UMPC) was considered. It weighs 1lb and has a 5” display, a VIA C7M ULV 1.2 GHz processor, a VIA VX700 graphics processing unit, 1GB of RAM, and a passive electromagnetic digitizer for stylus input. In terms of mobility and ubiquitous computing, this platform was ideal because it could be easily stored and carried by users, realizing the goal of being able to sketch spontaneously in any physical environment. Because of its light weight and compact form factor, moving the device around the design space was also effortless and intuitive. As motivated earlier, portability is critical because inspiration comes spontaneously, and a good sketching tool is always at hand to allow users to jot down their ideas. Also, being able to design in everyday environments with a wide range of rich visual stimuli rather than sterile designated work settings is beneficial for creative tasks.

Figure 5.2: OQO model 2.0 Ultra-Mobile PC (from http://www.digitaltechnews.com/.shared/image.html?/photos/uncategorized/2009/01/08/oqo_model_2_pda.jpg)

However, portability comes at the price of performance, and *Napkin Sketch* could not be run on the OQO model 2.0 with smooth frame rates. Hopefully, with the current technological advancements, similar platforms can be used to reach the true potential of *Napkin Sketch*. Despite the high cost and weak performance of the OQO model 2.0, it is still encouraging to consider the class of ultra-mobile devices. With a variety of cheaper alternatives such as smart phones, PDAs, or even portable gaming consoles, mobile devices may one day rival the ubiquity of pencil and paper to realize Weiser's vision of ubiquitous computing and the fundamental goals of *Napkin Sketch*.

Figure 5.3: Toshiba Portege M200 tablet PC (from http://pc-components.bestproductsreview.net/wp-content/Toshiba%20Portege%20M200%201.jpg)

Because of the technical limitations outlined above, two different tablet PCs with less mobility but more processing power were used in the implementation of the *Napkin Sketch* prototype discussed in this thesis. The first is the Toshiba Portege M200 (Figure 5.3). It weighs 4.4 lbs and has a 12.1” display, Intel Pentium M 1.8 GHz processor, a NVIDIA GeForceFX Go5200 graphics processing unit, 512 MB of RAM, and a passive electromagnetic digitizer for stylus input. This tablet runs *Napkin Sketch* smoothly but is heavier and harder to manipulate with one hand. Although the bigger display or drawing surface is beneficial for sketching, the weight and bulkiness of the device hinder the ease of use and portability envisioned for *Napkin Sketch*. One thing to note is the common electromagnetic digitizer used on many tablet PCs. The tablet generates electromagnetic signals which are received by the circuits in the pen, allowing the tablet to sense the stylus position without having the stylus touching the surface of the tablet. Likewise, pressing a button on the stylus can also be detected. These capabilities provide more flexibility in interface design because the hover state can be used to provide extra visual cues or functionalities, and the stylus button can be used to quickly switch modes such as for erasing.

Figure 5.4: LG C1 tablet PC (from http://jkontherun.files.wordpress.com/2007/06/lg_c1_tablet_pc_hq.jpg)

The second tablet PC examined and used was the LG C1 (Figure 5.4). It weighs 2.9 lbs and has a 10.6” display, a Intel Core Duo 1.2 GHz processor, a NVIDIA GeForce Go 7300 graphics processing unit, 2 GB of RAM, and a resistive touch screen for stylus input. The lighter weight and compact form factor make this tablet much more desirable for *Napkin Sketch* than the Toshiba Portege M200 while providing better performance as well. However, the only disadvantage of the LG tablet is the resistive touch screen which works based on pressure applied to the surface of the display. This means input is only recorded when the stylus makes contact with the drawing surface. Therefore, no stylus buttons are available, and the hover state cannot be used for interaction design.

Regardless of the compromises made due to technical constraints, the core interaction experience intended for *Napkin Sketch* can still be demonstrated using the current manifestations of the sketchpad. Tablet PCs still correspond well with the *Napkin Sketch* design goal of mimicking conventional sketching because they provide sufficiently large sketching surfaces, reasonable portability, and a sketching experience similar to drawing on real sketchpads. Applying Sharlin et al.'s (2004) input/output unification heuristic for tangible user interfaces, tablet PCs can achieve a tactile fusion of perception and action, since the display surface is used for both recording stylus input and visualizing the corresponding output. In contrast, devices such as the mouse or external graphics tablet decouple the input and output spaces, forcing users to consciously adjust to the remapping of the device manipulation actions to the resulting perception of interaction effects which usually occur on a separate display.

5.2 Lens Metaphor and Mixed Reality

In *Napkin Sketch*, the strokes drawn by the users on the sketchpad are digital and can only be visualized on digital displays. However, in order to physically manipulate the sketches and provide rich physical affordances for interaction and collaboration, the concept of tangible user interfaces is applied. The idea is to unify the visual output of the physical space, the physical napkin, and the digital sketch using mixed reality to allow users to tangibly move the napkin with their hand while seeing the digital sketch move in correspondence with the napkin on the display of the sketchpad. Following the concept of Ishii's (1997) graspable bits and phicons and Ullmer's (1997) token constraints metaphor, *Napkin Sketch* takes the approach of coupling digital sketches to physical napkins to make them graspable in the sense that the napkin acts as a physical handle for the sketch , but the sketch itself cannot be grasped. When this mixture of digital and physical entities is visualized through mixed reality (Figure 5.5), the digital sketches appear to be anchored on top of the physical napkins, and manipulation of the napkins results in the corresponding manipulation of the sketches. This allows the digital sketches to be intuitively turned, moved, and examined.

Figure 5.5: Mixed reality using the lens metaphor with sketchpad and napkin

The unification of the digital sketches and physical napkins through mixed reality is achieved using the popular interactive lens metaphor employed by various other mixed reality works (Ullmer and Ishii, 1997; Billinghurst et al., 2001). With a front facing webcam, live video of the physical space in front of the sketchpad can be shown on the sketchpad display (Figure 5.5). This creates a transparent or lens-like effect, allowing napkins placed in the physical environment to be seen on the sketchpad. One Creative Live! Cam Notebook Ultra webcam is used for each of the two tablet PCs. This webcam has a wide angle lens, providing 640 by 480 video at 30 frames per second and is either clipped on the top edge of the tablet PC (Figure 5.5) or attached to its back with tape. The napkins are simply implemented with regular paper printed with mixed reality markers (Figure 5.5; Figure 5.7). When these markers are revealed to the webcam, the ARToolKitPlus (Wagner and Schmalstieg , 2007) library running on the tablet PC interprets the video using image processing and derives the relative 3D position and orientation of the napkin to the sketchpad. In actual implementation, this relationship between sketchpad and napkin is represented as a coordinate transformation. Therefore, to visualize sketches or any other digital content as anchored on top of the napkin, the coordinate transformation is simply applied to the sketches. The result of looking through the sketchpad at the napkin is the appearance of digital virtual sketches occupying the correct physical space on top of the physical napkin.

5.3 Design Space Navigation

One of the significant values of sketches is the ability to easily use them to explore and understand design subjects. In a 3D design setting, exploration requires examining sketches or subjects from different viewpoints in 3D space. In most 3D design systems that make use of interfaces designed for keyboard and mouse, design space navigation often requires the use of special modes and extra interface controls to perform rotation and translation in a serial fashion because the input devices do not provide enough degrees of freedom to achieve a one to one mapping with 3D manipulations. This is a bottleneck for achieving an intuitive and fluid 3D design system. Research has shown that users spend a significant amount of time inspecting drawings in a computer-supported pen-based system (Lim, 2003). This translates to a heavy cognitive load when having to manipulate conventional camera controls while sketching or designing in 3D.

With *Napkin Sketch*, users interact with the sketchpad and napkin by sitting naturally at a table, holding the sketchpad, with the napkin being placed on the tabletop in front of the user. The user manipulates the sketchpad or lens with one hand while sketching on its surface with the other, with the digital 3D design space being continuously and persistently presented on the sketchpad. The often cumbersome task of switching views and moving around a virtual 3D design space with the mouse is dramatically simplified by making the interaction physical and straightforward. Instead of executing several rotation and translation commands in a serial fashion, the physicality of the sketchpad and napkin and their spatial relationship to each other can be intuitively understood and exploited by users. To navigate the design space, users simply use the spatiality of the interaction setting, by moving the sketchpad or lens around the napkin or by moving the napkin itself using the hand holding the stylus. The mapping is direct and significantly reduces the users' cognitive load. For example, to view sketches in detail, users can simply zoom in by physically moving closer to the napkin with the sketchpad, or they can zoom out by leaning back and moving farther away from the napkin. These tangible techniques for 3D design space navigation is similar in essence to traditional 2D sketching practices, where the paper is constantly adjusted with one hand while sketching to gain access to empty space.

Due to the sitting position and the weight of the tablet PC, moving the sketchpad relative to the napkin may be difficult or impossible in some scenarios if users have to move their body in uncomfortable ways such as having to reach across large distances. However, this method of design space navigation does allow users to keep the stylus on the sketching surface, minimizing the disruption of the navigation task and allowing users to quickly continue sketching. In contrast, moving the physical napkin itself, with its minimal weight, requires much less effort, and the range of movement is also much greater. However, moving the napkin requires users to temporarily take the stylus off the sketching surface in order to perform the task of design space navigation. Despite the current shortcomings of each method, they can complement each other. When users wish to make fine adjustments or move short distances, they can move the sketchpad relative to the napkin and quickly resume sketching. On the other hand, when users need to perform more complex navigation tasks, moving the napkin itself would be easier. Although this requires the user to actively pause sketching, the interruption may not be entirely unwelcomed because the manipulation usually results in a need to mentally re-evaluate a significant change in viewpoint or indicates a lengthy exploration of the design space by the user. These two complementary tangible methods for design space navigation afforded by the *Napkin Sketch* hardware contribute to the overall ease of use of the interface by leveraging the user's innate ability to manipulate physical objects and interact in the physical environment.

5.4 ARToolKitPlus and Marker Tracking

The concept of mixed reality by itself only denotes a combination of the digital and the physical environment. However, without tracking, visual coherence cannot be maintained to make the duality believable. As mentioned previously, in *Napkin Sketch*, tracking is performed visually via the webcam, markers, and the ARToolKitPlus (Wagner and Schmalstieg , 2007) tracking library. ARToolKitPlus (Wagner and Schmalstieg , 2007), an extended version of the popular ARToolKit (Kato et al., 1999) tracking library, is used to calculate the relative position and orientation of a physical camera and markers in real time. It supports up to 4096 ID-based marker patterns and provides optimizations for less powerful platforms such as mobile devices. These features are important because they help to realize *Napkin Sketch*'s potential for ubiquity and portability, since many napkins and sketchpads can be tracked and used simultaneously.

In order to perform six degrees of freedom 3D tracking of markers, the webcam is first calibrated. This onetime process produces a perspective projection matrix representing the viewing frustum of the camera. These values are always loaded as a part of the initialization of the system. During tracking, frames from the video provided by the webcam are passed onto the ARToolKitPlus (Wagner and Schmalstieg , 2007) tracking library. First, edge detection is performed on the video image to search for quadrangles representing the square markers. Then the interior areas of the found quadrangles are transformed by applying a perspective transformation to correct the perspective distortion, and pattern matching is used to distinguish one marker from another. After a marker has been detected, the pose estimation process derives a transformation matrix from the camera coordinate space to a local coordinate space representing the surface of the marker with the centre of the marker as the origin of the coordinate space (Figure 5.6). Therefore, by applying the perspective projection matrix and the matrix denoting the transformation from the camera coordinate space to the marker coordinate space, digital 3D content can be rendered accurately on top of the markers.

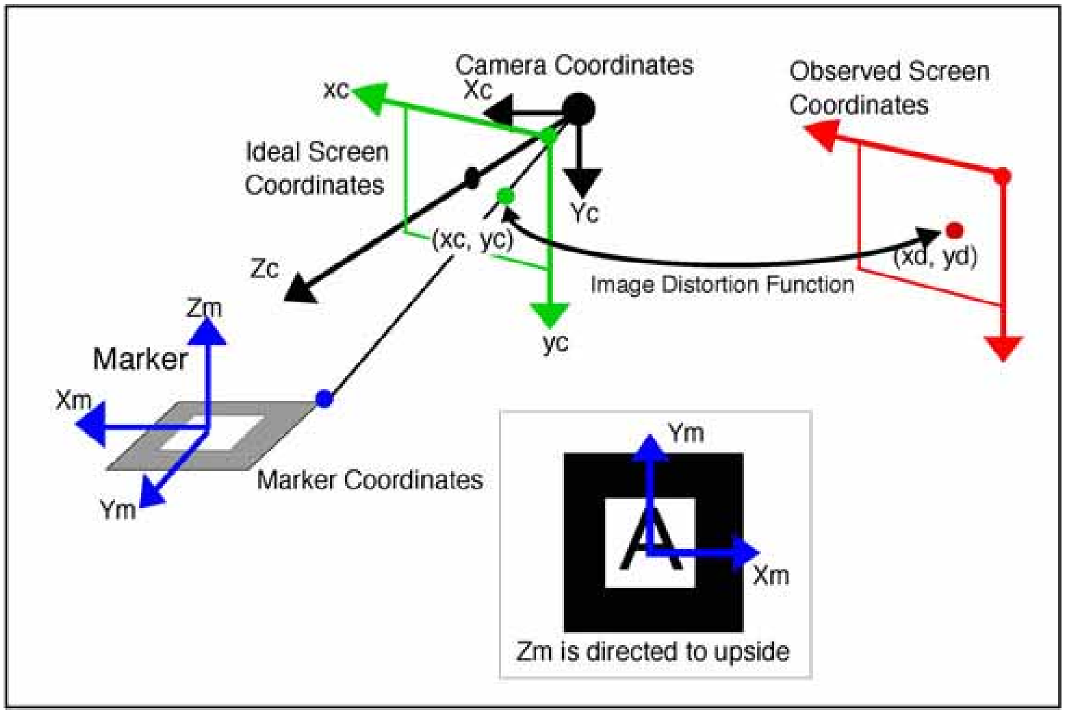


Figure 5.6: Coordinate spaces used in mixed reality marker tracking (from http://www.hitl.washington.edu/artoolkit/documentation/images/ATK-coordinates.jpg)

Because of the tracking technique used in *Napkin Sketch*, the size of the mixed reality markers is also important to note. Depending on the resolution and field of view of the camera, marker size may greatly impact the overall quality of the tracking. If a marker is too small, its pattern may not be seen clearly by the webcam from a distance. However, if the marker is too big, it may be easily cropped by the field of view of the webcam and does not form an image of the required quadrangle to be detected. Therefore, a careful compromise must be made based on the expected viewing distances of the sketchpad and napkin. ARToolKitPlus (Wagner and Schmalstieg , 2007) can also track a set of multiple coplanar markers with predefined spatial relationships as one big marker. If one or more markers from the set can be seen, then pose estimation can still be performed. The redundancy provides more robust tracking but requires more computational resources. Based on the information concerning marker size and marker arrangement, the following section discusses different approaches in decorating and tracking napkins with markers.

5.5 Napkins

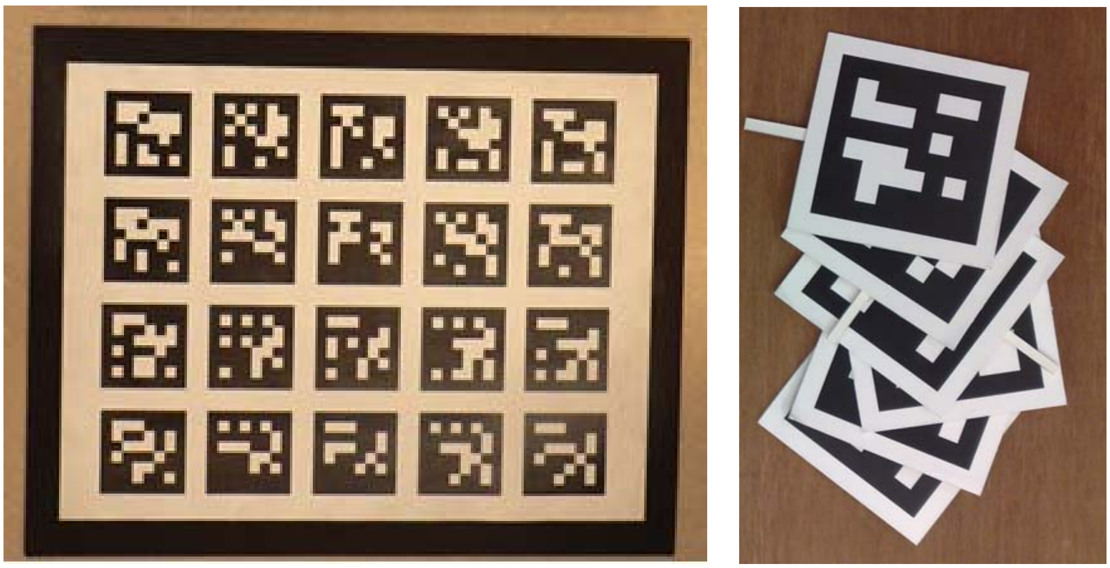


Figure 5.7: Multi-marker napkin (left) and single marker napkins (right)

The napkins used in *Napkin Sketch* are made of standard printing paper decorated with mixed reality markers and glued onto rigid cardboard. The backing makes the paper easier to manipulate and prevents it from curling when picked up or moved, resulting in more accurate tracking. Two types of napkins with varying dimensions and marker arrangement are considered. The multi-marker napkin is 8.5” by 11” (Figure 5.7). It is printed with four rows of five mixed reality markers, measuring 40mm by 40mm each. This napkin corresponds to a standard letter sized paper often used in paper notebooks and sketchpads. The relatively small size of the markers and the redundancy of the multi-marker approach ensures a good coverage in the field of view of the webcam, and tracking is fairly stable and robust. Users can put their hand over the napkin to manipulate it. Most of time, this only occludes some markers but not all of them. The multi-marker napkin works well when only one is used, but its size and computational demands do not scale well to the use of multiple multi-marker napkins. The single-marker napkin is 100 mm by 100 mm (Figure 5.7). It's printed with only one marker, measuring 80 mm by 80 mm. This single-marker napkin corresponds to a large Post-it note. Users may view and interact with many single-marker napkins concurrently because the compact size of the napkins allows them to more easily fit into the field of view of the webcam. The larger marker size compensates for the lack of redundancy to provide stable tracking, and a small strip of cardboard is attached to one side of the napkin as a manipulation handle to prevent occlusions by the user's hand.

In terms of implementation, napkins are relatively simple, ubiquitous, and low-fidelity, demonstrating a design choice which reflects Buxton's (2007) characteristics of sketches as being inexpensive, disposable, and plentiful. Even with the limitations of ARToolKitPlus (Wagner and Schmalstieg , 2007), a total of 4096 single-marker distinct napkins can be easily created and used in parallel. They can be readily discard just by simply casting them away or crumpling them up and throwing them into the garbage. In *Napkin Sketch*, because digital sketches are persistently coupled with physical napkins, they inherit these qualities as well. Rather than taking a one-to-many approach by using one napkin as merely a physical handle for manipulating multiple digital sketches, *Napkin Sketch* follows Sharlin et al.'s (2004) suggestion of using a fixed one-to-one mapping to allow unconstrained exploration of digital problems in the physical environment.

Due to the sketch and napkin mappings, a successful unification of the digital content and the physical environment is achieved. Not only can users take advantage of the spatial qualities of *Napkin Sketch* for the tangible navigation of the design space, they can also make use of the physical environment for the intuitive spatial organization of the sketches. Usually, in a digital desktop metaphor, multiple documents are dealt with by displaying them one on top of another due to the limited dimensions of the display. Therefore, remembering where documents are and finding them may be difficult. However, the physical environment is more expansive, three-dimensional in nature, and provide more space for organization. Users may leverage their spatial understanding to place napkins at certain locations to form spatial groupings of sketches with similar characteristics. For example, napkins placed close to the user's interaction sphere may contain sketches which represent the most promising ideas. Whereas, napkins placed on the periphery may contain sketches of failed or flawed ideas. Because the sketches are attributed to physical locations, they can be quickly retrieved, and although the display of the sketchpad is relatively small, multiple sketches can still be managed due to the intuitive way the sketchpad or lens can be moved around the physical interaction space and due to the fact that physical napkins can be spatially located with the naked eye even when the sketchpad is not pointed at them. These tangible and spatial uses of napkins reflect the rich interaction of conventional physical sketching tools and media as shown by Kolli and Hennessey's (1993) case study and the Coffee Cup Scenario which opened this thesis.

5.6 Summary

The hardware components of *Napkin Sketch* are fundamentally and physically different from the computer-supported tools designed for desktop computers. Following the design motivation for portability and ease of use, the metaphors of sketchpad and napkin are used and implemented in hardware, to enable the functionality of the main input and output components of the system. They are similar to their real life counterparts in the sense that a sketchpad is used for sketching, and napkins are to be sketched on. However, unlike a real sketchpad and napkins, sketches made on the sketchpad appear on the napkins rather than on the surface of the sketchpad. Also, the user cannot sketch directly on the napkins themselves without the mediation of the sketchpad. Nonetheless, the overall interaction experience resembles typical napkin sketching but with necessary deviations to accommodate the added complexity of 3D sketching. The combination of the sketchpad and the napkin provides a light weight and relatively inexpensive handheld mixed reality interface which is easy to set up and use. Because of the strong visual coherence of the virtual scene and the physical environment, navigating around the design space is based on simple spatial relationships, and as result, is extremely intuitive and efficient. In the following chapter, the interfaces designed to take advantage of these unique hardware capabilities are discussed.

