Freeform User Interfaces for Graphical Computing

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Abstract

It is difficult to communicate graphical ideas or images to computers using current WIMP-style GUI. Users have to decompose the graphics desired in their minds into simple elements such as points, lines, or boxes, and manipulate those elements using click-and-drag operations. On the other hand, people have long used simple drawings based on freeform strokes to express arbitrary visual messages quickly. Freeform User Interfaces is an interface design framework that leverages the power of freeform strokes to achieve fluent interaction between users and computers in performing graphical tasks.

In Freeform UI, users express their graphical ideas as freeform strokes using pen-based systems, and the computer takes appropriate actions based on the perceptual features of the strokes. The results of processing are displayed in an informal manner to facilitate exploratory thinking. Freeform UI is different from typical pen-based systems in that it analyzes the perceptual structure of the drawings instead of applying simple pattern-matching. This dissertation explores the concept of Freeform UI and shows its possibilities with the following four example systems.

Beautification and prediction for 2D geometric drawing allow the user to construct precise illustrations without using complicated editing commands.
Path-drawing technique for virtual space navigation enables the user to explore 3D virtual space efficiently even when the rendering speed is slow.
Stroke-based architecture for electronic whiteboards provides a basic framework for building task-specific applications using freeform strokes as the only input.
Sketch-based 3D freeform modeling allows the user to create natural-looking rotund 3D models quickly just by drawing 2D outlines.

Independently, each of these systems contributes to the improvement of existing applications. But taken together, they form a concrete basis for discussing the nature of Freeform UI and clarifying its limitations and possibilities. While Freeform UI is not suitable for precise, production-oriented applications because of its ambiguity and imprecision, it does provide a natural, highly interactive computing environment for pre-productive, exploratory activities in various graphical applications.

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Chapter 1

Introduction

1.1.Motivation

User interfaces evolve as the purpose of computing changes. When computers were first introduced, their primary role was numerical calculation. At that time, the user interface was “batch-based operation”: the user submits a job to a computer and waits for the result of its calculations. The next stage was computers supporting corporate information management, with applications such as databases. Interactive teletype and command-line interfaces became dominant at this point, introducing more people to the world of computation. As computers grew increasingly popular and inexpensive, the primary purpose of computing became supporting knowledge workers in office environments. Office productivity tools, such as spreadsheets and word processors, were the most important applications. These applications could not have become wide-spread without the invention of WIMP-style GUI (graphical user interfaces based on windows, icons menus, and a pointing device, typically a mouse). GUI, originally designed by Xerox and Apple, allows general knowledge workers to work with computers without specific computer skills or training.

GUI has been the predominant user interface paradigm for almost 30 years. But because the purpose of computing is changing, we clearly need next-generation user interface framework. In the near future, computers' main application will no longer be as a tool for supporting knowledge workers in office environments. As they become smaller and still less expensive, they will become ubiquitous and their goal will be to support every aspect of human life. At that stage, a new form of user interfaces, post-WIMP [139] or non-command [100] user interfaces, will be needed. In [100], Nielsen argued that current GUI is essentially the same as command-line user interface in that

users have to translate their tasks into machine-understandable sequences of commands. Pressing buttons or selecting items in menus in GUI is essentially identical to typing commands in command-line user interface. In non-command user interfaces, computers take appropriate action based on the users activity, allowing the user to concentrate on the task itself without worrying about commands.

Candidates for post-WIMP, non-command user interface include virtual realities and augmented realities, multi-modal and multi-media interfaces, natural language interfaces, sound and speech recognition, portable and ubiquitous computers. Each new interface is designed to support specific new uses of computers. The increasing number of applications dealing with three-dimensional information require virtual reality techniques and various three-dimensional input devices. The need to support people in situations where one cannot use hands or keyboards has spurred the growth of voice input technologies. Highly complicated, spatial applications gave birth to the idea of physical (graspable or tangible) interfaces that can provide more affordable, space-multiplexed input channels. The essence of the next-generation user interface is its diversity. While current user interfaces are characterized simply as "WIMP-style GUI," post-WIMP or non-command user interfaces will be characterized as collections of task-oriented, tailored interfaces. An important task for user interface research is to identify an emerging application domain and find the ideal user interface for that domain beyond WIMP-style GUI.

This dissertation explores a user interface framework, *Freeform User Interfaces*, as a post-WIMP, non-command user interface in the domain of graphical interaction. Current point-click-drag style interaction is suitable for specific kinds of graphical interaction, namely object-oriented graphics such as block diagrams or flow charts. However, the point-click-drag interface does not work well for expressing arbitrary graphical ideas or geometric shapes in computers. The user has to do this manually by placing many control points one by one or combining editing commands in a nested menu. On the other hand, people have been using pen and paper to express graphical ideas for centuries. Drawing freeform strokes is a convenient, efficient, and familiar way to express graphical ideas. Freeform UI is an attempt to bring the power of freeform strokes to computing.

1.2.Freeform User Interfaces

Freeform User Interfaces represent an interface design framework that uses pen-based input devices for computer-supported activities in graphical domains. In Freeform UI, the user expresses visual ideas or messages as freeform strokes on pen-based systems, and the computer takes appropriate action by analyzing the perceptual features of the strokes. This is based on the observation that freeform sketching is the most intuitive, easiest way to express visual ideas. Freeform UI is an attempt to establish a non-command user interface for two- and three-dimensional graphical applications in that the user can transfer visual ideas into a computer without converting the ideas into a sequence of tedious command operations.

Although Freeform User Interfaces assume pen-based devices as input channels, it differs from traditional pen-based interfaces in that it extracts significantly richer information from the user's freeform strokes than does simple pattern-matching. Most pen-based systems are based on handwriting character recognition and gesture recognition, which are basically pattern-matching strategies. The system maps each of the user's freeform strokes to a predefined character or command, such as undo or delete. This is essentially command-based interaction in that each operation in these traditional pattern-matching systems is equal to pressing a button or selecting an item in a menu. In contrast, Freeform User Interfaces transform the freeform strokes into rich internal representations based on the perceptual characteristics of each stroke instead of mapping them to predefined characters or commands.

This dissertation presents four independent example systems embodying the idea of Freeform User Interfaces. While each of these systems contributes independently to the improvement of existing applications, taken as a whole they form a concrete basis for discussing the nature of Freeform UI, including its strengths and limitations. Below we here introduce the four example systems. Each is described in detail later in this dissertation.

1.2.1. Beautification and prediction for 2D geometric drawing

These techniques allow the user to construct precise illustrations such as shown in Figure 1 without using complicated editing commands. The idea is to automate

complicated drawing operations by having the computer infer possible geometric constraints and the user's next steps from the user's freeform strokes. Interactive beautification receives the user's free stroke input and beautifies it by considering possible geometric constraints among line segments by generating multiple alternatives to prevent recognition errors. Predictive drawing predicts the user's next drawing operation based on the spatial relationships among existing segments on the screen. A prototype system is implemented as a Java™ program, and our preliminary user study showed promising results.

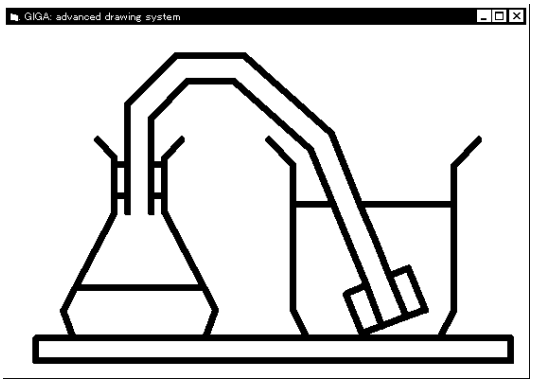


Figure 1. A diagram drawn using interactive beautification and predictive drawing.

1.2.2. Path-drawing technique for virtual space navigation

This technique allows the user to navigate through a virtual 3D space by drawing the intended path directly on the screen. After drawing the path, the avatar and camera automatically move along the path (Figure 2). The system calculates the path by projecting the stroke drawn on the screen onto the walking surface in the 3D world. Using this technique, with a single stroke the user can specify not only the goal position, but also the route to take and the camera orientation at the goal. A prototype system is tested using a display-integrated tablet, and experimental results suggest that the technique can enhance existing walkthrough techniques.

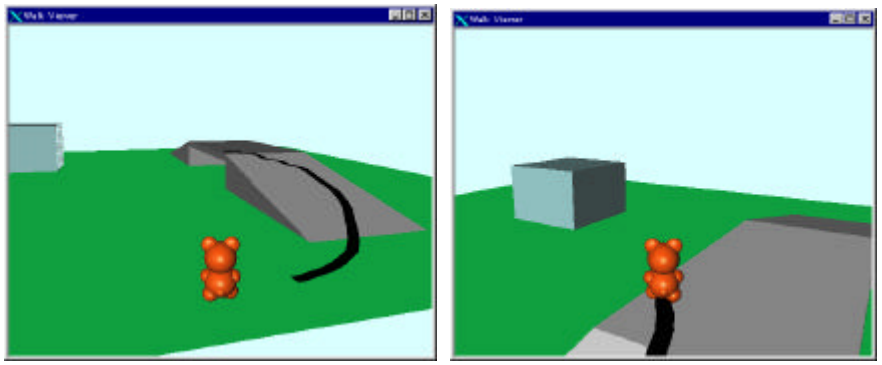


Figure 2. An example of a path-drawing walkthrough.

1.2.3. Stroke-based architecture for electronic whiteboards

This is a software architecture for our pen-based electronic whiteboard system, called Flatland. Flatland is designed to support various activities for which personal office whiteboards are used, while maintaining the outstanding ease of use and informal appearance of conventional whiteboards. The GUI framework of existing window systems requires too many, complicated operations to achieve this goal, and so we designed a new architecture that works as a kind of window system for pen-based applications. Our architecture is characterized by its use of freeform strokes as the primary element for both input and output, flexible screen space segmentation, pluggable applications that can operate on each segment, and built-in history management mechanisms. This architecture is carefully designed to achieve simple, unified coding and high extensibility, which were essential to the iterative prototyping of the Flatland interface. While the current implementation is optimized for large office whiteboards, this architecture is useful for the implementation of various pen-based systems.

Figure 3. Flatland example.

1.2.4. Sketch-based 3D freeform modeling

This technique allows the user to quickly and easily design freeform models, such as stuffed animals and other rotund objects, using freeform strokes. The user draws several 2D freeform strokes interactively on the screen and the system automatically constructs plausible 3D polygonal surfaces. Our system supports several modeling operations, including the operation to construct a 3D polygonal surface from a 2D silhouette drawn by the user: the system inflates the region surrounded by the silhouette, making wide areas fat and narrow areas thin. Teddy, our prototype system, is implemented as a Java™ program, and the mesh construction is done in real-time on a standard PC. Our informal user study showed that a first-time user typically masters the operations within 10 minutes, and can construct interesting 3D models within minutes.

Figure 4. Teddy in use on a display-integrated tablet.

Freeform User Interfaces are characterized by the following three features: the use of pen-based stroking as input, perceptual processing of strokes, and informal presentation of the result. Pen-based stroking input allows the user to express their graphical ideas quickly and intuitively. In addition, the informal nature of pen-based sketching encourages the user to freely explore various possibilities without careful consideration beforehand. Perceptual processing of strokes mimics the human ability to infer a variety of meaningful information from simple drawings. Such information may include, for example, implicit geometric relations among the strokes or a possible three-dimensional shape represented by a two-dimensional drawing. It automatically infers the user's high-level idea and intention from the freeform drawing and can delegate tedious fine-grained command operations. In short, perceptual processing allows the user to perform complicated operations with a minimum of input. Informal presentation is important to in creating for the user the appropriate impression and expectations about the system's behavior. Freeform UI is inherently ambiguous and transient to encourage informal, pre-productive activities. Informal presentation can implicitly and effectively present Freeform UI's inherent qualities to the user and can avoid possible frustration and confusion caused by misunderstanding.

Although ambiguity and imprecision are the major strengths of the Freeform User Interface, they are at the same time its fundamental difficulty. The result of a computation based on ambiguous strokes can be different from the user's expectation. This is also a problem of perceptual processing. Perception is personal in nature, and it is impossible to represent everyone's expectation correctly. The imprecise nature of Freeform UI prevents it from application to activities of refinement and detailing. Based on our implementation and user study experience, we found that the following techniques are useful for mitigating the problem of ambiguity and imprecision. First, the construction of multiple interpretations is useful to minimize the problems of ambiguity. By presenting multiple interpretations, the probability increases that the user will find the version she expected to find. Second, the informal presentation can hide the details and thus prevent the user from expecting precise operation. The user naturally understands the ambiguous nature of the system, and frustrations caused by misconceptions can be minimized. Third, quickly responding fluent interaction allows the user to explore various possibilities without heavy overhead. If it takes time for a user to specify an operation and for a computer to return a result, it is frustrating to repeatedly try various inputs when the system repeatedly returns the wrong result.

Freeform UI can be applicable to a wide range of applications involving graphical information processing that can be tedious when using standard GUI. Examples include sketching on PDAs, taking notes on notebook computers, communicating over window-size computers, supporting medical operations, or creating designs for 2D and 3D presentations. Overall, Freeform UI is useful for creative, informal, and exploratory thinking activities in the graphical domains.

1.3. Contributions

This dissertation introduces the concept of Freeform User Interfaces and discusses its strengths and limitations using four stroke-based interaction techniques and systems as examples. The thesis postulated by this dissertation is that the freeform stroke is a powerful interface for communicating graphical ideas to computers. The contributions of the research include the following:

The concept of Freeform User Interfaces. We characterize Freeform User Interfaces by stroke-based input, perceptual processing of strokes, and informal presentation. This combination is suitable for informal, creative activity using a computer in a graphical application domain. The essential difficulties are inherent ambiguity and inaccuracy in interpreting freeform strokes, but this problem can be minimized by presenting multiple possibilities, controlling the user's expectation by the informal presentation, and providing a carefully designed quickly responding interaction style.

The four independently useful techniques and systems. Interactive beautification and predictive drawing are useful techniques for drawing 2D geometric illustrations. Path drawing navigation is a useful technique for navigating through virtual 3D space. Flatland is a useful software system for personal electronic whiteboards. Teddy is a powerful tool for constructing simple 3D models quickly. Each contributes innovative ideas, strong implementation, and valuable insight into each application domain.

1.4. Organization

We first review related work in this field in Chapter 2. We briefly overview the various

research projects to explore next-generation, non-command user interfaces. We also review many pen-based techniques and systems in depth to clarify the context of this research.

In Chapter 3, we propose the concept of Freeform UI as a pen-based non-command user interface for graphical applications. We define the concept with three properties, and discuss possible application domains where Freeform UI can be useful.

We then describe our example systems in detail. Chapter 4 describes our 2D geometric drawing system, and introduces interactive beautification and predictive drawing. An evaluation of the beautification technique is provided. Chapter 5 introduces the path drawing technique for 3D virtual space navigation, and provides the results of an informal user study. Chapter 6 presents the stroke-based software architecture for personal electronic whiteboards. The architecture can be a platform for implementing various applications based on Freeform UI. Chapter 7 introduces the sketch-based interface for constructing freeform 3D models.

Next, in Chapter 8, we revisit the concept of Freeform UI and discuss its strengths and limitations based on the example systems discussed in the preceding chapters. Several guidelines for designing effective Freeform UI are presented.

Finally, Chapter 9 summarizes the dissertation and discusses several future directions.

Chapter 2

Background

This chapter introduces the dissertation's background. We first review various research efforts aimed at designing next-generation user interfaces. These efforts are not technically related to pen-based computing directly, but they broaden the context of our efforts and illustrate general ideas and principles necessary for designing non-command user interfaces. Then, we review existing technologies and previous efforts in pen-based computing in detail. Some important related work is discussed again in Chapter 8.

2.1. Non-command User Interfaces

The goal of this dissertation is to explore next-generation, non-command user interfaces in graphical application domains. Although research projects pursuing non-command user interfaces in other domains are not directly related to our stroke-based techniques, we briefly review representative projects to illustrate a broader perspective on the entire user interface research area. The following research projects are just a small sampling of the vast research efforts now underway to create next-generation user interfaces beyond WIMP-style GUI.

The concept of non-command user interfaces was introduced in [100]. In that paper, Nielsen argued that all previous generations of user interfaces, including batch-based, time-sharing command line, and graphical user interfaces, are all characterized as command-based interfaces, where the user *explicitly* commands the computer to do something. In contrast, Nielsen wrote next-generation user interfaces can be characterized as non-command user interfaces, where the interaction between humans and computers is not based on explicit command operation by the user. In non-command

user interfaces, the computer automatically interprets the user's action and does appropriate operations without having received explicit commands, allowing the user to concentrate on the task itself rather than controlling the computer. Examples he listed of next-generation, non-command user interfaces included virtual realities, head-mounted displays, sound and speech, pen and gesture recognition, animation and multimedia, limited artificial intelligence, and highly portable computers with cellular or other wireless communication capabilities.

2.1.1. 3D Interface and Virtual Reality

WIMP-style GUI is basically designed for 2D desktop applications. The increasing number of 3D applications necessitates post-WIMP, specialized interfaces [139]. The WIMP interface for 3D applications today typically consists of a number of 2D widgets around the 3D world view, causing a significant cognitive distance between the end user action (2D widget control) and the system response (change in the 3D world). We will review interaction techniques based on 3D input devices and stereo vision as examples of post-WIMP user interfaces for 3D applications.

A natural approach for manipulating 3D objects is to use a six-degree-of-freedom tracking device as input [111]. The user can translate and move objects in a 3D scene simply by manipulating the physical handle with the tracker. This approach can be more powerful when the system supports two-handed interaction using two six-degree-of-freedom trackers [54, 110]. It is also possible to add force-feedback functionality to these 3D input devices [107]. These interfaces can be called non-command user interfaces because the user can manipulate 3D objects directly by moving their hands in the air, without explicitly manipulating graphical interface widgets in the 2D screen.

Virtual reality systems with head-mounted display with trackers are one extreme of these approaches [141]. There is also growing interest in room-size immersive environments with 3D image projection to the walls around the user [25]. These systems convince users that they are in the artificial three-dimensional space by presenting stereoscopic vision and allowing them to interact with the environment by moving their limbs or bodies. The important feature is that the view presented to the user is calculated based on the user's head position and orientation, rather than depending upon the user's explicit camera control using 2D widgets, such as sliders or

buttons. The result is that the user can concentrate on the task in the three-dimensional world without worrying about camera control or object manipulation.

2.1.2. Augmented Reality

The approach opposite from virtual reality is augmented reality, which uses computers to augment objects in the real world instead of enclosing people in an artificial world [150]. While a wide range of systems can be considered augmented reality systems, we review some systems that overlay computer generated images onto everyday physical objects in a scene using projectors and see-through displays.

The Digital Desk [149] is an attempt to computationally augment the physical desktop with paper documents. A computer display is projected down onto a desk and video cameras observe the user's activity on the desk. The goal of the project is to seamlessly merge physical and electronic artifacts. For example, users can specify drawings on a physical paper using their fingers, and copy the drawings to some other area. The duplicated image is synthesized by the computer and projected onto the desk surface.

The KARMA system [37] presents to the user additional information on top of physical objects using a see-through, head-mounted display and tracking devices. For example, the user can see the internal components of a laser printer or instructions to repair it. The system accesses expert systems and knowledge bases to understand the properties and behaviors of the physical artifacts. The main interest of the KARMA system is to accurately align computational images to corresponding physical objects, but it is important to note that their interface requires no explicit control of computers. The system generates appropriate images automatically, based on the spatial relationships between the user's head and the objects without the user explicitly controlling the computer.

While the KARMA system addresses the problem of presenting information accurately to specific objects such as a printer, the NaviCam system [116] proposes an interface for presenting corresponding information for spatially distributed objects across a room or a building. This system uses a hand-held display with a video camera. The image observed by the camera is presented on the display along with computer generated image. This interaction is analogous to a magnifying glass: the user looks at the target

object *through* the device to obtain additional information. The system uses a two-dimensional bar code and vision-based recognition technique to recognize which object the user is looking at and to determine what information to present.

From the viewpoint of non-command user interfaces, augmented reality systems use the user's natural interaction with physical objects as input to perform appropriate actions without explicit command operations by the user. With the Digital Desk, the system responds to the user's manipulation of physical papers, while KARMA and NaviCam present information attached to a physical object when the user looks at the object through the see-through display. As a result, the user can focus on the task in the real world, rather than on the abstract manipulation of the computer.

2.1.3. Multimodal Input

Human beings communicate with each other using various modalities, such as voice, gaze, and bodily gestures. Multimodal interfaces try to take advantage of these modalities beyond simple point-and-click operations.

Many commercial products based on voice recognition have appeared recently [97], but their targets are dictation and simple command operations using word recognition. Since voice recognition is essentially error-prone, it is important to design interfaces considering this nature. A solution is to combine voice with another modality, such as gesture. Bolz's Put-That-There system [14] allows users to point at objects on a map using their fingers and to speak commands to modify the objects. By using this pointing gesture, a user can simply say "Put that there" instead of "put the orange square to the right of the blue triangle," thus minimizing the system's recognition error and the user's cognitive overhead.

Gaze is a difficult modality to use as input because it is impossible to tell whether the user is looking something intentionally or merely resting the gaze unintentionally [64]. A good solution is to use gaze as a secondary, supporting input. An interactive fiction system called The Little Prince [132] changes its scenario based on the pattern of the user's eye movement. In this system, the computer modifies its behavior without the user's explicit command input.

Bodily gesture has been used mainly for entertainment applications. The HoloWall system [85] emits infrared light from a translucent wall, and recognizes the user's bodily gestures by observing the reflected light from the body. Applications include a paddleball game using the body as a paddle, a "life" game using body shape as initial input, and interaction with artificial animals reacting to the user's body. MIT's pfinder system [157] is used to recognize the user's bodily interaction with an artificial dog "living" in a wall-sized display [20]. These systems allow the user to interact with artificial animals without explicit command operations, by observing the user's natural bodily action.

2.1.4. Ubiquitous Computing

The ubiquitous computing project [145][146] proposes an environment that is surrounded by hundreds of wireless, interconnected computers. In this environment, the relation between the user and the computer is one-to-many, instead of the current one-to-one relation. The project introduced several computing devices with varying scales including active badge, PARC tab, pad, and LiveBoard. Active badge [144] is a small device attached to individuals, and it constantly transmits the identity and location of the person to the computing infrastructure. PARC tab is a palm-sized device with a touch-sensitive screen that stores personal information. One can hand the information to a colleague's tab using a wireless infrared connection. The LiveBoard [138] is a wall-sized electronic whiteboard system designed around pen-based input. Compared with the WIMP-style interface for a single console, the ubiquitous computing environment provides interfaces with a much wider bandwidth. The environment can make use of rich information, such as the user's location and the device the user is interacting with, and thus it requires less explicit control by the user.

2.1.5. Summary

We reviewed a small representative sample of various research activities now underway to develop next-generation user interfaces. The important observation is that most systems reduce the amount of the user's explicit control by automatically inferring the user's intention from the natural actions taken in each application domain; such actions include head motion, gazing, manipulation of physical objects, speech, and movement in

a physical world. Like these systems, Freeform UI infers the user's intention from freeform drawings using pen-based input.

We can learn several lessons from the systems we have just discussed. First, interfaces must be specialized to their target application domains. While WIMP-style GUI is used universally for every application today, next-generation interfaces are characterized by their diversity. Freeform UI is designed for informal activities in graphical computing domains, and we must be aware that it does not work well in other domains. Second, to design effective interfaces, it is important to understand the essential strength of each input stream. For example, gaze was not successful as an explicit cursor control. Gaze is best suited to finding the target of the user's attention in the screen. We focus on the fact that pen-based sketching is the best way to express graphical ideas rapidly, instead of using a pen for direct manipulation of objects. Finally, new forms of interfaces can evolve only by implementing actual working prototypes and accumulating experience with them. Prototyping and user studies are the only ways to innovate. We implemented the four example systems and tested the ideas behind each using prototype systems according to the lesson.

2.2. Pen-based Computing

Pen-based computing has a long history of research and development in both hardware and software [86]. In this section, we briefly review existing products and technologies. First, we explain the current status of commercial pen-based hardware products. Next, we review basic interaction techniques in pen computing, including handwriting recognition, fast text input methods, and gesture/shape recognition. Finally, we review several experimental research projects related to pen computing. We divided the projects into four categories (handheld, whiteboards, exploratory, and drawing) for convenience's sake, but these areas interrelate closely with each other.

2.2.1. Pen-based Input Devices

Today, several kinds of pen-based computing devices are available, including tablets, display integrated tablets, electronic whiteboards, pen-based portable computers, and PDAs. Illustrators and graphic designers use tablets to draw pictures. Tablets are small

and relatively cheap, but they require additional cognitive overhead because the graphical objects on the screen are distant from the physical location of the pen. Display integrated tablets offer more natural interaction similar to real pen and ink, but they are not widely used because they are currently quite expensive. The largest market for display integrated tablets today is healthcare institutions. Physicians use these devices to take notes on electronic medical records. Some commercial electronic whiteboards are available including both rear-projected and front-projected ones. They are mainly used in meeting situations to record, share, and print handwritten notes on a board. Pen-based portable computers are mainly used in retail stores and warehouses with custom software, such as car price calculations based on various options or counting goods in stock. In most cases, people use standard window systems with these pen-based devices, and they use pens to just press buttons or select menus other than for handwriting recognition. Personal digital assistants (PDAs), which are palm-sized computers, have become increasingly popular recently. People use these devices for personal information management. Fast text input methods such as Graffiti are widely used on these devices.

a) Hand held PDA (Sharp Zaurus [160]) b) Pen-based portable computer (Mitubishi AMiTY [2])

c) Display integrated tablet (Mutoh MVT-14[92]) d) Electronic whiteboard (SMART Board[130])

Figure 5. Examples of pen-based devices.

2.2.2. Handwriting Character Recognition

Handwriting recognition[1] has been the primary interest of researchers from the beginning of pen computing [27]. The idea was to let the user input texts into computers without a keyboard. Handwriting recognition was expected to be intuitive as well as an efficient text input method for novice users who are not familiar with keyboard typing.

The early systems required the user to write characters separately in a sequence of boxes. Some commercial products still use this strategy for reliable recognition [160]. Advanced recognition techniques allow the user to write printed characters in a free space. In this case, the system has to divide the set of strokes into independent characters first, which can introduce more recognition errors. Recent systems also allow the user to write cursive, continuous texts freely [58]. This kind of technique was used in the Apple Newton™ [19].

In spite of vast research efforts and commercial attempts, handwriting recognition has not yet become widespread. The primary reasons are recognition errors and the fact that handwriting text input is significantly slower than typing on a keyboard. In a desktop computing environment, almost all use a keyboard. As a text input method for small devices, such as PDAs and mobile phones, simplified character input (described in the next section), software keyboards, and buttons are what most people use. It is not clear whether character recognition will become dominant in the future, but it can be said that the interface based on handwriting recognition should be designed in an error-tolerant manner or should be used in applications in which a certain, if small, amount of error is acceptable.

2.2.3. Fast Text Input Methods

Because handwriting recognition is too error-prone and slow, there have been several

[1] In this dissertation, handwriting recognition refers to *on-line* handwriting recognition, which recognize characters written on the electronic tablets in real-time. *Off-line* recognition, which recognizes characters that have been scanned from paper, is not discussed further. Good reviews on handwriting recognition can be found in [137].

attempts to explore alternative methods for fast and reliable pen-based text input. One way is to use simple, artificial “alphabets” that are easier for the computer to recognize, and faster for the user to write. Unistrokes [47] uses symbols shown in Figure 6 for text input. These symbols can be drawn with a single stroke, and common letters are mapped to single line strokes for faster input. The problem is that it takes time for a novice user to learn these special symbols. Graffiti [74] uses a similar approach, but it uses symbols closer to an actual alphabet. Graffiti is widely used in commercial PDAs. T-Cube [140] also uses single strokes to input characters, but it is based on piemenus [55] and a stroke's shape is not related to its corresponding alphabetic shape.