Chapter Six: *Napkin Sketch* Software

The sketchpad and napkin of the system establishes the basic input and output functionality of *Napkin Sketch*, allowing users to sketch with a stylus and tangibly navigate the design space. Theoretically, this metaphor and implementation can be applied to a variety of approaches in design applications for interpreting sketch input and representing output, ranging from simple 2D paint programs to complex 3D CAD software. If ported to use the sketchpad and napkin metaphor, existing sketch-based systems such as Igarashi et al.'s (2006) Teddy can benefit from the added portability and intuitive navigation of the design space. However, in order to better satisfy the design motivations of mimicking conventional pencil and paper, *Napkin Sketch* customizes the technique of projective 3D sketching to complement the unique interactive potential of the sketchpad and napkin. Projective 3D sketching is a two-step modeling process, where users first define a 3D surface in the design space where their sketches will be projected, and then they sketch on the sketchpad as they view the 3D design space on top of the napkin. The recorded 2D strokes are projected onto the 3D surface in a way such that the projected 3D stroke looks identical to the original 2D stroke (Piccolotto, 1998; Kallio, 2005; Dorsey et al., 2007). This visual correspondence along with the directness of sketching on the tablet PC provides a natural sketching experience for users. Because no explicit structures need to be interpreted for the sketches, users are free to use solid, overlapping, and stippled strokes to indicate contours or hatching and scribbling to suggest surfaces.

Kolli and Hennessey (1993) suggested that an image-based approach for computer-supported design tools can better support concept sketching than object-oriented or recognition-based approaches. This functional requirement relates to various characteristics of sketching because image-based approaches permit casual interaction, enable fast and fluid design, support flexible and expressive usage, and do not impose unnecessary representational structures. Sketches are great for the exploration of ideas because their meaning is not explicit. It is open to interpretation, and through interpretation, meaning is established, and new discoveries may be made. For example, the Coffee Cup Scenario illustrates a situation where the process of sketching helps to identify a flaw in the original idea. Following the concept of freeform interaction (Moran et al., 1995), *Napkin Sketch* attempts to maintain the same image-based approach as conventional 2D napkin sketching, where sketched strokes are not modified based on internal interpretations of the tool but are rather given meaning through the external interpretations of the viewers.

6.1 3D Sketches

3D sketches are the core representation of *Napkin Sketch*. The concept of 3D sketches may be new to some, but they are not difficult to comprehend. In the real world, wire sculptures are analogous to 3D sketches because wire is easily malleable and can be manipulated in a freeform nature (Figure 6.1). 3D sketches can also be thought of as decomposing a conventional 2D sketch into individual strokes, lifting them off the paper, and recomposing them in 3D. In conventional 2D sketching, the line is the primitive used to compose designs on a single planar surface. 3D sketches also inherit the same approach but liberate the line from the flatness of 2D sketches by allowing them to take on 3D qualities. This is achieved in two ways. First, lines can be intrinsically 3D. For example, moving a stylus through the air or tracing along a non-planar surface creates a

3D line. Therefore, a sketch containing a 3D line is a 3D sketch. Second, sketches composed of only planar lines are also 3D, if the lines are sketched on different planar surfaces. A cube is a good example because each face of the cube contains four straight lines on a planar surface, but when these planar lines are put together, they form a 3D sketch. Another important characteristic of conventional 2D sketches is the lack of explicit structures for the composition of the line primitives. This reflects the concept of freeform interaction and the expressive nature of sketching. Lines don't need to connect to each other, and they can intersect each other freely. Although wire sculptures cannot achieve complete freeform interaction due to physical constraints (i.e. wires cannot be easily suspended in air), the 3D sketches in *Napkin Sketch* do retain this critical attribute of conventional 2D sketches.

Figure 6.1: Wire sculptures are analogous to 3D sketches (from http://kimhunter.ca/images/wire_art_sculpture.jpg)

Although 3D sketches may appear similar to 3D mesh models rendered as wireframes, they are fundamentally different because of their modeling primitives and the representational structures they require. 3D mesh models often use triangles or quads as the modeling primitives which are arguably less flexible than lines. Lines can be used to define boundaries, fill in space, and produce various textures such as hatching. Triangles and quads are mainly used to represent patches of a surface. Furthermore, a representational structure between the triangle or quad primitives is often necessary as their vertices are frequently shared by other adjacent primitives. Applying the concept of freeform interaction (Moran et al., 1995), it is evident that working with 3D mesh model representations may potentially restrict the expressive nature of conventional 2D sketching due to their modeling primitives and explicit representational structures. Therefore, *Napkin Sketch* is designed to simply record user input as 3D sketches rather than attempting to construct 3D mesh models by interpreting strokes.

6.2 From 2D to 3D

In conventional 2D sketching, perspective drawing is often used to convey 3D designs on the 2D surface of the sketching medium from a particular point of view. The established viewpoint determines the eye level, the placement of the horizon, and the vanishing points to which receding parallel lines converge. In essence, sketching in perspective is a manual and empirical projection of the 3D scene onto the 2D surface of the paper (Figure 6.2). The disadvantage of conventional 2D perspective sketching is that the resulting 2D sketch is only valid for the viewpoint from which it was sketched. It is impossible to lift up the paper, rotate it, and visualize the sketched design from a different viewpoint.

Therefore, several 2D perspective sketches are usually generated from multiple viewpoints to convey the 3D design as a set of related but spatially discontinuous images.

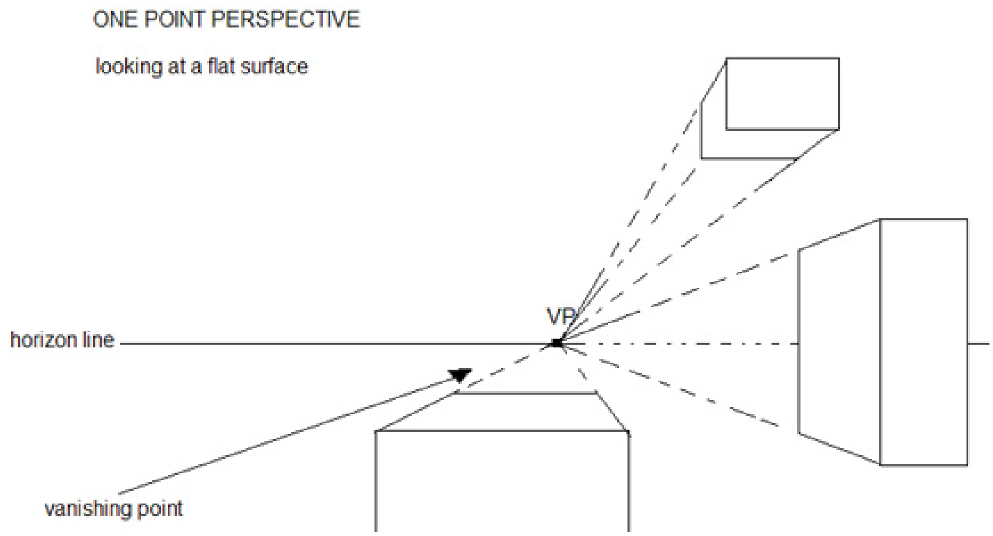


Figure 6.2: Artists use the concepts of linear perspective to generate realistic representations of 3D space (from http://www.arteducationstudio.com/one%20pint%20perspective.jpg)

In *Napkin Sketch*, perspective sketching can also be used to create 3D sketches. Users select a viewpoint from which sketches will be made by moving the sketchpad or lens to the desired position relative to the napkin. Then, they sketch in perspective on the flat surface of the sketchpad in the same way they would replicate the 3D scene from that viewpoint on paper. However, since the sketched 2D stylus input is projected onto appropriate 3D surfaces, the resulting strokes become part of the unified 3D design space and can be seen from other viewpoints (Figure 6.3). For example, receding parallel edges may still be sketched as converging lines, but the 3D projection process maintains their parallel relationship which would be evident from certain viewpoints. This approach produces a single 3D representation of the design that is valid from any viewpoint while allowing users to retain familiar perspective sketching techniques.

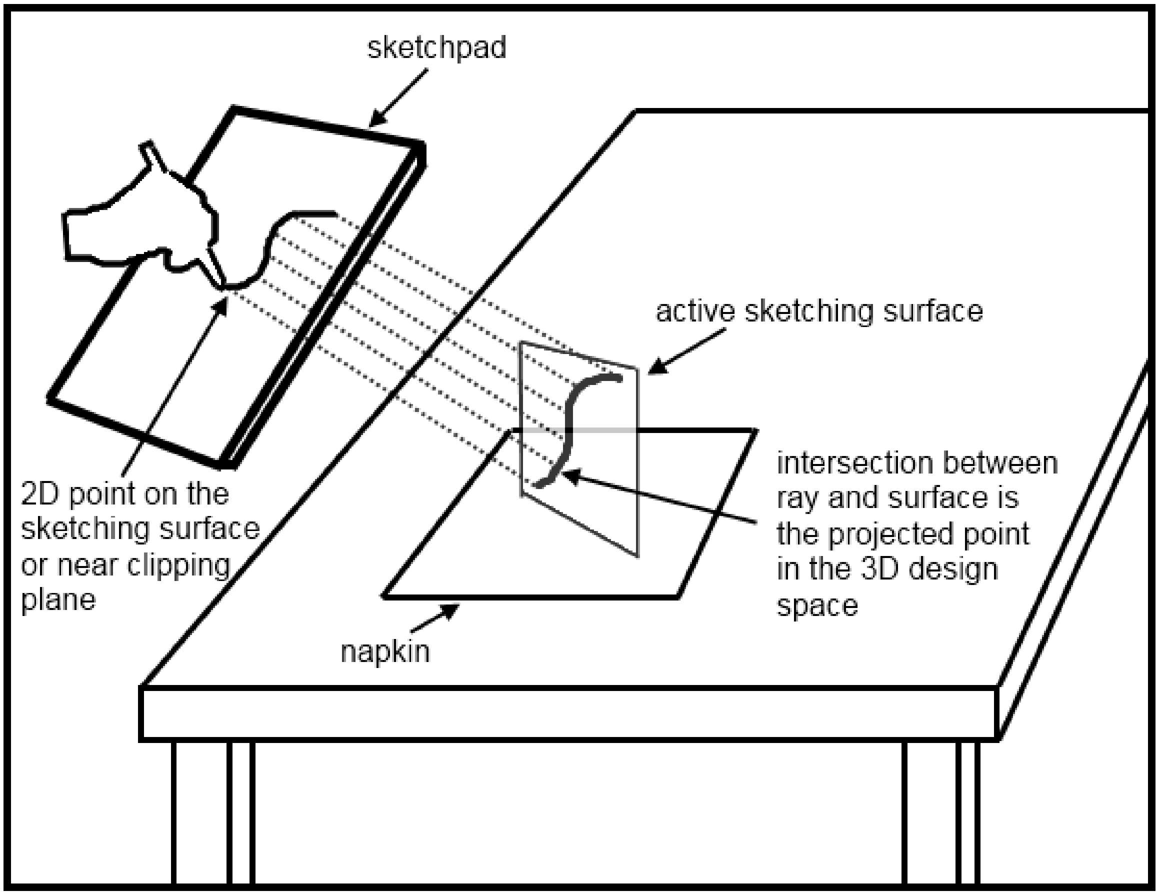


Figure 6.3: 2D strokes drawn on the sketchpad are projected onto 3D surfaces on top of the napkin

In *Napkin Sketch*, 2D stylus inputs on the surface of the sketchpad become 3D strokes in the 3D design space of the napkin through coordinate transformations and projection. The process is similar to ray casting in rendering (Shirley and Marschner, 2009), where rays originating from the viewpoint passing through the 2D positions on the near clipping plane of the viewing frustum are cast into 3D space to determine intersections with geometry (Figure 6.3). In *Napkin Sketch*, stylus input is first recorded in the 2D coordinate space of the application window. Then, by applying the viewport transformation, the 2D point is normalized as a 3D point on the near clipping plane of the viewing frustum defined by the perspective projection matrix from the webcam calibration. Next, this point along with the origin of the camera in the viewing frustum (0, 0, 0) are transformed from the camera coordinate space into the napkin coordinate space via a transformation matrix provided by ARToolKitPlus (Wagner and Schmalstieg , 2007). Finally, a ray, formed by these two calculated 3D points with the transformed origin of the camera as the origin of the ray, is cast into the 3D design space of the napkin. The actual projected position of the stylus input is determined by the closest point of intersection between the ray and the current active sketching surface in the design space (Figure 6.3). If no intersection is found, then no stylus input is recorded. This approach for projective 3D sketching is direct and intuitive because the act of drawing on a 2D surface and the effect of having sketched strokes appear exactly where the stylus touches the sketchpad are congruent with conventional 2D sketching. This projection technique is also used to select existing strokes in the 3D design space. The user can sketch a selection stroke via a selection mode, and rays formed by the camera origin and the stylus input points within the stroke are cast into the design space. A stroke becomes selected if intersected by a ray. In a complex scene, many strokes may be selected at once because they appear on top of each other from certain viewpoints. To deal with this selection ambiguity, users can simply change their point of view to minimize occlusion.

6.3 Stroke Filtering Process

As mentioned previously, the modeling primitive of a 3D sketch is a line or a stroke. A stroke is defined simply as an ordered series of points recorded starting when the stylus touches the surface of the sketchpad to when it is lifted off the surface. Because digital input relies on sampling, undesirable effects such as noise, irregular point distributions, and unnecessary redundant points need to be filtered out. Filtering or cleaning input strokes is important because it improves the efficiency of the system and provides an easy-to-work-with foundation for various system operations based on strokes. Filtered strokes usually have less points which are spatially distributed evenly. Therefore, they require less memory to store, can be rendered faster, and can be readily used as input to generate desirable parametric surfaces. However, because *Napkin Sketch* also strives to minimize modifications to user input and maintain a what-you-sketch-is-what-you-see approach, the challenge of stroke filtering is to efficiently re-parameterize the points representing a stroke without significantly modifying its original appearance, thus preserving the user's original intent for the stroke's path and style.

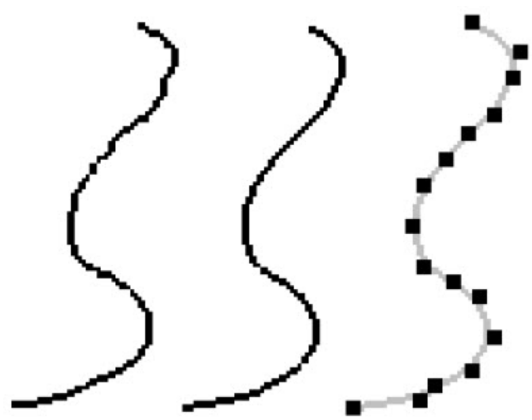


Figure 6.4: 2D Stroke processing: unfiltered stroke directly from user's input (left), after applying the reverse Chaikin filter (middle) and the final stroke show its control points (right) (Cherlin et al., 2005)

The filtering technique used is popular in sketch-based modeling applications (Cherlin et al., 2005). The basic concept is to first remove noise from the input using Chaikin reverse subdivision (Samavati and Bartels, 2004) and then fit a B-Spline curve to the filtered stroke. When Chaikin reverse subdivision is applied to the raw input, the number of points representing the stroke is reduced by half, removing high frequency stroke features. This process can be repeated to further reduced noise and the number of points, but with every reverse subdivision, the output deviates more from the original input. Through visual observation, applying this process once or twice achieves the intended effect (Figure 6.4). Since Chaikin reverse subdivision is based on quadratic B-Splines, the filtered points are used as control points for generating a quadratic B-Spline curve which closely approximates the original user input. Higher order B-Splines such as cubic B-Splines can be used to produce smoother curves, but the increased deviation from the original strokes is undesirable. To maintain a consistent spacing between adjacent points of created strokes, the B-Spline curve parameterization is scaled based on the length of the original input stroke.

6.4 Frames

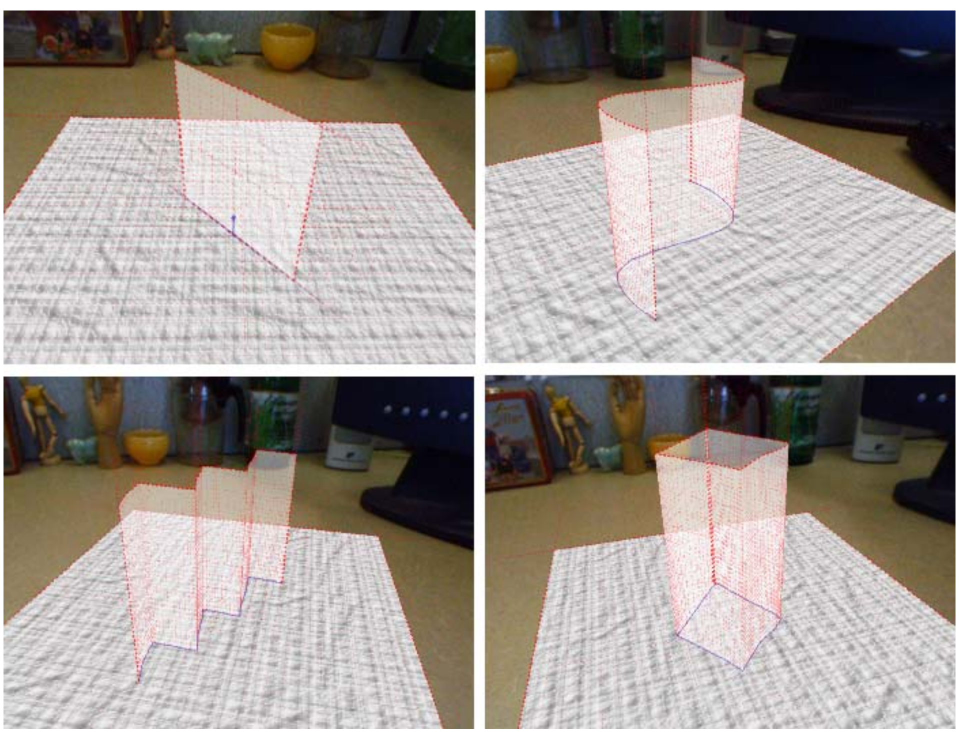


Figure 6.5: Different frames or sketching surfaces created on top of the napkin

The concept of frames is essential in *Napkin Sketch*. They are temporary 3D surfaces that are placed in the 3D design space for the sketches to be projected onto. In terms of freeform interaction, frames are the implicit structures defined to guide the 3D sketching process (Moran et al., 1995). Cognitively, users can think of the surfaces of the 3D geometry they wish to design as frames or parts of frames, or the frames themselves can be interpreted as a sort of flexible canvas or medium that can be spatially positioned anywhere in the 3D design space to be sketched on (Figure 6.5). Although frames may appear to be mesh surfaces, it is important to stress that they are not created to represent explicit geometry. Rather, frames are used as perceptual drawing guides to assist in 3D sketching. For example, a vertical plane can be temporarily perceived as the wall of a house. The user can then sketch the appropriate boundaries of the wall on the plane to make the idea more concrete or scribble and fill in the area to further solidify the concept. These 3D sketching techniques not only mimic conventional 2D sketching but also show the flexibility of freeform interaction and projective 3D sketching. During the evolution of the sketch, the user is not forced to commit to any explicit geometric structure. A sketch, no matter how complex and refined, is just a composition of lines. Some lines can be added to make the interpretation of the sketch more unyielding, and some lines can be removed to leave more holes in the sketch for interpretation.

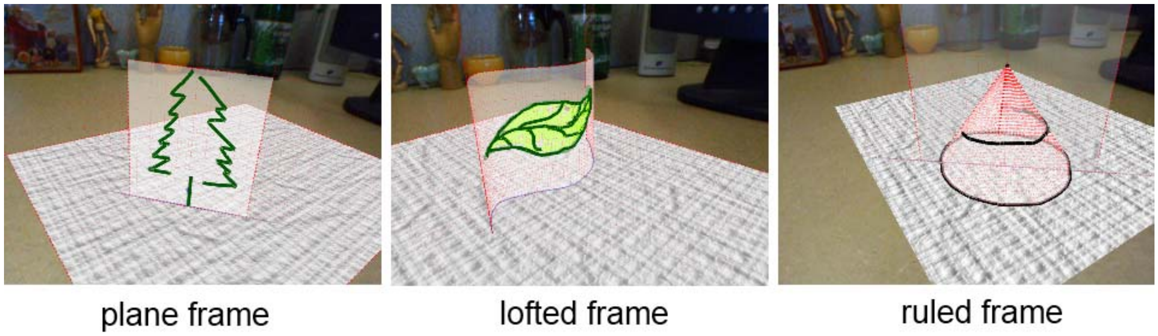


Figure 6.6: Three type of frames

A 3D sketch is a combination of strokes drawn on many frames of varying position, orientation, and geometric composition. Currently, three types of frames are supported in *Napkin Sketch*: plane frames, lofted frames, and ruled frames (Figure 6.6). These represent the primitive media that can be used for sketching. Theoretically, any 3D surface can be used as a frame, but arbitrary and complex surfaces are more difficult to instantiate and harder for users to understand and interact with. The most important frame in any 3D sketch is the plane denoting the surface of the napkin. This is a logical starting point and reference frame because a 3D sketch created on the sketchpad is visually anchored to the top of a corresponding napkin. Therefore, the napkin surface represents the ground plane often seen in 3D design applications (Figure 6.7). In *Napkin Sketch*, only one frame is active or can be sketched on at any time during the sketching process. This frame is denoted as the active frame (Figure 6.7). Using this approach avoids confusion as frames can possibly occlude each other, since some frames such as planes have infinite extent. Adhering to the concept of the napkin as the ground plane of the 3D design space, frames can only be situated on top of the napkin, and ones with infinite extent are truncated at their intersection with the napkin plane. This ensures that no strokes can be sketched underneath the napkin and maintains visual coherence with the physical environment, since strokes cannot go through the tabletop (Figure 6.7).

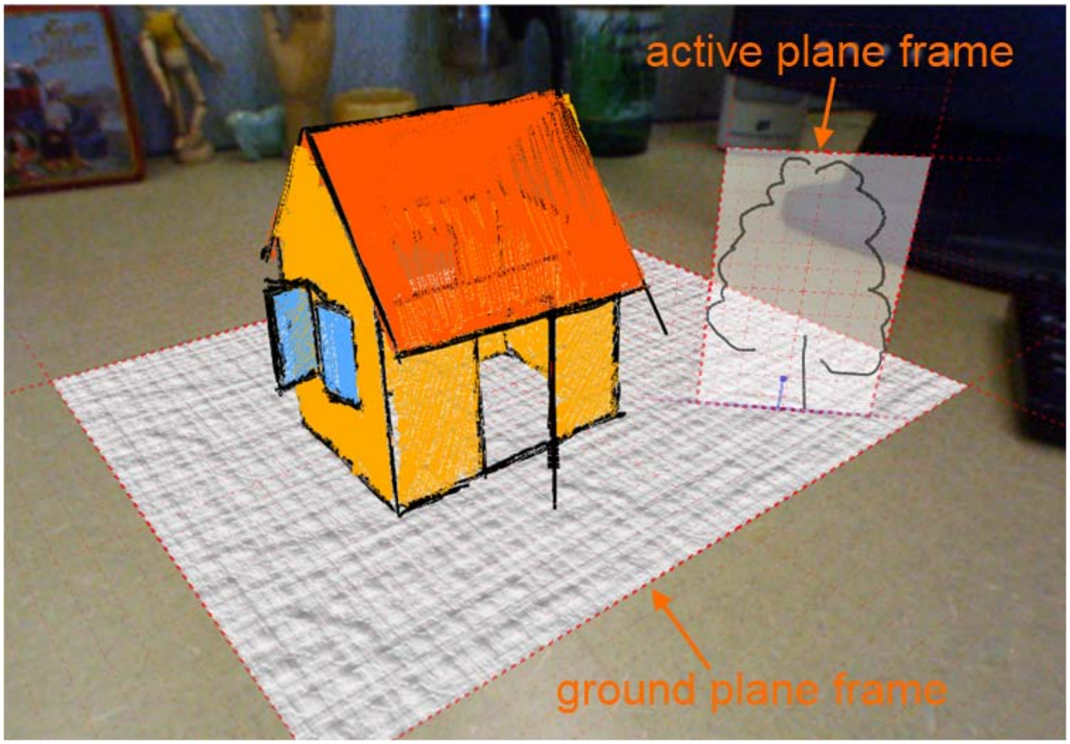


Figure 6.7: A 3D sketch created with only plane frames

The simplest and most important frame is the plane frame (Figure 6.6 left). A plane is infinitely vast and expansive. It is the easiest to understand because its flat surface closely resembles conventional media such as paper, and users can better anticipate the resulting 3D projection of the 2D stylus input. A straight line sketched on a plane frame remains straight just like sketching on paper. Plane frames can be used to sketch many objects or parts of objects such as walls, stairs, or chairs. In fact, numerous objects, especially man-made ones, are composed of many interconnected planar surfaces. The one obvious limitation is that only planar strokes can be sketched on plane frames.

A lofted frame can be visualized as moving a curved or straight stroked through 3D space in a straight line, and the trail left by the stroke denotes the surface of the frame (Figure 6.6). If a straight stroke is lofted, then the frame is planar, but lofting a curved stroke produces a non-planar surface. Either way, a lofted frame is only infinitely extensible along the straight line through which it is moved. Lofted frames are very flexible and can be used to create a number of familiar surfaces. For example, lofting a circular stroke produces a cylinder, lofting a rectangular stroke creates a box, and lofting a zigzag stroke results in a stair-like surface turned on its side. Certainly, it can also be used to create more freeform surfaces such as curvy leaves (Figure 6.6 middle).

A ruled frame is represented by a ruled surface. It can be visualized as a surface formed by filling in the space between two existing strokes with straight lines (Figure 6.6 right). If both strokes are coplanar, then the resulting ruled frame is planar. Ruled frames are finite and are used only for quickly defining the surfaces between strokes for sketching. For example, a ruled frame can be defined to fill in the gap between a small circular stroke and a large circular stroke, representing a tapered cylinder (Figure 6.6 right).

6.5 Frame Instantiation

As in similar works involving projective 3D sketching, the major interaction bottleneck of the approach is the creation and positioning of frames for the sketches to be projected on. Others (Dorsey, et al. 2007; Kallio, 2005; Piccolotto, 1998) have taken the conventional 3D manipulation approach of translating and rotating the frames to the desired location in the 3D design space using interaction handles or different modes for rotation and translation. This non-trivial process can be disruptive to the creative thinking of the users as they must stop sketching, correctly position a frame, and then resume sketching again. In *Napkin Sketch* the actions of sketching and switching frames are closely intertwined. Sketch-based gestural commands are interpreted by the system to quickly instantiate frames in the desired location of the 3D design space, allowing most frames to be created and positioned with only a few operations. Not only is this approach practical and effective, it also demonstrates how gestural techniques can be incorporated to support freeform interaction.

In *Napkin Sketch*, the approach for frame creation and positioning tries to minimize the interruption this process can cause to users. The idea is to take advantage of the implicit geometric relationships of the strokes in a sketch. Strokes rarely float in space, visually disconnected from others. For example, when sketching a house, the lines sketched for the front wall of the house are perpendicular to the receding lines of the side wall of the house. Therefore, when finished sketching the front wall of the house on one plane, it is natural to switch to a plane that is perpendicular to the previous plane and intersects the previous plane at one of the edges sketched for the wall. This allows the user to quickly continue to sketch the side wall of the house, following its contour (Figure 6.8). The concept of creating contextually relevant new frames based on previous frames and strokes is applied to quickly generating all three types of frames.

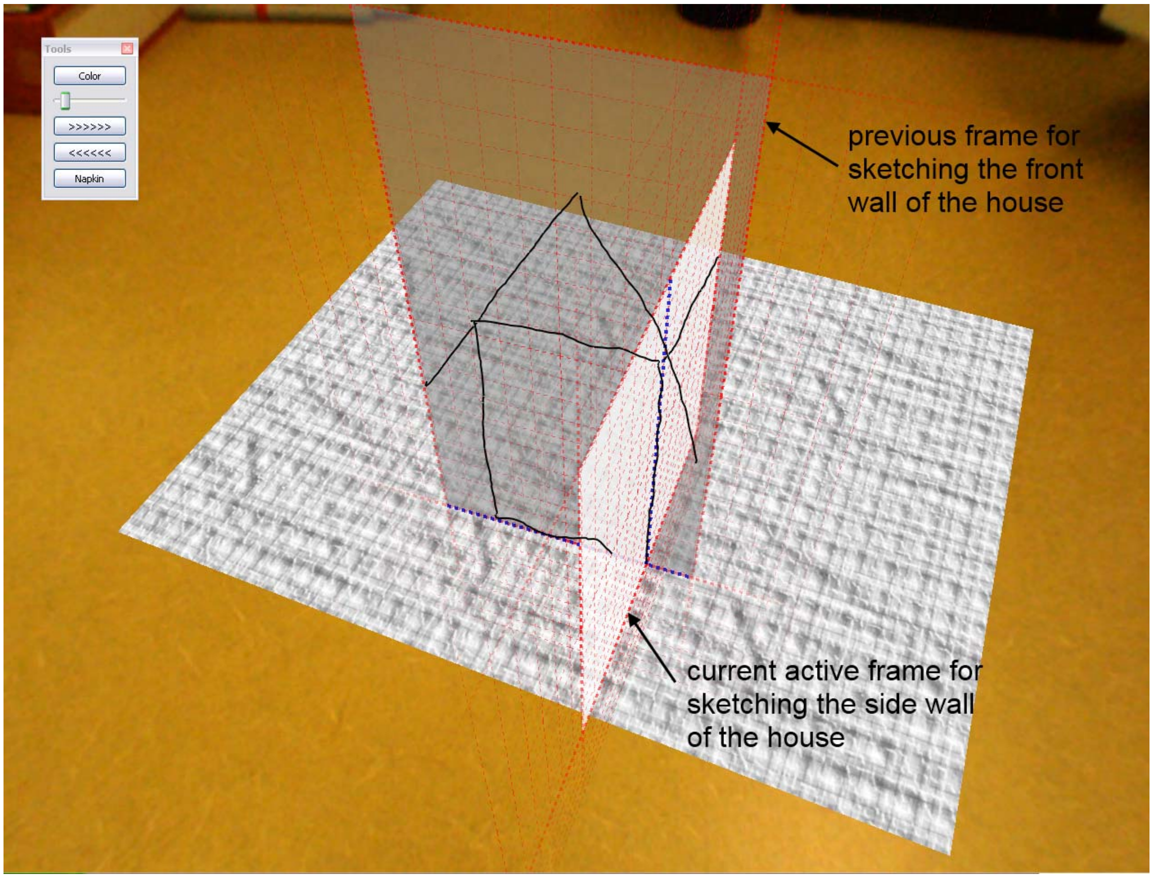


Figure 6.8: The sketch of a 3D house showing the transition from sketching lines on the front wall to sketching lines on the side wall

The most important and most common type of frames used with *Napkin Sketch* is the plane frame. To instantiate a new plane frame, a novel one stroke gesture-based technique is used. It allows users to sketch a straight line as a special frame creation stroke (Figure 6.9 b) on the current active frame (Figure 6.9 a) in order to create a new plane frame (Figure 6.9 c) which is perpendicular to the previous frame and intersects the previous frame at where the line is sketched. For example, if a frame creation stroke is sketched on the napkin ground plane, a perpendicular plane frame would be created at the location where the stroke is made and oriented to be parallel with the stroke (Figure 6.9 a). However, the one stroke technique only allows new plane frames that are perpendicular to the previous plane frame to be created in one step. Therefore, an additional rotation interaction handle is used to rotate the created plane frame along the axis of the sketched frame creation stroke to cover all possible plane frame orientations (Figure 6.9 d). The following is a more detailed explanation of the instantiation of new plane frames.

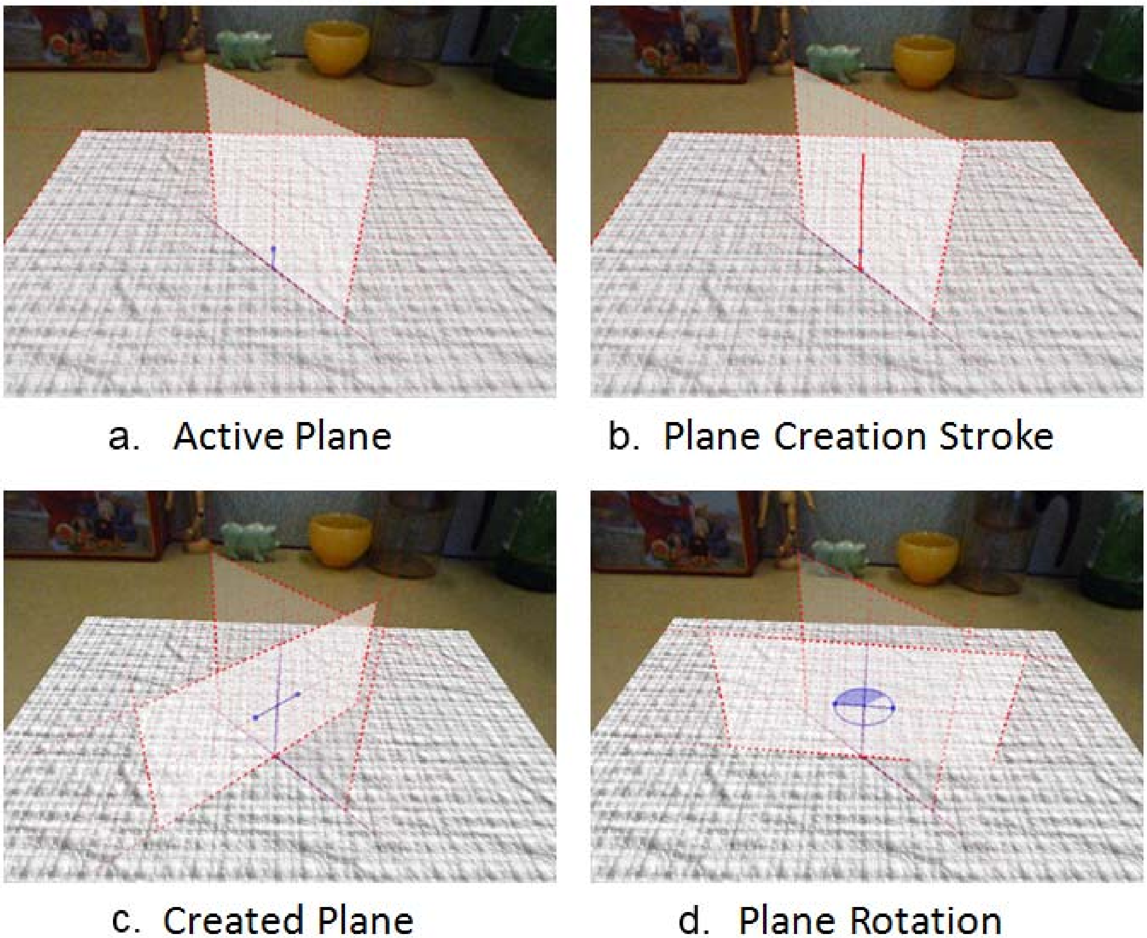


Figure 6.9: Step by step process of creating and positioning a new plane frame

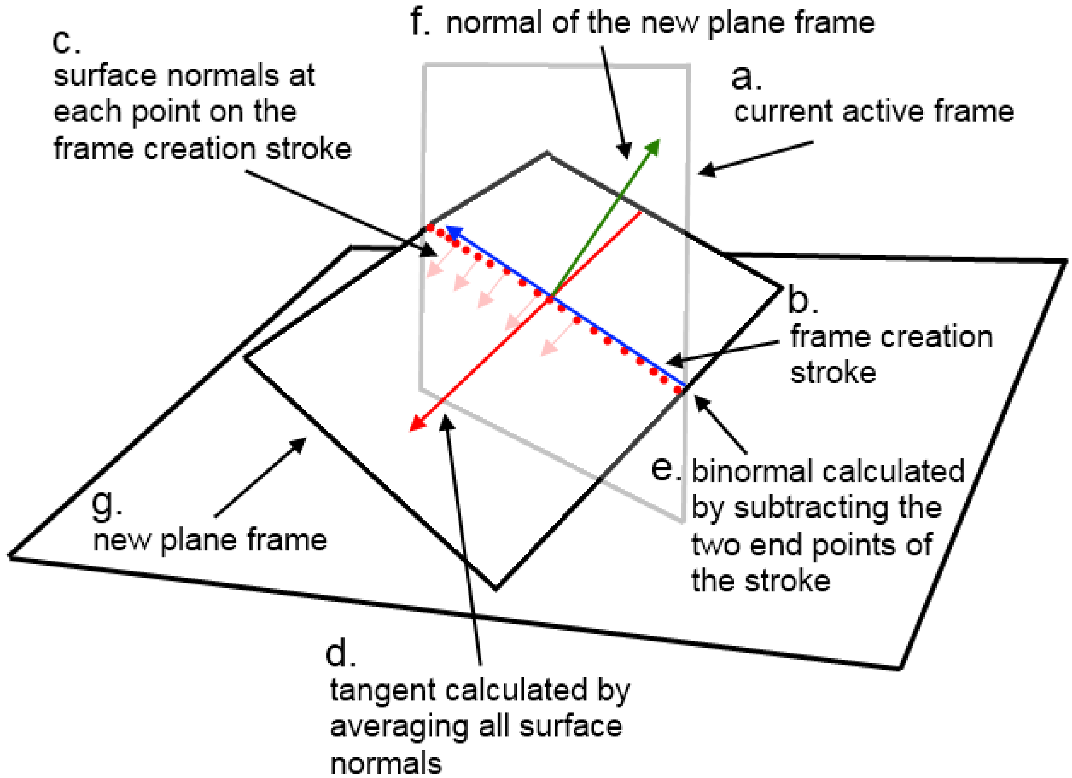


Figure 6.10: The creation of a new plane frame based on a frame creation stroke

To create and position a new plane frame in the 3D design space, the user first sketches a straight frame creation stroke (Figure 6.10 b) projected onto the surface of the current active frame (Figure 6.10 a). The system distinguishes between regular and frame creation strokes by using an explicit mode for frame creation. This mode can be activated either by toggling a button provided by the graphical user interface or by sketching while holding down the right-click button of the stylus if available. After the stroke has been sketched, it is then filtered and processed by the gesture or sketch recognition engine to determine if the stroke is a straight line. Because a sketched straight line may not be straight once projected into the design space, the evaluation of its straightness is performed on the raw stylus input before its projection. Upon recognition, each of the points in the frame creation stroke is then used to calculate a surface normal for the current active frame at the location denoted by the point (Figure 6.10 c). By averaging these surface normals of the current active frame, a vector termed the tangent (Figure 6.10 d) of the new plane frame is derived. Then, the normal (Figure 6.10 f) of the new plane frame can be calculated as the cross product of the tangent and the vector formed by the end points of the projected frame creation stroke termed the binormal (Figure 6.10 e). With the normal of the new plane frame along with points from the frame creation stroke that lie on the plane, the equation representing the new plane frame (Figure 6.10 g) can be easily calculated. Orienting the new plane frame along the surface normal of the active frame is a logical choice because the real world has many perpendicular or near perpendicular relationships such as walls and floor or tree trunks and ground. Also, being able to quickly create perpendicular planes on the ground plane allows users to efficiently compose a pseudo-3D scene of billboards.

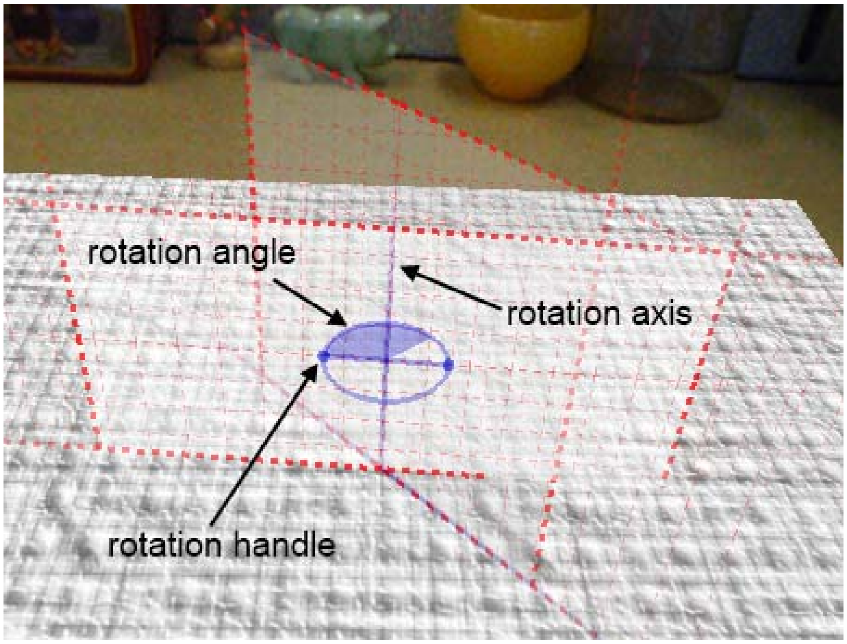


Figure 6.11: The onscreen rotation widget for plane frame adjustment

However, creating the new plane frame along the surface normal of the active frame may not always be desired. To further adjust the orientation of the new plane frame from its originally instantiated orientation along the surface normal of the active frame, users can manipulate an onscreen widget to rotate the new plane frame along the axis of the sketched frame creation stroke or the binormal (Figure 6.11). This rotation along with the initiate sketched frame creation stroke covers all possible plane frame orientations that can be achieved. New plane frames not oriented along the surface normal of the active frame can also be created in two or more sketched frame creation strokes without rotation, but his makes the frame instantiation process more complex and less intuit

Instantiating a lofted frame is a more general case of instantiating a plane frame. A lofted frame or surface is created by extruding a frame creation stroke along the tangent (Figure 6.12). The direction of the tangent is most often perpendicular to the current active frame. This means that a lofted frame can only extend infinitely along the directions of the tangent. The plane frame is a special case of lofted frames because it can also extend along the frame creation stroke that instantiated it or the binormal (Figure 6.10) but requires this stroke to be a straight line. Hence, sketch recognition is employed to detect this special case. If a sketched frame creation stroke is not recognized as a straight line, then it is interpreted as input for creating a lofted frame. The tangent representing the average of the surface normals and the opposite of that vector are used as the directions for extending or lofting the input stroke into a surface. Currently, lofted frames cannot be rotated after being instantiated in a near perpendicular orientation because rotation around a curved axis is difficult to conceptualize.