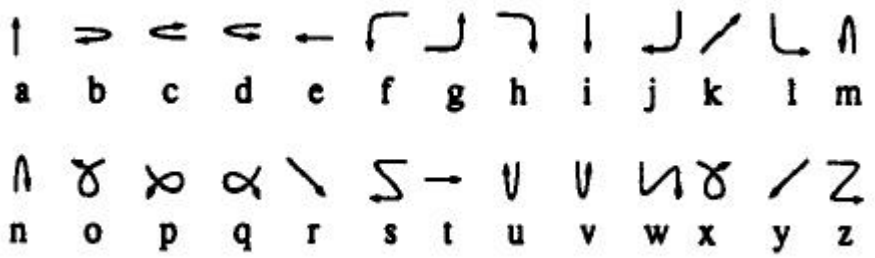


Figure 6. Unistroke [47].

These techniques allow the user to input single characters using single strokes, but some recent techniques allow the user to input a sequence of characters (e.g., a word) at a single stroke. In Cirrin [79], 26 characters of the Roman alphabet are laid out around a circular region, and the letters passed through by a stroke will be entered (Figure 7, left). A problem with this technique is that it requires precise control of pen movements in passing through small regions. Quickwriting [106] uses a similar approach, but minimizes the problem of fine control by introducing *zoning traversal.* The writing area is divided into a grid of 3x3 character sections with a central resting zone (Figure 7, right). The user draws a stroke visiting multiple zones, and a character is entered each time the stroke returns to the central area. The character to be entered is determined by the starting zone and the ending zone during a loop. For example, the path shown in Figure 7 (right) types the word “the”. The user can gradually learn frequently used words as single gestures and can thereby enter texts quickly. These systems are distributed on the Internet, and are widely used.

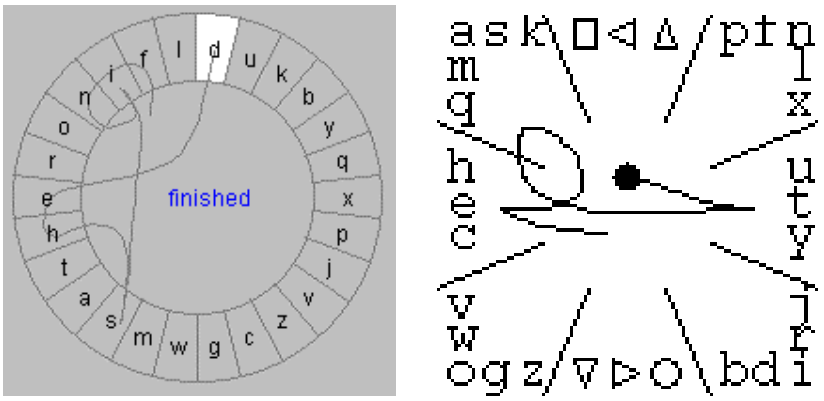


Figure 7. Cirring [79] and QuickWriting [106].

POBox [84] combines software keyboards with prediction. When the user types the first few characters of a word on the software keyboard, the possible entire words are automatically predicted based on the built-in dictionary, and they appear in whole form below the software keyboard (Figure 8). If the desired word appears, the user can tap the word to automatically complete the typing. If the desired word does not appear, the user can continue typing, refining the prediction. This technique is especially useful for languages with many characters such as Japanese, and it is widely used as a primary text input method on PDAs.

Figure 8. POBox [84].

These predictions appear when the user types “i” in Japanese.

2.2.4. Gesture and Shape Recognition

While handwriting recognition allows the user to input texts, gesture recognition allows the user to input commands, such as undo and delete, using freeform strokes. Gestures

were used for document editing and mark-up in early research projects on electronic paper systems [155, 18]. More recently, they have become widely used in commercial pen-based products such as Apple's Newton™ [99], Go's PenPoint™ [45] and Microsoft Windows for Pen Computing™ [88]. Using gestures, the user can input commands quickly within the work space without moving the cursor (pen) to buttons or menus at the periphery. The problem with gestures is that the user has to memorize them first. Before memorizing all gestures, the user has to frequently consult a gesture chart, which can be critically time-consuming.

Shape recognition allows the user to put graphical objects at a target location quickly. For example, the user can sketch a rectangular shape to put a rectangle object on the screen without having to choose a rectangle in a menu and then having to specify size and location using direct manipulation. This kind of technique is used in object-oriented diagram editors [159] and various applications involving the spatial arrangement of objects [50,73].

Handwriting recognition, gesture recognition and shape recognition are based on similar technologies. In general, these recognition techniques use pattern-matching algorithms. The system classifies an input stroke as one of a number of predefined characters, gestures, or shapes. A common approach is to use generic classification methods, such as neural networks [82] or statistical methods [121]. In this case, the system designer trains the classification engine first using massive examples. This approach is much more powerful, robust, and generic than hard-coding a recognition routine for each pattern. However, recognition accuracy still depends on the design of the recognition engine (e.g., which feature of a stroke to extract as input) and of the training set.

2.2.5. Handheld Devices

In this section, we review recent research projects targeted for pen-based handheld devices. While early researches and products focused on recognition techniques for handwriting recognition and gesture recognition, recent projects focus on various application-specific interaction techniques.

FX Pal has several interesting projects related to handheld pen-based computing. The

Dynomite project [151] introduced pen-based system for personal note-taking activities. Dynomite is unique in that it synchronizes handwritten notes on the screen with recorded sounds (voices). If the user clicks a part of a handwritten note, the system plays a sound sequence recorded when that part was written. Xlibris [128] is a portable document-reading device for "active reading," where the user adds various notations, such as underlines and comments, on top of the document. The system allows the user to search and reorganize the document based on these notations. NotePals [28] introduced networked system for sharing personal handwriting notes. The users take notes on their PDAs in mobile environments, and upload their personal notes to a shared server. As a result, any user can read any other user's notes over the Internet.

Sony CSL introduced a pen-based interaction technique for exchanging information across multiple devices [117,118]. As one drags and drops an icon within a single computer, one *picks* up an icon from a device and *drops* it into another device. In this way, one can transfer a file across computers without worrying about file names and computer names, which was required when transferring files using floppy disks, email or ftp. Using this pick-and-drop technique, one can hand a file from one's PDA to a partner's PDA, can pick a file for one's PDA from an electronic bulletin board, or can select a color in a handheld electronic palette and paint a picture on an electronic whiteboard as if using a physical palette and canvas.

2.2.6. Electronic Whiteboards

Some commercial electronic whiteboard systems are available, but people generally use standard graphical user interfaces for various operations other than simple scribbling. Research projects for electronic whiteboards explore interaction techniques specialized for large screen spaces and beyond simple click-and-drag operations.

A research group at Xerox PARC has been working on pen-based meeting-support software running on LiveBoard [36]. Tivoli [112] uses a combination of static interface widgets and gestures for editing meeting notes. It introduced the "wipe" operation, which allows the user to change the properties of strokes at once. Tivoli also introduced an automatic grouping mechanism for the material on the board [89], and a set of gesture-based techniques for organizing the materials [90]. Recently, it developed a mechanism for defining semantic relations between the objects on a board [91]. Using

this mechanism, the user can add desired computational support for a specific meeting. These systems are deployed at Xerox PARC and used in actual meetings.

Nakagawa's group at Tokyo University of Agriculture and Technology has developed an experimental whiteboard system called IdeaBoard [96]. It introduced several interface widgets optimized for pen-based operations on large surfaces. For example, they allow the user to scroll the screen by dragging the scrolling area around the work space, and to slide the screen by dragging the surface. Nakagawa's group also implemented several applications for use with the system, such as a word processor and an animation design program.

Geissler *et al.* developed a wall-sized interactive display and introduced several interaction techniques suitable for the extremely large display [43]. For example, they designed a simple gesture set to throw a window to a distant location without dragging it all the way manually.

Kramer discussed a mechanism for organizing information on electronic whiteboards flexibly [69]. Instead of organizing visual elements by static windows, they used dynamic, freeform patches for grouping relevant information on the board. These patches are translucent, and the user can overlap multiple patches to construct a desired workspace temporarily. This mechanism is appropriate for stroke-based applications for meetings because the structure of information in these environments is dynamic and changes constantly during the discussion.

2.2.7. Sketch-based Systems for Exploratory Thinking

Many research projects use pen-based input because it is a natural choice for special computing environments, such as mobile computing on PDAs or meeting-support using electronic whiteboards. In contrast, several projects use pen-based input because of its ability to facilitate exploratory thinking.

SILK [73] is one of these experimental systems specifically designed for exploratory activity. It is a system for a designer to design graphical user interfaces. The designer quickly sketches the GUI widgets using freeform strokes on a tablet, and the handwritten widgets become active immediately allowing the user to interact instantly

with the sketched interface. For example, the “knob” in a sketched scroll bar can be dragged up and down. The recognized widgets preserve their sketchy appearance instead of being replaced by predefined graphics. The use of gesture-based input can free the designer from tedious operations required in standard interface builders, and the informal presentation prevents the designer from worrying about details too much.

The Electronic Cocktail Napkin [49,50] also uses pen-based drawing as input for conceptual and creative design activities. It works as a front-end interface for information retrieval, simulation, design critiquing, and collaborative work. It recognizes simple primitives, such as boxes, lines, circles, and triangles, and also recognizes the configuration of these primitives. This system's designers emphasized the importance of contextual recognition, where the meaning of a primitive relies on the context surrounding it. For example, a blob can be recognized as a circle or a box depending on the drawings around the blob.

The Music notepad [138] is a system for editing musical score using pen-based gestural input. The user can input notes and rests, and edit them using simple gestures without using a standard WIMP-style interface. Its designers argue that a sketch-based interface is much closer to sketching music with a real pen and paper, and is thus desirable for informal scoring of music than a WIMP-based UI.

Lakin's vmacs [72] is an electronic design notebook for engineers. The designer draws arbitrary sketches on a blank canvas, and the system later tries to find its hierarchical structure in the drawing by applying various visual parsers. The idea of visual parsing was derived from grammatical parsers for natural languages.

2.2.8. Drawing Applications

An important advantage of pen-based input, other than allowing handwritten text and gestures, is that it is the most intuitive method for drawing pictures on computers. People find it difficult to draw arbitrary shapes using a mouse, but pen-based interaction is significantly closer to shape-drawing using pen-and-paper and thus people find it intuitive and desirable. The user can benefit from pen-based drawing significantly even in simple drawing programs designed for mouse-based interaction (e.g., Microsoft's Paint program in Windows), but researchers have been exploring

various systems and interaction techniques to make the most of pen-based drawing.

Some commercial products such as Apple's Newton™ [99], GO's Penpoint™ [45], and freeform stroke drawing mode in typical drawing editors (SmartSketch™ [131], Corel Draw™, etc.) provide various computational supports for pen-based freeform drawings. They convert freeform strokes into vector segments, automatically connect nearby points, and recognize basic primitives, such as ovals and rectangles.

The PerSketch system [127] facilitates the editing of informal drawing by recognizing perceptual structures in freeform drawings. In standard object-oriented drawing systems, each primitive, such as an oval or rectangle, has a permanent identity. Even when an oval overlaps a rectangle, they are still recognized as two separate objects unless the user groups them together. However, in informal line drawings, the user naturally can perceive multiple possible grouping structures in overlapping strokes (Figure 9). To allow the user to interact with these perceptual groups efficiently, the system decomposes the strokes into small elements and returns the appropriate group of strokes upon the user's request.

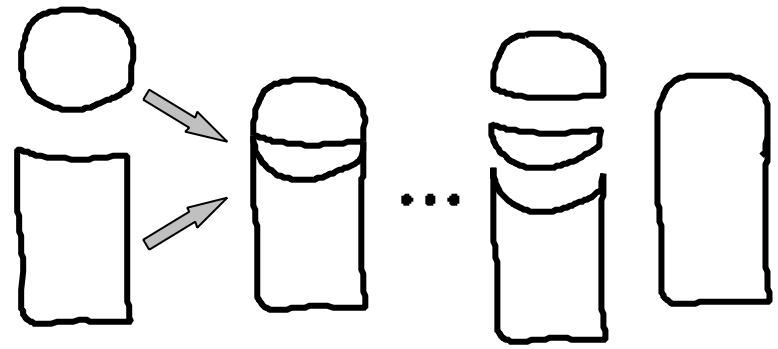


Figure 9. PerSketch [127].

In common drawing programs, the user has to edit curves positioning control points manually using a mouse, but it is difficult to design desired curve shapes using control points. Baudel's technique [6] allows the user to directly draw desired curve shape on the screen using a pen-based device; the system calculates appropriate control points and parameters. In addition to drawing a new line, the system also supports *over stroking* for modifying an existing curve. Cohen *et al.* extended the technique for editing 3D curves [22]. The user can specify the 3D curves by drawing the curve as it appears

from the current viewpoint and its shadow on the floor plane.

The SKETCH system introduced the gesture-based 3D scene construction technique [161]. A simple gesture creates a 3D primitive object and places it in a 3D scene (Figure 10). The system calculates the object's position based on the assumption that every object in the scene should be on some other object. For example, when the user draws three lines requesting a box in the 3D scene, the system put the box on top of the existing box. In addition, the plate on the floor is automatically lifted in 3D space when the user draws a leg under the plate, without changing the 2D appearance in the 2D window. As a result of these implicit placing rules, the user can construct 3D scenes without using 2D widgets and can concentrate on doing the task (constructing a 3D scene) instead of spending time interacting with nested menus and commands.

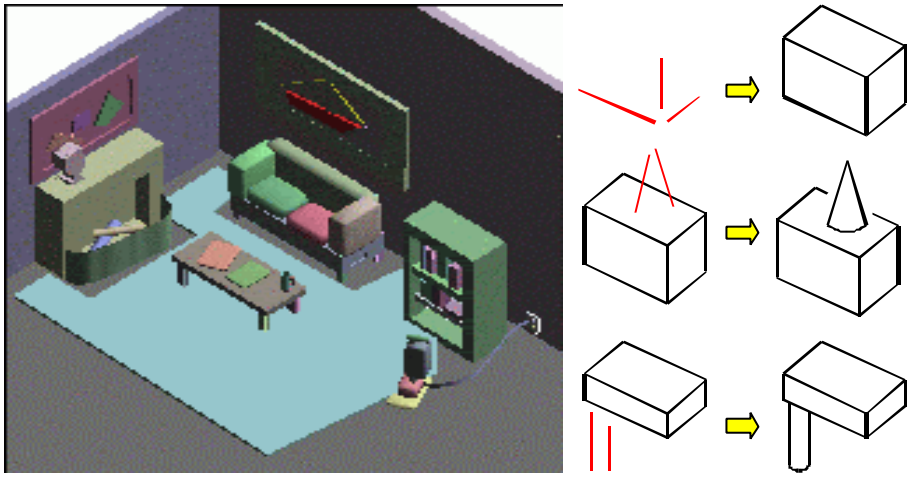


Figure 10. The SKETCH system [161].

The user can construct 3D scenes such as shown at left using simple gestures shown at right.

2.2.9. Summary

The strengths of pen computing can be summarized as follows.

1. The user can use handwriting characters for text input.
2. The user can use gestures for quick access to command operations.
3. The user can use a pen when a keyboard is not available (e.g. PDAs)

4. Sketching is a casual interaction and is thus useful in supporting creative activities.
5. Drawing strokes using a pen is the best way to draw pictures.

Traditionally, the research has focused on the first three properties, aiming at the development of pen-based techniques for doing things conventionally done by a mouse. Handwriting recognition is an attempt to replace keyboard typing. Gesture recognition was designed to replace menu selection and button clicking. Interaction techniques developed for PDAs tried to achieve operations done on desktop computers.

In contrast, researchers have started working on the last two properties recently. These are attempts to do something not possible or extremely tedious when using a mouse as the input device. The goal of this dissertation is to push this effort further and present a framework for making the most of these strengths. We discuss the relationship between our Freeform UI framework and similar previous research efforts in Chapter 8.

To be specific here, however, it can be said that existing attempts have not achieved fluent communication of graphical ideas as seen among human beings. A person can communicate a significant amount of implicit messages to another person through a simple drawing. For example, when one sees a drawing shown in Figure 11(left), one can perceive many implicit messages, such as “this represents a bear,” “this is almost horizontally symmetric,” “this consists of three parts,” “this represents a certain 3D geometry,” “this is cute.” Human-computer interaction can be much more fluent and comfortable if computers can have this kind of ability. This dissertation introduces our efforts to implement this ability in computers.

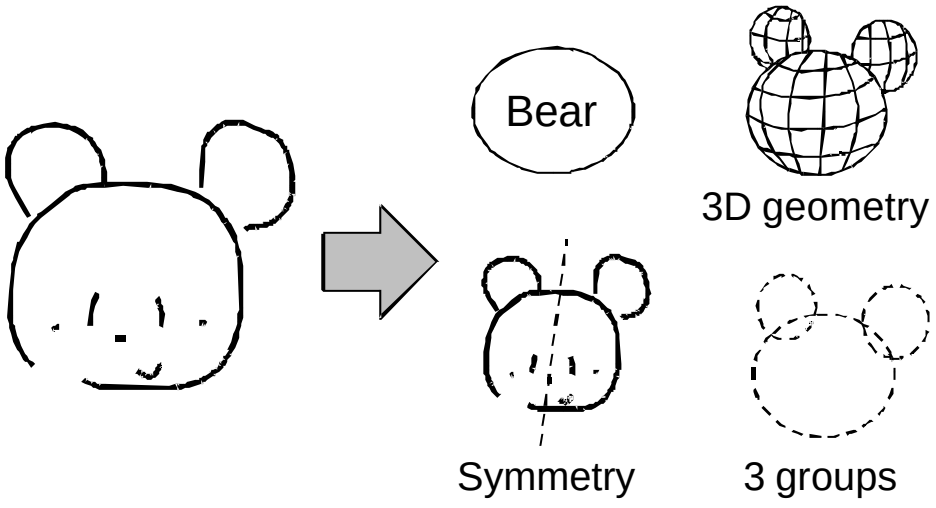


Figure 11. A simple drawing communicates many ideas.

Chapter 3

Freeform User Interfaces

In this chapter, we propose the concept of Freeform User Interfaces as pen-based interface design frameworks for informal graphical computing beyond traditional GUI. The concept defined in this chapter is examined further in the following four chapters with various application-specific systems. Chapter 8 revisits the concept to analyze its nature based on the four example systems.

3.1. Problems and Research Goals

This dissertation proposes the concept of Freeform UI with four example systems. In this section, we explain the problems we try to address and goals to be fulfilled by the body of work presented in this dissertation.

In the broadest context, the goal of this work is to explore the new form of user interfaces beyond traditional command-based interfaces. As computers become more powerful and ubiquitous, the applications running on them become more complicated and diverse. Traditional command-based interfaces are not appropriate for these new computing environments, and researchers are exploring alternative interface frameworks that can achieve fluent human-computer interaction. However, one important property of next-generation user interfaces is *diversity*. Although the currently predominant WIMP-style GUI is used for almost all application domains, next-generation user interfaces will be a collection of various interfaces specialized for each application domain [100]. Our goal is to explore next-generation, non-command user interfaces in the domain of pen-based graphical computing, and to provide insights for designing better interfaces for emerging computing environments.

The problem we try to address is that it is still difficult to communicate arbitrary graphical ideas to computers using WIMP-style GUI. Direct manipulation allows the user to grab objects on the screen directly and move them to the desired places. This strategy works well for object-oriented diagrams, such as flow-charts and node-link diagrams. However, direct manipulation is not good for expressing arbitrary *freeform shapes* rapidly because it requires explicit manipulation of multiple points to control curves. Furthermore, traditional GUI-based diagram editors require the user to combine various editing commands to impose additional structures to the drawings. For example, to draw a symmetric diagram, the user has to duplicate a half of the diagram, flip it, and move it. Selecting appropriate commands from a large menu causes both operational and psychological overhead. Our research goal is to propose alternative interaction techniques for expressing graphical ideas rapidly without tedious manipulation of control points or complicated editing commands.

Another problem in current computing environments is that they do not support exploratory, creative processes that occur in the early stages of intellectual activities [72,95]. Computers are generally used in production activities, such as editing documents, preparing presentations, and drawing diagrams for publication, because computers make it possible to prepare professionally-looking cleaner documents than is possible by pen and paper. However, these application programs are too complicated to use in earlier processes, such as conceiving an idea, outlining long documents, or sketching rough conceptual designs. People use traditional pen and paper in these kinds of exploratory processes because of their simplicity, and move on to a computing environment later, when basic ideas have gelled into some clear form. Our goal is to remove this barrier and to design interfaces that can support exploratory, creative activities.

Finally, another goal of this work is to bring out the real strength of pen-based input. Pen-based devices are becoming popular and available to everyone, but interaction techniques for pen-based computing have not been explored enough. Popular pen-based computing environments support handwriting recognition and gesture-based control. Other than that, pen-based systems still use standard GUI widgets, such as buttons, scroll bars, and pull-down menus. Some pen-based systems use shape recognition but the user's strokes are limited to a predefined shape set. An important strength of a pen-based interface is that it is easy to draw arbitrary freeform strokes representing

various graphical ideas. Computers can use these freeform strokes as an interface beyond simple scribbling programs, recording freeform strokes as-is, like with a physical pen and paper.

3.2. Freeform User Interfaces

Freeform UI is an interface design framework using pen-based input for computer-supported activities in graphical domains. In Freeform UI, the user expresses visual ideas or messages as freeform strokes on pen-based systems, and the computer takes appropriate action by analyzing the perceptual features of the strokes. This is based on the observation that freeform sketching is the most intuitive, easiest way to express visual ideas. The fluent, lightweight nature of freeform sketching makes Freeform UI suitable for exploratory, creative design activities. Freeform UI embodies a non-command user interface for two- and three-dimensional graphical applications in that the user can transfer visual ideas into target computers without converting the ideas into a sequence of tedious command operations.

Specifically, Freeform UI is characterized by the following three basic properties: the use of pen-based stroking as input, perceptual processing of strokes, and informal presentation of the result. We describe each property in detail in the following sections.

3.2.1. Stroke-based Input

Freeform UI is characterized by its use of strokes as user input. A stroke is a single path specified by the movement of a pen and is represented as a sequence of points internally. Stroking is usually recognized as a dragging operation in a standard programming environment: it is initiated by “button press” event, followed by a sequence of “mouse move” event, and terminated by “button release” event. However, stroking is actually a significantly different interface model than dragging. In short, stroking corresponds to physical drawing activity using real pen and paper, while dragging corresponds to a physical grab-and-move operation of objects. During a stroking operation, the trajectory of the pen’s movement is shown on the screen, and the system responds to the event when the user stops stroking by lifting the pen. The system’s reaction is based on the entire trajectory of the pen’s movement during the stroking, not just the pen’s position

at the end (Figure 12). In contrast, in a typical dragging operation, the current cursor position is shown on the screen. Possibly, the object shape specified by the current cursor position is shown as a feedback object, but the trajectory of the cursor movement is not shown. The system's action is based on the final cursor position and possibly the starting position of dragging. In stroking, the user first imagines the desired stroke shape and then draws the shape on the screen at once, while the user constantly adjusts the cursor position observing the feedback objects during dragging.

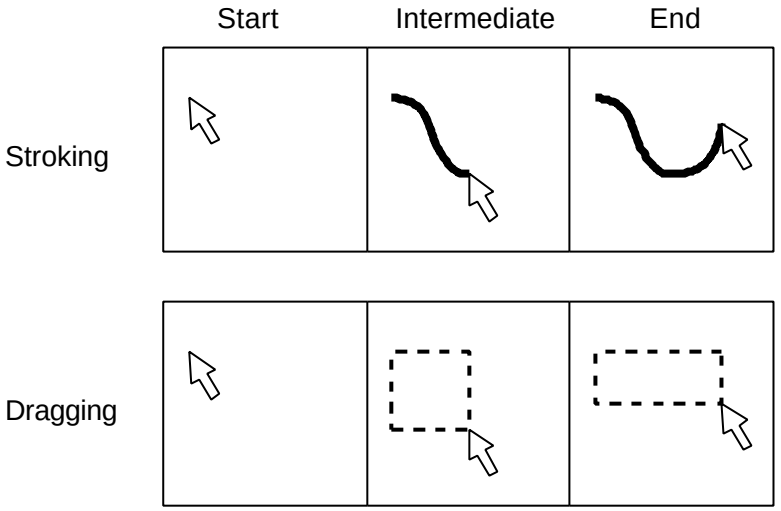


Figure 12. Stroking vs. dragging.

Pen-based stroking is an intuitive, fast, and efficient way to express arbitrary graphical ideas in computing environments. This is because a pen-based stroking operation, or sketching, has been for centuries the primary interaction technique for expressing graphical ideas, and is therefore familiar to us. Specifically, stroking is suitable for quickly entering rough images that internally consist of many parameters from the computer's point of view. On the other hand, mouse-based dragging is suitable for more-delicate control of simple parameters. Dragging has been the dominant interaction technique because traditional computer-based drawing applications are designed for the careful construction of precise diagrams. The argument of this dissertation is that graphical computing in the future should support informal drawing activities and thus require a pen-based stroking interface.

We use the term "pen-based input" to refer to pen devices based on various technologies

[86], including light pens, pressure-sensitive tablets, electromagnetic digitizers, etc. It is possible to use a tablet with a separate display, but a display-integrated device is the best device for drawing strokes. Several input devices other than pens can be used for Freeform UI. Users can draw freeform strokes using a finger on a pressure-sensitive display surface or in a vision-based finger-tracking environment [149]. Small physical *handles* may be used for drawing strokes on tablets. The important feature is one-to-one correspondence between physical location in the input device and cursor location in virtual space. Other pointing devices, such as a mouse, trackball, force-sensitive stick [123] and pressure-sensitive touchpad, are not appropriate for drawing strokes because they control virtual position by indirectly specifying the relative location or velocity of the cursor movement. The input devices that are suitable for Freeform UI may be called "drawing devices" in contrast to the more general "pointing devices."

3.2.2. Perceptual Processing

The next important property that characterizes Freeform UI as a non-command user interface, and that makes Freeform UI different from plain pen-based scribbling systems, is its advanced processing of freeform strokes inspired by human perception. Scribbling programs such as those used in commercial electronic whiteboards simply convert the user's pen movement into a painted stroke on the screen without any further processing. Character-recognition and gesture-recognition systems convert a stroke into a predefined character or command, using pattern-matching algorithms. In these recognition systems, the output of the recognition is represented as a single symbol. The stroking operation in these systems is essentially equivalent to key-typing and button-pressing. "Perceptual processing" refers to mechanisms that infer information from simple strokes that is richer than mere symbols. The idea behind perceptual processing is inspired by the observation that human beings perceive rich information in simple drawings, such as possible geometric relations among line primitives, three-dimensional shapes from two-dimensional silhouettes. Perceptual processing is an attempt to simulate human perception at least in limited domains.

The goal of perceptual processing is to allow the user to perform complicated tasks with a minimum amount of explicit control. In traditional command-based interfaces, the user must decompose a task into a sequence of machine-understandable, fine-grained command operations, then input the commands one by one. As we discussed in Chapter

2, non-command user interfaces try to avoid this process and allow the user to directly interact with tasks without worrying about low-level commands. Freeform UI frees users from detailed command operations by this perceptual processing of freeform strokes. For example, Pegasus frees the user from tedious geometric operations such as rotation and duplication by automatically inferring desired geometric constraints, and Teddy eliminates the manual positioning of many vertices in 3D space by automatically constructing 3D geometry from the input stroke. This simplicity also significantly reduces the effort spent on learning commands. In traditional command-based systems, the user has to learn many fine-grained editing commands to do something simple. In Freeform UI, on the other hand, the user can do a variety of things simply after learning a single operation.

It is important to consider the context surrounding a stroke in addition to the stroke itself. A single stroke itself contains severely limited information, but human beings perceive rich information from the spatial relationships among the target stroke and other strokes in the scene. In Pegasus, the system infers possible geometric constraints from the spatial relationship among the input stroke and existing line segments. The path-drawing navigation system calculates the path in a 3D scene by projecting the input stroke onto the walking surface. In Teddy, the resulting shape is defined by the current object shape, camera angle, and input stroke.

To make perceptual processing work effectively, it is crucial to restrict an interface to a specific target domain. Since freeform strokes have limited information and are highly ambiguous, it is essentially impossible to infer the user's intention correctly without assuming a specific task domain. This limits the user's freedom and reduces the flexibility of the system in a sense: the user cannot draw freeform drawings in Pegasus and cannot construct rectiliniear objects in Teddy. However, Freeform UI provides greater freedom to explore a wider design space within each task domain than is possible with command-based operations. The serious problem with typical command-based interfaces is that massive freedom and flexibility overwhelm the users. As a result, the interaction tends to be a combination of relatively obvious operations and the user's activity is constrained by the command set provided by the system. In contrast, Freeform UI frees the users from having to learn numerous command operations and lets them explore a large design space within each domain.