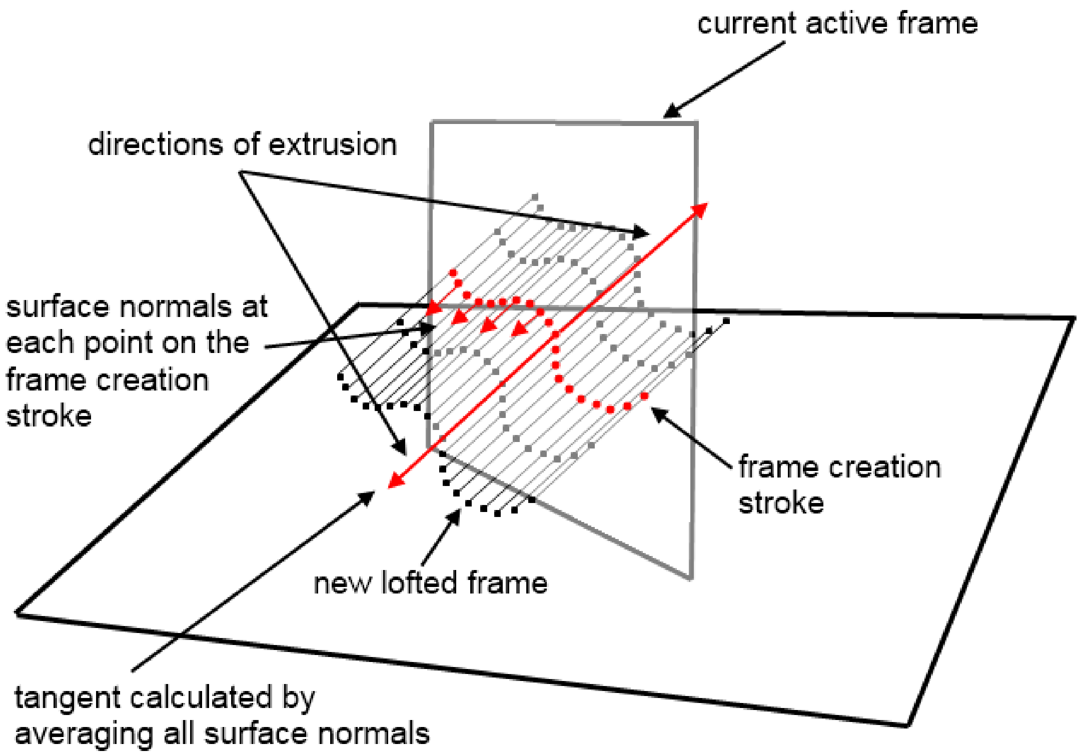


Figure 6.12: The creation of a new lofted frame based on a frame creation stroke

Ruled frames are surfaces that are created by connecting two strokes or curves with straight ruled line segments in between. Lofted frames can be thought of as special ruled frames which are created by joining two of the same strokes with straight line segments. However, unlike lofted frames and plane frames, ruled frames cannot be extended infinitely in any direction. Although limited, the function of ruled frames is quite practical, allowing users to easily fill in areas defined by two profile strokes or sketch on interesting surfaces such as the cone. Interestingly, ruled frames are not instantiated by sketching frame creation strokes. Rather, they are simply created by referencing two existing strokes in the scene as the two profile strokes that are connected to create the surface in between (Figure 6.13). Once the profile strokes are determined, both strokes are re-sampled to have the same number of points. Then, each pair of corresponding points from the two strokes is linearly interpolated to calculate the points of the immediate curves representing the surface of the ruled frame. Since ruled frames serve the purpose of allowing users to fill in the gaps between existing contours, they do not need to be reoriented once instantiated.

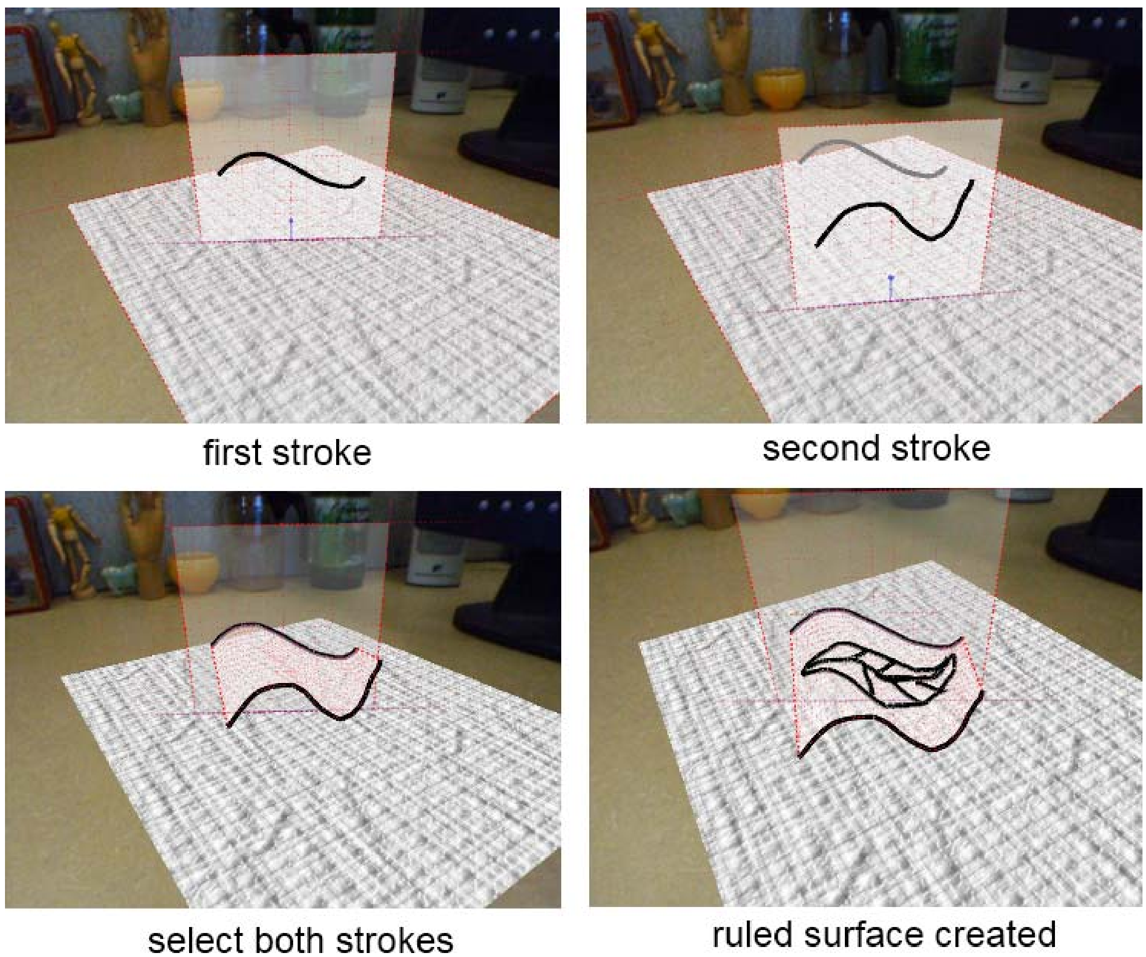


Figure 6.13: Step by step illustration of the creation of a ruled frame

6.6 Frame Management

In *Napkin Sketch*, a 3D sketch is composed of many strokes sketched on different frames, and because the frame creation techniques described in the previous section is mostly based on previous frames, it can often be difficult to recreate the same frame twice if modifications need to be made on a previous frame. For example, if the user is sketching on a frame to create the roof of a house, it may be difficult to go back to the frame that one of the walls was sketched on to add a window because the context of when the user first created that frame to sketch the wall has changed. Therefore, it is important to have efficient methods for quickly switching between frames. This corresponds with the need to effortlessly transition between implicit structures and freeform interaction (Moran et al., 1995). Currently, when a new frame is created or a previous frame is revisited, it becomes the active frame for sketching and is stored in an ordered list, representing a history of the frames used or visited. Sometimes, the user may want to backtrack to previous frames to instantiate a new frame in a desired location. With the house example (Figure 6.8), a user may sketch the front wall of the house, finish working on one side wall, and then sketch the other side wall. Although a continuous flow of sketching may take the user to the back wall first and then around to the other side wall, jumping from one side wall to the other is also a logical workflow, since the user may already be comfortable with the way one side wall is sketched and want to replicate it immediately on the other side. Supporting alternative workflows is important because *Napkin Sketch* strives to retain the flexibility of conventional sketching.

One technique for frame management is to allow users to quickly navigate back and forth in the list of frames. Since a history of frame switching and frame creation is maintained, users can cycle through previously visited or created frames to make additions to the strokes already sketched on them or use them as starting points for creating new frames. Currently, this functionality is accessed via backward and forward onscreen buttons or physical hardware buttons on the tablet PC (Figure 6.14). This technique works well when the number of frames used is small.

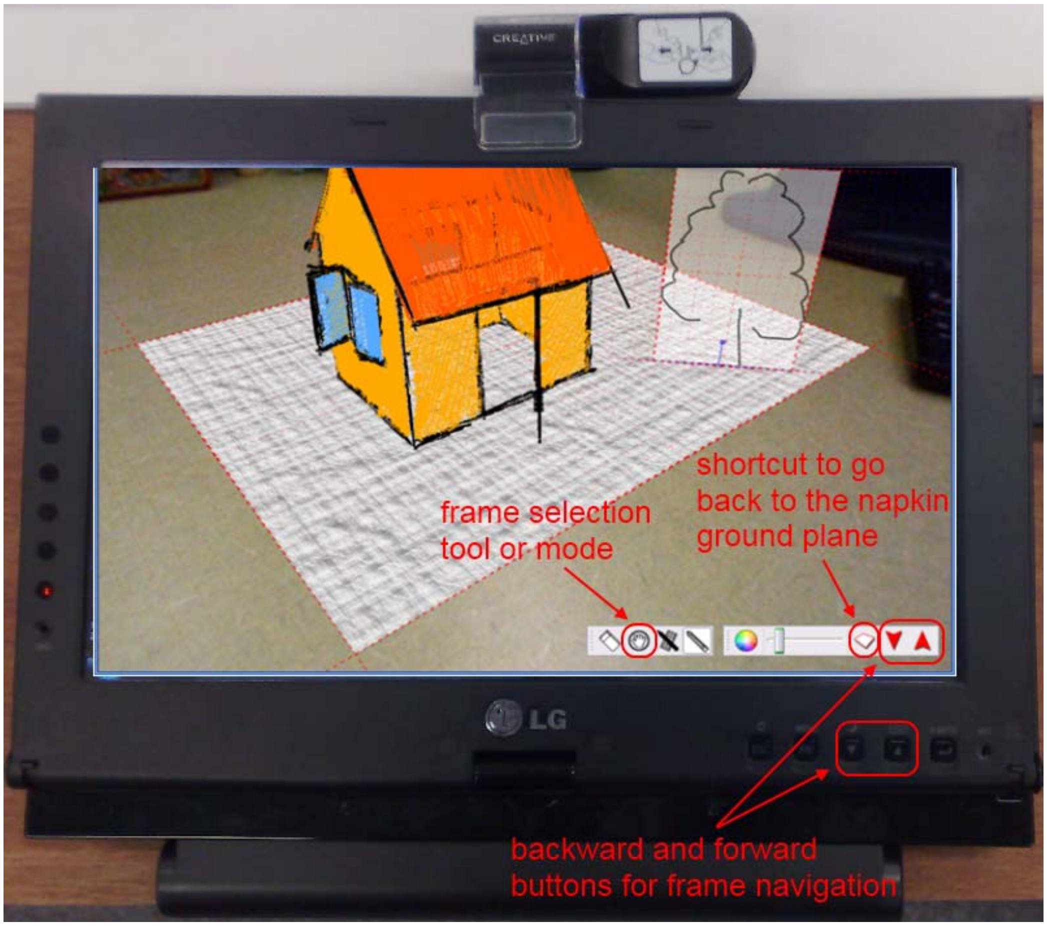


Figure 6.14: Onscreen and hardware interfaces for frame management

Being able to revisit previous frames using backward and forward navigation is useful, but it is limited to navigating the history in a linear fashion, which can be slow and cumbersome if the target frame has not been visited recently or when there are a large number of frames used. An alternative method for accessing previously used frames is by allowing users to select a stroke and bring up the frame it was sketched on. Therefore, in *Napkin Sketch*, each recorded stroke keeps track of the frame it was sketched on. To select the frame that a stroke was sketched on, the user must first select the frame selection tool or mode (Figure 6.14). Then, the frame can be selected by simply crossing over the desired stroke with the stylus. This approach is fast and direct and helps to simplify frame navigation and reuse. For example, in Figure 6.15, the user can easily switch between the three fins of the shape to make modifications by simply selecting the existing strokes.

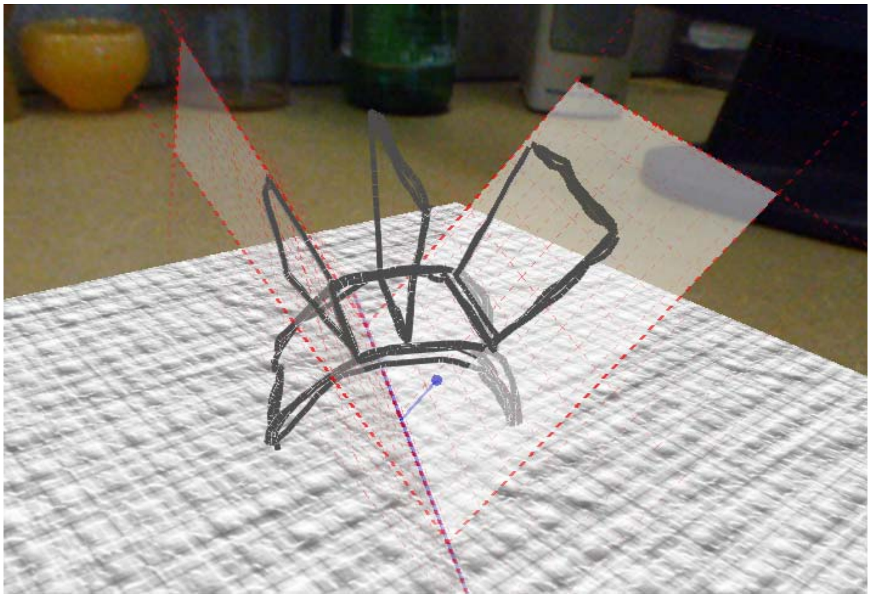


Figure 6.15: Frame selection allows users to easily switch between the fins of this shape to make modifications

One more feature implemented in *Napkin Sketch* to assist in frame management is the ability to quickly switch to the napkin ground plane. As mentioned earlier, the napkin ground plane is an important plane frame that anchors the 3D design space, providing a good starting point for sketching or creating frames. Therefore, a shortcut which can be accessed via an onscreen button (Figure 6.14) is implemented to allow users to easily set the napkin plane frame as the current active frame in case users become disoriented in the 3D design space. As demonstrated in this section, various techniques for frame management are employed in an attempt to lessen the increased cognitive load of 3D sketching and having to explicitly establish frames as temporary structures for sketches. In the following section, techniques for frame visualization are described which further assist the user in 3D sketching and spatial understanding.

6.7 Frame Visualization

Although frames are meant to be implicit structures to guide sketching, they still need to be displayed to the users to help them understand their interactions in the 3D design space. Since it is easy to become lost in virtual 3D space without proper visual cues, the appearance of frames in *Napkin Sketch* is carefully designed. Because plane frames and lofted frames have infinite extent, they are difficult to visualize. In practice, quads or finite surface meshes must be rendered to indicate their position in 3D. However, if rendered too big, the visualization would cover the display, and it would be difficult to judge its location and orientation. If rendered too small, it may be challenging for users to judge the positions of their sketches outside the visual boundaries of the frame. This problem is dealt with in two ways. First, the initial size of the newly created plane frame or lofted frame is inferred from the length of the frame creation stroke. Then the height of the new frame is set as twice the width of the frame creation stroke. This provides a reasonable initial representation of the new sketching surface. Second, if the user sketches outside the initial visual boundaries of frames that can extend infinitely, then the visual representation of the frame is automatically resized to include the sketches that are out of bounds. This adaptive frame extension technique ensures that all strokes sketched on a frame is visualized as appearing on the frame’s surface rather than floating in the air and prevents frames from being displayed as bigger than necessary. Since ruled frames are finite, they are straightforward to render and do not require frame resizing.

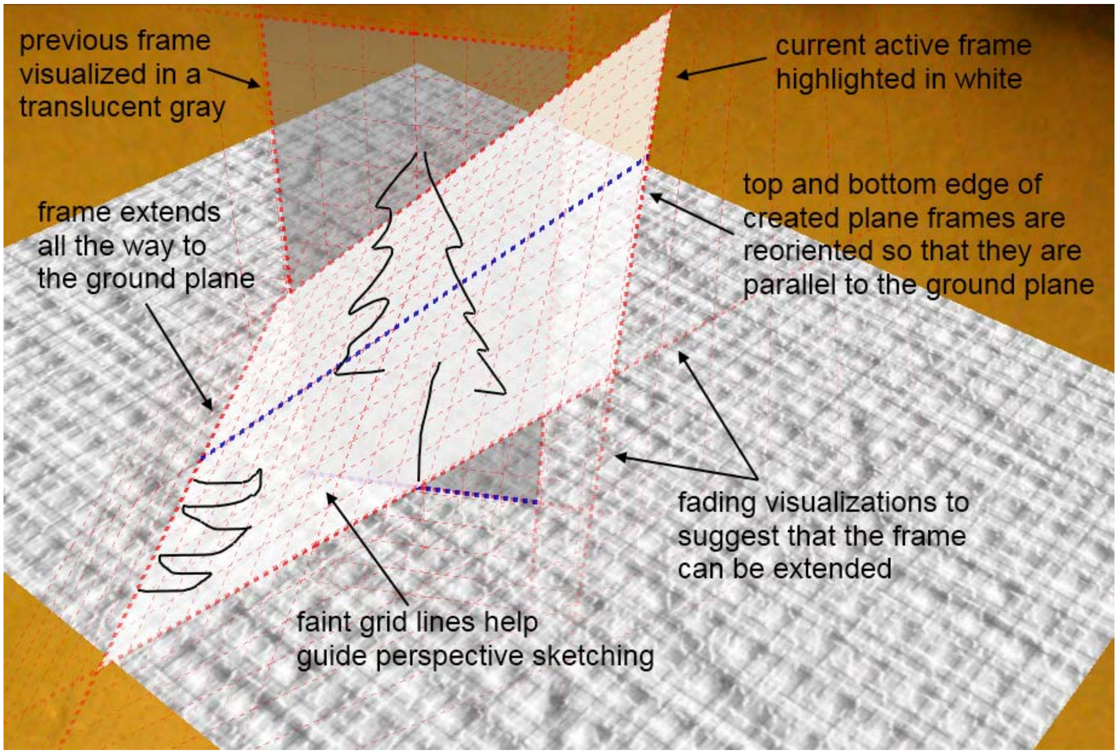


Figure 6.16: Visualization of plane frames

The boundaries of all frames are rendered as thick stippled red lines. For plane frames and lofted frames, the boundaries which extend infinitely gradually fade into space to indicate the infinite nature of the frame (Figure 6.16). The frame creation stroke once sketched is replaced with a solid blue line (Figure 6.16), which for plane frames indicates the axis of rotation. The frame surface itself is highlighted in translucent white if the frame is the current active frame. Because lighting is not applied to the 3D surfaces of the frames, slight visual adjustments and alternative visual cues are provided to help users understand the position and orientation of the frames in the 3D design space. For a new plane frame, the quad representing the visual boundaries of the frame is rotated around the axis formed by its centre and its normal so that the top and bottom edges of the frame are parallel to the surface of the napkin (Figure 6.16). Also, the visual boundaries of a plane frame are automatically extended so that the bottom edge of the frame touches the napkin (Figure 6.16), provided the plane frame is not parallel to the napkin and the extension does not make its visual boundaries too big. These visual adjustments for the plane frame help users to better perceive the sketching surface and allow users to easily judge the 3D positions of their sketches relative to the important napkin plane frame. To further assist users in perspective sketching and understanding the 3D design space, faint red grid lines following the contours of the frame surface are displayed, and the previous plane is shown in a translucent gray along with the current active frame highlighted in white (Figure 6.16).

6.8 Plane Frame View Switch

Even with visual aids like grid lines discussed in the previous section, sketching in perspective and in 3D can be a challenging task for some users. Sometimes, the perspective distortion of the scene can affect users' spatial judgement such as when frames in the 3D design space appear at oblique angles to the sketching surface. Therefore, the ability to tangibly move around the scene is critical in helping users find views of the 3D design space that they prefer for sketching.

One popular view is where a plane frame is shown parallel to the sketching surface of the sketchpad. This view is useful because it allows users to sketch on the plane frame without perspective distortion. However, there are situations where moving the napkin or sketchpad to reach such a view of the plane frame is difficult or impossible. For example, to achieve a view where the napkin plane frame is parallel to the sketching surface, the user must hold the sketchpad flat directly on top of the napkin. To solve this problem, *Napkin Sketch* allows users to temporarily suspend the normal view of the napkin with sketches and frames anchored on top of its surface and switch to the desired parallel view of the current active plane frame (Figure 6.17). Conceptually, this process can be thought of as taking the plane frame floating in 3D space, flattening it out on a tabletop, and leaning over it to sketch just like in conventional 2D sketching. This view switch makes the design space appear less coherent with the physical environment, but it is helpful for users who are not comfortable with perspective sketching.

To make the view switch appear seamless, the transformation from the normal napkin view to the parallel plane frame view and vice versa is animated using quaternion and spherical interpolation (Shirley and Marchner, 2009). In essence, this process gradually transforms the virtual camera to the desired location for the parallel plane frame view, which is just a set distance along the normal of the plane frame (Figure 6.17). Tracking via the napkin is still performed in the parallel frame view. However, movement of the virtual camera is restricted to only translations along the x, y, and z axis of the plane frame’s local coordinate space. Rotations of the virtual camera are not supported as this would relinquish the parallel relationship between the plane frame and the sketching surface.

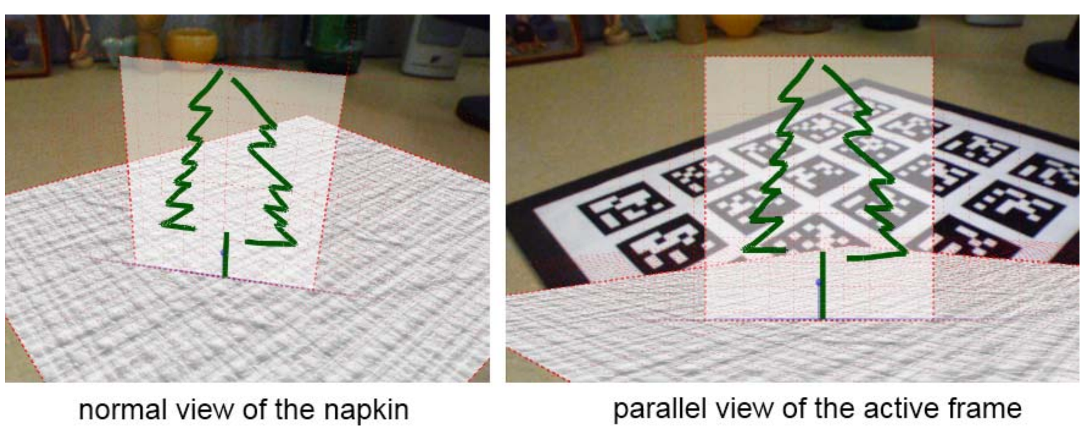


Figure 6.17: Before (left) and after (right) of the plane frame view switch

6.9 Graphical User Interface

Because *Napkin Sketch* is a sketch-based system attempting to deliver a fluid interaction experience, an effort was made to reduce the number of onscreen interactive controls used to access functionality. However, a small set of user interface components is still required to used the system. The interface components of *Napkin Sketch* can be specified in two categories: global interactive controls and napkin interactive controls. Some of these have already been briefly described in previous sections.

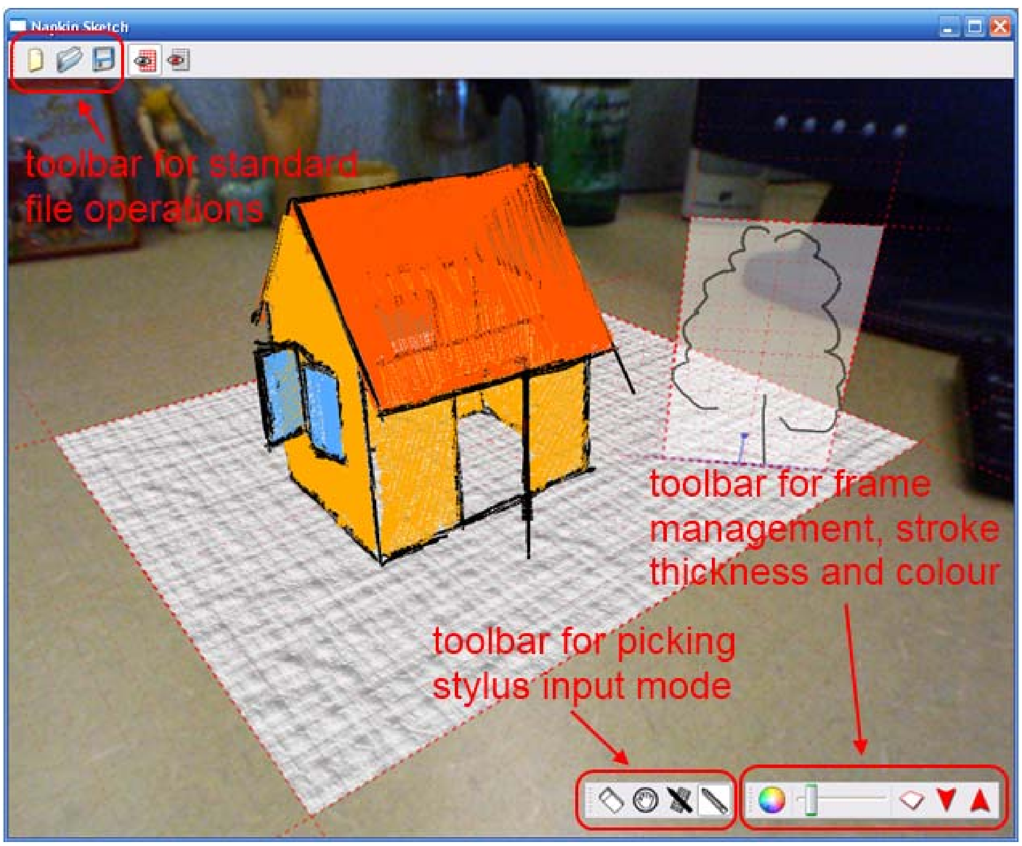


Figure 6.18: Global interactive controls of the *Napkin Sketch* onscreen interface

The global onscreen interactive controls of *Napkin Sketch* (Figure 6.18) has one set of standard toolbar buttons for opening and saving existing sets of sketches and creating new sets of sketches. Another set of mutually exclusive toolbar buttons can be toggled to select one of four available modes for stylus input: eraser, stroke or frame selection, frame creation, and normal ink for sketching. Lastly, another toolbar provides interactive controls for stroke thickness, stroke color, and frame management functionalities.

Because of feature such as the plane frame view switch and to support the use of multiple napkins in a sketching session, a set of onscreen interactive controls is made available for each napkin to manage various napkin properties (Figure 6.19). In order to avoid visual clutter, the napkin interactive controls are hidden until triggered. Users can bring up the controls by tapping once on the desired napkin with the stylus. This gesture reveals the controls around the napkin arranged in a circular fashion (Figure 6.19). The controls are only displayed for a few seconds before fading out and becoming hidden again. While the controls are visible, functionality can be invoked by tapping on the appropriate icon with the stylus. The set of napkin interactive controls include convenient functionality such as the ability to load existing sketches, clear the entire napkin, and temporarily hide frame visualizations to get a better view of the sketch without distractions (Figure 6.19). Other functionality such as lock and unlock and stamp are used for collaborative scenarios. These will be discussed in the next chapter.

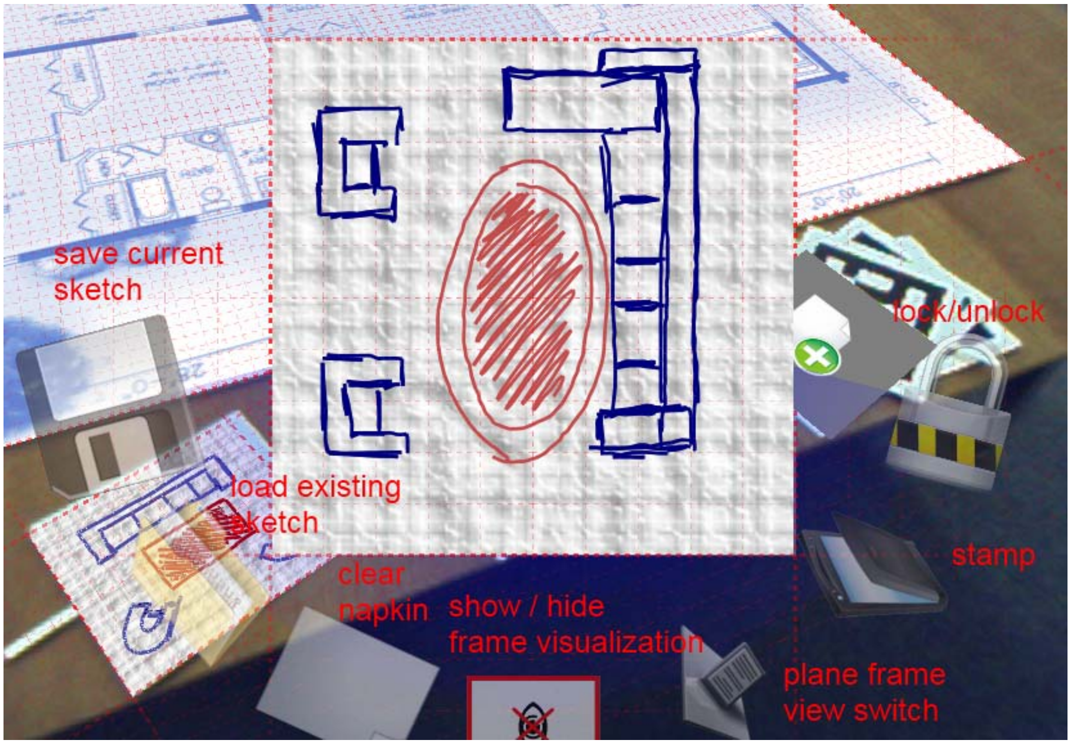


Figure 6.19: Onscreen interactive controls available for each individual napkin

6.10 Summary

Projective 3D sketching, grounded in the principles of freeform interaction, is the focus of *Napkin Sketch*'s software design. The concept of 3D sketches as a combination of strokes used to implicitly suggest 3D forms rather than explicitly construct mesh surfaces is the foundation of the system. In this chapter, the process of projective 3D sketching is outlined in detailed, and various nuances and challenges of the technique are identified such as having to specify frames for strokes to project onto and having to sketch in perspective. Software design solutions which leverage the unique hardware setup of *Napkin Sketch* are also presented to deal with the added complexities of sketching in 3D. For example, an in-depth discussion of various frames as temporary implicit structures for sketching is provided, along with the details of novel gesture-based techniques to quickly create new frames in desired locations. The goal of *Napkin Sketch*'s software design is not only to support the hardware, but it also pays great attention to achieving fast and fluid interactions and helping users to gain a better spatial understanding of the design space. Design details such as the frame visualizations have been carefully conceived, and some features have been refined through user testing. Further discussion of the user evaluation findings which motivates and validates some of the design concepts will be presented in chapter eight.

Chapter Seven: Collaboration with *Napkin Sketch*

The essence of sketching is the exploration of ideas, and sketches seldom exist in isolation. They are "social things" and embody shared awareness, collaboration, communication, juxtaposition, and critique (Buxton, 2007). Looking back once again at the Coffee Cup Scenario which opened this thesis, it is evident that the social practice of sharing between people which defines the culture of design is as important if not more important than being able to simply generate sketches (Figure 7.1). *Napkin Sketch* strives to support collaborative activities such as passing, comparing, and assembling sketches, as seen in the Coffee Cup Scenario, in order to facilitate the type of co-located collaboration supported by conventional 2D sketching and to augment it with the power of automation and 3D visualization.

Figure 7.1: Collocated designers collaborate using sketches

Because the interaction involved in *Napkin Sketch* is similar to conventional 2D sketching, the idea of facilitating collaboration with *Napkin Sketch* is a conceptually straightforward extension. Instead of having one user with one sketchpad, multiple users can sit around a tabletop and interact together with multiple sketchpads (Figure 7.2). Users still sketch on their own napkins with their sketchpads, but now they can also see and manipulate the sketches created by collaborators with other napkins on the tabletop. Since the napkins and the design space of *Napkin Sketch* are physical, 3D sketches can be passed, compared, and assembled just like conventional 2D sketches (Figure 7.2). Unlike other collaborative computer tools where the support for collaboration may drastically increase the complexity of interaction, *Napkin Sketch* attempts to leverage the affordances of interacting in the physical environment and the spatial understanding of users to make collaboration seamless (Ullmer and Ishii, 1997). Furthermore, to highlight the unique advantages of computer-supported tools, effortless and intuitive replication of sketches and explicit privacy support are also explored. In the following sections, several design approaches and key features of the collaborative functionalities of *Napkin Sketch* are presented along with the motivations that inspired their design.

Figure 7.2: Users engaging in collaborative sketching with *Napkin Sketch*

7.1 Mobile Digital Tabletop

The design of the collaborative sketching experience with *Napkin Sketch* employs a novel interaction paradigm which can be described as a mobile digital tabletop. Unlike stationary digital tabletop interaction (Deitz and Leigh, 2001), where users gather around the device and interact with digital content directly on the display surface of the tabletop, a mobile digital tabletop facilitates co-located collaboration using mobile devices mediated by the use of physical objects such as napkins to manipulate digital content in the physical environment (Figure 7.3). The concept is essentially to expand the digital interaction space which is usually bound by the display size of the mobile device to the physical shared space of real physical tabletops. In such a scenario, the device itself is no longer a container for digital content but rather a portal through which the expanded digital shared interaction space can be viewed and manipulated by both digital and physical means (Ullmer and Ishii, 1997). Because digital content is coupled with the physical locations of the napkins, it can be easily accessed by anyone with a capable mobile device acting as the portal. The advantage of a mobile digital tabletop is that it is less expensive, low-fidelity and portable, requiring only mobile devices, tracking enabled physical objects such as napkins, and any suitable shared surface for interaction instead of a large and stationary digital interactive surface. However, unlike stationary digital tabletops, interacting with digital content on this conceptual mobile digital tabletop can be less direct because some activities are performed through the mobile device such as sketching or manipulating onscreen controls.

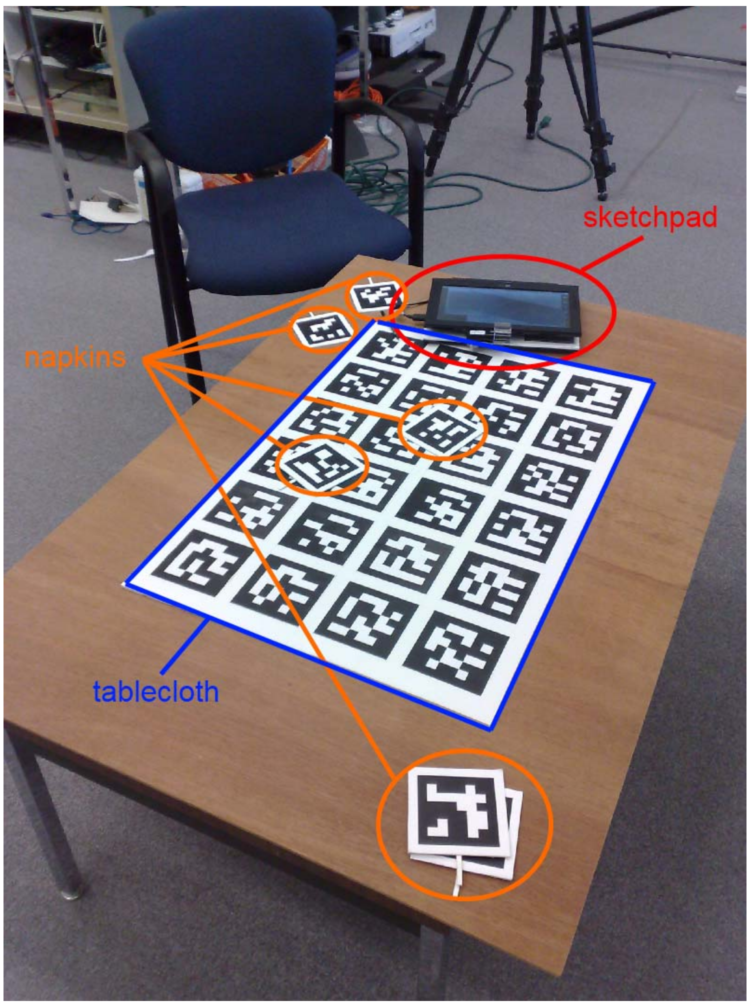


Figure 7.3: The mobile digital tabletop and its components

A mobile digital tabletop is similar in functionality to the stationary digital tabletop in terms of its ability to support co-located collaboration. Therefore, many of the concepts in tabletop interaction research such as ownership, orientation, partitioning, workspaces, and awareness (Tang, 1991; Kruger et al., 2003; Scott et al., 2004) can also be applied and extended to a mobile digital tabletop. Because of the tangible interactions supporting *Napkin Sketch*, users can leverage the physical environment and physical artifacts used by the system to engage in social behaviour typical of normal tabletop interaction. For example, different workspaces can be established when using a mobile digital tabletop by organizing napkins in piles at various locations on the tabletop or by placing them in varying orientations. Awareness, ownership, and privacy are also implicitly supported by the effects of proximity as dictated by the social protocols of the physical interaction space. For example, objects situated close to a user or within a user's personal space around the mobile digital tabletop implicitly belong to that user and should not be moved or used unless given permission.

Although there are many similarities to the stationary digital tabletop, what makes the concept of a mobile digital tabletop interesting are its unique capabilities which extend the support of co-located collaboration. One important characteristic of a mobile digital tabletop is that the virtual design environment is visualized using multiple personal mobile devices each representing a unique point of view of the shared interaction space. By applying the concept of a mobile digital tabletop for collaborative sketching, *Napkin Sketch* can take advantage of such characteristics to infer where collaborators are focusing their attention, where they are located relative to each other and distinguish input from different collaborators. In turn, these capabilities enable

Napkin Sketch to explore interesting concepts such as explicit ownership, explicit workspaces, and explicit privacy control, which are all described in detail in the following sections.

7.2 Explicit Napkin Ownership

In *Napkin Sketch*, most of the interaction with napkins occur on the sketchpad such as sketching and other editing operations. This is both a strength and weakness. With this approach, actions can be projected across the interaction space, allowing collaborators to modify napkins that may be out of their reach, but it causes problems with awareness and the implicit sense of ownership and shared and private workspaces. In order to deal with this problem, *Napkin Sketch* is designed to enforce explicit ownership, leveraging the ability to distinguish input from collaborators.

All unclaimed napkins in the physical interaction space can be claimed by any collaborator joining the session with their own sketchpad. Unclaimed napkins can be distinguished from claimed napkins because each napkin is visualized as a gray new napkin icon as seen through the sketchpad (Figure 7.4). After locating an unclaimed napkin, the collaborator can then establish explicit ownership of the napkin by tapping on the napkin with the stylus of the sketchpad, and the gray new napkin icon fades out to reveal the normal visualization of the napkin, indicating to other collaborators that it can no longer be claimed (Figure 7.4). Currently, only the owner of a claimed napkin can sketch on it, and ownership cannot expire or be transferred. Although it is interesting to consider the possibility of having multiple users sketch on a single napkin concurrently, the scenario is not practical because anytime a user moves the napkin, the viewpoints of all users are affected. The idea of a shared design space where sketches can be assembled and reviewed together is explored in following section.

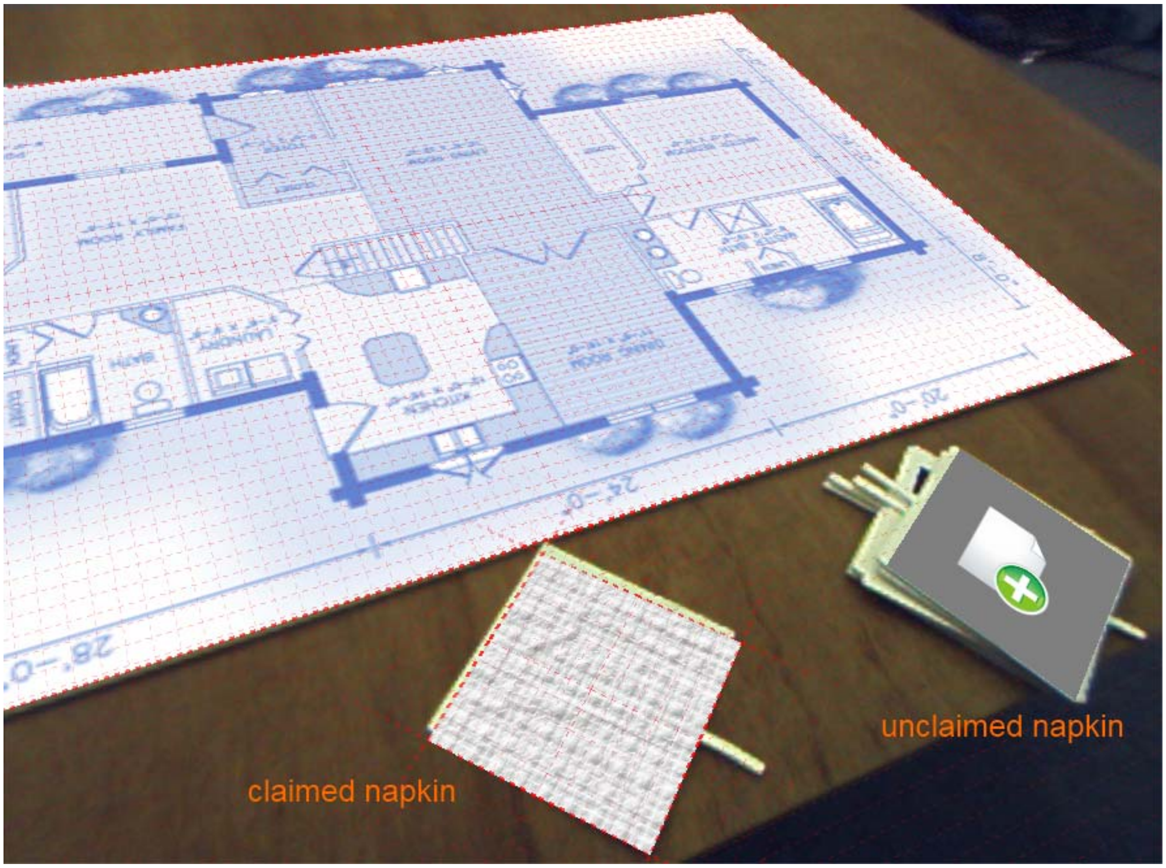


Figure 7.4: Visualizations of claimed and unclaimed napkins

7.3 Tablecloth and Explicit Workspaces

Unlike stationary digital tabletops, where often only one device is interacted with by multiple users, a mobile digital tabletop can have a variety of devices and physical props working together. For *Napkin Sketch*, sketchpads and napkins are the bare minimum requirement. However, other devices and objects can also be added to the ecology of its mobile digital tabletop to enhance the interaction experience in different usage scenarios. For example, a stationary external display equipped with a camera looking at the napkins can be placed next to the physical interaction space to allow the virtual sketches to be visualized by casual observers without a sketchpad. Another useful element experimented with in *Napkin Sketch* is a tablecloth (Figure 7.3). Its purpose is to establish the tabletop surface as a single unified shared workspace, where sketches can be combined and reviewed together. As noted in the previous sections, the allocation of personal and shared workspaces can be facilitated implicitly through physical proximity, but in *Napkin Sketch*, actions can be projected across great distances and the ownership of napkins is enforced explicitly. Therefore, implicit proximity-defined workspaces are less effective, because of the potential lack of awareness when collaborators are modifying napkins at a distance. Also, although individual napkins can be used to create shared points of reference in the physical space, in a collaborative scenario, multiple napkins are used by different collaborators, so it becomes difficult to identify a central shared space. With the current design of *Napkin Sketch*, only the relative positions of the sketchpad to napkins is tracked, which means there are many disjoint physical interaction spaces local to the napkins rather than one unified interaction space for the entire tabletop surface.