In addition to restricting the interface to a specific domain, it is also inevitable to

impose certain implicit rules to make the perceptual processing work. The system recognizes the user's freeform stroke based on specific predefined rules, but it may go against the user's intuition. For example, in Teddy, the extrusion operation consists of two strokes, but the user may want to extrude the surface using one or three strokes. The idea of perceptual processing is to design the interface to make the system's behavior conform to the intuitive expectations of most users, but it can be counterintuitive to a specific user. Ultimately, each individual user needs his or her own perceptual processing scheme to attain a desired result perfectly. Automatic adaptation or explicit manual customization might be able to mitigate the problem to a certain extent, but interface designers should be aware of this limitation when implementing perceptual processing systems. This limitation also implies that the user must learn the system's behavior to a certain extent. The learning in Freeform UI is different from learning in traditional command-based systems in that the system's behavior varies depending on each context, and the behavior is difficult to explain in the form of a static document. It is important to provide appropriate feedback to the user to facilitate learning by experience.

"Perceptual processing" does not mean a specific algorithm or technology. It is a kind of design principle for making efficient, intuitive interfaces. A command-based operation in traditional computer programs corresponds to a single-step operation against an internal data structure. For example, in 3D modeling systems, a 3D model consists of vertices, edges and faces; command operations were designed to manipulate these elements directly. In contrast, perceptual processing encourages the system designers to reorganize operation primitives so that each operation corresponds to the user's single *procedure* which may consist of multiple internal operations from the system's point of view. For example, the extrusion operation of Teddy is a simple procedure from the user's point of view, but it actually causes multiple operations, such as vertex deletion, creation, or replacement, against the internal data structure.

3.2.3. Informal Presentation

The last property of Freeform UI is informal presentation of contents. The system displays the materials to manipulate or the result of computation in an informal manner, using sketchy representation without standard, cleaned-up graphics. This informal presentation is important not only for an aesthetically pleasing appearance,

but also to arouse appropriate expectations in the user's mind about the system's functionality. If the system gives feedback in precise, detailed graphics, the user naturally expects that the result of computation will be precise and detailed. In contrast, if the system's feedback is in informal presentation, the user can concentrate on the general structure of the information without worrying about the details too much. The importance of informal presentation in exploratory design activities has been discussed in many papers [12,46,124,156].

Several experimental systems implemented sketchy presentation techniques. Strothotte *et al.* introduced a non-photorealistic renderer for an architectural CAD system [134]. The system used cubic lines for representing straight line segments to make them appear hand-drawn. The SKETCH system [161] also used non-photorealistic rendering to give a sketchy appearance to a 3D scene being constructed. The system intentionally displaced the vertex position when rendering projected 2D line segments. While these early systems addressed the rendering of silhouette lines and edges only, more elaborate systems draw shadows and shades using pen-and-ink style [154]. Teddy uses a real-time pen-and-ink rendering technique developed by Markosian *et al.* [80]. It efficiently detects the silhouette lines of a 3D model, and renders the silhouettes in various styles.

While these systems are designed for 3D graphics, some systems introduced sketchy rendering for 2D applications. The EtchaPad system [87] used synthesized wiggly lines for displaying GUI widgets in order to give them an informal look. It used Perlin's noise function [105] to create wiggly lines that look hand-written. Other systems employ the user's freeform strokes as-is to represent recognized primitives without cleaning up the drawings. SILK [73] allows the user to interact with the GUI widgets sketched on the screen. The Electronic Cocktail Napkin system [50] also retains and displays the as-inked representation of hand-drawn graphical primitives. Pegasus used intentionally thick line segments to show beautified drawings to give them an informal look.

3.3. Target Domain

The traditional graphical user interface has been predominantly used for almost all applications running on desktop computational environments. However, as the forms of computing devices and the purposes of computing get diverse, each application area

requires a specific interface paradigm beyond WIMP-style GUI. 3D applications require 3D interfaces, and real world computing applications require special interfaces such as augmented reality. This section discusses what kinds of applications require Freeform UI.

First, Freeform UI is an interface for 2D and 3D graphical applications. While some pen-based interface systems use handwriting characters and gestural commands for textual applications [18], Freeform UI emphasizes *drawing* aspects of pen-based computing. Freeform strokes are associated with specific graphical representations through perceptual processing, and the resulting graphics are presented in an informal manner.

Second, Freeform UI is for exploratory, informal activities such as note-taking, brainstorming, the early stages of design, and real-time communication. This is in contrast to the fact that traditional graphical user interfaces are suitable for more production-oriented activities such as desktop publishing and editing presentation slides. Freeform UI supports exploratory activities by its simple input stream (freeform strokes) and its informal presentation. However, Freeform UI is not appropriate for production-orientated applications because the combination of freeform strokes and perceptual processing has inherent ambiguity.

More specifically, Freeform UI might be useful in the following applications and situations: sketching on pen-based portable devices in mobile environments, graphical note-taking on notebook computers in meeting environments, drawing diagrams during presentations using electronic whiteboards, communicating and collaborating over pen-based systems, supporting for the early stages of 2D and 3D design activity and novices' exploring of graphical systems.

Examples of applications not suitable for Freeform UI are object-oriented diagram editors, such as node-link diagrams, state transition diagrams, structured flow-charts and binary trees. These diagrams essentially represent symbolic, abstract data structures rather than some geometric information. In other words, the semantics behind the diagram are important and not the specific appearance itself. Gesture-based interfaces may be useful to edit these diagrams quickly, but they are not Freeform UI. Professional CAD systems are another example application that is not suitable for Freeform UI. Although Freeform UI is useful in the conceptual design phase, it is too

ambiguous and informal to use in the final production stage. In this stage, detailed precision operation is required and command-based operations are appropriate for it.

Another important question is whether Freeform UI is for novice users or experts. The answer is that novices and experts both benefit from Freeform UI, but in different ways. Freeform UI allows novice users to interact with the application without intensive training. Freeform UI does require first-time users to learn a minimal number of interaction rules, but the interaction style resembles real pen-and-paper sketching, and it is much easier than learning many command-based operations. The novice users may not be able to construct elaborate things at first, but they can do something interesting soon, which is essential to ensuring that the first-time user can overcome the initial psychological barrier.

On the other hand, expert users can benefit from Freeform UI because it allows them to quickly construct rough sketches of the intended final product. Although experts can control command-based applications fluently, command-based interfaces are too fine-grained and require multiple complicated steps to get the final result. This is inevitable in creating a detailed, precise final product, but it is completely undesirable in the early stages of design. Experts can use Freeform UI initially for quick prototyping, and then shift to a command-based interface for detailed production.

3.4. Approach

This chapter proposed the concept of Freeform UI. Freeform UI is an attempt to design next-generation, non-command user interfaces for graphical applications beyond traditional GUI. We defined Freeform UI according to three basic properties: the use of pen-based stroking as input, perceptual processing of strokes, and informal presentation of the result. We then explained exploratory activities in graphical computing domains as the designated application area for Freeform UI.

The concept itself is essentially a collection of design guidelines for building better interfaces for pen-based graphical applications, rather than a single, solid idea representing a specific technology or algorithm. Our approach is to implement independent example systems for specific application domains based on the concept of Freeform UI, and analyze the strengths and limitations of the concept based on

experiences with these example systems. In this dissertation, we introduce four example systems based on Freeform UI. Their application domains include geometric drawing, 3D virtual space navigation, electronic whiteboard, and 3D modeling. Each system is useful in each application domain, but more importantly, they embody the idea of Freeform UI as a whole and suggest the future of user interfaces. The following chapters introduce the four example systems in detail, and Chapter 8 discusses the strengths and limitations of Freeform UI based on these examples.

Chapter 4

Beautification and Prediction for 2D Geometric Drawing

This chapter introduces two novel interaction techniques for rapid geometric design, *interactive beautification* and *predictive drawing*, and a prototype system called Pegasus. The motivation is to solve the problem with current drawing systems: too many commands, and unintuitive procedures to satisfy geometrical constraints. Interactive beautification receives the user's freeform stroke and beautifies it considering geometrical constraints among segments. A single stroke is beautified at a time, preventing accumulation of recognition errors or catastrophic deformation. The system supports geometric constraints such as perpendicularity, congruence, and symmetry, which were not seen in existing freeform stroke recognition systems. In addition, the system generates multiple candidates as a result of beautification to solve the problem of ambiguity. A user study showed that the users can draw the required diagrams faster and more precisely using the interactive beautification than direct manipulation techniques. Predictive drawing predicts the user's next drawing operation based on the spatial relationship among existing segments on the screen. The user can duplicate, flip, and repeat existing drawings just by clicking intended segments displayed by the prediction mechanism. Using these techniques, the user can draw precise diagrams with geometrical relations rapidly without using any editing commands explicitly.

4.1. Introduction

Commercial Object-Oriented (OO) drawing editors, such as MacDraw and CAD systems, have various editing commands and special interaction modes. A user can construct a

diagram with geometric constraints by combining these commands appropriately. For example, symmetry can be achieved by the combination of duplication, flipping, and location adjustment, while perpendicularity can be achieved by duplication and 90 degree rotation. In addition, CAD systems often have special interaction modes such as a mode for drawing perpendicular lines. However, invoking these commands or switching to the special editing modes requires additional overhead, and selection of appropriate commands or interaction modes is difficult, especially for novice users [59].

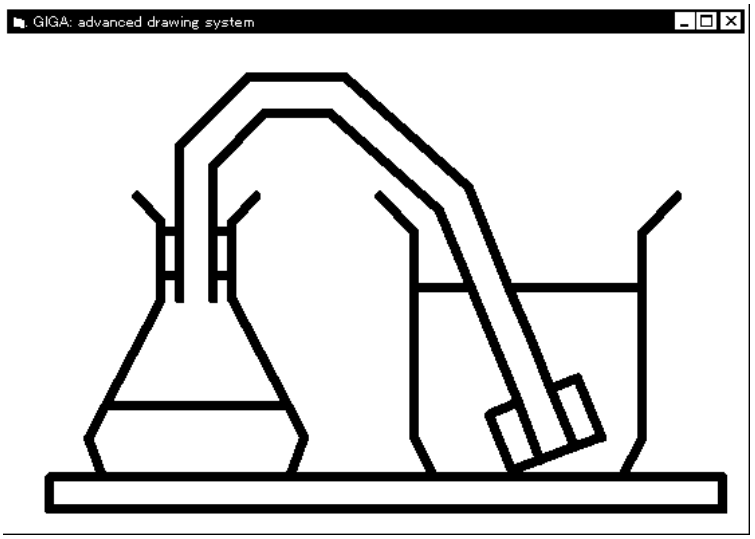


Figure 13. A diagram drawn on the prototype system Pegasus.

This diagram was drawn without any editing commands such as rotation, copy, or gridding.

To solve these problems, we propose new interaction techniques for drawing, *interactive beautification* [60] and *predictive drawing* [61]. Interactive beautification is a technique for rapid construction of geometric diagrams (an example is shown in Figure 13) without using any editing commands or special interaction modes. Interactive beautification can be seen as an extension of freeform stroke vectorization [21] and diagram beautification [104]. It receives a user's freeform stroke and beautifies the stroke considering various geometric constraints among segments. The intuitiveness of the technique allows novice users to draw precise diagrams rapidly without any training.

Interactive beautification is characterized by the following three features; 1) stroke by stroke beautification, 2) automatic inference and satisfaction of higher level geometric constraints, and 3) generation and selection of multiple candidates as a result of beautification. These three features work together to achieve rapid and intuitive drawing, avoiding the problem of ambiguity.

Predictive drawing further enhances interactive beautification by actively predicting the user's next drawings based on the spatial relationship among existing segments on the canvas. When a new segment is added to the screen, the system searches the canvas for reference segments whose shapes are identical to the new segment. Then, the system copies the drawings around the reference segments to the vicinity of the newly drawn segment. This simple prediction mechanism can efficiently support various drawing patterns such as duplication, flipping, and iteration. The result of prediction is displayed on the screen in form of multiple candidates, and the user can select desired one by clicking on it. The user can draw precise diagrams just by continuously clicking segments shown on the screen as long as the prediction finds appropriate candidates.

Interactive beautification and predictive drawing are currently implemented on a prototype system named Pegasus (an acronym for "Perceptually Enhanced Geometric Assistance Satisfies US!"), and user evaluations using it shows promising results. This chapter introduces interactive beautification and predictive drawing, and describes the implementation of the prototype system in detail.

The remainder of chapter is organized as follows: the next section describes related work in diagram drawing on computers. Then, we describe interactive beautification using several examples, and it's algorithm detail. A user study performed to confirm the effectiveness of the technique is described. Next, we describe the user interface and the algorithm of predictive drawing in detail. We introduce the prototype system Pegasus and example drawings. Finally, we consider the limitation of our current implementation and conclude the chapter.

4.2. Related Work

At a glance, the system may seem similar to existing sketch-based interfaces including

commercial products such as Apple Newton, GO Penpoint, and freeform stroke drawing mode in typical drawing editors (SmartSketch, Corel Draw, etc.). These systems convert freeform strokes into vector segments and satisfy primitive geometric constraints such as connection. The difference is that interactive beautification considers complex, global constraints such as parallelism, symmetry, or congruence, which enhances the range of geometric models. In addition, the generation and selection of multiple candidates is unseen in the existing systems.

Gesture based systems [3,159,122,73] also employ freeform stroke input, but they convert input strokes into independent primitives, while interactive beautification converts them into simple line segments satisfying geometric relations. Gross et al. pointed out the importance of context in solving the problem of ambiguity [49,50], which has influenced our idea.

Beautification systems [104,15,71] are basically batch-based, which can lead to unwanted results because of ambiguity in the user's input. Interactive beautification prevents such results by interactively presenting multiple candidates and requesting the user's confirmation.

While interactive beautification systems control the placement of two vertices (start and end) simultaneously, many existing drawing systems assist the placement of a vertex by controlling the movement of the mouse cursor. Snap Dragging systems [9,10,44] extends gravity-active grids by letting users specify various geometric relations, and some systems such as Rockit[67] and Aldus Intellidraw automatically infer possible gridding constraints.

Compared to these techniques, the advantages of interactive beautification are as follows: 1) Freeform stroke drawing is more intuitive and less cumbersome than careful manipulation of the cursor, especially for a pen-based interface [6]; and 2) The system can gather more information from a freeform stroke trace than cursor placement. For example, equality of interval between parallel lines cannot be detected from the placement of a single vertex.

Rockit is similar to our system in that both automatically infer possible constraints and provide easy access to alternative possibilities. However, Rockit is suitable for specification of perpetual spatial relationships among movable objects, while we focus

on construction of static line-based illustrations.

Saund et al.'s work [127] shares our motivation, to support natural human perception of underlying spatial structures, but does not support the construction of precise diagrams.

Constraint based systems [16,17,53,66,98,136] facilitate the construction of complex diagrams with many constraints, but require considerable amount of effort to specify the constraints. Interactive beautification aims at an opposite goal: to reduce the effort by focusing on relatively simple diagrams.

Prediction mechanisms have been explored in several research efforts [26,83], but their predictions are mainly based on the regularity found in the operation sequence (repeated operation, etc.). Our prediction mechanism is different in that we make use of regularities found in static spatial configurations in a given drawing.

Graphical search and replace [71] and visual rule based system [52] search for diagrams that match the reference pattern specified by the user, and replace them with the specific goal pattern. Our predictive drawing works in a similar way, but is unique in that it performs the search implicitly to assist simple drawing activity.

4.3. Interactive Beautification

4.3.1. User Interface

Basically, interactive beautification is a freeform stroke vectorization system; it receives a freeform stroke and converts it into a vector segment, inferring and satisfying geometric constraints.

First, the user draws an approximate shape of his desired segment with a freeform stroke using a pen or a mouse (Figure 14a). Then, the system infers geometric constraints the input stroke should satisfy by checking the geometric relationship among the input stroke and existing segments (Figure 14b). Finally, the system calculates the placement of the beautified segment by solving the simultaneous equations of inferred constraints, and displays the result to the user (Figure 14c). In

addition, the system generates multiple candidates to deal with the ambiguity of the freeform stroke (Figure 14d).

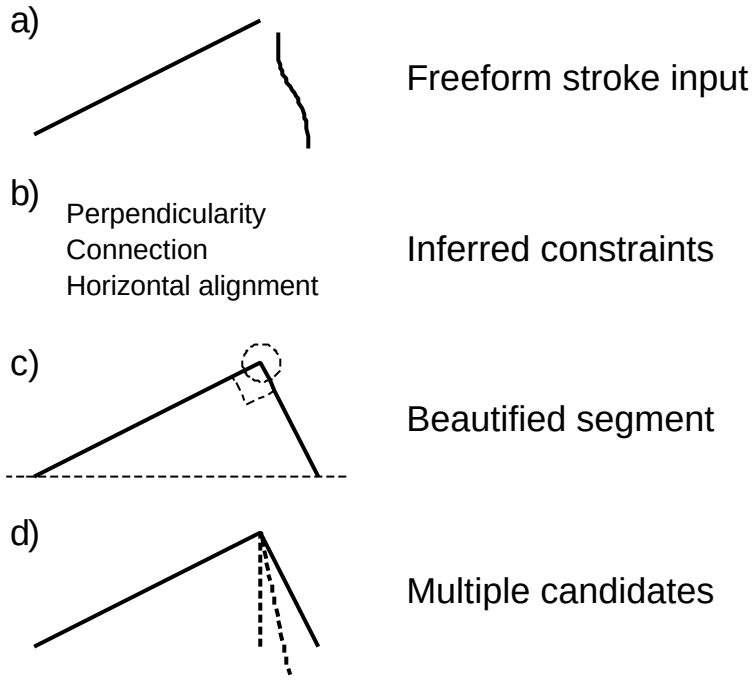


Figure 14. Basic operation of interactive beautification.

The characteristics of interactive beautification are 1) stroke by stroke beautification, satisfying higher level constraints such as congruence, perpendicularity, or symmetry, and 2) generation and selection of multiple candidates. We describe the details of the interaction in the following subsections.

4.3.1.1. Stroke by Stroke Beautification Satisfying Geometric Constraints

This subsection describes how diagrams are constructed using stroke by stroke freeform stroke beautification, satisfying various geometric constraints. To make it simple, we assume that the system generates only one candidate as a result of beautification in this subsection. The next subsection describes the generation of multiple candidates in detail.

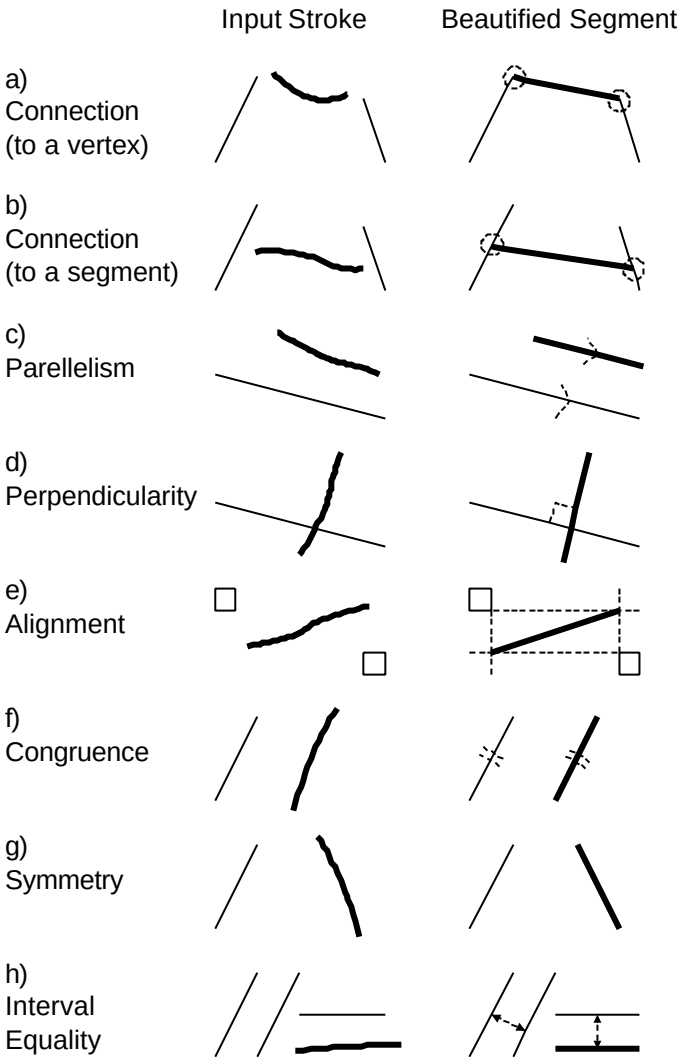


Figure 15. Supported geometric relations.

Figure 15 shows some examples of supported constraints, input strokes, and beautified segments & feedback. Figure 15a,b describe the connection constraint. If the user draws a freeform stroke whose start or end point is located near a vertex of an existing segment, the system automatically detects the adjacency and connects the point to the vertex or the body of a segment.

Figure 15c,d illustrate parallelism and perpendicularity constraints. The system compares the slope of the input stroke and those of existing segments, and if it finds an existing segment with approximately the same slope, it makes the slope of the beautified segment identical to the detected slope. Similarly, if the system finds an

existing segment approximately perpendicular to the input stroke, it converts the stroke into a precisely perpendicular segment.

Figure 15e shows vertical and horizontal alignment constraints. When a freeform stroke is drawn, the system individually checks the x and y coordinates of the vertices of the input stroke, and makes the coordinates precisely identical to the existing ones if they are near.

Figure 15f,g illustrate congruence and symmetry constraints. When a new input stroke is drawn, the system searches for a segment almost congruent to the stroke among the existing segments. If such a segment is found, the system makes the input stroke exactly congruent to the segment (Figure 15f). Similarly, the system searches for a segment that is similar to the vertically or horizontally flipped input stroke. If such a segment is found, the system makes the input stroke exactly congruent to the flipped one (Figure 15g).

Figure 15h describes interval equality. This relation is detected by comparing the interval between the input stroke and an existing line segment parallel to the stroke, and intervals between existing parallel segments. This mechanism can be used to draw a pipe with a constant width or to draw cross stripes or grids (Figure 16). Construction of these diagrams is particularly difficult with menu-based systems, where the user must copy, rotate, and move the segments.

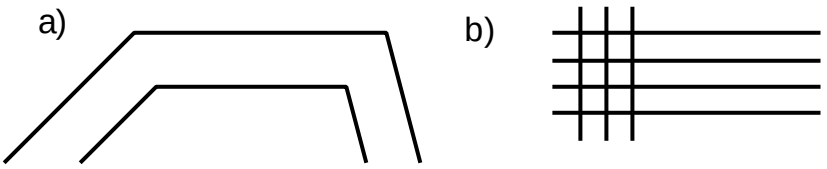


Figure 16. Example use of interval equality among segments.

In actual drawing, the geometric constraints described above are combined and work together to produce a precise diagram. In Figure 17a, relations such as connection, perpendicularity, and y-coordinate alignment are simultaneously satisfied. In Figure 17b, interval equality, y-coordinate alignment and flipped congruence (symmetry) work together to generate the arch (the unnecessary line fragments can be removed easily by an `erasing' gesture, which is explained later).

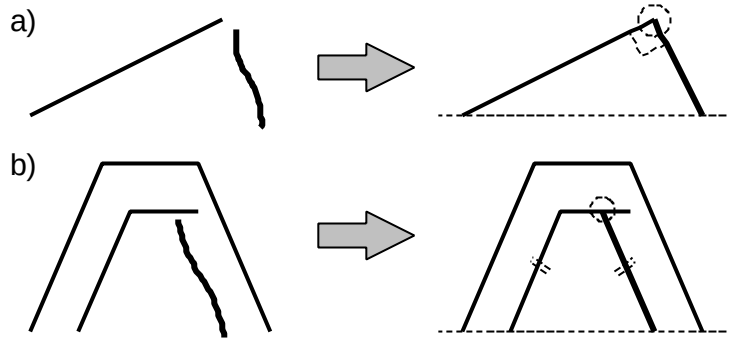


Figure 17. Construction of a diagram with many constraints

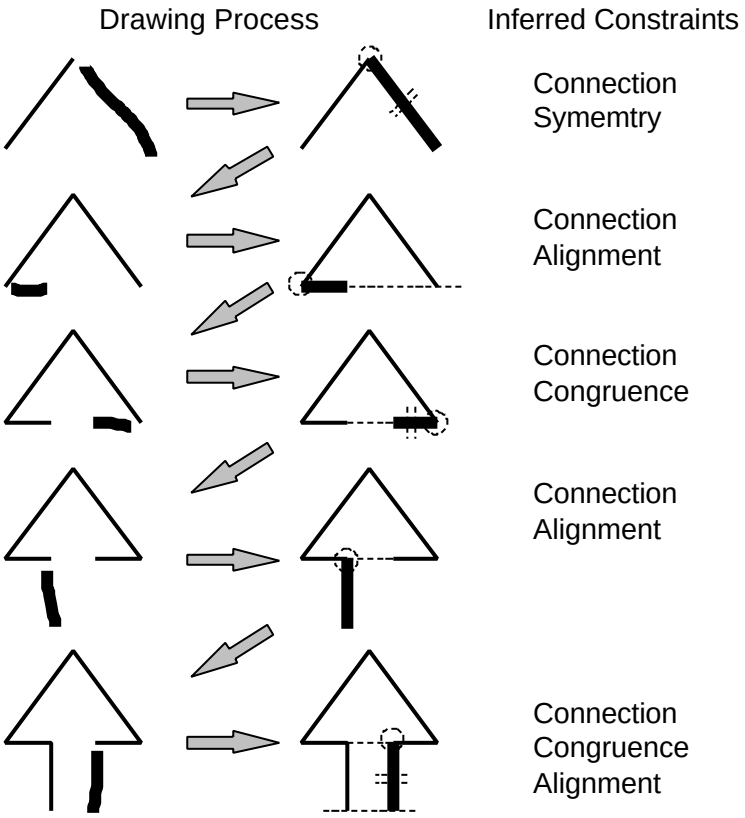


Figure 18. Construction of a symmetric diagram.

Figure 18 illustrates how a symmetric diagram is constructed using interactive beautification. For each input stroke, the system infers appropriate constraints and

returns a beautified segment. Notice that, except for the slope sides which constitute the arrowhead, the symmetry for the rest of the arrow shape is achieved solely by locally defined relationships (alignment, congruence and connection constraints) without resorting to some special constraints to achieve global symmetry.

4.3.1.2. Generation and Selection of Multiple Candidates

The inherent difficulty with any freeform stroke recognition system is that a freeform stroke is ambiguous in nature. The user draws an input stroke with an intended image in mind, and the system must infer the intended image based on the shape of the freeform stroke. However, it is not an easy problem to reconstruct the intended image from the ambiguous input stroke. For example, when the system observes an input stroke shown in Figure 19a, it is difficult to guess which segment in Figure 19b is the one the user intended. Existing systems do not consider these multiple possibilities, and just return a single segment as a result. If the user is not satisfied with the result, he must draw the stroke again, but the revised stroke may also fail.

To solve the problem, interactive beautification infers all possible candidates and allows the user to select one among them (Figure 19c). If the user is not satisfied with the primary candidate, he can select other candidates by tapping on them directly (Figure 19e). During the selection, the system visually indicates what kinds of constraints are satisfied by the currently selected candidate. Visualized constraints ensure that the desired constraints are precisely satisfied. In addition, they assist the selection of a candidate in a cluttered region, where it is difficult to find the desired one. The selection completes when the user taps outside the candidates or draws the next stroke (Figure 19d,f).