Figure 7.5: The tablecloth and the partitioning of explicit workspaces

The tablecloth is introduced to deal with the aforementioned problems. Unlike napkins, a tablecloth which can be tracked by sketchpads is not intended to be moved around but rather serves to establish a fixed point of reference for the entire interaction space. In the current implementation, the tablecloth is materialized as a four by three grid of markers adhered to the back of a poster board and placed in the center of the table (Figure 7.5). The size of the poster board was carefully chosen so that the table has ample space around the borders of this tablecloth for collaborators to place their napkins. With such a physical configuration, two distinct workspaces are defined: a shared workspace on the surface of the tablecloth and a private workspace on the edges of the table around the tablecloth (Figure 7.5). Although the current tablecloth does not cover the entire table, future tablecloths can be made with more flexible materials that can be draped over the surface and printed with visually distinct patterns to distinguish between the different workspaces.

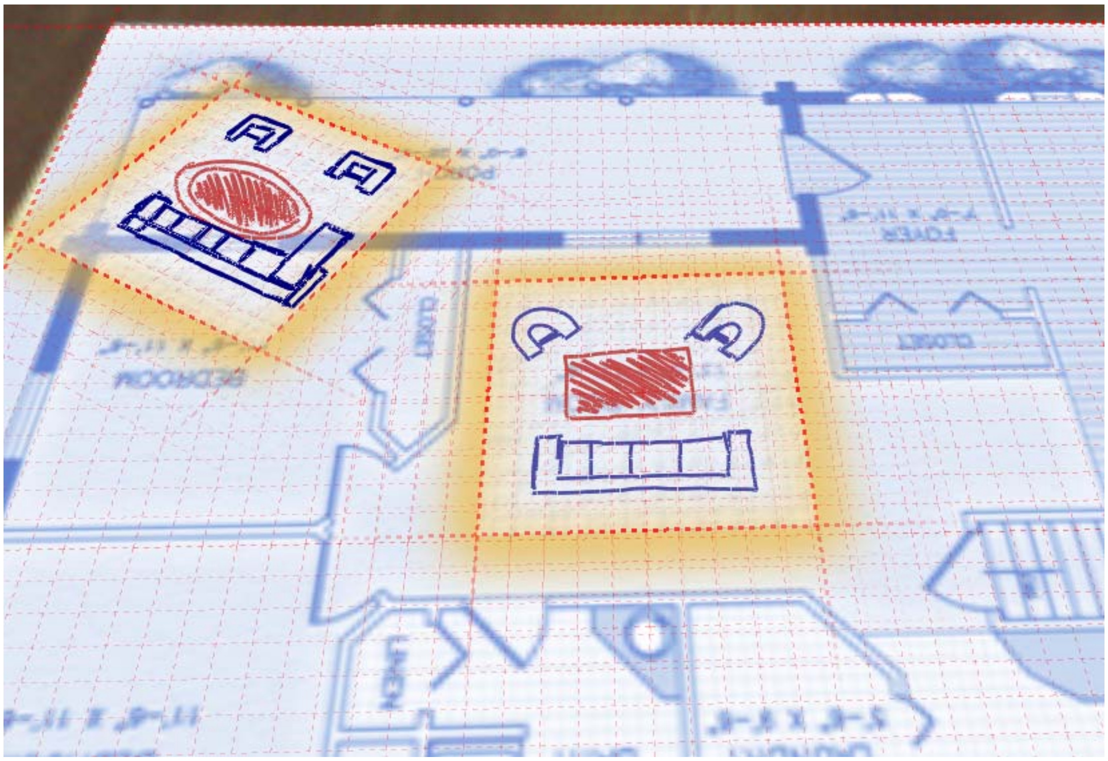


Figure 7.6: Tablecloth augmented by a floor plan with transparent napkins on top

Similar to napkins, the visualization of the tablecloth can be augmented to fit the design scenario. For example, a floor plan can be displayed as the surface of the tablecloth for interior designers (Figure 7.6). This allows users to try out various positions and orientations for their designs sketched on napkins by simply overlaying the napkins on the tablecloth at the desired locations. Because multiple markers are used on the tablecloth, it can be tracked even if napkins and other objects are occluding parts of its surface. Napkins can be placed on top of the tablecloth and moved around, and the content sketched on them can be assembled or compared. When placed on top of the tablecloth, the background of the napkin becomes transparent so that it does not occlude content underneath it (Figure 7.6). This is analogous to the use of transparencies for comparing and assembling conventional 2D sketches.

7.4 Stamping

Although assembling sketches can be achieved by placing napkins next to each other, overlapping napkins can be problematic because of clutter and the loss of tracking due to occlusion by other napkins. Therefore, a stamping technique is developed to allow collaborators to copy sketched content from napkins directly onto the surface of the shared workspace defined by the tablecloth. This allows sketches to be assembled without having to physically assemble individual napkins. To stamp sketches, the napkin is first positioned in the desired location. Then by determining the inverse transformation for sketches in the coordinate space of the napkin to the coordinate space of the tablecloth, the sketches are copied onto the tablecloth via the stamp icon available in the list of napkin menu options (Figure 7.7). Once stamped, a copy of the sketches remains at the set location even if after the napkin is removed. Currently, sketches copied to the tablecloth cannot be erased unless the entire tablecloth is cleared, and they cannot be copied back to a blank napkin. Composition of sketches on the tablecloth can only be achieved via stamping from napkins, and direct sketching on the tablecloth is not yet supported.

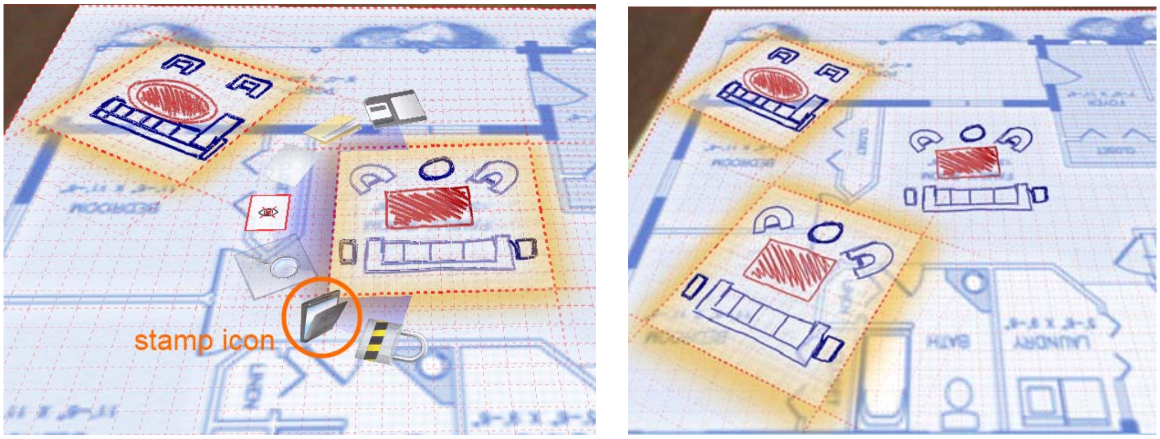


Figure 7.7: The before (left) and after (right) of the stamping operation, transferring the sketch on the surface of the napkin to the surface of the tablecloth

7.5 Copying

In conventional 2D sketching, copying is a mundane and cumbersome task, but it is trivial for computer-supported tools. Stamping allows sketches to be copied from the napkin to the tablecloth, but as the Coffee Cup Scenario shows, replicating existing designs on fresh new napkins is also important because sometimes existing designs serve as the templates or starting points for new designs, and users often do not want to make modifications directly on the original. As noted in the case study by Kolli et al. (1993), designers often make a number of copies of a sketch to explore alternative design solutions such as different colour combinations. Copying also serves as a method to share sketches among collaborators without having to transfer napkin ownership. Currently, only the owner of a napkin can sketch directly on it, so even if a napkin is physically passed by its owner to a collaborator, the user receiving the napkin cannot sketch on it. Napkin copying solves this problem because a user can first take ownership of a blank napkin then copy the contents of a collaborator’s napkin to make modifications.

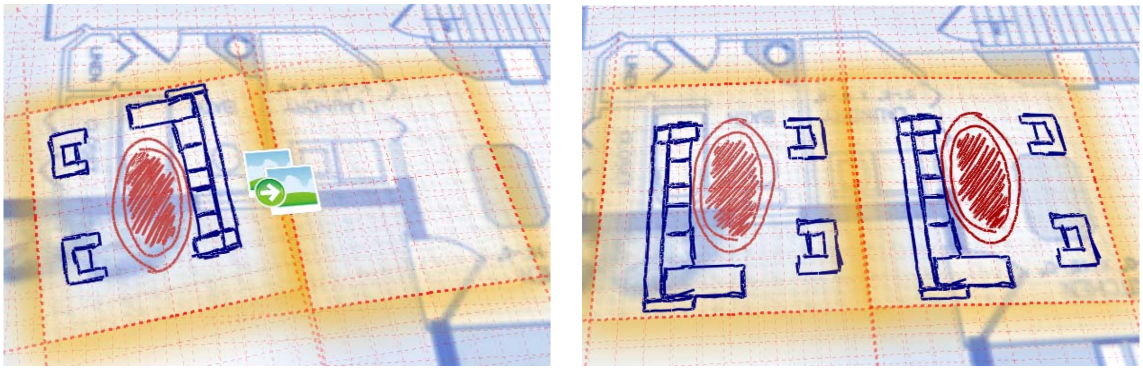


Figure 7.8: Before (left) and after (right) of the copying operation

To invoke the copy functionality, the user first places a blank napkin next to the napkin to be copied. When the napkins are close enough, a copy icon with an arrow indicating the direction of copying is displayed between the two napkins (Figure 7.8 left). The action to copy can be executed by invoking the icon with the stylus. This transfers the contents of the napkin to be copied to the blank napkin (Figure 7.8 right). The copied content then appears on the blank napkin with an animated top down wipe effect as a visual confirmation that the operation has been performed. It is interesting to note that this copying procedure takes advantage of spatial context to invoke appropriate functionality, since copying in conventional 2D sketching also requires napkins to be placed in close proximity. Also, the act of physically placing a napkin next to another provides further awareness of a user's actions and intentions to collaborators. Unlike purely digital operations which can be performed entirely in the background of the system without being noticed by users, physical operations are more visible to co-located collaborators. To move napkins, users may have to reach across the design space, so when others see this, they know that perhaps someone is interested in copying a particular sketch. The concept of associating relevant functionality to spatial context will be explored further in the following section.

7.6 Explicit Privacy Control

Privacy control is sometimes problematic for digital tabletops because digital content is only displayed on the shared horizontal surface and can be difficult to hide from the view of your collaborators. Although it is beneficial to make content publically accessible for the purpose of sharing, sometimes it is also necessarily to control the information being shared. For example, in strategic negotiations, the timing of when information is shared with others is critical (Yamaguchi et al., 2007). Also in multi-player board games like Clue, withholding information is just as important as sharing it. Although it is difficult to make a case for privacy control in collaborative design, one can imagine a situation where two designers with conflicting views must collaborate on a design task, or perhaps some designers just do not feel comfortable sharing their design until it reaches a certain stage of maturity.

In real world co-located interaction, privacy control isn’t supported explicitly, but people find ways to achieve this. For example, cards can be held so they are only visible to the person holding them and not to others. Similarly, traditional 2D drawings can be sketched on paper attached to a clipboard that is held up at an angle to prevent others from looking at what is being sketched. Privacy control is not necessarily a binary decision of visibility. The viewing distance of objects in the physical space affects privacy as well. Certainly, objects farther away from the viewpoint naturally appear blurrier and are perceived with less detail. Therefore, this visual property of the physical environment can be used to intuitively provide varying levels of privacy by simply placing objects in the shared space at varying distances from the viewpoint of the collaborators.

In *Napkin Sketch*, privacy can be supported both implicitly by mimicking real world practices and explicitly by leveraging the flexibility of digital visualizations. Because *Napkin Sketch*'s mobile digital tabletop design provides access of the interaction space through multiple personal display devices, each display can be tailored to show customized content based on explicit privacy settings.

Figure 7.9: Privacy control user interface and visualization

Currently, there are only two levels of privacy settings: shared and private. This essentially represents the basic binary visibility decision, determining whether a napkin owned by one user can be seen by other collaborators or not. More granularity in privacy control can perhaps be implemented by mapping privacy levels to sketch transparency. To set the privacy of a napkin to either shared or private, users can toggle a locked and unlocked icon displayed as part of the napkin controls (Figure 7.9). For the owner of the napkin, a red border surrounding the napkin indicates that the current privacy setting is private and that no collaborator can view the contents being sketched on the napkin

(Figure 7.9). For other collaborators, a private napkin is simply shown as a large gray locked icon and no sketches are displayed. When the privacy setting is toggled to shared, the red border fades away from the napkin for the owner, and for other collaborators, the napkin is displayed with its sketches as seen by the owner (Figure 7.9).

Another interesting point of real world privacy practices is that the action to control access of information is usually performed seamlessly as physical manipulations of the objects in the interaction space. *Napkin Sketch* also supports smooth and intuitive transitions of privacy settings by associating the explicit privacy settings of shared and private with the explicit workspaces of shared and private as defined by the tablecloth (Figure 7.5). Because the entire area covered by the tablecloth is defined as the shared design area, where various design ideas are tested and assembled, it is logical to assume napkins placed within this design area are to be shared. Therefore, *Napkin Sketch* detects when napkins are placed in the shared design area by tracking their location relative to the tablecloth, and automatically switches a previously private or locked napkin to a shared or unlocked napkin (Figure 7.9). This design attempts to reduce the cognitive load of collaborators by relating an abstract concept such as privacy to spatial manipulations much like the technique employed for invoking the copying functionality described in the previous section.

7.7 Network Architecture

To facilitate the synchronization of sketched content across multiple collaborators, *Napkin Sketch* employs a peer-to-peer network architecture. The goal is to allow users to serendipitously form an ad hoc network of devices used for co-located collaboration. Users must be able to seamlessly join and leave collaboration sessions, reflecting the flexibility and low-fidelity of conventional 2D collaborative sketching and design. Similar to other peer-to-peer applications, when *Napkin Sketch* first starts up on a device, it searches the network for existing peers. If none is found, then the device sets itself up as a peer. Any subsequent devices searching the network would find the created peer and attempt to join it. Currently, there is no mechanism to detect the proximity of peers, so any device on the network in which the existing peers reside is allowed to join, and there can only be one group of peers per network. To create and define separate peer groups by proximity, Bluetooth signals may be emitted and received by devices to determine if users are close enough for co-located collaboration.

In the current prototype of *Napkin Sketch*, the list of possible peers is predetermined, and peer discovery is a simple process of attempting to connect to all of them. For a more robust and scalable implementation, dynamic lists of peers can be stored by each peer and passed onto new peers that discover them. Currently, when an existing peer detects a connection from the new peer, it sends back an acknowledgement along with the content of all the sketches that it owns and adds the new peer to its update list. This allows the new peer to see all the existing sketches on top of the napkins in the physical design space and prevents it from attempting to sketch on napkins already being used. Peer updates involve changes such as napkin ownership and privacy settings, addition of new strokes, creation of new frames, copying of napkins, and stamping of sketches on the tablecloth. Peers are only responsible for making modifications on the napkins which they own. For each update, the peer making the modification sends the corresponding data along with information concerning the napkin it is associated with to all the peers in its update list. This ensures the digital content of the design space remains synchronized across multiple peers, giving collaborators the perception of a unified design space.

7.8 Summary

Motivated by the importance of collaboration in the activity of sketching, this chapter outlines the design concepts and implementation of the collaborative sketching experience facilitated by *Napkin Sketch*. Because of its tangible nature, *Napkin Sketch* allows users to share, organize, and assemble sketches on a tabletop surface in order to provide awareness for co-located collaborators. Furthermore, the advantages of digital systems are also leveraged to provide useful editing functionality such as stamping and copying and to explore interesting concepts like explicit ownership, explicit workspaces, and explicit privacy control. In the design of the collaborative features of *Napkin Sketch*, the use of spatial context is applied to ensure smooth and intuitive interaction and to provide awareness for collaborators. In the next chapter, the effectiveness of such approaches is evaluated.

Chapter Eight: Evaluating *Napkin Sketch*

In this chapter, three evaluation efforts base on the 3D sketching and collaborative design experiences of *Napkin Sketch* are discussed. They were all design critiques which include reflections based on the *Napkin Sketch* design goals and are generally informal and exploratory. Each critique was performed at a critical stage of the work, and the first evaluation contributed greatly to the design of several key features of the system. The evaluation approach was to perform casual observational exploratory studies. Qualitative data was collected from post-test interviews, and the third evaluation was videotaped for further analysis.

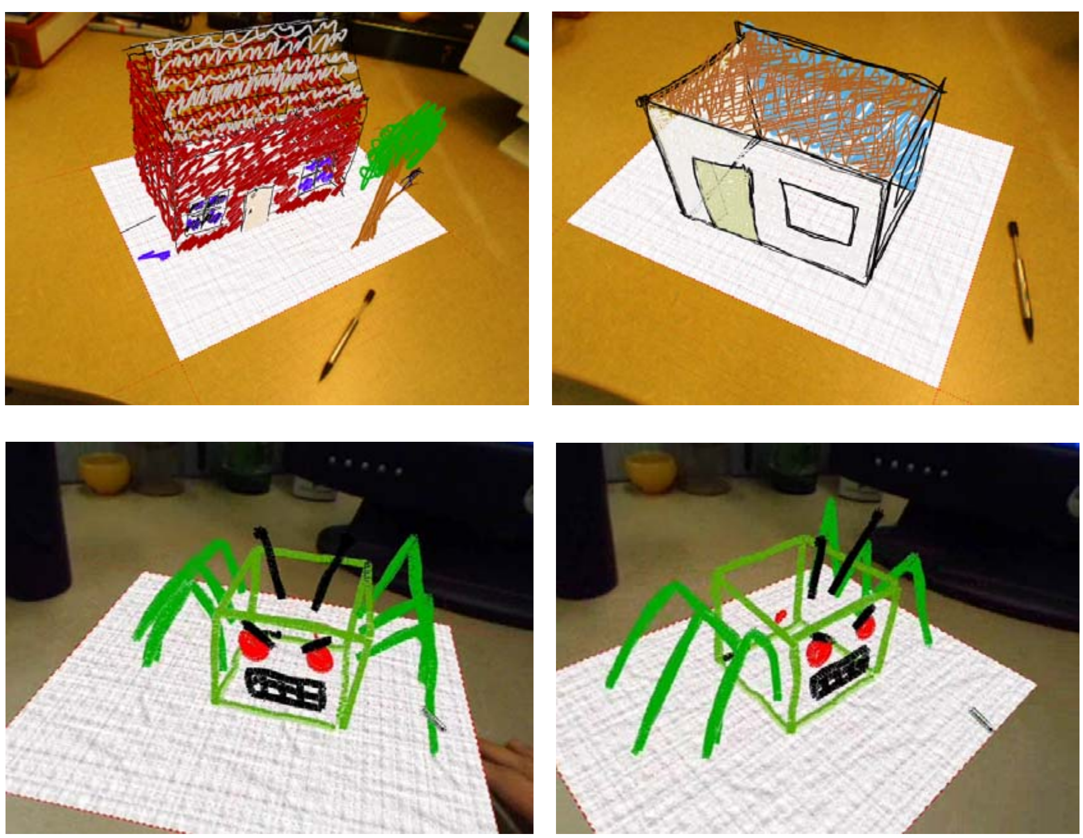
Because the design goals of *Napkin Sketch* are more abstract and subjective such as being able to support ambiguity or expressiveness, they are difficult to evaluate using typical quantitative methods. Although it has evolved into a complete and operational system, the concepts explored in *Napkin Sketch* are still in the early design phase, and the system itself represents only a sketch of the design concepts (Greenberg and Buxton, 2008) created based on the motivations outlined early. Furthermore, because the design of *Napkin Sketch* is focused on its culture of use in terms of leveraging ubiquitous computing for in situ and collaborative sketching scenarios, it is not productive to concentrate evaluation efforts solely on validating the usability of the system outside these usage scenarios (Greenberg and Buxton, 2008). Therefore, instead of focusing on comparing the usability of *Napkin Sketch* to similar systems or traditional tools and media, the goal of these evaluations are mainly to understand the effectiveness of the design in terms of achieving the overall vision of the sketching experience.

The first evaluation provided the most insight on the 3D sketching experience of *Napkin Sketch* and helped to inform the design of the system in terms of improving overall usability and removing obstacles that negatively affected the goals of *Napkin Sketch*. The second evaluation was also useful because it validated the improvements resulting from the first evaluation and also helped to identify further problems that need to be addressed. The last evaluation explored the collaborative sketching experience of *Napkin Sketch* and also provided useful insights that may be used to inform future works. In the following sections, these three evaluations are presented in detail. It is important to keep in mind that these evaluations are preliminary and some aspects of the evaluations are flawed, but they still provide a compelling story of how *Napkin Sketch* can be used for 3D sketching and collaborative design.

8.1 First 3D Sketching Evaluation

The first evaluation was conducted mainly to assess the feasibility of *Napkin Sketch*ing as a viable 3D sketching tool and the effectiveness of its projective 3D sketching technique. The design goals that were focused on include flexibility, fluidity, expressiveness, and the support of ambiguity which are reflected in features such as the tangible navigation of the design space and the one stroke frame creation technique. Although other features such as frame selection by crossing over sketched strokes (Section 6.6), view switching to make the active frame parallel to the sketching surface (Section 6.8), and the creation of lofted and ruled frames (Section 6.5) were not implemented at the time, the system was fully functional and its feature set matched the core feature set of similar projective 3D sketching systems (Piccolotto, 1998; Kallio, 2005; Dorsey et al., 2007).

This evaluation was conducted in a research laboratory with seven participants recruited from within the laboratory. None of the participants had previous experience with *Napkin Sketch* or sketching in 3D. They were provided with a brief tutorial on how to use the interface, but no explicit instructions were given on what they should create with the system. Participants used the LG tablet PC sketchpad (Section 5.1) along with one multi-marker napkin (Section 5.5) and were observed sketching their desired creations while verbalizing their thoughts about the interaction using the think aloud method, and open-ended interviews were carried out afterward. Each session took around thirty minutes with the actual sketching activity taking up around fifteen minutes.



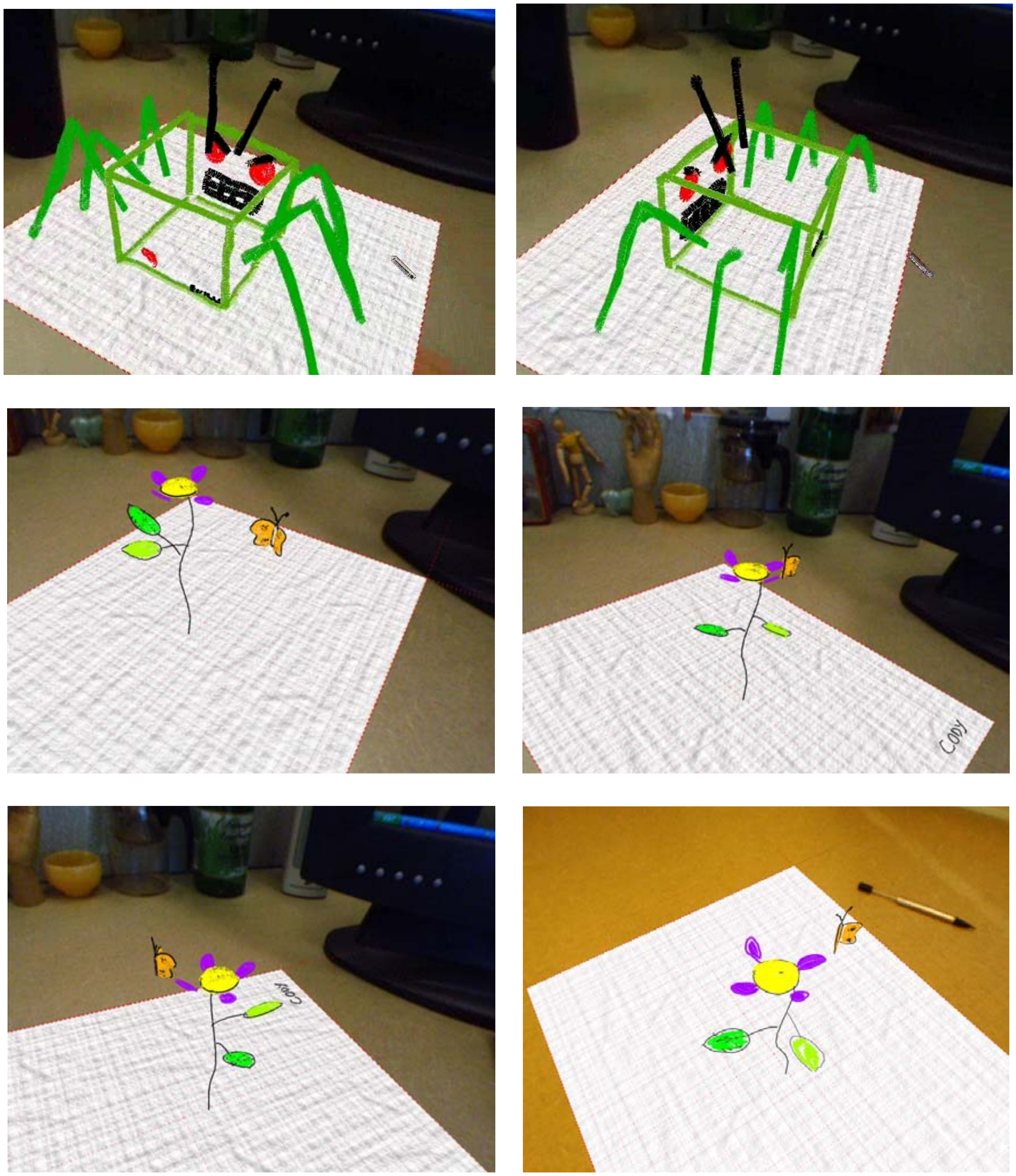


Figure 8.1: Example user sketches from the first 3D sketching evaluation

Overall, the results were positive and encouraging (Figure 8.1). However, at the same time some major areas for improvement were revealed. It was exciting to see that users interacted with *Napkin Sketch* using familiar pencil and paper techniques. Without explicit instructions, participants took advantage of the flexibility of the system to engage in sketching practices that are analogous to those observed in conventional 2D sketching. For example, one participant started drawing in very thin gray lines to try out the basic structures for his sketch and later went back to emphasize the lines with thicker and darker strokes when he was satisfied with the results. Another example where participants intuitively used conventional 2D sketching techniques was observed when they sketched crosshatched strokes or scribbled large zigzag strokes as ways to suggest surfaces within their designs (Figure 8.1). Although participants were informed ahead of time that they can sketch thick coloured strokes, they were not told how to use this feature. While some participants did ask about whether or not they can use an automatic fill operation to more efficiently cover a surface, they eventually applied conventional 2D sketching practices to suggest surfaces in their 3D sketches.

In terms of general usability, it was also encouraging to see that many of the interface features designed seemed to be useful to the participants. For example, most of the participants were observed to have used the grid lines displayed on the plane frames for drawing in perspective and judging spatial distance, especially when sketching geometric shapes such as box frames (Figure 8.1). Participants also commented that other visual cues such as showing the previous frame in a translucent gray and extending the visual boundaries of new plane frames created to the surface of the napkin were valuable in helping them understand how to sketch in the 3D design space. As was hoped, the biggest impact to design space navigation and understanding was made by the tangible manipulations of the sketchpad and napkin. Many participants commented on the intuitiveness of the technique, and they were also observed to have frequently changed the view of the design space using the napkin to minimize perspective distortions while sketching on different plane frames.

Despite these positive observation, there were also several unexpected issues with the use of the system. Although the visual cues and the tangible design space navigation technique were found to be useful, some of the participants still became lost on occasion as to how to connect lines in the 3D design space or make proper sketches in perspective. In fact, several of the participants mentioned that they were not able to produce correct perspective sketches even with conventional 2D sketching. Therefore, many participants made errors when sketching receding lines on plane frames from oblique points of view. These errors became obvious when participants switched to alternative views of the sketch and seemed to negatively affect the participants' confidence in sketching in perspective. Several participants voiced their discomfort in sketching from one point of view because of the potential unexpected results from the perspective distortion errors. Due to this problem, participant made frequent use of the grid lines as sketching guides and changed views of the design space often so that they can sketch on plane frames with less perspective distortion. One participant even sketched explicit guide lines to help connect lines in 3D and later erased them when they were no longer used.

While the tangible manipulations of the napkin and sketchpad helped users to quickly and fluidly select desirable views of the design space for perspective sketching, it was found to be awkward to use in two situations. One was observed when participants wished to view the design space in profile, and the other was observed when they wished to view the design space from overhead. For the participants who lost confidence in perspective sketching, they seemed to always want to sketch from a view where the current active plane frame is parallel to the sketching surface of the sketchpad. For example, one participant stood up and held the sketchpad parallel to the napkin to make sure she was able to sketch a perfect square (Figure 8.1) on the surface of the napkin, and similarly she also tried to stand the sketchpad on its side perpendicular to the napkin to sketch another square that is perpendicular to the first square on the surface of the napkin (Figure 8.1). Because of the weight and the bulk of the hardware, these manipulations of the sketchpad were difficult to perform, and it was also difficult to sketch while holding the sketchpad and standing up or while the sketching surface is perpendicular to the participant.

Another interesting observation from the evaluation was that participants engaged in different workflows when using the projective 3D sketching technique. Although the one stroke frame creation technique along with the ability to revisit previous frames appeared to be easy to use and understand, some participants had different ways of using the plane frames for sketching than others. For example, some participants tended to always create new frames from the current active frame and work their way around a geometry in a sequential fashion, while others tended to use one previous frame as the reference frame and always went back to that frame for creating new frames. One participant wanted to create a set of frames all at once and cycle through them to sketch without having to stop and create new frames. For those participants that tended to always refer to a reference frame to create new frames, they spent more time to cycle through frames to find the one they are looking for as the overall number of frames used for their sketches increased. Sometimes, participants paused for a few moments prior to sketching to plan how they would construct the sketch and the frames in a sequential fashion.

Based on the observations in this section, some of positive interaction examples relating to the way participants applied conventional 2D sketching practices to 3D sketching may seem trivial because they appear to be a result of the system design or the functionalities made available to participants. However, it is still pleasantly surprising and reaffirming to see participants intuitively interact with *Napkin Sketch* in similar ways to pencil and paper. The over sketching example using faint and solid lines demonstrates natural top-down design thinking and the transition of ideas from being more ambiguous and suggestive to being more concrete and declarative. This behaviour is often naturally emerging when it comes to conventional 2D sketching but can be hard to obtain in computer-supported design tools which usually only supports concrete representations. Similarly, although the practice of filling in surfaces with strokes may have emerged because it was the only available method for accomplishing the task, the participants' crosshatched strokes and scribbles hint at the expressive potential of this 3D sketching technique. Furthermore, the frequent tangible manipulations of the 3D design space through physical movements of the napkin is also reminiscent of conventional 2D sketching, where the paper is often rotated to allow easy access to certain areas of the paper for sketching. Although creating one sketch representation from multiple viewpoints cannot be done with pencil and paper, this practice is common for creating 3D sculptures which requires the artist to constantly work on the design from different points of view. Overall, being able to observe these analogues to conventional 2D and 3D artistic techniques is promising because they indicate that *Napkin Sketch* supports and encourages these naturally emerging practices and hopefully also suggests that the important qualities of sketching such as flexibility, expressiveness, and the support of ambiguity which are often associated with these practices are integrated by *Napkin Sketch* as well.

One of the lessons learned from this first evaluation is that perspective sketching is difficult for users, and the most common way to deal with this problem seems to be to avoid it by changing the viewpoint of the sketch. Although this practice is made easier with the tangible manipulations of the sketchpad and napkin, it still requires extra cognitive processing from users to find a view that was comfortable for sketching, and as indicated in the observations, tangibly changing the viewpoint was also difficult in two scenarios. Therefore, further improvements to visual guides for perspective sketching are needed to make users more confident about sketching in perspective from a static point of view while supporting a more ergonomic way of manipulating and sketching from the two problematic viewpoints indicated. For example, on top of the existing grid lines, *Napkin Sketch* can allow users to easily define temporary guide lines so that they don't have to sketch their own, and the plane frame view switch feature described in Section 6.8 is implemented to allow users to temporarily change the orientation of the 3D design space without moving the sketchpad or the napkin so that the current active frame becomes parallel to the sketching surface.

Another important lesson learned from this evaluation is that users envision their 3D sketches and the approaches to sketch them in a variety of different ways, and the one stroke frame creation technique along with the simple back and forth cycling of previous frames only supports fluid projective 3D sketching with a limited number of workflows for creating each sketch. As mentioned in the observations, users who favored using one or two sketching surfaces as reference frames had to spend more time to switch back to this frame before sketching. This points the need for more flexibility in the creation and management of sketching frames to accommodate the various ways users can potentially perceive the construction of a 3D sketch. One solution may be to allow frames to be saved as favorites and have shortcuts for quickly going back to them. An alternative solution described in Section 6.6 is to remember the frames existing strokes are sketched on and allow users to go back to a previous frame by simply selecting one of the existing stroke.

8.2 Second 3D Sketching Evaluation

Following the lessons learned in the first evaluation, the second evaluation was briefly conducted to assess improvements motivated by the findings from the first evaluation such as frame selection by crossing over sketched strokes (Section 6.6) and view switching to make the active frame parallel to the sketching surface (Section 6.8) and the addition of new features for creating lofted and ruled frames (Section 6.5). The goal was to see the effects of these iterative enhancements to the flexibility, fluidity, and expressiveness of *Napkin Sketch*. This evaluation was conducted in a research laboratory with two participants recruited from within the laboratory. Neither participant had previous experience with *Napkin Sketch* or sketching in 3D. The setup and procedure implemented for this evaluation were the same as the first evaluation described in the previous section.

The positives from this evaluation were that the improvements based on the first evaluation were well received. One participant commented on the utility of being able to switch the view of an active plane frame to be parallel with the sketching surfaces so that he could draw a perfect circle without having to guess how it should look in perspective. At first the participants also had a tendency to sometimes stand up or manipulate the sketchpad awkwardly to avoid perspective distortion, but after they became comfortable with the new feature, they preferred to use the automatic view switch rather than moving their body around the napkin. Both participants also made heavy use of the new frame selection technique to navigate back to previous frames, and their interaction with the creation and manipulation of the frames appeared to be quicker and smoother compared to the first evaluation. Also, participants seemed to be more motivated to explore different configurations of sketching frames to construct their sketches.

On the negative side, although lofted and rule frames provide more flexibility for sketching, they appeared to be more difficult to understand and interact with. Participants had no trouble creating these types of frames, but when they tried sketching on them, they had difficulties judging the projected locations of their sketches on the often curved 3D surface which prompted them to constantly sketch and review the results from multiple viewpoints. Furthermore, depending on the type of frame created and the viewpoint of the participants, there were also situations where the surface of the frame occluded itself. For example, one participant tried to sketch a helix using a cylinder-shaped lofted frame. Since he was not able to sketch on the back side of the cylinder, he had to stop sketching, rotate the napkin to show the back side of the lofted frame, and then continue sketching.

Overall, this short evaluation shows that the design goals of *Napkin Sketch* can be better realized by making improvements to key usability issues. By making design space manipulation easier and frame management smoother, this version of *Napkin Sketch* appears to be more fluid, flexible, and expressive. For example, unlike the first evaluation where participants sometimes paused and thought about how to structure the use of frames to fit the limitations of the system, participants in the second evaluation seemed to engage in a more ad hoc use of frames to satisfy their sketching needs rather than having to plan out a sketching sequence in advance. The ease of use of the frame selection technique not only adds flexibility and fluidity to the way users can interact with frames and sketches, but it also encourages expressiveness by making it easier for users to quickly explore different sketching possibilities. On the flip side, although the lofted and ruled frames provide flexibility in 3D sketching, their usability issues prevent users from making use of them in a fluid and expressive ways. This may be because there is no direct analogy to sketching on non-planar surfaces in conventional 2D sketching. At this point it is unclear if such skills can be developed over time or if a different approach to sketching non-planar strokes needs to be explored.

8.3 Collaborative Sketching Evaluation

The third and final user evaluation was conducted to explore the support of co-located collaboration in *Napkin Sketch*. The focus of this evaluation was to see how collaborative sketching would be carried out by participants using sketchpads, napkins, and tablecloth with the interaction approaches described in Chapter Seven and identify potential bottlenecks for collaboration. This evaluation was not intended to assess how to collaboratively construct a 3D sketch but rather examined how multiple sketches could be exchanged, compared, assembled, and used as props for demonstration in a collaborative design scenario. The final full-featured version of *Napkin Sketch* was used for this evaluation which includes all the functionalities described in Chapters Five, Six, and Seven.

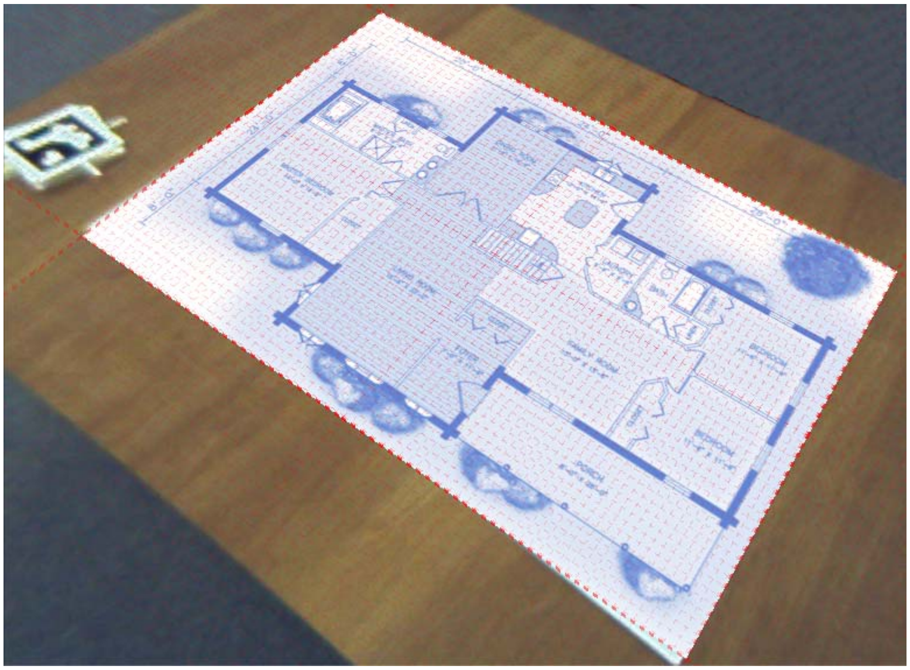


Figure 8.2: The floor plan used as the backdrop to the collaborative task of sketching ideas for furniture placement and decoration

This evaluation was conducted in a research laboratory with three pairs of participants recruited from within the laboratory. Only one participant participated in the second evaluation, while the others had no previous experience with *Napkin Sketch*. Each pair of participants was asked to engage in an open-ended interior design task, where the participants were encourage to collaborate with each other to come up with ideas for the placement of furniture and decorative elements within the floor plan of a house using only 2D sketches (Figure 8.2). The decision was made to use 2D instead of 3D sketches because the novelty and limitations of 3D sketching could have unpredictable effects on the collaboration aspects of the interaction. Therefore, only 2D sketches were used, following the assumption that all participants would be more familiar with 2D sketching, thus allowing them to focus more on collaboration.

One of the interesting features of *Napkin Sketch* outlined in Chapter Seven Section 7.6 is explicit privacy control. While it is not the focus of the exploration, the evaluation was designed to try to create a scenario where privacy would be a factor in the interaction. This was attempted by giving each participant a different hidden design agenda to carry out along with trying to collaborate with the other participant. Before the evaluation began, one participant was secretly asked to favour aesthetics in their design suggestions, while the other participant was secretly asked to favour function in their design suggestions. The idea was that the introduction of this minor conflict in design principle might create situations where participants want to keep some sketches private to perhaps present later at a strategic moment to make a bigger impact in supporting their own design agenda.

The setup for the evaluation consisted of a coffee table fitted with a large tablecloth that defined the center of the table as the shared design space (Figure 8.3). Participant were asked to start the design session by sitting across from each other so that each participant had a different viewpoint of the design space (Figure 8.3), but they were allowed to move around the table freely. Other than the minor twist involving the design agendas, each pair of participants was simply instructed to work together for thirty minutes to sketch design elements that would fit in the floor plan displayed as the background of the tablecloth (Figure 8.2). Participants did not have to complete the design and were encouraged to make modifications to improve their design to take into account the opinions of both participants. All participants were provided with a brief tutorial on how to use the collaborative aspects of the interface such as copying (Section 7.5), stamping (Section 7.4), and explicit privacy control (Section 7.6), including the basics technique for composing sketches by first creating the sketch on a napkin then stamping the sketch onto the tablecloth, but they were not shown the 3D sketching functionalities. One participant used the LG tablet PC (Section 5.1) as the sketchpad, while the other used the Toshiba tablet PC (Section 5.1), and each participant was given six single-marker napkins (Section 5.5) to use or share. Participants were observed while sketching and collaborating, but they were not explicitly required to verbalize their thoughts about the interaction. Instead, the natural conversation and interaction between the participants were videotaped, recorded, and reviewed later. Each session took around forty five minutes including the designated thirty minute design session.