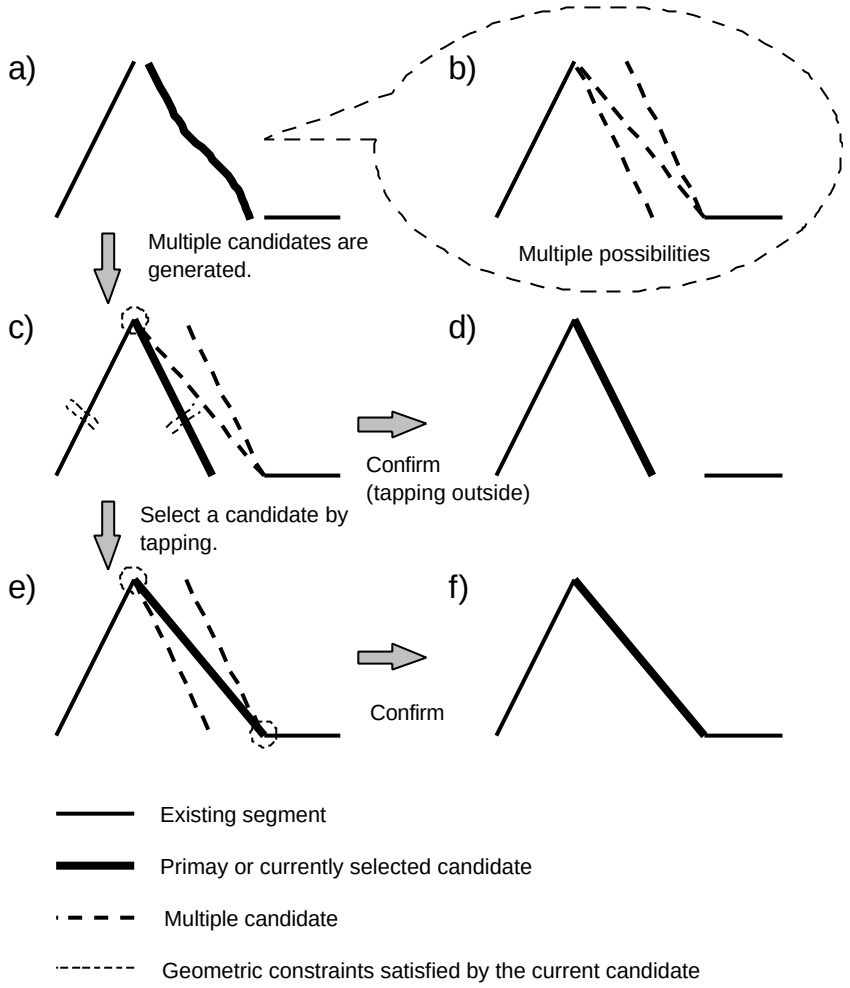


Figure 19. Interaction with multiple candidates.

The user can select a candidate by tapping on it, and satisfied constraints are visually indicated.

Generation of multiple candidates, together with visualization of the satisfied constraints, greatly reduces the failure in recognition, and makes it possible to construct complex diagrams such as Figure 13} using freeform stroke only. Additional overhead caused by candidate selection is minimized because the user can directly go to the next stroke without any additional operation when the primary candidate is satisfactory.

4.3.1.3. Auxiliary Interfaces

In addition to freeform stroke drawing and selection by tapping, the current system supports a floating menu and an erasing gesture. The floating menu is a button on the screen, and the user can place the button anywhere by dragging it. Menu commands appear when the user taps on the button, similar to a pie menu [55]. Currently, “clear screen” and “undo” commands are implemented in the menu.

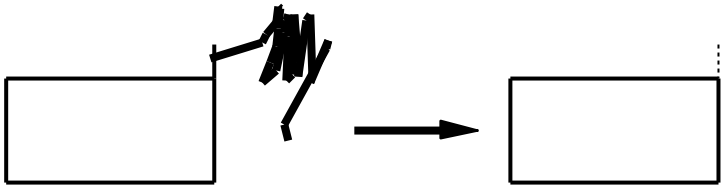


Figure 20. Trimming operation.

The erasing gesture is made by scribbling. If the system detects the gesture, it deletes the nearest line segment to the start point of the scribbling gesture. As the system partitions the line segments at every cross point and contact point beforehand, the user can easily *trim* the unnecessary fragments (Figure 20). Trimming is a frequently used operation on any drawing system, and this easily accessible trimming operation greatly contributes to the efficient construction of complex geometric diagrams.

4.3.2. Algorithm

This section describes the algorithm of interactive beautification in detail. From a programmer's point of view, the interactive beautification system works as follows (Figure 21) When the user finishes drawing and lifts the pen from the tablet, the system first checks whether the stroke is an erasing gesture or not. 2) If the input stroke is not an erasing gesture, the beautification routine is called. It receives the stroke and the scene description as input and returns multiple candidates as output. Then, the generated candidates are indicated to the user, allowing him to select one. 3) *The settlement routine* is called when the user finishes selection, that is, starts to draw the next stroke or taps on outside the candidates. The settlement routine adds the selected candidate to the scene description and discards all other candidates. 4) If an erasing gesture is recognized, the erasing routine detects the segment to be erased and removes

the segment from the scene. The settlement routine is called after the erasing routine to refresh the scene description. The settlement routine also performs some preliminary calculations to accelerate the beautification process (sorting the vertex coordinates, for example).

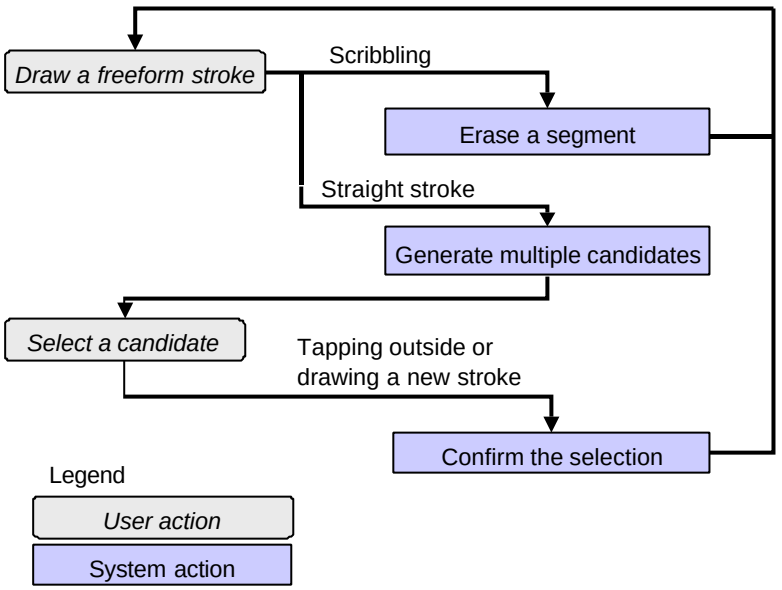


Figure 21. Operational model of interactive beautification.

We now describe the algorithm of the beautification routine in detail. The beautification routine consists of three separate modules (Figure 22). First, a constraint inference module infers the underlining constraints the input stroke should satisfy. Next, a constraint solver generates multiple candidates based on the set of inferred constraints. Finally, an evaluation module evaluates the certainty of generated candidates and selects a primary candidate. The separation of the constraint inference and the constraint solving remarkably improves the efficiency of multiple candidates generation, because the system performs the most time-consuming task of checking all combinations of segments only once, instead of performing the task for each candidate.

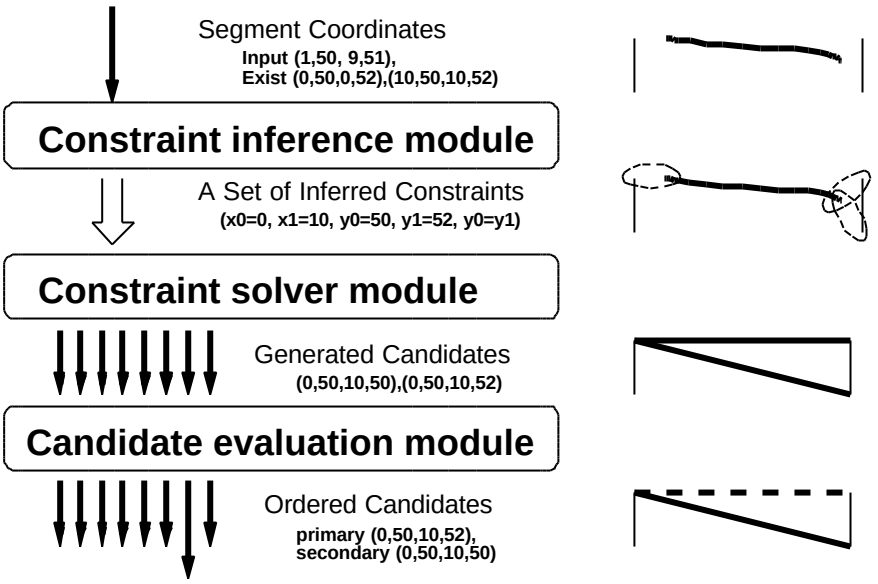


Figure 22. Structure of the beautification routine.

Constraints are represented as numerical equalities binding four variables (coordinates of the new segment). The constraint inference module communicates the inferred geometric relations in a form of numerical equalities, and the constraint solver solves the simultaneous equations. Figure 23 shows the currently supported geometric relations and the corresponding numerical equalities.

Geometric Relations	Corresponding Equalities
Connection (start point on a vertex)	**x0 = const y0 = const**
Connection (end point on a vertex)	**x1 = const y1 = const**
Connection (start point on a line)	**y0 = const * x0 + const**
Connection (end point on a line)	**y1 = const * x1 + const**
Alignment (start -x)	**x0 = const**
Alignment (start -y)	**y0 = const**
Alignment (end -x)	**x1 = const**
Alignment (end -y)	**y1 = const**
Vertical line	**x0 = x1**
Horizontal line	**y0 = y1**
Congruence (Symmetry)	**x1 - x0 = const y1 - y0 = const**
Parallelism (Perpendicularity)	**y1 - y0 = const * (x1 - x0)**
Interval equality	**y0 = const * x0 + const y1 = const * x1 + const**

Figure 23. Relation between geometric relations and equalities.

4.3.2.1 Constraint Inference module

First, the system searches the table of parameters of all the existing segments, in order to find values that are `adjacent' to those of the input stroke and generates constraints that would constrain the parameters of the input stroke variables. To be specific, the system examines and compares the 5 parameters of the input stroke (x, y coordinates of start/end vertex, and the slope of the stroke). As a result, constraints to represent geometric relations such as x and y coordinate alignment, parallelism, and perpendicularity, are generated. As the parameters of all segments in the scene are sorted in the settlement routine, the computational complexity of this routine is O(log n) while n is the number of existing segments. Perpendicular segments are found by storing 90 degrees rotation of the existing slopes.

Next, all the segments in the scene are examined to find various geometric relations between the existing segments and the input stroke, such as congruence, connection and symmetry. In addition, to find the equality of intervals among segments, this routine calculates the interval between the input stroke and each approximately parallel segment in the scene, and searches for stored intervals that are adjacent. The computational complexity of this routine is O(n log n).

This two-phased constraint inference process generates a set of constraints to be satisfied. To reduce unnecessary overhead in constraint solving, the system checks for duplication whenever a new constraint is created during the inference.

4.3.2.2 Constraint Solver

After the constraint inference, the system calculates the coordinates of the beautified segment based on the inferred constraints. As the inferred constraints are usually over-constrained (they cannot be under-constrained because all variables are automatically bound to the original coordinates of the input stroke), the system searches for all the possible combinations of inferred constraints to generate multiple candidates.

The constraint solver is a modification of the equality solver of CLP(R)[65] with an extension to generate multiple candidates from over-constrained equalities. Similar to the equality solver of CLP(R), the initial state consists of an empty valuation, and the system tries to apply the constraints one by one to the intermediate valuation. The difference is that the system maintains a set of valuations instead of a single valuation, and the new valuation is *added* to the valuation set without *discarding* the previous valuation when a constraint is successfully applied.

Figure 24 shows how the solver works using a simplified example with two variables and four constraints. First, the solver creates an empty valuation (1), and then, applies the first constraint `(x=1)` to the valuation. Naturally, the constraint is successfully applied and a new valuation is created `(1,-)`(2). Note that the initial valuation `(-,-)` is preserved instead of being replaced by the new valuation (3). When the solver tries to apply the constraint `(x-y=0)` to the valuation `(1,2)`, the application fails and no new valuation is created (4). On the other hand, the constraint can be successfully applied to the empty valuation `(-,-)`, creating a new valuation with a suspended (delayed)

constraint (5). The suspended constraints are solved when enough variables are ground or enough equalities are given (6). Identical valuations are detected and unified by the solver to prevent redundant calculations (7). Finally, the system returns the fully grounded valuations as multiple candidates (8).

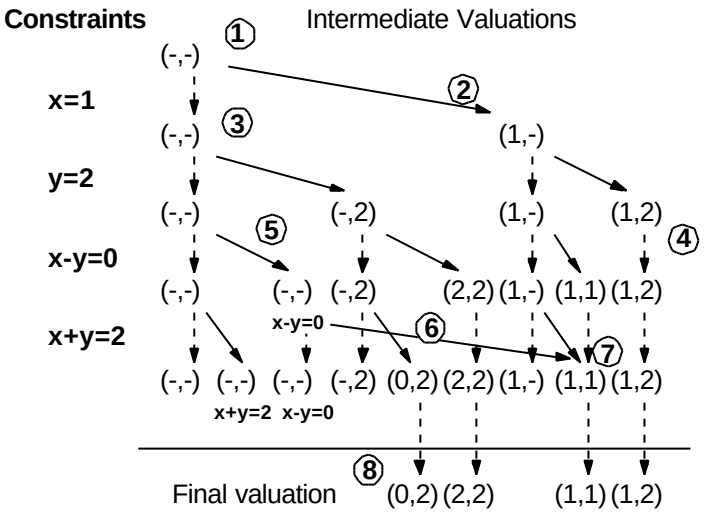


Figure 24. Algorithm for constraint solving.

To improve efficiency, intermediate valuations are stored in a tree structure whose root node is the initial empty valuation. This representation is natural because every valuation is created as a child of another valuation with additional grounded variables or additional suspended constraints. If a constraint fails to be applied to a valuation, it means that the constraint cannot be applied to all of its descendants, and the system can avoid wasteful calculations.

The basic method to solve simultaneous equations is Gaussian elimination, because the current implementation supports only linear equations. Other algorithms (e.g. Newton's method [23,53]) would be required to support non-linear constraints, such as line length equality or tangency of curved segments. Pair equalities for such constraints as connection to a vertex, congruence, and interval equality (see Figure 23) are bound by an *and* condition; both equalities fail if one of them is not satisfied.

In summary, our constraint solver is a multi-way numerical equality solver with an extension to generate multiple solutions efficiently from over-constrained constraints. The complexity of computation is $O(2^n)$, but is substantially reduced by pruning

wasteful calculations using a tree structure and unifying identical intermediate valuations, and has not caused problems in interaction so far in our prototype system.

4.3.2.3 Candidate evaluation module

The evaluation process must follow the solver because it is necessary to consider the resulting coordinates as well as the satisfied constraints to calculate the certainty of a candidate. That is, candidates located close to the input stroke should be scored highly, but the location is unknown until the constraints are solved.

Currently, we use an ad-hoc scoring function to calculate the certainty of candidates considering type of satisfied constraints and the distance between resulting coordinates and original input stroke. A candidate with the highest score is selected as a primary one, and those whose scores are under a specific threshold are discarded.

4.3.3. Evaluation

This section describes an experiment performed to evaluate the interactive beautification using the prototype system compared to existing drawing systems in some diagram drawing tasks. We were particularly interested in whether or not interactive beautification would improve the task performance time (*rapidness*) and the completeness of the geometric constraint satisfaction in the diagrams (*precision*).

4.3.3.1. Method

Systems

The experiment was conducted on a Mitsubishi pen computer AMiTY SP (i486DX4 75MHz, Windows95) [2]. Along with our prototype system, we used a CAD system (Auto Sketch by AutoDesk Inc.) and an OO-based drawing system (Smart Sketch [131]). The CAD system is used as a representative for precise geometric design systems, and the OO-based editor is selected as a representative for easy-to-use rapid drawing editors.

Task

Subjects were required to draw three diagrams shown in Figure 25 using the editors. They were instructed to 1) draw as rapidly as possible, satisfying the required geometric relations as much as possible, 2) to quit drawing when drawing time exceeds the limit of 5 minutes, and 4) give the completion of drawing priority over the complete constraint satisfaction, if it appears to be too difficult.

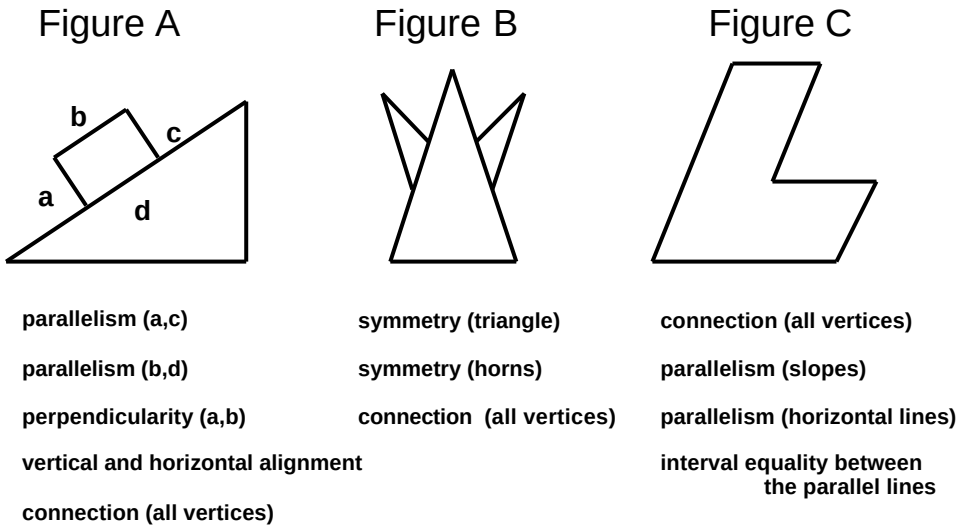


Figure 25. The diagrams used in the experiment, and required geometric relations.

Subjects

18 student volunteers served as subjects in the experiment. They varied in their proficiency in using computers and each software. 8 subjects were accustomed to typical window-based GUIs, but other subjects had little experience with computers.

Procedure

To avoid the effect of learning, the order of editor usage was changed for each subject in a balanced way. The experiment consisted of 18 (subjects) × 3 (systems) × 3 (diagrams) = 162 diagram drawing sessions in total. Each session lasted less than 5 minutes and they were video-recorded and examined later.

Prior to performing the experiment with each system, each subject was given a brief explanation of each system and a practice trial. This tutorial session lasted 5 - 10 minutes varying among systems and subjects. The CAD system generally required more

tutorial time than the others.

4.3.3.2. Result and discussion

Rapidness

Figure 26 shows the time required for each subject to complete each task. Each column corresponds to a drawing session of a subject. The order of subjects is sorted by the drawing time. As the drawing time was limited to 300sec., drawing sessions which exceeded the limit are indicated as 300sec. The time required with the prototype system was clearly shorter than with other systems, and all sessions finished within the limit, while many sessions exceeded the limit with the CAD system and the OO-based drawing editor.

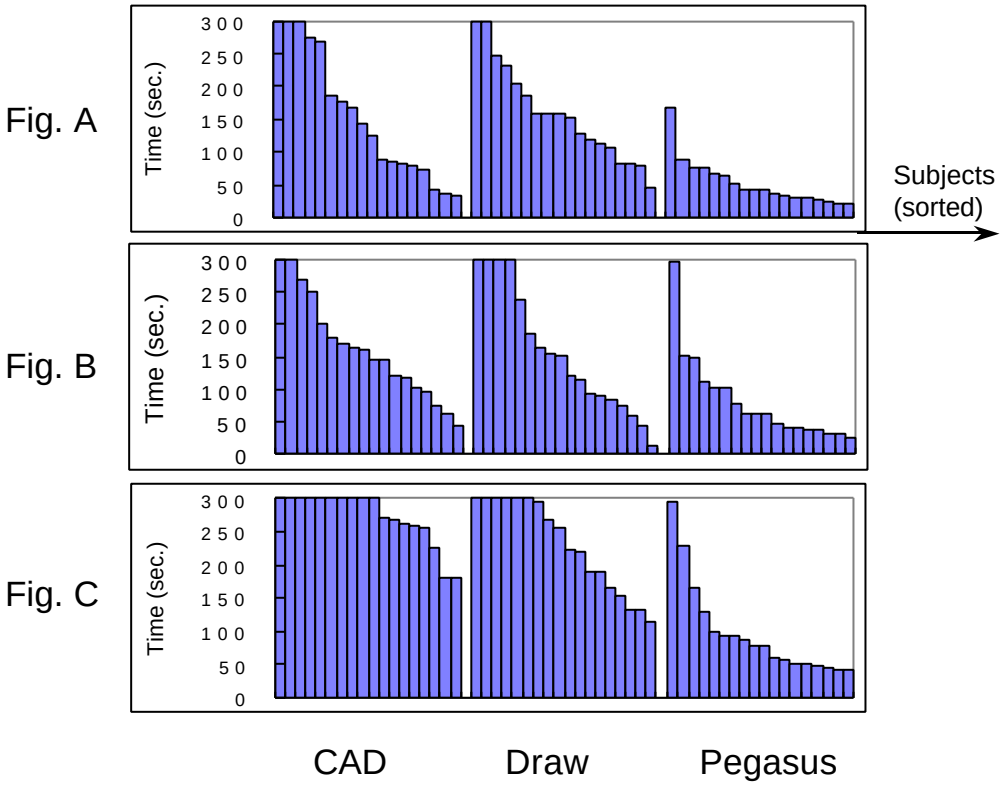


Figure 26. Drawing time required for each task.

Each column corresponds to a drawing session of a subject.
The order of subjects is sorted by the time required.

Figure 27 shows how many sessions finished within the limit. Many subjects failed to finish drawing tasks within the limit using the CAD system and the OO-based editor, while all subjects finished drawing using our prototype. Whether the required constraints are precisely satisfied or not is not considered in this graph.

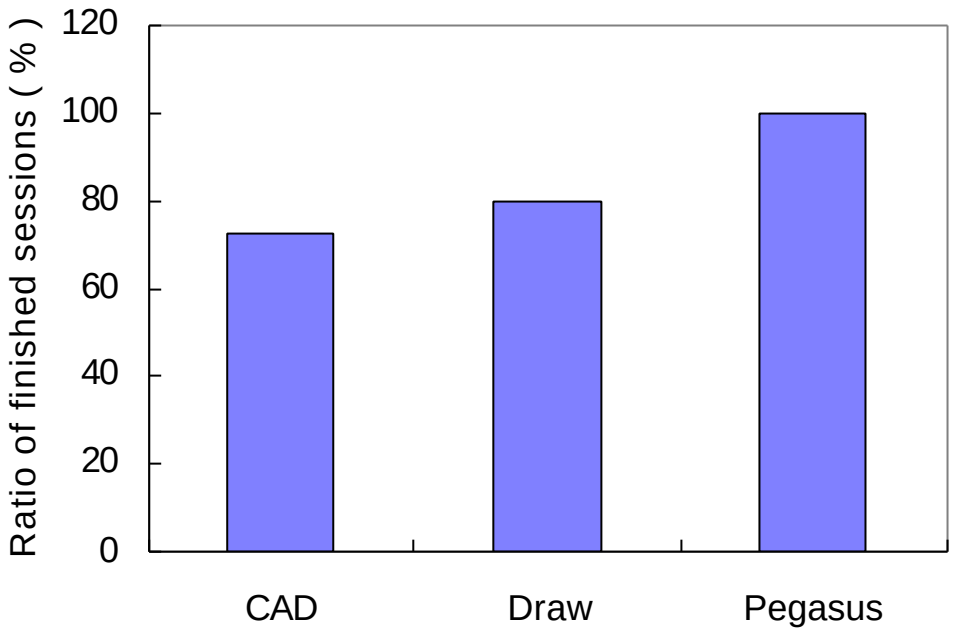


Figure 27. The ratio of finished sessions.

This figure shows in how many sessions subjects finished drawing within 300sec. among each $3 \times 18 = 54$ sessions.

It is impossible to calculate the exact mean drawing time and the mean variance because the recorded drawing time was limited to 300sec., but Figure 28 gives an approximation of the mean drawing time. Drawing time is averaged for each diagram-editor combination over those sessions that finished within the limit, and the averaged time for each editor is summed to estimate "total drawing time for a subject to draw three diagrams on each editor." According to the calculations, subjects were able to draw the three diagrams at least 48 % faster than the OO-based editor and 54 % faster than the CAD system. As the averages do not include sessions exceeding 300sec., the actual differences are greater.

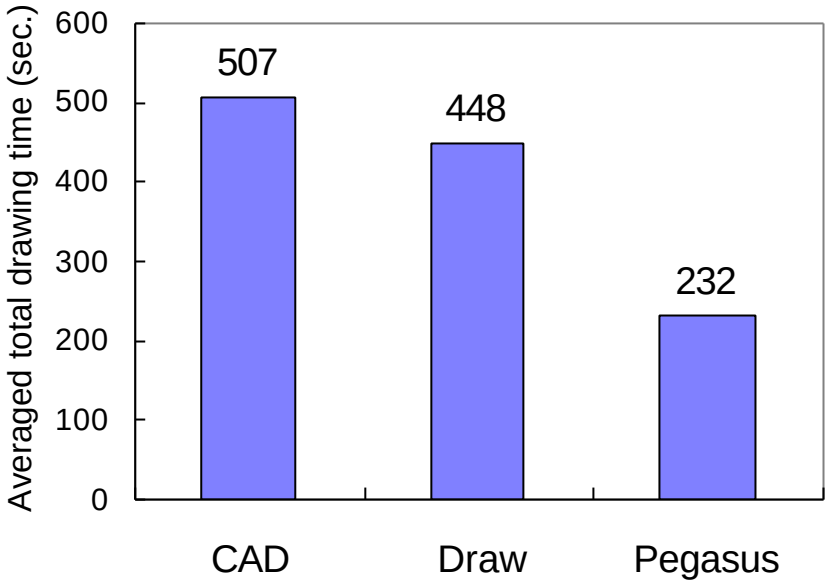


Figure 28. Estimation for time required for a subject to draw the three diagrams.

The prototype system exhibits considerable advantage.

Precision

Even if task performance time might be improved, the benefit could be nullified if the precision of the resulting diagrams is considerably worse. Figure 29 shows how many sessions finished satisfying *all* the required geometric relations shown in Figure 25. The sessions where the subjects finished drawing within 300sec. but failed to satisfy the required geometric relations completely are not counted. It is interesting to see that the OO-based system is superior to the CAD system in time performance, but the opposite holds true concerning the precision, which is in accordance with the natural expectation. Our prototype system showed better performance in both criteria than either the CAD or OO-based system.

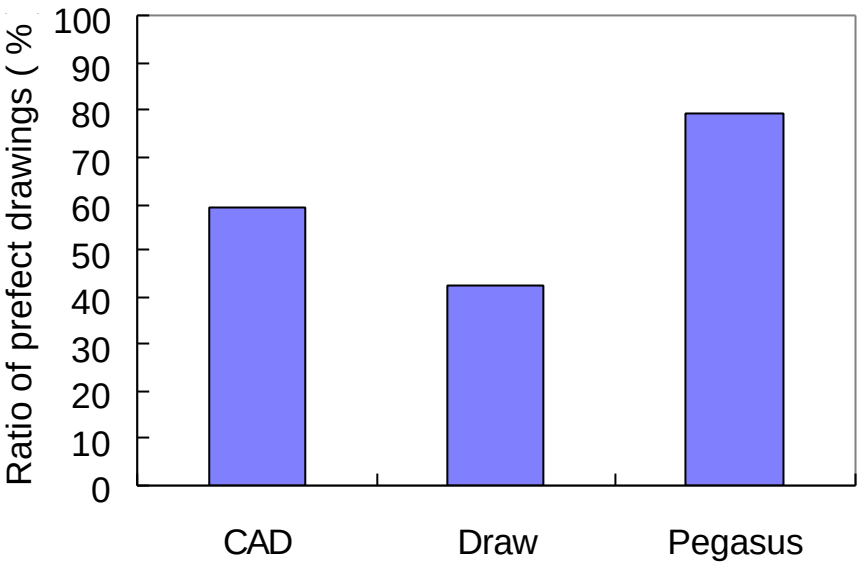


Figure 29. The ratio of diagrams where required constraints are perfectly satisfied. This graph shows in how many sessions subjects successfully satisfied all the required geometric constraints among each $3 \times 18 = 54$ sessions.

We must note, however, that this experiment is still a preliminary evaluation. Many important aspects of diagram drawing are not accounted for, such as line pattern variation, scaling, rotation. Curves, circles, and text did not appear in the diagrams. Also, various kinds of diagrams must be considered, such as node-link diagrams, informal illustrations and complex mechanical diagrams. In spite of these limitations, this preliminary experiment clearly shows a promising potential of the interactive beautification system, particularly its significant advantage in rapid and precise construction of simple geometric diagrams. Time performance and constraint satisfaction rate were considerably improved, even though interactive beautification is rather new for the subjects compared with other systems.