Figure 8.3: Participants in the collaborative sketching evaluation

From only three sessions, several interesting findings were made. Overall, it was very encouraging to see that participants engaged in collaboration in a similar fashion one would expect when collaboratively using paper sketches. Verbal communication combined with gestures and physical movements played a large role in the coordination between the participants. For example, one participant initiated a request for opinion with the statement “What do you think of the TV here?” followed by physically moving the sketch of the TV to the desired location on the tablecloth. The other participant saw the movements of the napkin in the physical space and was able to infer the location denoted by “here” and point his sketchpad in that general vicinity to reveal the other participant's sketch of the TV. Participants also had a good understanding of their partner’s physical location and work area. For example, one participant simply said, “I made flowers.”, and the other participant immediately pointed her sketchpad at the location where the flowers were being sketched.

Participants also indicated that *Napkin Sketch* provided good awareness for co-located collaboration. They commented on the benefit of being able to see each other’s sketches and physical actions in the design space. This facilitated the coordination required for participants to work concurrently on a few occasions to position sketches. For example, one participant wanted to stamp a sketch of a dinner table at a location far away from him but close to his partner. Because it was difficult for him to judge the accuracy of the position from his point of view, he asked his partner to make sure the sketch is placed at the correct location, while he moved the napkin.

Despite the similarities, there were also some interesting differences and potential issues in the ways participants communicated using the sketchpad and napkins compared to conventional co-located collaboration. Because the virtual sketches could only be seen through the display of the sketchpad, participants focused most of their attention looking down at the sketchpad while sketching and exploring the design space. Sometimes participants conversed with each other without making eye contact. These tended to be situations when participants were busy sketching or composing sketches, and the discussion was short. However, when participants engaged in longer discussions or when they had stopped sketching to think, they tended to look at each other while speaking.

Another interesting nuance when interacting with the mixed physical and virtual design space occurred when participants wanted to point at locations on the tablecloth that are out of their reach. For example, one participant leaned forward to point with his finger on the tablecloth to indicate where he wanted his partner to place a sketch. Because he had to lean forward, his head was in front of his sketchpad, and he could longer see the virtual shared design space with the floor plan as the background. Therefore, he had to lean back and forth a few times to estimate the approximate physical location. One participant even appropriated one of his spare napkins with the thin handles as a physical pointer to extend his reach.

This evaluation of collaboration using *Napkin Sketch* shows at the very least that the system is able to serve as a tool for collaborative design. Although not enough data was collected to evaluate all the aspects of collaboration using *Napkin Sketch* such as explicit privacy control, some important lessons can be learned from the interaction examples presented. For instance, it appears participants are leveraging their spatial understanding of the physical environment to engage in intuitive co-located collaboration with virtual sketches. This is evident in the example on the use of spatial references to refer to locations in the virtual design space which is made possible because interaction with the system is tightly integrated with the physical environment. Having this integration also enables intricate coordination between the participants to accomplish tasks concurrently. Another important lesson learned from this evaluation is that the handheld mixed reality lens metaphor of the sketchpad, while intuitive, suffers from physical limitations such as having to almost always focus on the display to receive the full visual output of the system. This creates annoying seams in the interaction between the purely physical and the mixed reality interaction spaces which can be observed in the examples on the lack of eye contact when speaking and the example on having to estimate the physical location of the virtual design space to point at without being able to see the visualization of the virtual design space. These limitations are potentially detrimental to co-located collaboration because facial expressions and body posture also play an important role in communication, and such subtleties can be missed when interacting with the sketchpad and napkin.

8.4 Summary

In this chapter, three informal preliminary evaluations are outlined. The first evaluation demonstrated the feasibility of *Napkin Sketch*'s 3D sketching approach and the effectiveness of important features such as the tangible navigation of the design space and the one stroke frame creation technique. It also provided further insight into the progression of the project and the design of the system such as the importance of the 3D visual guides for perspective sketching and the ability to allow users to temporarily switch the view of the sketching plane frame to be parallel to the sketching surface. With the second evaluation, the additions to the system showed that the usability of key functionalities can greatly affect the ways users interact with the system and the design goals of *Napkin Sketch*. For example, the expressiveness of the sketching experience are enhanced or hindered by the ease of use of features such as frame management. Finally, the third evaluation demonstrated that *Napkin Sketch* is sensitive to and can support social interaction within a co-located collaborative environment which is reflected in its support for awareness and natural verbal communication. Furthermore, it also uncovered important shortcomings of the system such as the tendency for collaborators to focus on their displays rather than the physical environment and the people around them. Overall, although all three evaluations were brief and preliminary, the valuable insight they provided will certainly help to inform the design of future systems.

Chapter Nine: Conclusion and Future Work

In this thesis, a 3D sketching and collaborative design prototype system has been presented. Inspired by the common scenarios of spontaneous bursts of creativity centered around the ubiquitous napkin and the powerful 3D visualization capabilities of computer systems, *Napkin Sketch* is conceived and realized as a system which attempts to marry 3D sketching techniques using new technology with the rich interactive capabilities of traditional tools like pencil and paper. In the following sections, the research goals and contributions of the work are reviewed, and future directions are discussed.

9.1 Revisiting Research Goals

This thesis is motivated by the desire to explore the possibilities of supporting 3D sketching in the early design stages, but the goals of the research are centered around discovering effective ways to replicate the rich interactive experience provided by traditional tools such as pencil and paper which are champions of creativity and ideation. Because supporting the creative process of early design is the focus, several essential characteristics of traditional sketching tools and media are first demonstrated in the Coffee Cup Scenario which opened this thesis, then analyzed with discussions of related work, and reflected upon in the rest of the thesis as goals which serve to motivate the design of *Napkin Sketch*. These characteristics and corresponding goals are:

1. ***Portability*: The system should be able to be used in a variety of environments and should be always on hand to allow for spontaneous creativity and ad hoc collaboration with peers.**
2. ***Flexibility*: The system should support different ways of sketching and design and allow users to easily switch between them.**

3. ***Fluidity*: The system should strive to reduce the cognitive load of users in trying to use the interface to assist them in their creative process.**
4. ***Expressiveness*: The system should capture the subtle but rich information expressed in sketches from over sketched lines to crosshatched strokes to random scribbles.**
5. ***Ambiguity*: The system should use appropriate visual representations to accurately reflect the intended maturity of ideas and support the process of iterative design, where ambiguous concepts are refined and solidified over time.**
6. ***Sociability*: The system should support co-located collaboration with peers and allow sketches to be easily exchanged, compared, assembled, and used as props for demonstration.**

Based on these goals, the following section reviews the contributions of the thesis and looks at how these goals have influenced and driven the outcomes of the work.

9.2 Revisiting Research Contributions

Along with the three design critiques conducted which provide insight for future directions of the research and served to iteratively refine the design of *Napkin Sketch*, the research presented in this thesis, as reflected in the *Napkin Sketch* prototype, offers three main contributions:

1. ***A portable hardware device and supplementary physical props which allows users to tangibly explore the 3D design space and manipulate the sketching media***

2. ***An enhanced perspective 3D sketching software interface that incorporates gestures and other effective techniques to reduce the complexities of 3D sketching to better support creative thinking***
3. ***A collaborative sketching environment which makes use of the hardware and software to support and extend the social activities of sketching***

In the following subsections, these contributions are discussed in more detail by reflecting on the thesis goals.

9.2.1 Napkin Sketch hardware

Unlike most computer-supported sketch-based systems, *Napkin Sketch* took on the challenge of designing interfaces for a mobile device instead of a desktop system. This design choice is significant because it is critical to the goals related to portability and sociability. When the research commenced, one of the lightest tablet PCs available on the market was used as the sketchpad of the system but still brought along the challenges of having to design for a small screen. Instead of following the common approach of making the virtual design space relative to the display, *Napkin Sketch* anchors the virtual design space on top of physical props or napkins. Using the handheld mixed reality tracking and visualization technique, *Napkin Sketch* allows users to freely explore the design space by tangibly manipulating the napkins or by moving the sketchpad in the physical design space. Despite the small screen, users can readily understand the handheld mixed reality lens metaphor and seem to perceive the visualization provided as only a limited yet extremely dynamic and flexible view of the much more expansive physical design space. *Napkin Sketch* also allows multiple napkins to be used simultaneously, and switching from one to another can be simply achieved by physically moving one napkin away and moving the other napkin closer to the user. All of these simple and intuitive interaction paradigms, enabled by the use of a mobile device and handheld mixed reality tracking and visualization, also benefit the fluidity of the interface. Compared to the typical approaches of design space navigation, where various modes and controls are used to apply a series of constrained transforms to the design space, *Napkin Sketch* infers the appropriate design space transformation from the spatial relationship between the sketchpad and the napkin which can be easily and intuitively manipulated and understood by users.

9.2.2 Napkin Sketch software

The 3D sketching experience of *Napkin Sketch* is based on a projective 3D sketching technique in order to maintain the familiarity of sketching on a 2D surface. Projective 3D sketching is chosen over gesture-based techniques because it can better support ambiguity and expressiveness. Following the concept of freeform interaction, *Napkin Sketch* only uses lines and curves as the modeling primitives instead of trying to construct more complex structures such as mesh geometry. This approach allows *Napkin Sketch* to maintain a close representation of the strokes sketched as intended by the user without having to replace them with an alternative representation that fits the expected data structures of the system. Users can scribble, cross over intersections, or leave edges unconnected. *Napkin Sketch* does not make assumptions about what the user is trying to sketch but rather simply records the input and displays it. Because of this, ambiguity can be easily supported using the same traditional sketching techniques. For example, a surface framed by lines can be made less ambiguous by simply filling in the space in-between with thicker or crosshatched strokes.

Achieving the goals related to expressiveness and ambiguity is made easy since *Napkin Sketch* does not try to infer user intentions when sketching. However, this design choice makes it harder to achieve the goal related to fluidity because users must explicitly define the necessary sketching surfaces or frames before sketching. Several techniques were explored and discussed, attempting to help users to intuitively and quickly define sketching frames. The most important of those techniques is the novel one stroke frame creation gesture used to quickly create lofted or plane frames using contextual information such as the previous sketching frame and the spatial relationship to important reference points like the ground plane. Although inferences are made about the user's intentions in the frame creation process, additional functionality is also provided to allow created frames to be quickly adjusted if they do not meet the user's expectations. Because assumptions are only made for the establishment of implicit structures for sketching, gesture-based frame creation techniques do not directly affect the expressiveness and ambiguity of the sketches. Other contributions for improving the fluidity of the projective sketching experience include various frame management techniques such as being able to select previous frames by selecting a stroke that was sketched on the frame or select a frame representing the surface between two strokes by selecting both strokes. The goal related to the flexibility of sketching is also demonstrated with these features, as users are not restricted to sketching on different frames in sequence but are rather able to easily switch to and sketch on any frame they desire.

9.2.3 Collaborative Sketching with Napkin Sketch

On top of designing a 3D sketching experience similar to pencil and paper, another important contribution of this thesis is the establishment of a collaborative sketching environment modeled after the interesting interaction examples in the Coffee Cup Scenario. The choice to explore the use of mobile devices not only makes *Napkin Sketch* more accessible as a sketching tool that can be brought to anywhere and used at anytime, it also makes the spontaneous and ad hoc collaboration shown in the Coffee Cup Scenario possible and arguably natural with the use of mobile devices instead of pencil and paper. The need to support ad hoc collaboration was also taken into consideration when implementing *Napkin Sketch*'s networking infrastructure, allowing collaborators to easily discover and join collaborative sessions with others.

Another design feature of *Napkin Sketch* that serves duo purpose like the use of mobile devices is the use of the handheld mixed reality sketchpad and the physical napkins. By anchoring the design space on top of napkins in the physical environment, collaborators can easily perceive a coherent 3D visualization of the sketches from any point of view. This allows collaborators to leverage their innate understanding of manipulating physical objects to accomplish tasks such as exchanging sketches or placing sketches next to other sketches for comparison. *Napkin Sketch* also explores how useful editing functionality can be seamlessly incorporated into the tangible manipulations of sketches in the design space to provide awareness for other collaborators. For example, using the proximity of napkins detected through mixed reality tracking, *Napkin Sketch* requires users to place napkins close together to invoke the copy functionality, which implicitly communicates their intent via their physical actions.

Although not as portable as sketchpads and napkins, the tablecloth concept along with the stamping technique are introduced as a way for multiple sketches to be assembled in a static shared space. This physical prop also provides opportunities for

Napkin Sketch to explore the concepts of privacy controls and shared and private workspaces.

9.3 Future Work

The design and implementation of *Napkin Sketch* takes a holistic approach to achieving the goal of creating a 3D sketching tool for collaborative design reminiscent of traditional tools and media. Many of the techniques explored in this work can offer practical solutions to concrete problems that arise in trying to accomplish the specific design goals reviewed in the Section 9.1, but they can also be applied in interesting ways to other design problems that are not focused on 3D sketching such as the concept of the mobile tabletop. There are many ways for the research in this thesis to be extended. First and foremost, *Napkin Sketch* does offer a unique and complete 3D sketching and collaborative design experience. However, as a research prototype it still suffers from some obvious but fixable usability issues, but the real effectiveness of the design approaches explored needs to be properly assessed with much more thorough and formal usability studies. In the following subsections, potential incremental improvements to *Napkin Sketch* are outlined, and new research areas based on techniques and concepts explored in *Napkin Sketch* are discussed.

9.3.1 Improving Napkin Sketch

Although the current hardware for *Napkin Sketch* is usable and quite effective as a mobile sketchpad for demonstration and design critique purposes, it is still very cumbersome to use because of its weight, thickness, the makeshift camera taped to the back, and the lack of buttons on the stylus. With the recent technological advancements in mobile computing, the usability of *Napkin Sketch* would be greatly increased by simply using a tablet (i.e. iPad 2) that is thinner and lighter and has a built-in camera and longer battery life. The ideal hardware for *Napkin Sketch* would be a compact multi-touch tablet with a stylus that is pressure sensitive and supports buttons for mode switching. The availability of multi-touch input and stylus buttons would help to further improve the fluidity of the projective 3D sketching experience as the extra input capabilities can be used to offload some of the mode switching functionalities required. For example, touch input can be used exclusively for creating and manipulating sketching frames, while pen input would be used only for sketching. For a more realistic sketching experience that resembles pencil and paper, a good quality pressure sensitive stylus would also be needed to capture the thickness and transparency of the strokes. Certainly, the *Napkin Sketch* software would also need to be improved to support more artistic and expressive visualizations of the sketched strokes.

One of the observed usability issues of *Napkin Sketch*'s projective 3D sketching technique is the requirement for users to have a good understanding of linear perspective and a good sense of 3D space. Despite the visual aids provided by *Napkin Sketch*, this implicit requirement makes it difficult for users without artistic training to achieve predictable results. One way to lower the learning curve could be to use Dorsey et al.'s (2007) technique of allowing users to first make several regular 2D sketches from various points of view and later project them to sketching frames and fuse them together to create the 3D sketch. This alternative work flow would allow novice users to comfortably create individual 2D sketches which may be incorrect in terms of linear perspective and later make modifications or corrections when the strokes are projected to 3D sketching frames.

Another way to aid the user in sketching correctly in perspective would be to provide smart guides based on the contextual spatial relationships of sketched strokes. Unlike typical inference-based techniques that snap sketched strokes to an assumed position, these guides would be implicit and purely visual and intended as references that the user can trace along much like the sketching frames. For example, when sketching receding parallel lines, novice users may have difficulty judging how the lines should converge toward the vanishing point. In this situation, the system can provide visualizations of the vanishing point along with an example parallel line that the user can trace over.

9.3.2 Beyond Napkin Sketch

One of the interesting concepts that this thesis, and the *Napkin Sketch* prototype try to support and promote is the ability to design anywhere, allowing the design to be inspired by the surrounding environment. Typically, interesting objects within an environment are captured and elaborated on either by replicating the object through sketching or by taking pictures. Pictures may be insufficient for representing the object because they are 2D, and sketching the object in 3D from scratch can be time consuming. Therefore, it may be helpful to be able to quickly capture the 3D geometry of the desired object to aid in the sketching process. If the *Napkin Sketch* sketchpad is equipped with a depth sensing camera instead of a regular webcam (i.e. Kinect), then any arbitrary 3D object in the physical environment can be used as an instant reference for sketching. For example, by simply aiming the sketchpad at a vase, 3D surface geometry of the vase can be created instantly from the depth data provided by the camera. This surface can then be used as an implicit sketching frame for the user to trace over or as a tracking reference for annotations to be made directly on top of the vase. Such advanced tracking capability would also allow users to compose the 3D design space in the physical environment with a mix of real objects and virtual sketches, and multiple users working together around a tabletop surface would provide more accurate tracking because depth data can be provided from multiple points of view.

Another *Napkin Sketch* theme that can be further explored is the concept of a mobile digital tabletop. With the increased ubiquity of mobile computing especially in the tablet form factor, the concept of the mobile digital tabletop (Section 7.1) and the corresponding techniques applied in *Napkin Sketch* appear to be an attractive way to support ad hoc mobile collaboration. Essentially, any surface can be used to as a shared space to review and exchange information with minimal setup required. Other distinct advantages provided by this approach include explicit control of private and shared information access and coherent visualizations of 3D content from multiple points of view. It would be interesting to explore these capabilities by implementing, for example, a strategy-based game, where it is critical to explicitly control the access to personal information, or a 3D maps application for search and rescue collaborative scenarios.

Although the mobile digital tabletop supports awareness through physical presence, one of the disadvantages of the approach is that users are mostly focusing their attention on the displays of their mobile devices to visualize the shared workspace. This may make gaze awareness and communication through eye contact difficult. Further research is needed in this area to understand the distractions that this limitation causes to co-located collaboration and contrast the results to co-located collaboration with digital tabletops, where interaction can also be very display-centric. Because the spatial context of collaborators and where they are focusing their attention can be inferred via the tracked position and orientation of their mobile devices, virtual awareness indicators can potentially be used to mitigate this problem. For example, simple gaze vectors can be rendered to augment the mixed reality visualization of the shared workspace to indicate where collaborators are looking.

9.4 Closing Remarks

In this thesis, the design and implementation of an operational high-fidelity prototype for 3D sketching and collaborative design has been presented. Inspired by the simple but rich interaction scenarios facilitated by traditional tools and media, *Napkin Sketch* is an advanced sketching system that tries to stay true to the style of interaction implied by its name. Various interaction techniques such as handheld mixed reality, tangible props, projective 3D sketching, and collaboration using mobile devices around a tabletop are explored and combined to create a cohesive and novel sketching experience. While many aspects of the system can still be improved, the current preliminary evaluation demonstrates promise, and there is great potential to extend the research in this work with new and improved technologies and to understand its effect on sketching and early design better through more extensive and structured usability studies. Hopefully, the ideas and results presented in this thesis will serve as inspiration to develop more intuitive computer-supported design tools that support creativity, expressiveness, and collaboration in much the same way that pencil, paper, and napkins do.

APPENDIX A: STUDY MATERIALS

This appendix contains materials related to the user studies described in Chapter 8 of this thesis. It includes:

- The informed consent from given to participants who participated in this study

A.1. Informed Consent Form

UNIVERSITY OF CALGARY

Department of Computer Science
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CONSENT FORM

Research Project Title: Napkin Sketchin – Handheld Mixed Reality 3D Sketching

Investigators: Ehud Sharlin and Min Xin

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

Purpose: The purpose of this research is to evaluate the use of a novel mobile 3D sketching interface.

Participant Recruitment and Selection:
To be a recruited for this study, we ask that you allow us to use and analyze your results from the study.

Procedure:
The study should require one hour of your time. You will be using the sketching interface to develop design ideas collaboratively with one other research participant. Afterward, you will be asked interview questions about your usage of the interface for developing design ideas and how you used the interface for collaboration.

Confidentiality:
Collected data may be used for a Masters degree, public presentations, and for online display. Your anonymity will be strictly maintained. Reports and presentations will refer only to a participant identification number and will be in a secure filing cabinet or on a secure computer. Participation in this study is strictly voluntary and has no effect on academic standing.

Computer records/data will be stored on a secure computer within a secure office space. Paper records/data will be stored in a secure filing cabinet within a secure office space. Records/data will be stored for a period of three years, at which point paper records will be shredded and computer records will be deleted. Only the researchers and their assistants will have access to the records/data.

The study may be videotaped to be reviewed privately at a later time by only the investigators, and no content from videos will be used in any publications or public presentation.

☐ I do not give permission to be videotaped during the study.

☐ I agree to be videotaped during the study.

Risks:
There are no known risks, however, if you feel uncomfortable you are free to quit at any time. All information collected from a person that withdraws will be destroyed.

Investigators:
Ehud Sharlin is an Assistant Professor and Min Xin is an MSc student, both in the Department of Computer Science at the University of Calgary.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time. Your continued participation should be as

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informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. If you have further questions concerning matters related to this research, please contact:

Ehud Sharlin (ehud@cpsc.ucalgary.ca) or Min Xin (mxin@ucalgary.ca)

This research study has been approved by the Conjoint Faculties Research Ethics Board. If you have any questions or issues concerning this project that are not related to the specifics of the research, you may also contact the Research Services Office at 220-3782 and ask for Bonnie Scherrer.

Participant's Name	Date
Participant's Signature or Signature of Parent/Guardian	Date
Investigator's/Witness's Signature	Date

A copy of this consent form has been given to you to keep for your records and reference.

APPENDIX B: THESIS PRESENTATION VIDEO

M. Xin, E. Sharlin, and M.C. Sousa. 3D Sketching and Collaborative Design with *Napkin Sketch* (Video). University of Calgary Technical Report, 2011-1000-12, April 2011, Department of Computer Science, University of Calgary, Alberta, Canada.

https://dspace.ucalgary.ca/handle/1880/48488

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