4.4. Predictive Drawing

Geometric illustrations often contain numerous identical local configurations. `Duplicate` command is used in existing drawing editors to generate identical configurations. By contrast, by using interactive beautification, duplication is *implicitly*

achieved by drawing a similar sketch. Predictive drawing mechanism further assists the construction of identical configurations actively. If the user draws a line segment whose shape is identical to some existing segment, the system automatically predicts that the user may draw similar segments around the newly drawn segment. The predicted segments are displayed on the screen, and the user can select one by tapping on it if it happens to be the intended segment.

In the following subsections, we first describe the behavior of predictive drawing from the end user's point of view, and then describe its algorithm using several examples.

4.4.1. User Interface

Predictive drawing mechanism works in combination with interactive beautification. We describe how predictive drawing works from the user's point of view using the example shown in Figure 30. In the figure, thick lines indicate line segments added to the scene most recently, and gray line segments indicate predicted segments.

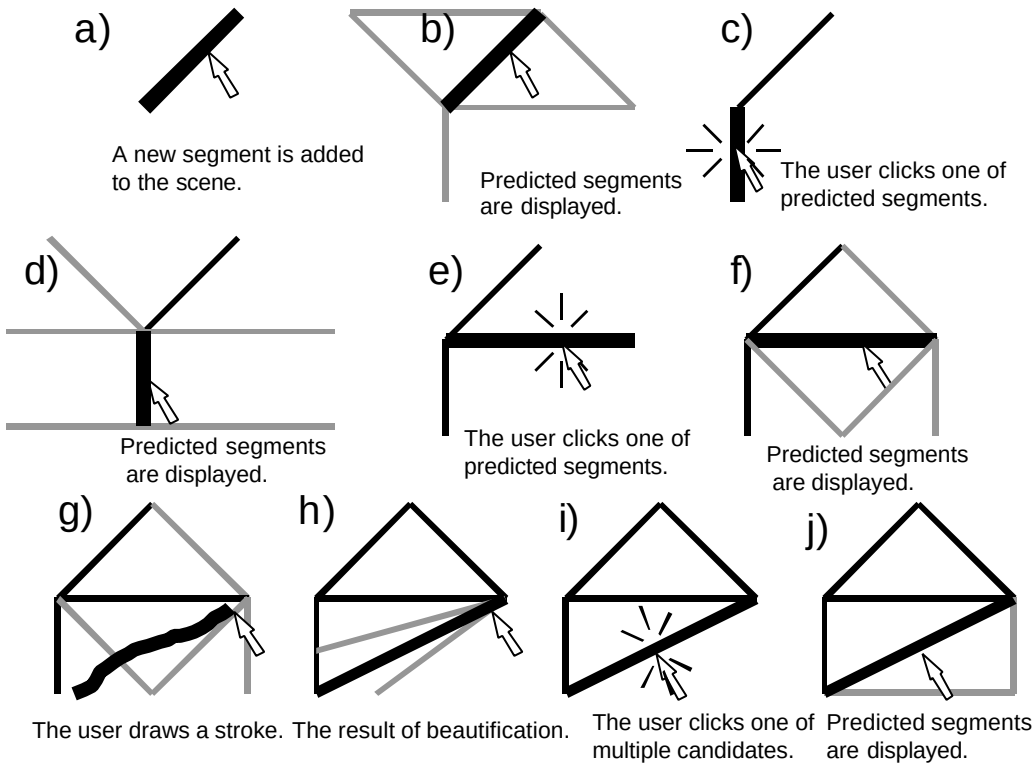


Figure 30. Predictive drawing: the user's view.

1. A new segment is added to the scene as the result of interactive beautification or predictive drawing (Figure 30a).
2. The system predicts the next drawings and shows them (*predicted segments*) around the newly added segment (*trigger segment*) (Figure 30b).
3. User can click a predicted segment to add it to the scene (Figure 30c).
4. The selected segment now works as the new trigger segment, and next drawings are predicted (Figure 30d).
5. The user can continue drawing operation by repeating step 3 and 4 (Figure 30e,f).
6. If the user does not like any of the predicted segments, he draws desired segment using a freeform stroke to switch to interactive beautification process (Figure 30g-i).
7. Predictive drawing restarts when a new segment is added to the scene (Figure 30j).

The most important feature of predictive drawing is that the user can construct various drawings just by successive clicks as long as prediction succeeds. It is also important that the user can smoothly switch to interactive beautification process when prediction fails. As the result of these implicit invocation and termination of prediction, it augments interactive beautification without imposing additional input. The user can also start prediction by clicking existing segment in the scene (Figure 31). In that case, the system generates candidate segments around the clicked segment.

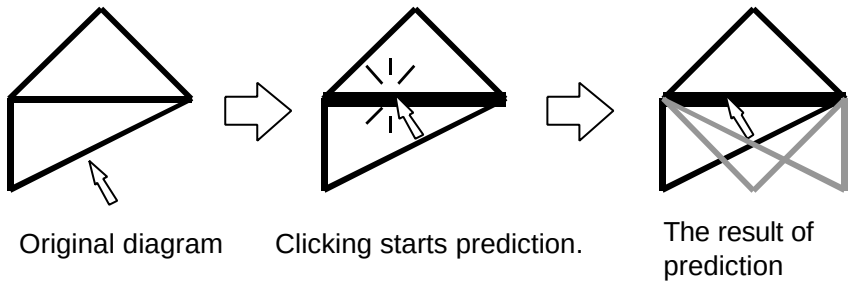


Figure 31. Starting prediction by clicking an existing segment.

4.4.2. Algorithm

We describe the algorithm we use in the current implementation. However, this algorithm is independent of the interface described in the preceding subsection, and it is possible to use various algorithms other than this particular example.

This algorithm is based on the following simple idea: when the user draws a new segment that is identical to a part of some existing diagram, he may want to draw similar diagrams around the new segment. Specifically, the algorithm works as follows (Figure 32)

1. When a new segment (trigger segment)(**g**) is added to the scene, the system searches for the existing segments (reference segments)(**a**) whose length and angle are identical to the trigger segment.
2. The system records the spatial relationships among the reference segments and the segments (context segments)(**b,c,d**) directly connected to the reference segments.
3. The system generates predicted segments(**h,i,j**) around the trigger segment in such a way that the relation between each predicted segment and the trigger segment is identical to that of the context segment and the reference segment.
4. The user clicks a predicted segment (**j**). **i** and **n** is generated because **j** is identical to **d**. **k,l,m** are generated because **j** is identical to **d**.

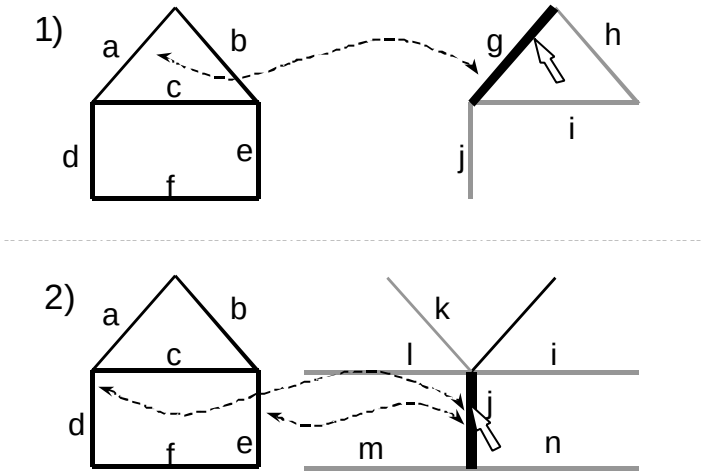


Figure 32. The algorithm of predictive drawing.

In this way, the user can duplicate an independent diagram, and can draw repetitive diagrams by successive clicking.

In addition, the system automatically supports the construction of symmetric diagrams and rotated diagrams by adding flipped and rotated segments to the reference segments (Figure 33). **e** and **f** are predicted because **d** is horizontally symmetric to **a**. **h** and **g** are predicted because **d** is vertically symmetric to **a**. **j,k,l**, and **m** are predicted because **i** is

±90-degree rotation of **a**. **p** and **q** are predicted because **n** is identical to **a,** while **r** and **q** are predicted because **n** is 180-degree rotation of **a**.

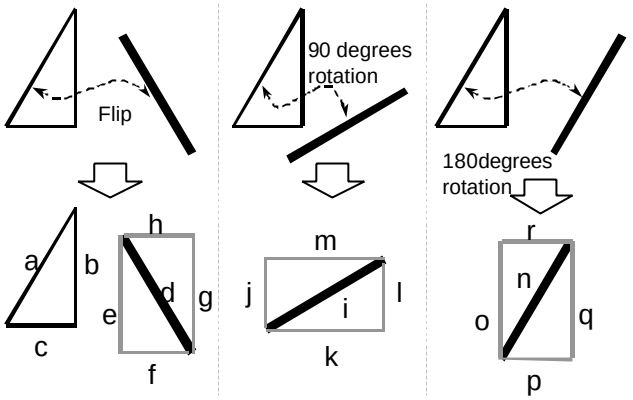


Figure 33. Extension to the basic prediction.

It is also possible to use the newly added segment (target segment) itself as a reference segment (Figure 34). In this case, It is not necessary that reference segments exist in the scene beforehand.

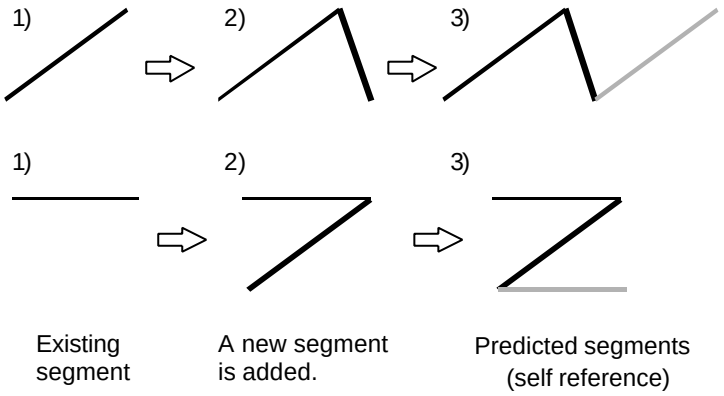


Figure 34. Prediction based on self reference.

In the actual drawing process, multiple segments in the scene matches as reference segments, and many candidate segments are generated as predicted segments. Figure 35 shows how the user draws repetitive diagram and symmetric diagram using this prediction mechanism.

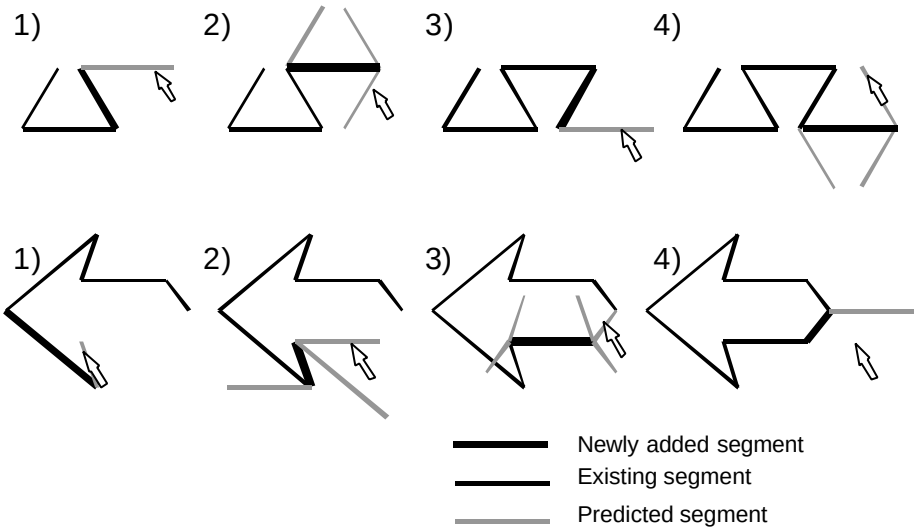


Figure 35. Construction of various diagram using prediction.

4.5. Prototype System Pegasus

The prototype system, Pegasus, was first developed under Microsoft Visual Basic and Visual C++ on Windows 95. The user interface part of the code that manages the input operations and visual feedback was written in Visual Basic for ease of implementation and frequent revision. The beautification routine was written in Visual C++ in order to accelerate the most time consuming process. Recently, we ported the entire program to Java™ to add miscellaneous features such as zooming, and opened it to the public as a Java applet at www.mtl.t.u-tokyo.ac.jp/~takeo/java/pegasus/pegasus.html.

Pegasus can work on any computing environment that supports Java 1.1. However, as Pegasus is basically designed for pen-based input, Pegasus is developed and tested mainly on portable pen computers (Mitsubishi AMiTY SP) and pen-based electronic blackboard system (Xerox Liveboard). As pen-based freeform stroke input and mouse based freeform stroke have considerably different characteristics, the preprocessor of the recognition algorithm needs to be tuned to some degree to be used with mouse based input.

We show some of pictures that have been produced with Pegasus. Figure 36 implies the usage of the technique in classrooms. Menu-based operations have prevented the use of precise diagrams on electronic whiteboard systems during verbal communication, but the simplicity of interactive beautification may encourage the use of more precise

diagrams. Figure 37 shows 3D illustrations. The construction of these diagrams is achieved using parallelism and congruence among segments. It is notable that these diagrams are easily constructed using simple 2D constraints, instead of some special techniques for 3D models. Figure 38(left) shows an example of geometric design. Figure 38 (right) gives an example of symmetric illustration. As horizontal symmetry is achieved without any additional operation, a designer can concentrate on *design* itself, instead of struggling with complex operations.

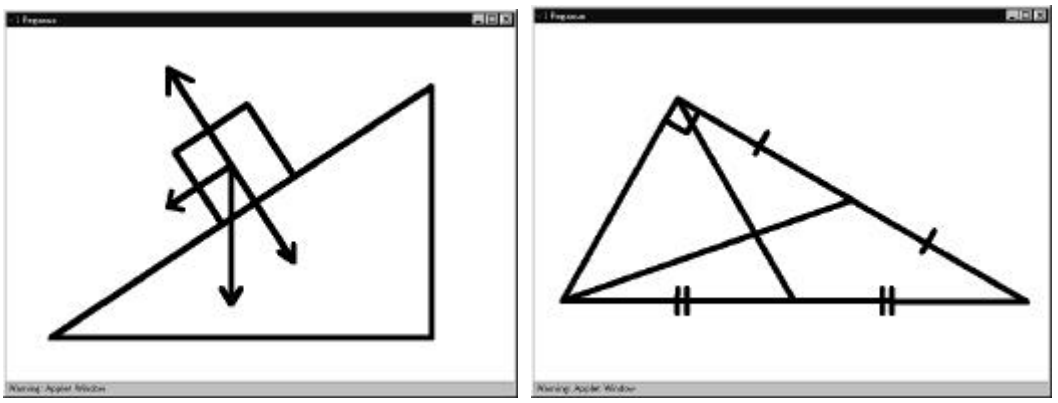


Figure 36. Diagrams for Physics and Mathematics.

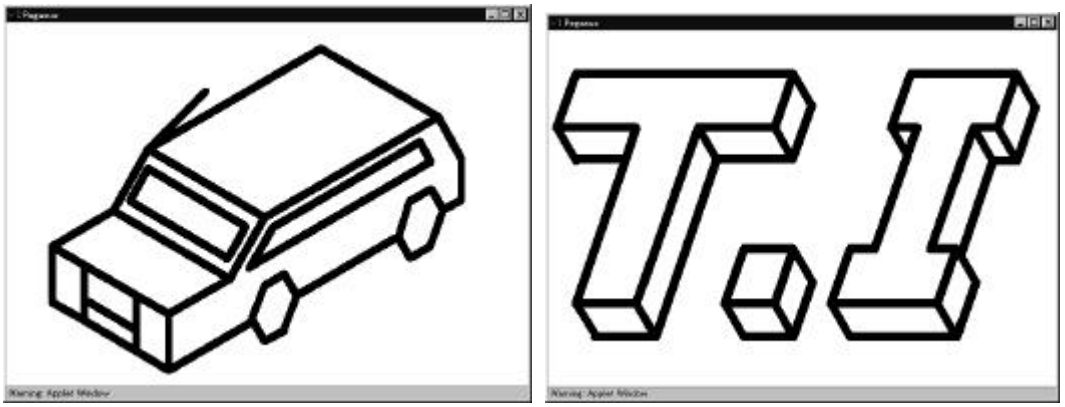


Figure 37. 3D Illustrations.

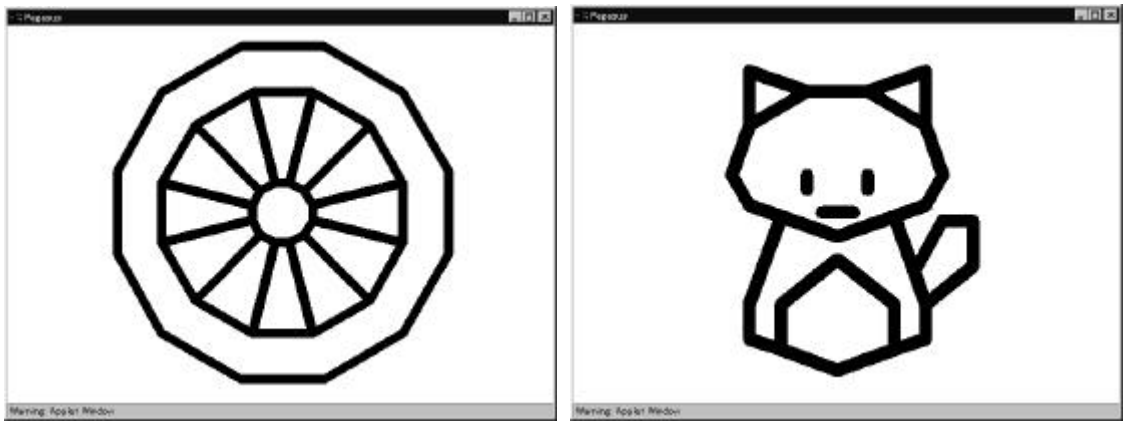


Figure 38. Geometric Illustrations.

4.6. Limitations and Future Work

A unsolved problem with interactive beautification and predictive drawing is that it is difficult to select the intended candidate among many overlapping candidates. This problem becomes serious when one draws complex diagrams. Possible solutions are to reduce the number of generated candidates and to improve the user interface for candidate selection.

The number of candidates can be reduced by restricting the number of inferred constraints in the constraint inference module and the number of valuations in the constraint solving module, and removing the unwanted candidates in the evaluation module. Various heuristics and user adaptation may be required to find intended constraints and candidates.

Improvement of the user interface is also required. One solution is to magnify the cluttered region to help the user to distinguish the desired one from the others. Another technique is to let the user specify the reference segment and display those candidates that satisfy constraints related to the specified reference segment.

We plan to implement curves, text, and line pattern variations to see whether interactive beautification can work as an established interaction technique. Implementation of arcs and curves give rise to various difficulties, but is strongly desirable because satisfaction of curve-related constraints is especially difficult with

conventional menu based editors.

We would like to perform more user studies to answer various questions: what kinds of constraints are required for rapid geometric design, how fast users can master the effective use of the technique, and to what extent the generation of multiple candidates facilitates the interaction, etc.

Integration of interactive beautification into 3D scene construction systems such as [161] is also being considered. The most challenging issue may be how to *display* half-constructed 3D models and multiple candidates without confusing the user.

4.7. Conclusion

We have proposed *interactive beautification* and *predictive drawing*, techniques for rapid geometric design. Interactive beautification receives a freeform stroke and converts it into a precise segment. The technique is characterized by stroke-by-stroke beautification, recognition of global geometric constraints, and generation and selection of multiple candidates. Predictive drawing predicts the user's next drawings automatically based on the spatial relationship among the segments on the canvas. These techniques support *precise* geometric design preserving considerable *dexterity*. Our prototype system, *Pegasus*, is implemented on pen computers, and user evaluations showed promising results.

This technique can be used for geometric modeling on traditional CAD systems, but more informal, simple drawing using pen-based input seems to be the most promising target. To be specific, interactive beautification and predictive drawing appear to be an ideal technique for note-taking on pen-based PDA systems and graphical explanation on electronic whiteboards during meeting or in classrooms. Finally, these techniques can be used to support creative design processes [72], which has been done with traditional pen and paper rather than on computers because of complex operations.

Chapter 5

Path-drawing for Virtual Space Navigation

This chapter introduces an interaction technique for walkthrough in virtual 3D spaces, where the user draws the intended path directly on the scene, and the avatar automatically moves along the path. The system calculates the path by projecting the stroke drawn on the screen to the walking surface in the 3D world. Using this technique, the user can specify not only the goal position, but also the route to take and the camera direction at the goal with a single stroke. A prototype system is tested using a display-integrated tablet, and experimental results suggest that the technique can enhance existing walkthrough techniques.

5.1. Introduction

Efficient 3D navigation techniques are required to meet the increasing popularity of virtual spaces. Existing walkthrough techniques can be divided into roughly two categories. One is *driving*, where the user continuously changes the camera position using advancing and turning buttons (arrow keys, joysticks, or button widgets on the screen). The other is *flying*, where the camera automatically jumps to the goal position that the user had specified using a pointing device [78]. Driving is commonly used for computer games, but can cause unwanted overhead when the walking is not the primary purpose of the interaction, because the user has to continuously press buttons during the movement. This problem gets serious especially when the rendering speed is slow, which is often the case with current desktop VR on PCs. Flying provides a solution to the problem, freeing the user from continuous control. All the user has to do is to click the target, then he can arrive at the target position instantly. However, flying suffers from its limited expressive power. The user cannot specify which route to take during

the movement, nor can he control the orientation of the camera directly.

5.2. Path drawing for 3D walkthrough

We propose a *path drawing* technique [62] for 3D space navigation, which is an extension of the flying technique. It allows the user to draw the desired walkthrough path directly on the screen using a free stroke. Then, the system automatically calculates the moving path in the 3D world by projecting the stroke onto the walking surface, and presents the movement of the avatar and the camera in an animated manner. The avatar's direction is fixed to the tangent of the projected stroke. The user can draw a new stroke during the movement to modify the path, which is important because the far end of a stroke can easily get out of control. Figure 39 illustrates an example of path drawing navigation.

The user can draw either a long stroke specifying the detailed intermediate route to follow, or just a short stroke near the goal position. Long strokes are useful when the user is interested in how to get to the target position, while the user can conveniently specify the goal position and camera direction at once using short strokes. The user can also *turn* at the current position by drawing a short stroke at his foot in the intended direction.

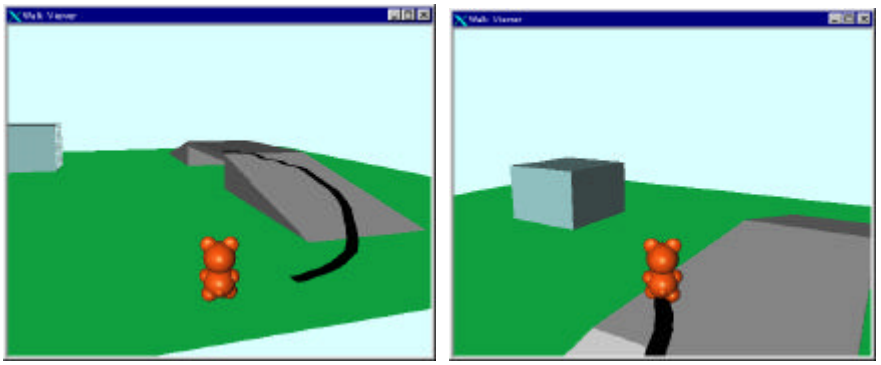


Figure 39. An example of path drawing walkthrough.

The user draws the desired path directly on the screen (left), and the avatar and camera move along the projected path (right).

This technique can work more effectively when the system is given a detailed structure

of the virtual space. For example, it is possible to achieve the automatic avoidance of obstacles when the direct projection of the user's stroke intersects the obstacles [108,158]. Climbing slopes and going through a gate can be detected by checking the polygon connectivity along the projected path (Figure 39).

A prototype system is developed using Inventor 2.1 on SGI graphics workstations. Automatic obstacle avoidance, slope climbing, and gate through are implemented and tested. However, these additional functions are turned off during the following evaluation.

5.3. Evaluation

5.3.1. Task

An experiment is performed to clarify the characteristics of path drawing against driving and flying techniques. Twelve subjects (computer science researchers) participate the study. Their expertise in 3D interaction is varied. Subjects are instructed to get to the specified goal as rapidly as possible, navigating through a virtual space while avoiding obstacles. Figure 40 shows the map of we used in the study. During the navigation, the camera is fixed just behind the avatar (Figure 41), and the avatar stops when it collides with an obstacle while traversing.

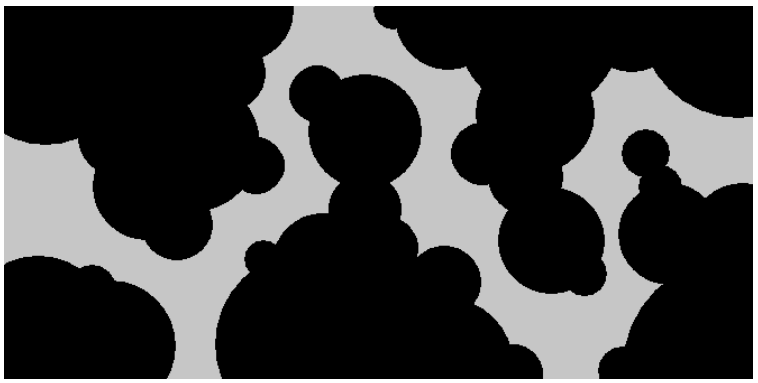


Figure 40. The world map used in the experiment.

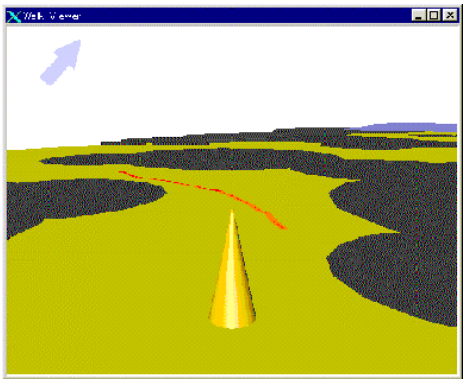


Figure 41. An example of subject's view in the experiment.

The subjects perform the task under the following six conditions, in a balanced order. Each subject performs the task in each condition for three times (which means that a subject performs the task 3×6=18 times in total). A standard keyboard is used for "driving", while a display integrated tablet is used for "flying" and "drawing".

1) Driving (fast): the user controls the avatar using arrow keys. The left and right keys correspond to turn operations. Each movement occurs every 0.1 sec. (assumed to be the best setting). The subjects were allowed to move and turn simultaneously.
2) Flying (animated): the user clicks the intended position directly, and the avatar smoothly moves toward the target in an animated manner. The moving speed is identical to that in 1). If an obstacle exists between the current position and the target position, the avatar stops in front of the obstacle.
3) Drawing (animated): the avatar moves along the drawn path in an animated manner. The speed is identical to that in 1). If an obstacle exists on the path, the avatar stops in front of the obstacle.
4) Driving (slow): The same condition as 1), except that the each movement occurs every 0.2 sec.
5) Flying (no animation): flying without animation. The avatar instantly jumps to the target position after a click. If an obstacle exists between the current position and the target position, the avatar stops in front of the obstacle.
6) Drawing (no animation): path drawing navigation without animation. The avatar's position and direction change instantly to the final state. If an obstacle exists on the path, the avatar stops in front of the obstacle.

First three conditions are designed to simulate normal navigation set-up. Last three

conditions are designed to simulate special condition where the screen rendering speed is extremely low because of poor computer performance or slow network connection. In this condition, driving technique requires constant control throughout the slow movement, which is significantly frustrating. Flying and drawing techniques use alternative “instant jump” technique to achieve efficient move in this condition.

5.3.2. Result

Figure 42 shows the averaged elapsed time to get to the goal. A subject performed the task three times each, and the fastest among the three was selected and averaged. Among the first three conditions, driving is the fastest and drawing is the slowest (statistically significant ($p<0.05$)). Among the last three conditions, flying and drawing are significantly faster than driving ($p<0.05$). There is no significant difference in flying and drawing.

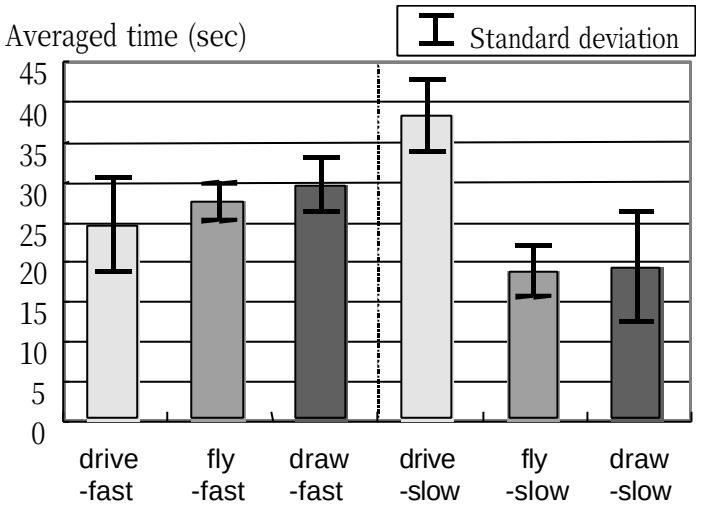


Figure 42. Averaged time to get to the goal.

Figure 43 shows the users’ subjective evaluation of each technique. Subjects gave relative scores ranging from 1 to 5 depending on the extent they like each technique as a general navigation technique. Drawing exhibits the highest scores in both fast and slow condition. Flaying technique in slow condition gets the lowest score.

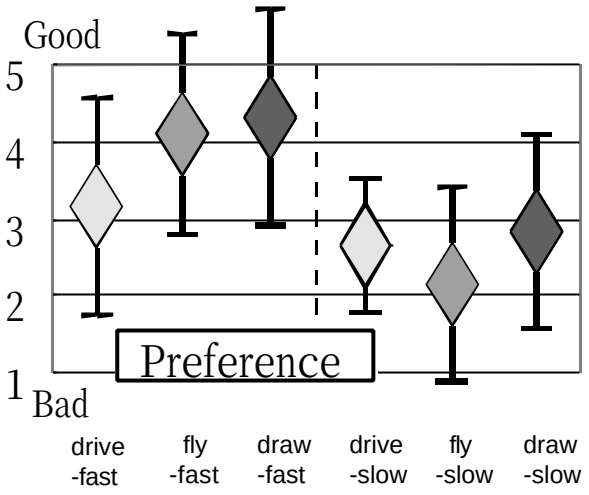


Figure 43. Subjective evaluations.

5.3.3. Summary

In the first three conditions, drawing and flying were slower in performance, but they got higher scores in subjective evaluations. This result suggests that drawing and flying can be optimal solutions in applications where the user's satisfaction has priority over efficiency, such as entertainment applications.

In the last three conditions, drawing and flying significantly improved the performance. Drawing and flying rendered the screen approximately 1/8 times of that in driving during the task. Rendering speed can be much slower in some computing environments, and this result suggests that drawing and flying can be a good solution.

Drawing and flying showed similar results in general. This is not surprising because drawing is an extension of flying. To be precise, drawing was slower a little in performance, but it showed better scores in subjective evaluations. Especially, the result suggests that drawing can improve the user's satisfaction when the rendering speed is not enough.

5.4. Discussion

Path drawing can be used with any pointing device, but is most suitable for a pen-based or touch panel system. It is also possible to use this technique in immersive VR environments with HMD and data gloves, where the user draws the path using the finger [40,109].

A limitation of path drawing is that it cannot be directly applied to completely free 3D movements (not constrained to a walking surface). However, path drawing is expected to be applicable to most applications because human activity in real world is constrained on 2D walking surface. A surface with small ups and downs or stairs can be handled by path drawing technique without any additional complications.

Another limitation is that the avatar must be present on the screen in order for a path to be drawn at the avatar's feet. However, this problem may not be so serious because path drawing can naturally coexist with flying and driving in real applications. The user can press arrow buttons or keys to move to a near target.

5.5. Conclusions and future work

We presented a technique for 3D virtual space walkthrough, in which the user specifies the intended path by drawing a free stroke on a virtual walking surface on the screen. This technique is superior to conventional *driving* in that the user does not have to continuously control the movement, and enhances *flying* by letting the user specify the route and direction at once. Experimental results show that the technique can be a good alternative at least for some users, improving subjective evaluation while maintaining a comparable operation speed.

Path drawing navigation is useful especially when the rendering speed is low or the communication delay is large, because the user can give detailed instructions to the computer at once, and the system can take time to perform time-consuming operations. We plan to apply this technique to remote robot control and wheelchair navigation [136], where the user draws strokes on camera images

Chapter 6

Stroke-based Architecture for Electronic Whiteboards

This chapter describes the software architecture for our pen-based electronic whiteboard system, called Flatland. The design goal of Flatland is to support various activities on personal office whiteboards, while maintaining the outstanding ease of use and informal appearance of conventional whiteboards. The GUI framework of existing window systems is too complicated and heavy-weight to achieve this goal, and so we designed a new architecture that works as a kind of window system for pen-based applications. Our architecture is characterized by its use of freeform strokes as the basic primitive for both input and output, flexible screen space segmentation, pluggable applications that can operate on each segment, and built-in history management mechanisms. This architecture is carefully designed to achieve simple, unified coding and high extensibility, which was essential to the iterative prototyping of the Flatland interface. While the current implementation is optimized for large office whiteboards, this architecture is useful for the implementation of a range of various pen-based systems.

6.1. Introduction

Office whiteboards are one of the most common tools in a personal working environment. People use whiteboards to take notes, organize to do lists, sketch paper outlines, and as a communication medium for discussions with office mates. In general, people use office white boards for informal, unstructured activities in contrast to well-organized activities on desktop computers [94].

Based on our observations, we are currently developing a computationally augmented

office whiteboard, called Flatland (Figure 44) [95]. Our research goal is to provide computational support such as storage, calculation, networking, and diagram beautification, while preserving the physical whiteboard's lightweight interaction style and informal appearance. We envision that these enhanced whiteboards will support informal activities that are difficult on current desktop computers. Our current hardware configuration is a touch sensitive large board (SMART Board [130]) and a LCD projector.

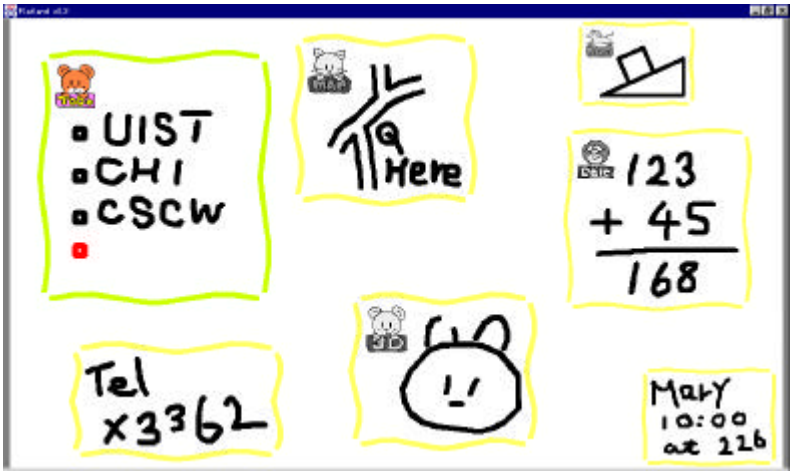


Figure 44. Flatland example.

In this chapter, we introduce the user interface and implementation of Flatland in detail. We introduce our new software architecture to support various stroke-based operations, and describe how our example applications are implemented on the architecture. This architecture can be seen as a variant of Kramer's representation-based architecture [70]. While the current implementation is optimized for electronic whiteboard systems with large physical surfaces, our architecture is applicable to various pen-based systems such as small hand held PDAs, display-integrated tablet systems, and huge wall size interfaces.

The software architecture we present is analogous to a pen version of GUI-based window system for desktop computers. Both divide the screen into several regions (windows in standard window systems and *segments* in Flatland) to provide independent workplaces. Both have mechanisms to support task specific activities within the region (applications and *behaviors*). The difference is that our target is informal, pre-production activities while existing window systems are designed for

well-structured, goal-oriented activities. To be specific, we observed the following design requirements, which led us to our unique architecture.

First, the user's input must be simple, and the system's output should be informal to encourage lightweight interaction. Standard window systems support a variety of operations such as typing, clicking and dragging, but these are too complicated for informal interaction. Likewise, their rectilinear widgets and printed text discourage pre-production activities. In order to provide the appropriate look and feel of real whiteboards, Flatland uses a unified notion of "strokes" for input and output. The user input is always in the form of handwritten strokes, and system feedback is given as a set of "handwriting style" strokes.

Second, informal activities on a whiteboard are dynamic: the structure of the drawings on the board can change over time, and each drawing can serve different purposes depending on the situation. This is quite different from well-organized, goal-oriented activities on desktop computers, and the traditional notion of static windows and applications turned out to be inappropriate. This observation led to two important design decisions: *dynamic segmenting* and *pluggable behaviors*.

Users do not have to decide on the organization of their board before they start working. They can simply pick up a pen and begin writing. The system will use heuristics to try to group strokes into segments as needed, and users can flexibly override the system's behavior by joining and splitting segments as desired. Likewise, behaviors—code that supports the semantics of a particular domain or application—can be flexibly attached to or removed from the segment on the fly. So a user can write a "to do" list on the board and then later apply a behavior to cause the strokes to begin to "act like" a to do list. Other behaviors could be applied to the same strokes over the lifetime of the segment. This flexible relationship is quite different from static, persistent relationship between windows and applications in standard window systems.

Finally, drawings on whiteboards can persist for a significantly long time and can be continuously changing. Additionally, each "chunk" of information on a board can be significantly small compared with a document in a desktop environment. Traditional file based open-edit-close style document management causes too much overhead to maintain this fine grained, ever-changing information. So instead, Flatland is equipped with automatic backup mechanisms and allows the user to recover the drawing at any

time in the past. This history maintenance mechanism actually records every event occurring on the board, and thus influenced the design of entire architecture.

The rest of the paper is organized as follows. After discussing related work, we briefly introduce how Flatland works from the user's point of view. Then we describe the overall architecture of the system in detail. Finally, we briefly note some implementation issues, and discuss limitations and implications of our architecture.

6.2. Related Work

This work is closely related to Kramer's seminal work on dynamic interpretations [69,70]. He introduced the idea of dynamic association between representation and internal data structure in the context of electronic whiteboards. He allowed the user to apply different interpretations (applications) to the same marks (freeform strokes on the screen). His goal was to capture the ambiguous nature of design activities.

We share basic ideas and research goals with him. The contribution of our work is to extend and complement his work. While he established the framework for the representation-centered architecture, we address various implementation issues with more details and introduce a variety of example applications. To be specific, we discuss how a stroke-oriented architecture enables flexible screen real-estate control and efficient history management.

Pen-based computing has become an active research area recently. In addition to research and commercial work on handwriting recognition, much work has been done on efficient text input methods [106] and gesture recognition [48]. Many systems use a pen-based sketching interface to encourage creative activities: SILK [73] uses it for GUI design, MusicPad [39] uses it for music composition, SKETCH [161] and Teddy [63] use it for 3D modeling. Pen-based techniques are commonly used on electronic board systems [43,112,118], with specialized interfaces designed for large boards. For example, a series of papers on the Tivoli system [81] proposes many interaction techniques to organize handwritten notes in meeting environment.

Although this previous work discusses the interaction techniques and specific applications for pen computers, relatively few papers discuss the software architecture

to support pen-based activities in general. Kramer's preceding papers and our work are the attempts to design software architecture suitable for hosting these pen-based applications in a unified way. In a broader perspective, Flatland can be seen as one of a group of efforts (such as Pad++ [7] and Magic Lens [11]) that explore alternative software architectures *beyond* existing GUIs.

6.3. Flatland User Interfaces

This section briefly illustrates how the Flatland system works from the user's point of view. Detailed discussion on the user interface design is found in [95].

6.3.1. Inking and Segmenting

As the very first level approximation, Flatland works just like a physical office whiteboard. The user can draw any handwritten stroke anywhere in the screen just by dragging the stylus on the surface (called *stroking*). Erasing is done by drawing a scribbling stroke with the stylus's modifier button down (called *metastroking*).

Unlike a physical whiteboard, painted strokes are automatically grouped together into clusters, which we call *segments*. Each segment is explicitly presented to the user by a boundary surrounding its strokes. When the user draws a stroke on some open space, a new segment is created for the stroke. If a stroke is drawn within or close to an existing segment, the stroke joins to the segment. If necessary, the user can also manually split or join segments (Figure 45).

To ensure visibility, segments are not allowed to overlap. The user can drag a segment by grabbing its boundary, but if the segment collides with another segment, the collided segment is pushed away. If no more space is available, the collided segment starts to shrink to give more space (Figure 46). When the user starts working on a shrunken segment, it restores its original size.

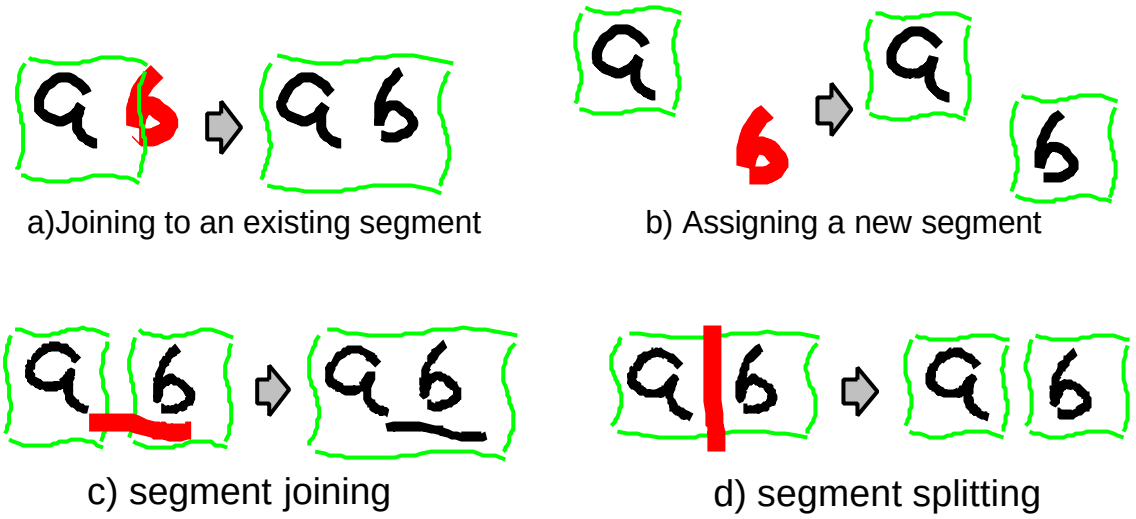


Figure 45. Segmenting.

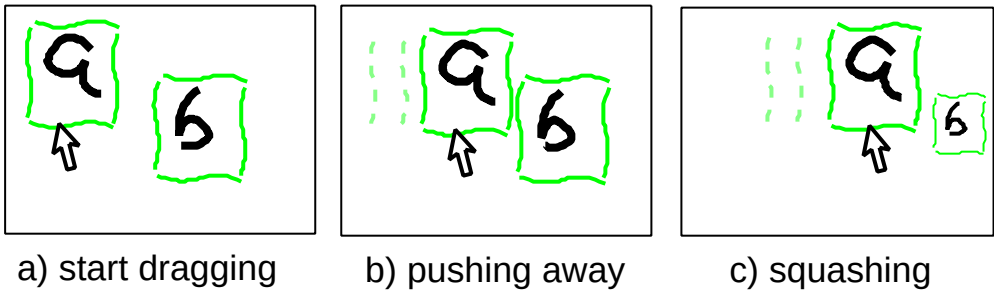


Figure 46. Moving and squashing.

6.3.2. Application Behaviors

In addition to functioning as a simple whiteboard, Flatland supports specific activities by allowing the user to attach *application behaviors* to segments. An application behavior interprets the user's freeform strokes, and gives appropriate feedback in "handwriting" style to preserve informal appearance. An active behavior is indicated as an animal figure in the corner of the segment. The following is the list of currently available application behaviors.

To do list: maintains a vertical list of handwritten items with check boxes. A new item is created when the user draws a short stroke (tap). A vertical stroke starting at a check box reorders the item, and a horizontal stroke deletes it (Figure 47).

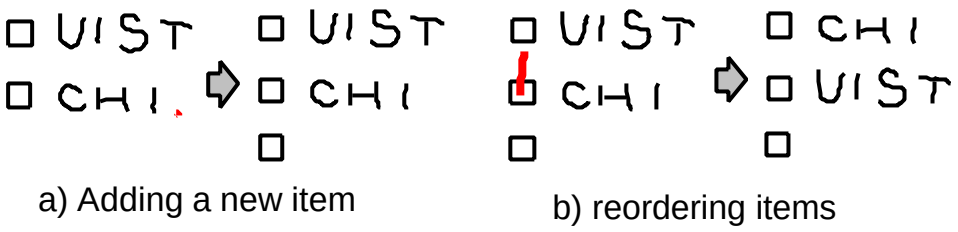


Figure 47. To Do behavior.

Map drawing: turns strokes into a double line representing a street. Intersections are handled appropriately for incoming stroke and erasing operations (Figure 48).

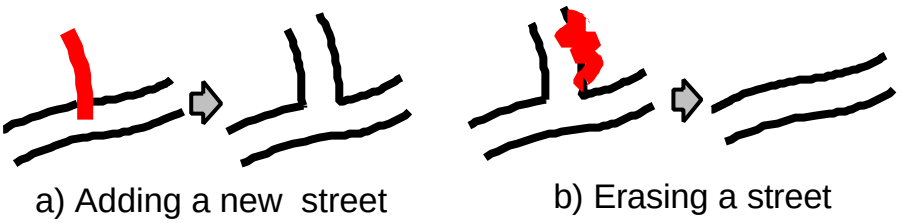


Figure 48. Map Drawing behavior.

2D geometric drawing: automatically beautifies freeform strokes considering possible geometric relations. The system generates multiple candidates as pink line segments, and the user can select a desired one by tapping on it. This behavior also predicts the next drawings based on the spatial relation among the new line segment and existing line segments [**61**]. The predicted line segments are displayed as pink line segments as well (Figure 49).

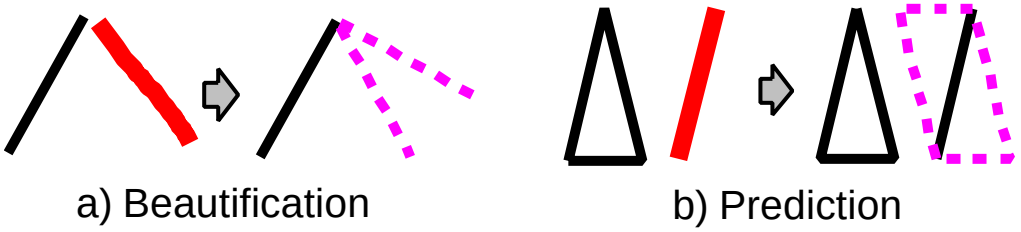


Figure 49. 2D Geometric Drawing behavior.

3D drawing: automatically constructs a 3D model based on the 2D freeform stroke input, and displays the result in pen-and-ink rendering style [**63**]. The user can rotate the model by metastroking. It also supports several editing operations such as cutting and extrusion (Figure 50).

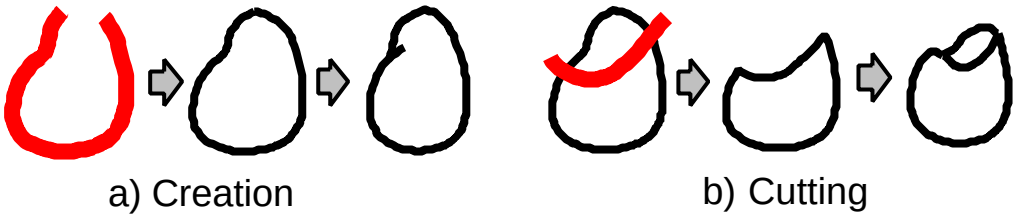


Figure 50. 3D Drawing behavior.

Calculation: recognizes handwritten formulas in a segment and returns the result of calculation. The user draws a desired formula using hand drawn numbers, and the system displays the result in handwriting style when the user draws a long horizontal line below the formula (Figure 51).

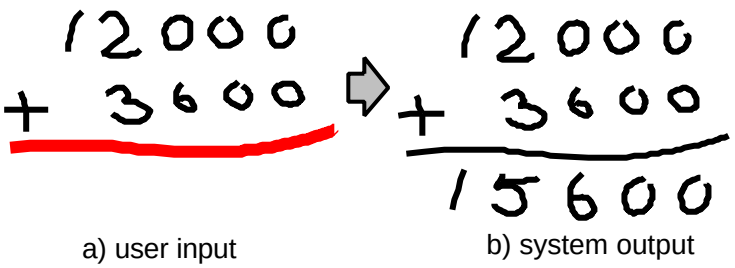


Figure 51. Calculation behavior.

Unlike application programs of standard window systems, these application behaviors can be flexibly applied to and removed from the segment, and different behaviors can be used in combination over time. For example, in order to draw a map, the user draws streets using the map behavior, draws buildings using the 2D geometric drawing behavior, and writes comments without any application behaviors.

6.3.3. History Management and Context-based Search

Another feature of Flatland is its automatic history maintenance mechanism. Every event on the surface is continuously recorded, and can be retrieved later. This mechanism frees users from explicit save operations, which are not suitable for informal activities on whiteboards.

The current implementation provides three interfaces for accessing automatically stored strokes and segments. The first is infinite undo and redo. Using undo and redo, the user can access any past state of the segment. Next is the time slider. Using the slider, the user can specify the time point directly, or use jump buttons to get to discrete "interesting" time points. Third is context-based search, which is implemented as a behavior. The search behavior allows the user to retrieve previous strokes and segments based on context information such as time, segment location, segment size and ink colors. Search results are shown as a set of thumbnails on the screen, and the user can work on the stored segment by clicking on a thumbnail.

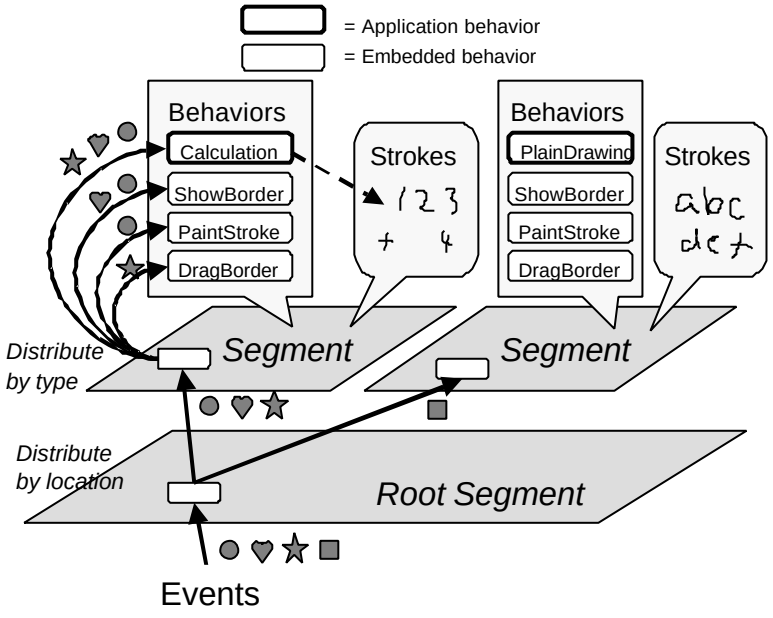


Figure 52. Overview of the Flatland architecture.

6.4. Flatland Architecture Overview

This section gives an overview of the entire Flatland architecture. Following sections describe each feature in detail.

The most basic primitive in the Flatland system is a *stroke*. The system receives user input as a stroke, and stores information as a set of strokes. All information processing in the system can be seen as manipulation of the stroke set on the screen. This simplifies the implementation, and matches the user's perceptual model of the physical whiteboard.

Strokes on the screen are grouped together based on spatial proximity, and are maintained by a *segment*. A segment allows the user to manipulate multiple strokes within the region as a group, and provides a workspace to accomplish specific tasks. Segments are different from standard windows in that they can be flexibly joined or split. Every segment is a part of the *root segment*, which handles the events that influence the entire whiteboard.

A segment delegates actual computations to *behaviors* attached to it. Behaviors respond to various events occurring on the segment, and modify the segment's stroke set or perform specific operations (such as painting). At any given time, a segment can have one "application" behavior and several "embedded" behaviors. Application behaviors provide task-specific functions and are explicitly attached to the segment by the user. Embedded behaviors provide basic services—such as inking and event storage—to the segment, and are not visible to the user. In contrast to applications of standard window systems, multiple behaviors can be attached to a segment, and a behavior can be attached or detached on the fly.

Figure 52 shows how the system maintains a set of segments, each of which holds a set of strokes and a set of behaviors[2]. When an event occurs, the root segment distributes it to a child segment, which dispatches the event to its behaviors. Then, a behavior can modify the segment's stroke set or perform other specific operations. We will see how this architecture efficiently supports each feature of the Flatland system in the following sections.

[2] In [140], strokes are called *marks* or *inks*, segments are called *patches*, and behaviors are called *interpretations*. *Properties* in [140] are handled as behavior specific internal structures in our framework.

6.5. Strokes as Universal Input and Output

Flatland is characterized by its use of strokes as a universal primitive for both input and output. The user's input always comes into the system in form of a freeform stroke (called an *input stroke*), and the system's feedback is presented as a collection of handwriting style strokes (called *painted strokes*). Since both output and input are in the form of strokes, the system is capable of using its own output as later input—we will see later some examples of behaviors that exploit this feature. In this section, we describe how input strokes are processed and how painted strokes are maintained in the Flatland architecture

6.5.1. Processing an Input Stroke

When a user draws an input stroke on a screen, the root segment first decides which segment to send it to. If the input stroke is within or close enough to an existing segment, the root segment sends the input stroke to it. If no segment is found, the system creates a new segment, and sends the input stroke to it.

The segment does not add the input stroke to its painted stroke set directly when it receives an input stroke. Instead, the segment sends the input stroke to its application behavior by calling the addInputStroke method of the behavior. It is the behavior, and not the segment itself, that adds or modifies the segment's painted strokes. This allows an application programmer to build custom application behaviors by just defining the addInputStroke method which receives input stroke from the segment, without worrying about low level events (stylus down, stylus move, etc.).

The application behavior analyzes the input stroke, and modifies the segment's painted stroke set. For example, the Calculation behavior adds multiple painted strokes showing the result of calculation when the user draws a horizontal line. The Map behavior adds two painted strokes based on an input stroke, and it also modifies the existing painted strokes to represent intersections appropriately.

When the user hasn't attached a specific application behavior, a default application behavior called *Plain Drawing* behavior is installed. This behavior simply adds each

incoming input stroke as a painted stroke to the segment's stroke set, mirroring the behavior of a physical whiteboard.

An application behavior adds a new painted stroke to the segment by calling the segment's addPaintedStroke method with the painted stroke as an argument. Behaviors can also remove an existing painted stroke by calling the removePaintedStroke method. These methods actually update the segment's stroke set, and perform some low level processing to adjust the segment size and to push away surrounding segments if necessary. Figure 53 illustrates this event processing flow.

User input based on simple pen down (stroking) is always handled as a single input stroke in this way. However, user input with the pen's modifier button down (called metastroking) is handled in the conventional button down-move-up event model, and processed variously depending on its location. Metastrokes are used to start pie/marking menus, drag/split a segment, erase a painted stroke, etc. We do not have enough space to discuss each of the metastroke operations in detail, but generally, metastrokes are processed in a similar manner to strokes: an metastroking event starts from the root segment, goes to the target segment, and is distributed to the appropriate behaviors.

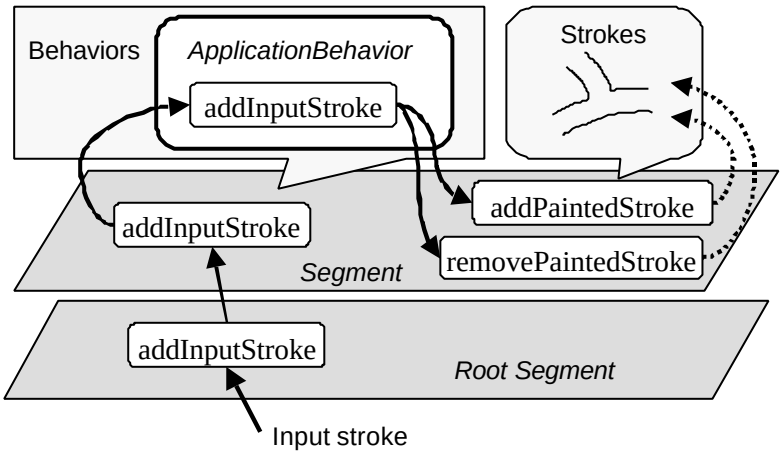


Figure 53. Input stroke processing.

6.5.2. Strokes as Universal Output

Flatland uses a stroke as the basic primitive for displaying information. In addition to directly showing the user's hand drawn strokes, system feedback is also presented in the form of freeform strokes. This decision primarily comes from aesthetic reasons to give informal appearance, but also helps simplify the entire architecture.

When an application behavior wants to give feedback to the user, it has to create an appropriate new stroke and add it to the segment's stroke set. Application behaviors are not allowed to directly paint on the screen using primitive operations such as drawText, drawLine and drawImage. For example, when the 2D geometric drawing behavior shows the result of beautification or prediction, it adds corresponding line segments in form of strokes to the segment's stroke set, instead of directly drawing lines on the screen. And the calculation behavior displays the result of calculation by adding a set of strokes representing numbers instead of drawing printed text directly on the screen.

This design has two benefits from the implementation's point of view. First, application programmers do not have to worry about low level painting operations, and they gain the appropriate informal appearance for free. Second, and more importantly, the system can recover the appearance of the board just by recording the segment's stroke set at each time point. If each behavior paints arbitrary things directly on the screen, the recovery of the screen snapshot would have to involve the behavior and could be highly complicated. We will discuss this in detail in the History Management section.

6.6. Dynamic Segmentation

The structure of drawings on a physical whiteboard is very volatile and flexible. Our dynamic segmenting mechanism is designed to capture this property. Dynamic segmenting frees the user from defining the structure of the board beforehand, and allows him or her to organize the board on the fly. Flatland segments are different from windows in a number of ways.

First, a segment is created automatically in response to the user's input stroke, while a window has to be explicitly constructed before stating interaction. Second, segments are not allowed to overlap. This results in "pushing away and squashing" effects, which allows more information to be presented while preserving visibility. Finally, segments can be dynamically merged or split.

6.6.1. Distribution of an Input Stroke

When the user draws a freeform stroke, the root segment calculates the distance between the stroke and existing segments. If the stroke overlaps or is close enough to a segment, the stroke will be send to the segment. If the stroke overlaps multiple segments, the system merges the corresponding segments, and sends the stroke to the resulting segment. If no such segment is found, the root segment generates a new segment, and sends the stroke to it.

6.6.2. Moving a Segment

The user can move a segment by making a metastroke starting at the segment's border. An embedded behavior called *Drag Border* responds to the event, and moves the segment according to the pen movement. It generates a surfaceMoved event to the application behaviors to update their internal structures. This surfaceMoved event also occurs when the segment is pushed away by another segment.

6.6.3. Pushing and Squashing a Segment

When the Drag Border behavior tries to move a segment, the segment asks the root segment for space. If any segment occupies the space, the root segment pushes it away to make space. The pushed segment then requests space for itself, and this continues until a segment is pushed against the screen boundary.
When this happens, the segment at the boundary starts to shrink to give space. When a segment shrinks, the actual coordinates of its strokes remain unchanged. Instead, the segment maintains a "scale" field, and the Paint Stroke embedded behavior renders the scaled strokes on the fly. In other words, the shrinking effect occurs only superficially. This frees application programmer from taking care of the scaling effect.

6.6.4. Merging and Splitting Segments

In order to merge segments, the root segment constructs a new segment, and calls its addPaintedStroke method using all strokes in the original segments as argument. After that, the system deletes the original segments. In order to prevent confusion, the current implementation does not allow the user to merge segments with application behaviors.

A segment is split when the user draws a splitting stroke (i.e. long vertical or horizontal line that cross the segment). This event is handled by the root segment instead of the segment that is being split. The root segment constructs a new segment, and transfer strokes one by one by calling the deletePaintedStroke method of the original segment and the addPaintedStroke method of the new segment. Again, the current implementation does not allow the user to split a segment with an application behavior.

6.7. Pluggable Behaviors

Behaviors provide a way to associate domain-specific computational processing with a particular segment. While behaviors are superficially similar to traditional applications running within windows, there are some fundamental differences.

First, a segment can have multiple composed behaviors active at a time, while a window cannot belong to multiple applications. Second, a behavior can be attached to and removed from a segment on the fly, even after the segment has been created (so users can “create first, process later”). Third, visual representation is maintained as a set of strokes by the segment, and behaviors do not directly render onto the screen (except for the Paint Stroke and Show Border behaviors).

6.7.1. Event Processing

A segment distributes a variety of events to its behaviors for them to perform appropriate action. This process is implemented based on the event listener model of the Java language. When a segment detects an event, it distributes the event to the behaviors equipped with the corresponding event listener such as SurfaceListener, StrokeListener and MetastrokeListener.

SurfaceListeners handle events related to the segment configuration. They react to changes in segment location, size, activation, and inactivation. They also react to requests for painting of the segment. Most embedded behaviors are instances of this event listener. For example, the Paint Stroke and Show Border embedded behaviors respond to requests for surface painting. Some application behaviors respond to this event to modify their internal structure.

StrokeListeners handle the incoming strokes drawn by the user. This event listener is used by application behavior to detect input strokes. MetastrokeListener handles the events related to metastrokes. The Drag Border behavior responds to this event, and some application behaviors use this event to handle specific gestures such as erasing.

6.7.2. Embedded Behaviors

Embedded behaviors are implicitly attached to the segment, and work as a part of underlying system service. It would have been possible to implement these services as a part of a segment, but we chose to implement them as separate entities to make the entire system highly extensible. For example, it is possible to give the system a completely different look and feel just by changing the embedded behaviors without modifying the segment itself. It is also easy to add new features as new embedded behaviors. Actually, our “moving a segment” feature came later in the development process; the Drag Border behavior was added without requiring much rewriting of the segment code.

6.7.3. Application Behaviors

This section describes the implementation of some application behaviors in detail. The Flatland infrastructure provides an API which programmers can use to build their own application behaviors, without worrying about low level implementation details of the entire system.

Basically, an application behavior receives an input stroke from the host segment, and modifies the set of painted strokes maintained by the segment. An application behavior can also respond to any other events to maintain some task specific semantics. For

example, most application behaviors respond to metastroke events to delete the closest painted stroke.

Figure 54. Behavior specific internal structures.

An application behavior does not maintain the stroke set—this is done by the segment—but it may require additional internal information about the strokes of the host segment. For example, the To Do behavior has a list of to do items, and each item has a pointer to its corresponding check box and strokes. The Map Drawing behavior has a network of streets and crosses, and each street has a pointer to two strokes (Figure 54). This internal information disappears when the behavior is detached from the segment, and is reconstructed when the behavior is re-attached, as described below in the section, Reapplication of Application Behaviors

Plain Drawing Behavior

This behavior is the default application behavior and works as a prototype for other application behaviors. The code for this behavior is quite simple. It adds a new input stroke to the segment's stroke set directly, and removes a painted stroke when it detects erasing gesture. This behavior does not cause any side effects on other painted strokes, and it maintains no behavior specific internal structure.

Map Drawing Behavior

This behavior maintains a graph representation of streets and intersections internally. Each street has pointers to the two painted strokes representing the street, and each intersection has pointers to the streets connected to it.

When an input stroke comes in, this behavior first examines whether the stroke

overlaps some existing streets. If no overlap is found, the behavior creates two painted strokes at the both sides of the input stroke, and adds them to the segment's stroke set. In addition, the behavior adds the new street to its street set. If the stroke overlaps some existing street, the behavior divides the street and the input stroke at the section, and reconstructs the appropriate graph topology. The behavior deletes the painted strokes associated with the modified street, and adds a set of new painted strokes. When the user tries to erase a painted stroke, the behavior erases the corresponding street. Then it reconfigures the internal graph representation and edits the segment's stroke set.

Calculation Behavior

This behavior works just as a plain drawing behavior until the user draws a long horizontal stroke requesting calculation. When this happens, the behavior searches for the set of strokes above the horizontal stroke, and hands them to a handwriting recognizer. The recognizer returns the symbolic representation of a formula. The behavior calculates it, and adds a set of painted strokes that represent result digits to the segment's stroke set. This behavior maintains no internal structure, and scans the entire segment each time. As a result, this behavior can accepts any painted stroke as input, including the painted strokes created by the behavior itself or those painted before the behavior is applied to the segment.

3D Drawing Behavior

This behavior has a 3D polygonal model internally, and renders the model by adding painted strokes representing visible silhouette edges to the segment's stroke set. When the user rotates the model, the behavior removes all previous strokes, and adds new strokes. Unlike other application behaviors, it directly responds to the low level metastroke events to implement rotation.

Search Behavior

This behavior is a part of the system infrastructure, and is significantly different from other application behaviors. While other application behaviors provide feedback by editing the segment's stroke set and letting the PaintStroke embedded behavior paint them, the search behavior paints buttons and search results to the screen by itself. This prevents the search result to be recorded as new strokes, and gives a distinctive look to the segment.

6.7.4. Reapplication of Application Behaviors

As we have mentioned already, behavior specific internal structure disappears when the behavior is removed from the segment, and the structure is recovered when the behavior is applied to the segment again. This section discusses the implementation of this reapplication process in detail. A naïve implementation may be to save the behavior specific structure *in the segment*, but this strategy fails because of our dynamic segmenting feature. Segments can be merged or split, which means that a segment is too fragile an entity to store these structures safely.

As an alternative strategy, we store the behavior specific structure *in the painted strokes*. Each stroke remembers the associated partial internal structure, and a re-applied behavior uses these partial structures to recover the entire structure. This allows segments to be split and joined appropriately.

For example, the To Do behavior gives each painted stroke a pointer to a corresponding to do item object. When the To Do behavior is reapplied to a segment, it examines all the painted strokes, and groups them based on the associated to do item objects. Each to do item can originate from different To Do behaviors. Then, the To Do behavior constructs a list of to do items, and organizes the strokes appropriately (Figure 55).

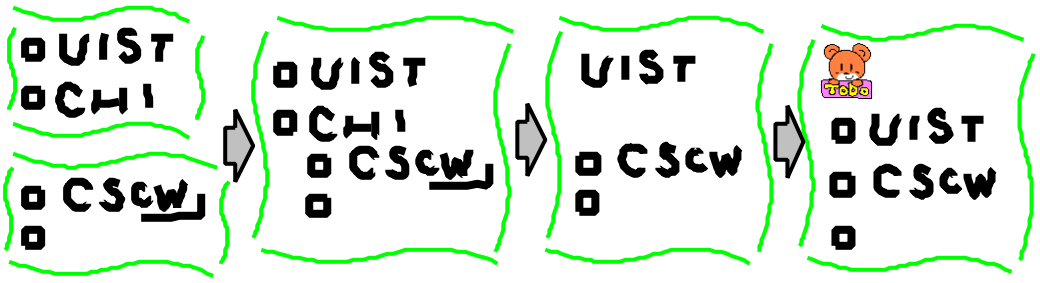


Figure 55. Re-application of a To Do behavior.

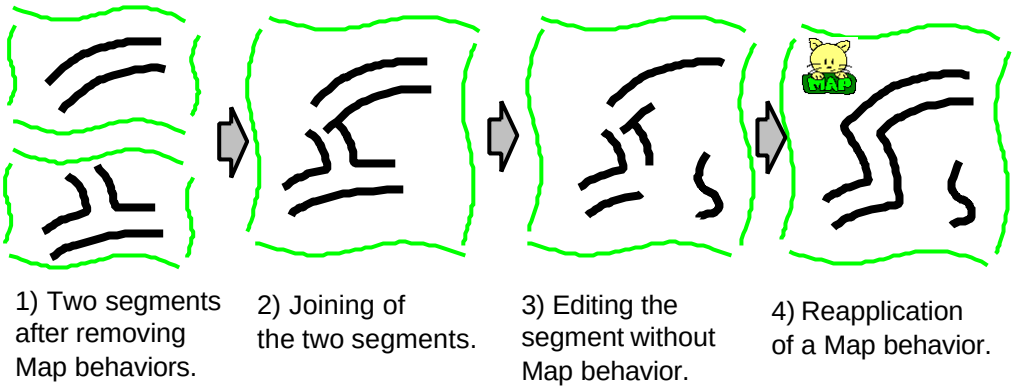


Figure 56. Re-application of a Map behavior.

The Map Drawing behavior embeds a pointer to the corresponding street object in a painted stroke. When a map drawing behavior is reapplied to the segment, it extracts the set of street objects embedded in the strokes, and constructs a complete street-intersection graph. Again, each street object can be generated by different Map Drawing behaviors (Figure 56). Strokes generated by other behaviors remain unchanged.

The 3D drawing behavior embeds a pointer to the 3D model in each stroke. When the behavior is reapplied to a segment, it extracts the 3D geometry from the stroke. If more than one 3D model is found in the stroke set, the 3D drawing behavior ignores the rest of them.

An application programmer has to write code to store and recover the internal structures when he or she uses internal structures. Currently, this part of coding is too complicated and difficult. It is our future work to find a more unified way to handle behavior reapplication.

6.8. History Management

One of the goals of Flatland was to create a "change safe" whiteboard. What this means is that users should be able to safely change any content on the board, knowing that they can recover it later if need be. To satisfy this requirement, Flatland must be able to reconstruct the contents of any given segment as requested by the user.

To implement this ability, Flatland uses the combination of two different mechanisms. One is a command object model, which maintains short-term history and supports infinite undo/redo and the *time slider*. Time slider allows the user to view segment status in the past [119]. The other is a persistent document management system based on associative memory, which maintains long-term history and supports context based search.

6.8.1. Undo/Redo Model

Our infinite undo/redo is based on the "command object" idiom [39]. Command objects are objects—in the object-oriented sense of the word—that encapsulate an operation that can be performed in an application. Each type of action that the user can take on the whiteboard is represented as a discrete class of command object. Instances of commands are "invoked" by calling a well-known method on them that causes them to perform their operation, updating the state of the board.

In our model, commands can be invoked and they can be reversed. That is, each command supports the ability to both "do" and "undo" its operation. Once this ability is added to the base command object pattern, command objects can be connected together in graphs to form complex histories that represent all of the possible states in which the application has existed. By traversing the graph, sequential sets of operations can be done or undone. This model of graphs of command objects as a means to represent time has been used by Timewarp [34] and other systems. (Although, unlike the generalized time model supported by Timewarp, Flatland doesn't allow divergent or revergent histories—in Flatland, the history graph is strictly linear, and thus avoids issues with conflicts [32].).

The time slider is implemented based on this infinite undo/redo model. When the user moves the slider forward, the system invokes redo methods of the command objects sequentially, and vice versa. Semantic jumping is implemented by putting markers in the command object sequence. If the user presses the jump button, the system searches for the next marker and jumps to the time point.

6.8.2. Supporting Undo/Redo with Extensible Behaviors

Flatland faced some unique problems in representing its state as a linear graph of command objects. In "traditional" uses of the command object idiom, each command is atomic—that is, it can reliably and completely do or undo its operation, and has no side effects that aren't represented by the state in the command object itself. As an example, when a command object in a drawing program is rolled forward, it must take care to store all information needed to completely reset the state of the application if it is rolled back. If performing the operation causes some change to be made to the graphics context of the application, the creator of the command must be aware of this side effect, and must account for it when performing the corresponding undo.

This situation is in contrast to the basic architecture of Flatland, where the use of extensible, pluggable behaviors means that essentially *every* interesting update to the state of the application *does* occur as a side effect to user input. The set of operations that can occur when a user draws a stroke on the board is dependent on the set of behaviors installed, and the current state of each of those behaviors. This leads to some problems in applying the command object idiom in the face of extensible behaviors.

One naïve approach would be to represent only the original user input in the command history. So if a user made a stroke, and the map behavior then drew two parallel strokes to represent a street, only the original stroke (which doesn't even appear on the screen after the map behavior is finished with it) would be present in the history. The problem here is that the history no longer represents the complete state of the application. Jumping to a different node in the history graph involves "replaying" the user input to the behaviors, causing them to perform all of the same operations they would in response to "fresh" user input. The computations done by behaviors can be arbitrarily complex, which means that jumping to distant states can be arbitrarily expensive.

Flatland uses an alternative approach, where any behavior expresses its updates in terms of new command objects. So in the example of the map behavior, the history would contain a behavior-specific command object indicating that a new street is present, followed by two painted strokes (added by the map behavior). This approach has a big advantage: changes based on user input are "pre-computed" by the behaviors,

and only their final outputs are represented in the history. The "side effects" of the input are turned into "foreground effects" and represented as first-class citizens in the history.

6.8.3. A Transaction Model for State Changes

This second approach does have a drawback: since behaviors write their operations into the command history, simple atomic roll-forward/roll-back is now inappropriate.

For example, with the Map behavior, suppose that a user has drawn a stroke that corresponds to a new street, and then needs to roll time back. The original stroke command is not represented in this history—it has been replaced by a set of commands representing the effects of the stroke. Clearly, rolling back atomically is probably not what the user wants to see: such a roll back would reveal the individual operations of the map behavior, rather than the semantic "chunk" of the whole set of operations.

To solve this problem, we adopted a transaction model for the commands in our histories. Each original user-level input begins a new transaction. As the Flatland event dispatch code runs and behaviors perform their operations, their effects are grouped into this new transaction. Figure 57 shows an example of a transaction. From this model, causality relationships are clearly indicated, as all operations in a transaction are effects of the same cause. Transactions are represented explicitly in the history as commands, and the history roll-forward/roll-back machinery is augmented to process entire transactions atomically.

```
121 OpenTransaction
122 BehaviorSpecificCommand (Map, addstreet, street#12a)
123 AddPaintedStrokeCommand(stroke#23a1)
124 AddPaintedStrokeCommand(stroke#23a2)
125 CloseTransaction
```

Figure 57. An example of transaction.

6.8.4. Local versus Global Timeline Management

One final timeline management issue we had to deal with was the distinction between the "local" timelines of individual segments and the "global" timeline of the entire board. We wanted the ability for users to interact with the timelines of individual segments without affecting others: the entire history of a segment should appear continuous, even though in "real" time, operations on other segments may be interspersed with it. But we also wanted the ability to roll forwards and backwards in global (whole-board) time. Global undo and redo means that the histories of all individual segments are "packed" into a single timeline ordered by "real" time, rather than "segment logical" time.

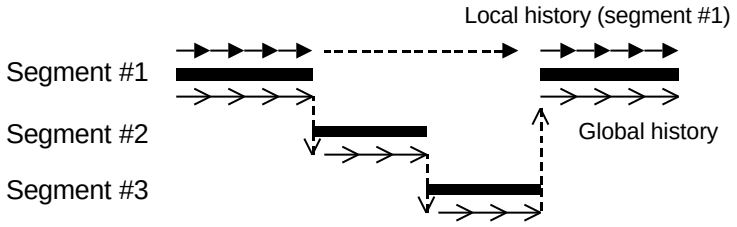


Figure 58. Local versus Global Timeline.

In the implementation, each segment maintains its own local history, and Flatland creates the illusion of a global history timeline by composing individual segment histories together. Because users can visit and leave segments as often as needed, segment histories can be arbitrarily interleaved in "global" time—so the global history is represented as a list of "chunks" of history from individual segments, stitched together (Figure 58).

6.8.5. Persistence

Since Flatland whiteboards are designed for long-term use—much as physical whiteboards are—we needed a way to ensure that all data on the board is saved persistently. We want to ensure that *everything* on the board is saved and recoverable, for the entire duration of the board's use, without requiring users to have to explicitly save or name files that correspond to segments. Clearly this would violate the informal nature of the system and, in many cases, the work required to explicitly save a

persistent data file would outweigh the benefit of using the board! We needed a much lighter-weight approach.

Flatland is built atop the Presto document management system [32]. Presto provides a loosely-structured "information soup" into which arbitrary content can be stored. Presto presents an associative memory programming model to its users—chunks of information can be tagged with arbitrary key/value pairs—which maps nicely into the Java implementation of Flatland (Presto tuples can be arbitrary serialized Java objects).

Flatland saves every "dirty" segment periodically to stable storage via Presto. Each segment is represented as a discrete Presto "document," with Flatland-specific objects tagged onto it as key/value data. The contents of each document are the serialized command objects that constitute the segment's history. The system maintains a "segment cache," which reflects all of the "live" segments currently on the board. If an old segment needs to be retrieved (either because the user searched for it, or an undo or time slider operation causes the segment to become live again), it is "faulted in" from persistent storage. Only the storage layer in Flatland needs to know about persistence—from the perspective of behavior writers, all segments are always "live" and in core at all times. From the user perspective, users never have to explicitly save at any time, and they never name the data that is saved.

6.8.6. Search

Our search behavior retrieves past segment states using this document management system. The system tries to intuit information about the context of a segment's use, and its content, and uses this information to satisfy queries. For example, users can search based on content attributes such as segment stroke density (using ambiguous terms like "dense" or "sparse" or "medium") and color ("mostly blue"). Context-based searches can use information about what behaviors were attached to the segment ("my map" or "my to do list"), and time of last use.

The search result is displayed as a set of thumbnails representing past states of the segments. The construction of this thumbnail is done by rolling the addPaintedStroke and removePaintedStroke command objects forward starting from a blank segment,

ignoring any behavior specific command objects in the segment history. This allows the system to reconstruct the segment appearance quickly. If the user tries to interact with the retrieved segment, the system reconstructs the behavior specific internal structures by rolling behavior specific command objects forward.

6.9. Implementation Notes

Flatland is implemented in Java, and is approximately 42,000 lines of code. Handwriting recognition (used by the Calculator behavior) is done by the Calligrapher online recognizer from Paragraph Corporation.

We did not pay much attention to performance tuning, but the overall speed is satisfactory on a standard PC as a proof of concept prototype. Some operations such as the display of search results cause delay, and require improvement.

Implementation of history management is not yet complete. Especially, our long-term persistent history causes a sort of time travel paradox. Multiple restorations of an old segment and time traversal over merged or split segments badly confuse the timeline management, and more research is required to address these problems.

6.10. Summary and Future Work

This chapter has introduced our efforts to build a software platform for a variety of pen-based applications. Our design goal was to support informal, pre-production activities on a whiteboard, in contrast to the well-organized activities supported on desktop computers. To achieve this goal, we have introduced the ideas of strokes as a basic primitive for both input and output, dynamic segmentation of the screen space, pluggable behaviors working on a segment, and persistent history management mechanism.

Our next step is to deploy the Flatland system in real office environment to observe its usage. However, this is difficult with our current hardware set up, and its requirement for front projection. We expect that a large plasma display with touch sensitive screen will be a good solution. We also plan to implement additional application behaviors that

support common activities on a white board such as paper outlining, communications, calendars, and so on.

Another interesting research direction is the application of our architecture to other pen computing environments. We believe that our architecture can provide a uniform framework for a variety of pen-based devices to work in corporation.

Chapter 7

Sketch-based 3D Freeform Modeling

This chapter introduces a sketching interface for quickly and easily designing freeform models such as stuffed animals and other rotund objects. The user draws several 2D freeform strokes interactively on the screen and the system automatically constructs plausible 3D polygonal surfaces. Our system supports several modeling operations, including the operation to construct a 3D polygonal surface from a 2D silhouette drawn by the user: it inflates the region surrounded by the silhouette making wide areas fat, and narrow areas thin. Teddy, our prototype system, is implemented as a Java™ program, and the mesh construction is done in real-time on a standard PC. Our informal user study showed that a first-time user typically masters the operations within 10 minutes, and can construct interesting 3D models within minutes.

7.1. Introduction

Although much progress has been made over the years on 3D modeling systems, they are still difficult and tedious to use when creating freeform surfaces. Their emphasis has been the precise modeling of objects motivated by CAD and similar domains. Recently SKETCH [161] introduced a gesture-based interface for the rapid modeling of CSG-like models consisting of simple primitives.

Teddy [63] extends these ideas to create a sketching interface for designing 3D freeform objects. The essential idea is the use of freeform strokes as an expressive design tool. The user draws 2D freeform strokes *interactively* specifying the silhouette of an object, and the system automatically constructs a 3D polygonal surface model based on the strokes. The user does not have to manipulate control points or combine complicated

editing operations. Using our technique, even first-time users can create simple, yet expressive 3D models within minutes. In addition, the resulting models have a hand-crafted feel (such as sculptures and stuffed animals) which is difficult to accomplish with most conventional modelers. Examples are shown in Figure 60.

We describe here the sketching interface and the algorithms for constructing 3D shapes from 2D strokes. We also discuss the implementation of our prototype system, Teddy. The geometric representation we use is a standard polygonal mesh to allow the use of numerous software resources for post-manipulation and rendering. However, the interface itself can be used to create other representations such as volumes [143] or metaballs [81].

Like SKETCH [161], Teddy is designed for the rapid construction of approximate models, not for the careful editing of precise models. To emphasize this design goal and encourage creative exploration, we use the real-time pen-and-ink rendering described in [80], as shown in Figure 59. This also allows real-time interactive rendering using Java on mid-range PCs without dedicated 3D rendering hardware.

Figure 59. Teddy in use on a display-integrated tablet.

An obvious application of Teddy is the design of 3D models for character animation. However, in addition to augmenting traditional 3D modelers, Teddy's ease of use has the potential to open up new application areas for 3D modeling. Possibilities include rapid prototyping in the early stages of design, educational/recreational use for non-professionals and children, and real-time communication assistance on pen-based

systems.

Figure 60. Painted models created using Teddy and painted using a commercial texture-map editor.

We publicly provide a videotape that demonstrates Teddy's user interface. Teddy is available as a Java applet at the following web site. http://www.mtl.t.u-tokyo.ac.jp/~takeo/teddy/teddy.htm

7.2. Related Work

A typical procedure for geometric modeling is to start with a simple primitive such as a cube or a sphere, and gradually construct a more complex model through successive transformations or a combination of multiple primitives. Various deformation techniques [77,126] and other shape-manipulation tools [39] are examples of transformation techniques that let the user create a wide variety of precise, smooth shapes by interactively manipulating control points or 3D widgets.

Another approach to geometric modeling is the use of implicit surfaces [7,81]. The user specifies the skeleton of the intended model and the system constructs smooth, natural-looking surfaces around it. The surface inflation technique [81] extrudes the polygonal mesh from the skeleton outwards. In contrast, our approach lets the user specify the silhouette of the intended shape directly instead of by specifying its skeleton.

Some modeling systems achieve intuitive, efficient operation using 3D input/output devices [29]. 3D devices can simplify the operations that require multiple operations when using 2D devices.

Our sketching interface is inspired by previous sketch-based modeling systems [32,161] that interpret the user's freeform strokes and interactively construct 3D rectilinear models. Our goal is to develop a similar interface for designing rounded freeform models.

Inflation of a 2D drawing is introduced in [152], and 3D surface editing based on a 2D painting technique is discussed in [153]. Their target is basically a 2D array with associated height values, rather than a 3D polygonal model.

The use of freeform strokes for 2D applications has recently become popular. Some systems [50,61] use strokes to specify gestural commands and others [6] use freeform strokes for specifying 2D curves. These systems find the best matching arcs or splines automatically, freeing the users from explicit control of underlying parameters.

We use a polygonal mesh representation, but some systems use a volumetric representation [39,143], which is useful for designing topologically complicated shapes. Our mesh-construction algorithm is based on a variety of work on polygonal mesh manipulation, such as mesh optimization [56], shape design [148], and surface fairing [138], which allows polygonal meshes to be widely used as a fundamental representation for geometric modeling and computer graphics in general.

7.3. User Interface

Teddy's physical user interface is based upon traditional 2D input devices such as a standard mouse or tablet. We use a two-button mouse with no modifier keys. Unlike traditional modeling systems, Teddy does not use WIMP-style direct manipulation techniques or standard interface widgets such as buttons and menus for modeling operations. Instead, the user specifies his or her desired operation using freeform strokes on the screen, and the system infers the user's intent and executes the appropriate editing operations. Our videotape shows how a small number of simple operations let the users create significantly rich models.

In addition to gestures, Teddy supports direct camera manipulation using the secondary mouse button based on a virtual trackball model [57]. We also use a few button widgets for auxiliary operations, such as save and load, and for initiating bending operations.

7.4. Modeling Operations

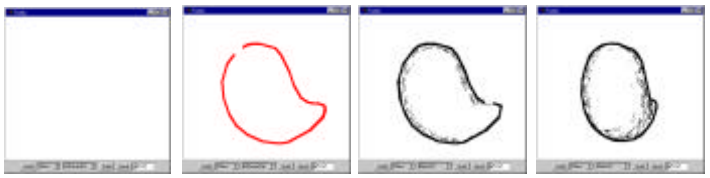
This section describes Teddy's modeling operations from the user's point of view; details of the algorithms are left to the next section. Some operations are executed immediately after the user completes a stroke, while some require multiple strokes. The current system supports neither the creation of multiple objects at once, nor operations to combine single objects. Additionally, models must have a spherical topology; e.g., the user cannot create a torus. An overview of the model construction process is given first, and then each operation is described in detail.

The modeling operations are carefully designed to allow incremental learning by novice users. Users can create a variety of models by learning only the first operation (creation), and can incrementally expand their vocabulary by learning other operations as necessary. We have found it helpful to restrict first-time users to the first three basic operations (creation, painting, and extrusion), and then to introduce other advanced operations after these basic operations are mastered.

7.4.1. Overview

Figure 61 introduces Teddy's general model construction process. The user begins by drawing a single freeform stroke on a blank canvas (Figures 3a-b). As soon as the user finishes drawing the stroke, the system automatically constructs a corresponding 3D shape (c). The user can now view the model from a different direction (d). Once a model is created, it may be modified using various operations. The user can draw a line on the surface (e-g) by drawing a stroke within the model silhouette. If the stroke is closed, the resulting surface line turns red and the system enters "extrusion mode" (h-i). Then the user rotates the model (j) and draws the second stroke specifying the silhouette of the extruded surface (k-m). A stroke that crosses the silhouette cuts the model (n-o) and turns the cut section red (p). The user either clicks to complete the operation (q) or

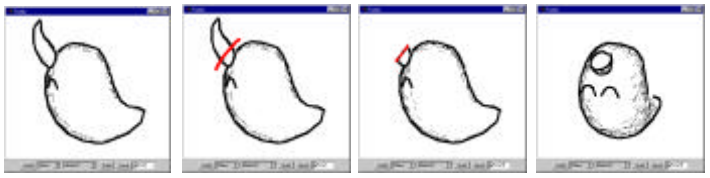
draws a silhouette to extrude the section (r-t). Scribbling on the surface erases the line segments on the surface (u-w). If the user scribbles during the extrusion mode (x-y), the system smoothes the area surrounded by the closed red line (z-z´).



a) initial state b) input stroke c) result of creation d) rotated view

e) painting stroke f) result of painting g) rotated view

h) before extrusion i) closed stroke j) rotated view k) extruding stroke l) result of extrusion m) rotated view



n) before cutting o) cutting stroke p) result of cutting q) result of click

r) extrusion after cutting s) result of extrusion t) rotated view u) before erasing v) scribbling w) result of erasing

x) closed stroke y) scribbling z) result of smoothing ź) rotated view

Figure 61. Overview of the modeling operations.

Figure 62 summarizes the modeling operations available on the current implementation. Note that the appropriate action is chosen based on the stroke's position and shape, as well as the current mode of the system.

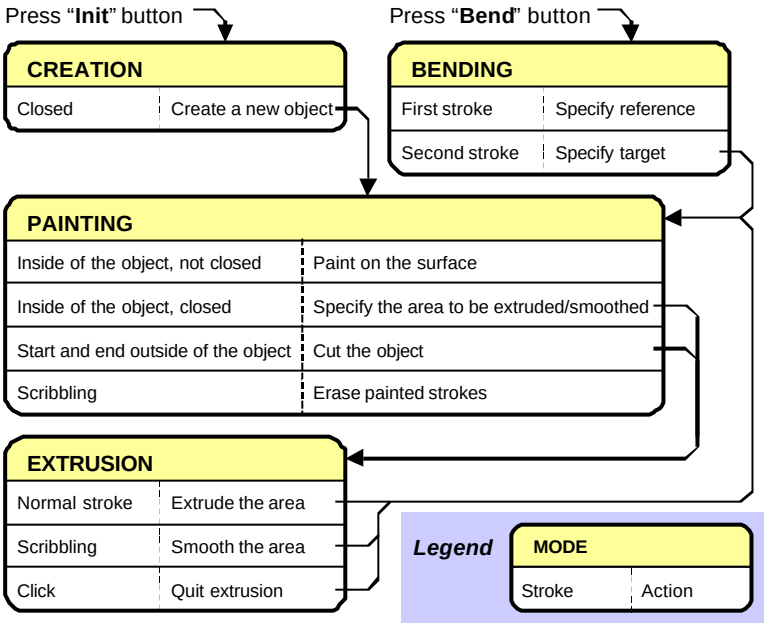
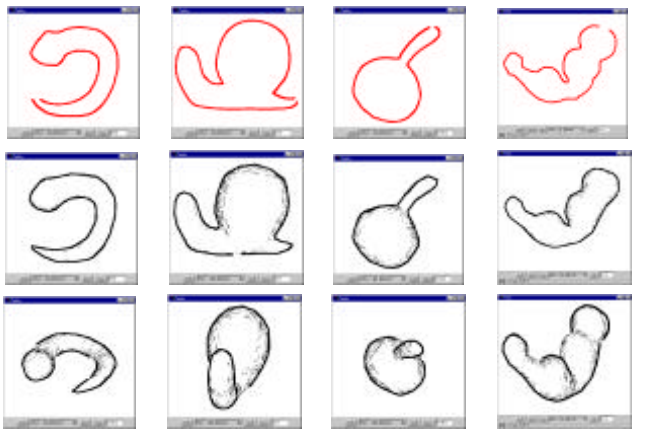


Figure 62. Summary of the gestural operations.

7.4.2. Creating a New Object

Starting with a blank canvas, the user creates a new object by drawing its silhouette as a closed freeform stroke. The system automatically constructs a 3D shape based on the 2D silhouette. Figure 63 shows examples of input strokes and the corresponding 3D models. The start point and end point of the stroke are automatically connected, and the operation fails if the stroke is self-intersecting. The algorithm to calculate the 3D shape is described in detail in section 5. Briefly, the system inflates the closed region in both directions with the amount depending on the width of the region: that is, wide areas become fat, and narrow areas become thin. Our experience so far shows that this algorithm generates a reasonable-looking freeform shape. In addition to the creation operation, the user can begin model construction by loading a simple primitive. The current implementation provides a cube and a sphere, but adding more shapes is

straightforward.



a) snake b) snail c) cherry d) muscular arm

Figure 63. Examples of creation operation.

(top: input stroke, middle: result of creation, bottom: rotated view).

7.4.3. Painting and Erasing on the Surface

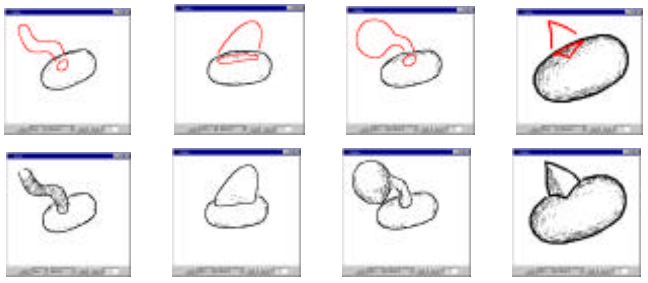
The object surface is painted by drawing a freeform stroke within the object's silhouette on the canvas (the stroke must not cross the silhouette) [51]. The 2D stroke is projected onto the object surface as 3D line segments, called surface lines (Figure 61e-g). The user can erase these surface lines by drawing a scribbling stroke[3] (Figure 61u-w). This painting operation does not modify the 3D geometry of the model, but lets the user express ideas quickly and conveniently when using Teddy as a communication medium or design tool.

7.4.4. Extrusion

Extrusion is a two-stroke operation: a closed stroke on the surface and a stroke depicting the silhouette of the extruded surface. When the user draws a closed stroke on the object surface, the system highlights the corresponding surface line in red,

[3] A stroke is recognized as scribbling when sl/pl > 1.5, where sl is the length of the stroke and pl is the perimeter of its convex hull.

indicating the initiation of “extrusion mode” (Figure 61i). The user then rotates the model to bring the red surface line sideways (Figure 61j) and draws a silhouette line to extrude the surface (Figure 61k). This is basically a sweep operation that constructs the 3D shape by moving the closed surface line along the skeleton of the silhouette (Figure 61l-m). The direction of extrusion is always perpendicular to the object surface, not parallel to the screen. Users can create a wide variety of shapes using this operation, as shown in Figure 64. They can also make a cavity on the surface by drawing an inward silhouette (Figure 65a-c). The current implementation does not support holes that completely extend to the other side of the object. If the user decides not to extrude, a single click turns the red stroke into an ordinary painted stroke (Figure 7d-e).



a) long b) thin c) fat d) sharp

Figure 64. Examples of extrusion.

(top: extruding stroke, bottom: result of extrusion).

a) digging stroke b) result c) rotated d) closed stroke e) after click

Figure 65. More extrusion operations.

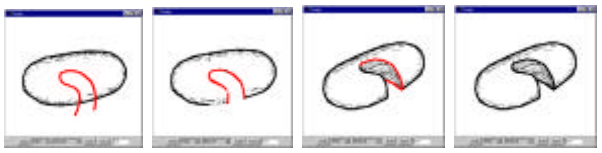
Digging a cavity (a-c) and turning the closed stroke into a surface drawing (d-e).

7.4.5. Cutting

A cutting operation starts when the user draws a stroke that runs across the object, starting and terminating outside its silhouette (Figure 61o). The stroke divides the

object into two pieces at the plane defined by the camera position and the stroke. What is on the screen to the left of the stroke is then removed entirely (Figure 61p) (as when a carpenter saws off a piece of wood). The cutting operation finishes with a click of the mouse (Figure 61q). The user can also `bite' the object using the same operation (Figure 66).

The cutting stroke turns the section edges red, indicating that the system is in "extrusion mode". The user can draw a stroke to extrude the section instead of a click (Figure 61r-t, Figure 67). This "extrusion after cutting" operation is useful to modify the shape without causing creases at the root of the extrusion.



a) biting stroke b) result c) rotated view d) after click

Figure 66. Cutting operation.

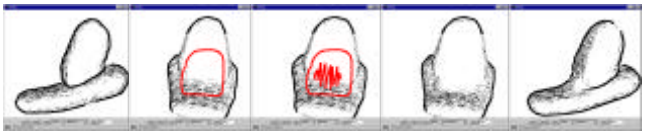
a) cutting stroke b) result c) rotated d) extruding stroke e) result

Figure 67. Extrusion after cutting.

7.4.6. Smoothing

One often *smoothes* the surface of clay models to eliminate bumps and creases. Teddy lets the user smooth the surface by drawing a scribble during "extrusion mode." Unlike erasing, this operation modifies the actual geometry: it first removes all the polygons surrounded by the closed red surface line and then creates an entirely new surface that covers the region smoothly. This operation is useful to remove unwanted bumps and cavities (Figure 61x-z', Figure 68a), or to smooth the creases caused by earlier extrusion operations (Figure 68b).

a) cleaning a cavity



b) smoothing a sharp edge

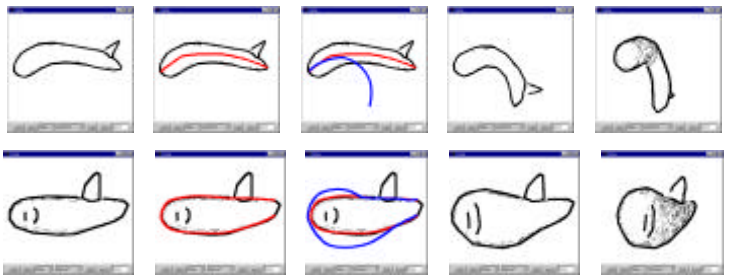
Figure 68. Smoothing operation.

7.4.7. Transformation

We are currently experimenting with an additional "transformation" editing operation that distorts the model while preserving the polygonal mesh topology. Although it functions properly, the interface itself is not fully gestural because the modal transition into the bending mode requires a button push.

This operation starts when the user presses the "bend" button and uses two freeform strokes called the *reference stroke* and the *target stroke* to modify the model. The system moves vertices of the polygonal model so that the spatial relation between the original position and the target stroke is identical to the relation between the resulting position and the reference stroke. This movement is parallel to the screen, and the vertices do not move perpendicular to the screen. This operation is described in [24] as *warp*; we do not discuss the algorithm further.

Transformation can be used to bend, elongate, and distort the shape (Figure 69). We plan to make the system infer the reference stroke automatically from the object's structure in order to simplify the operation, in a manner similar to the mark-based interaction technique of [6].



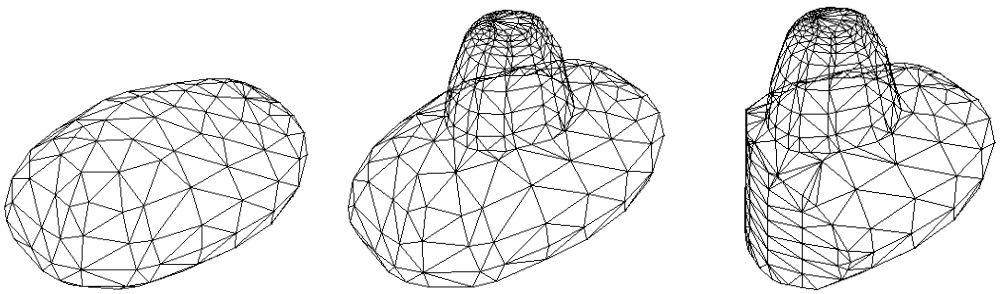
a) original b) reference stroke c) target stroke d) result e) rotated

Figure 69. Examples of transformation.

(top: bending, bottom: distortion)

7.5. Algorithm

We next describe how the system constructs a 3D polygonal mesh from the user's freeform strokes. Internally, a model is represented as a polygonal mesh. Each editing operation modifies the mesh to conform to the shape specified by the user's input strokes (Figure 70). The resulting model is always topologically equivalent to a sphere. We developed the current implementation as a prototype for designing the interface; the algorithms are subject to further refinement and they fail for some illegal strokes (in that case, the system indicates the problem and requests an alternative stroke). However, these exceptional cases are fairly rare, and the algorithm works well for a wide variety of shapes.



a) after creation b) after extrusion c) after cutting

Figure 70. Internal representation.

Our algorithms for creation and extrusion are closely related to those for freeform surface construction based on skeletons [7,81], which create a surface around user-defined skeletons using implicit surface techniques. While our current implementation does not use implicit surfaces, they could be used in an alternative implementation.
In order to remove noise in the handwriting input stroke and to construct a regular polygonal mesh, every input stroke is re-sampled to form a smooth polyline with uniform edge length before further processing [22].

7.5.1. Creating a New Object

Our algorithm creates a new closed polygonal mesh model from the initial stroke. The overall procedure is this: we first create a closed planar polygon by connecting the start-point and end-point of the stroke, and determine the spine or axes of the polygon using the *chordal axis* introduced in [106]. We then elevate the vertices of the spine by an amount proportional to their distance from the polygon. Finally, we construct a polygonal mesh wrapping the spine and the polygon in such a way that sections form ovals.

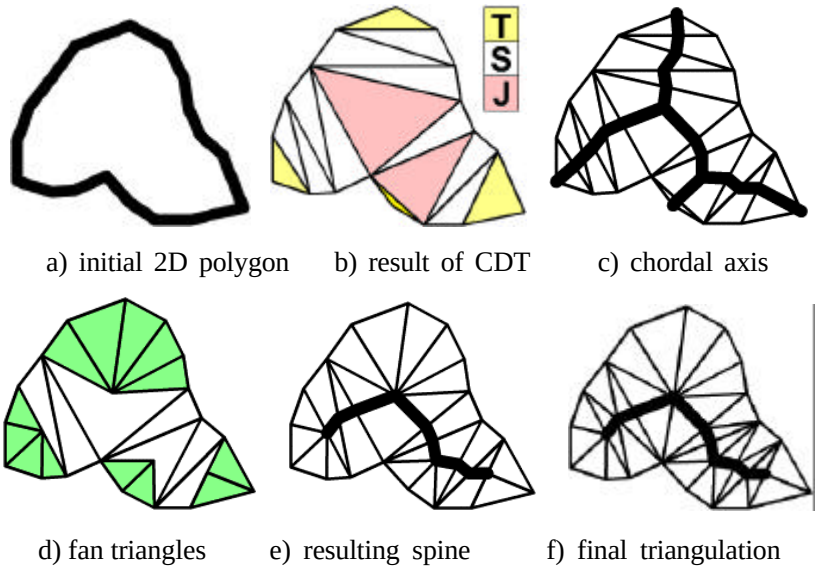


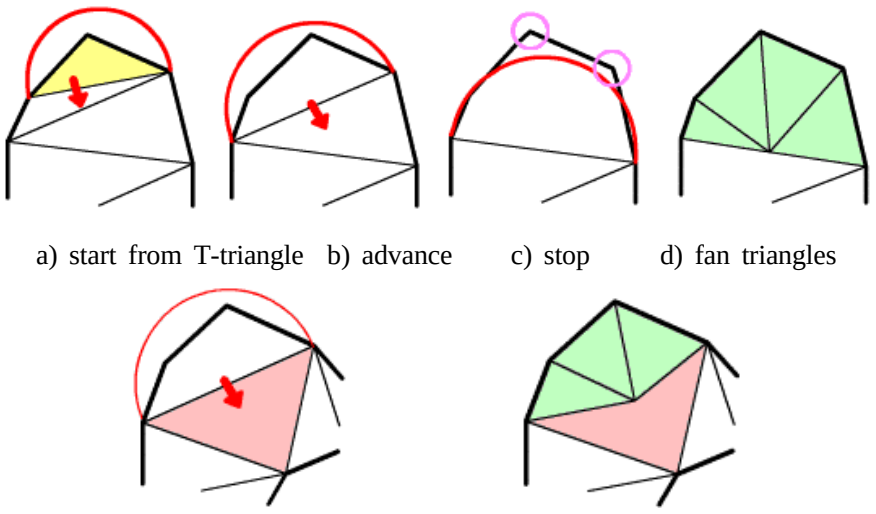
Figure 71. Finding the spine.

When constructing the initial closed planar polygon, the system makes all edges a predefined unit length (see Figure 71a). If the polygon is self-intersecting, the algorithm

stops and the system requests an alternative stroke. The edges of this initial polygon are called *external edges*, while edges added in the following triangulation are called *internal edges*.

The system then performs constrained Delaunay triangulation of the polygon (Figure 71b). We then divide the triangles into three categories: triangles with two external edges (terminal triangle), triangles with one external edge (sleeve triangle), and triangles without external edges (junction triangle). The chordal axis is obtained by connecting the midpoints of the internal edges (Figure 71c), but our inflation algorithm first requires the *pruning* of insignificant branches and the retriangulation of the mesh. This pruning algorithm is also introduced in [106].

To prune insignificant branches, we examine each terminal triangle in turn, expanding it into progressively larger regions by merging it with adjacent triangles (Figure 72a-b). Let X be a terminal triangle; then X has two exterior edges and one interior edge. We erect a semicircle whose diameter is the interior edge, and which lies on the same side of that edge as does X. If all three vertices of X lie on or within this semicircle, we remove the interior edge and merge X with the triangle that lies on the other side of the edge.



a) start from T-triangle b) advance c) stop d) fan triangles

e) advance to J-triangle f) fan triangles at J-triangle

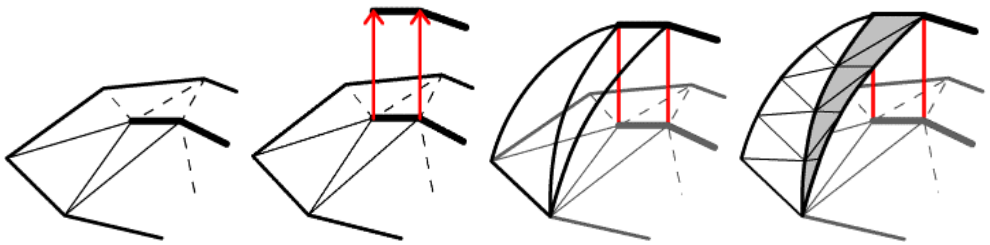
Figure 72. Pruning.

If the newly merged triangle is a sleeve triangle, then X now has three exterior edges and a new interior edge. Again we erect a semicircle on the interior edge and check that

all vertices are within it. We continue until some vertex lies outside the semicircle (Figure 72c), or until the newly merged triangle is a junction triangle. In the first case, we triangulate X with a "fan" of triangles radiating from the midpoint of the interior edge (Figure 72d). In the second case, we triangulate with a fan from the midpoint of the junction triangle (Figure 72e-f). The resulting fan triangles are shown in Figure 72d. The pruned spine is obtained by connecting the midpoints of remaining sleeve and junction triangles' internal edges (Figure 71e).

The next step is to subdivide the sleeve triangles and junction triangles to make them ready for elevation. These triangles are divided at the spine and the resulting polygons are triangulated, so that we now have a complete 2D triangular mesh between the spine and the perimeter of the initial polygon (Figure 71f).

Next, each vertex of the spine is elevated proportionally to the average distance between the vertex and the external vertices that are directly connected to the vertex (Figure 73a,b). Each internal edge of each fan triangle, excluding spine edges, is converted to a quarter oval (Figure 73c), and the system constructs an appropriate polygonal mesh by sewing together the neighboring elevated edges, as shown in Figure 73d. The elevated mesh is copied to the other side to make the mesh closed and symmetric. Finally, the system applies mesh refinement algorithms to remove short edges and small triangles [56].



a) before b) elevate spines c) elevate edges d) sew elevated edges

Figure 73. Polygonal mesh construction.

7.5.2. Painting on the Surface

The system creates surface lines by sequentially projecting each line segment of the input stroke onto the object's surface polygons. For each line segment, the system first

calculates a bounded plane consisting of all rays shot from the camera through the segment on the screen. Then the system finds all intersections between the plane and each polygon of the object, and splices the resulting 3D line segments together (Figure 74). The actual implementation searches for the intersections efficiently using polygon connectivity information. If a ray from the camera crosses multiple polygons, only the polygon nearest to the camera position is used. If the resulting 3D segments cannot be spliced together (e.g., if the stroke crosses a "fold" of the object), the algorithm fails.

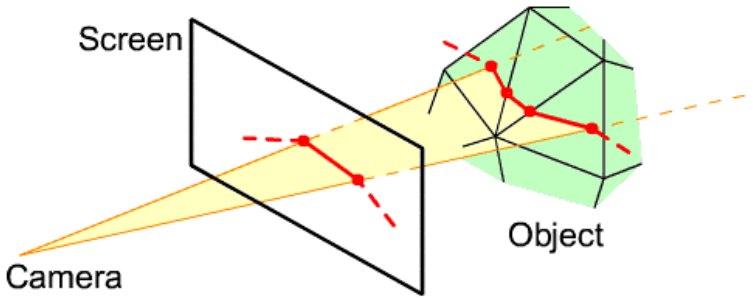


Figure 74. Construction of surface lines.

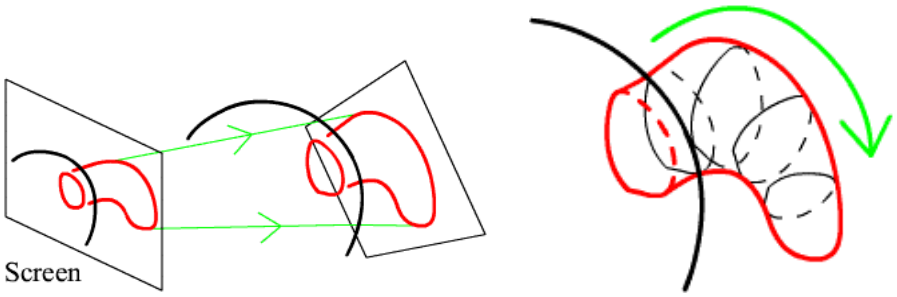
7.5.3. Extrusion

The extrusion algorithm creates new polygonal meshes based on a closed base surface line (called the base ring) and an extruding stroke. Briefly, the 2D extruding stroke is projected onto a plane perpendicular to the object surface (Figure 75a), and the base ring is swept along the projected extruding stroke (Figure 75b). The base ring is defined as a closed 3D polyline that lies on the surface of the polygonal mesh, and the normal of the ring is defined as that of the best matching plane of the ring.

First, the system finds the plane for projection: the plane passing through the base ring's center of gravity and lying parallel to the normal of the base ring[4]. Under the

[4] The normal of the ring is calculated as follows: Project the points of the ring to the original XY-plane. Then compute the enclosed "signed area" by the formula:
Axy = 0.5*sum(i=0, i=n-1, x[i]*y[i+1]-x[i+1]*y[i])
(indices are wrapped around so that x[n] means x[0]). Calculate Ayx and Azx similarly, and the vector v=(Ayz,Azx,Axy) is defined as the normal of the ring.

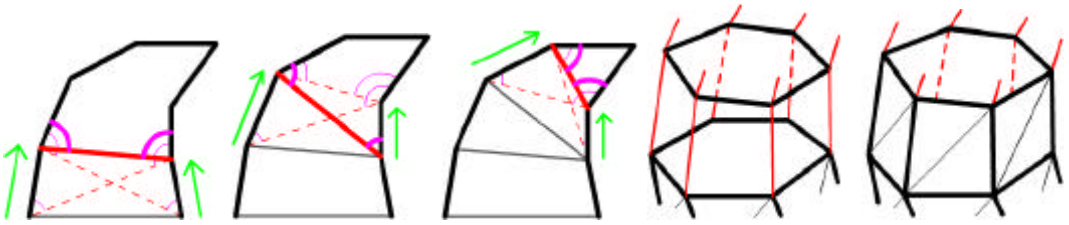
above constraints, the plane faces towards the camera as much as possible (Figure 75a). Then the algorithm projects the 2D extruding stroke onto the plane, producing a 3D extruding stroke. Copies of the base ring are created along the extruding stroke in such a way as to be almost perpendicular to the direction of the extrusion, and are resized to fit within the stroke. This is done by advancing two pointers (left and right) along the extruding stroke starting from both ends. In each step, the system chooses the best of the following three possibilities: advance the left pointer, the right pointer, or both. The *goodness* value increases when the angle between the line connecting the pointers and the direction of the stroke at each pointer is close to 90 degrees (Figure 76a). This process completes when the two pointers meet.



a) projection of the stroke b) sweep along the projected stroke

Figure 75. Extrusion algorithm.

Finally, the original polygons surrounded by the base ring are deleted, and new polygons are created by sewing the neighboring copies of the base ring together [1] (Figure 76b). The system uses the same algorithm to dig a cavity on the surface.

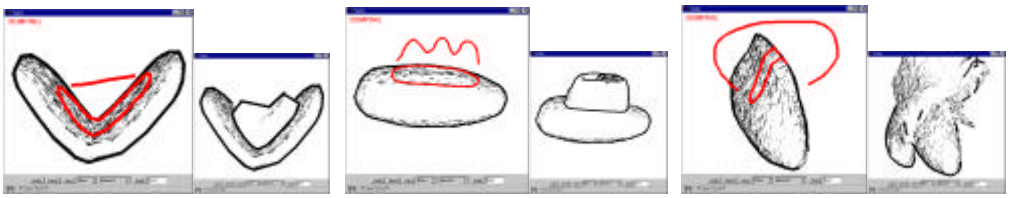


a) pointer advancing b) sewing adjacent rings

Figure 76. Sweeping the base ring.

This simple algorithm works well for a wide variety of extrusions but creates

unintuitive shapes when the user draws unexpected extruding strokes or when the base surface is not sufficiently planar (Figure 77).



a) flat extrusion b) wavy extrusion c) wrapping extrusion

Figure 77. Unintuitive extrusions.

7.5.4. Cutting

The cutting algorithm is based on the painting algorithm. Each line segment of the cutting stroke is projected onto the front and back facing polygons. The system connects the corresponding end points of the projected edges to construct a planer polygon (Figure 78). This operation is performed for every line segment, and the system constructs the complete section by splicing these planer polygons together. Finally, the system triangulates each planer polygon [118], and removes all polygons to the left of the cutting stroke.

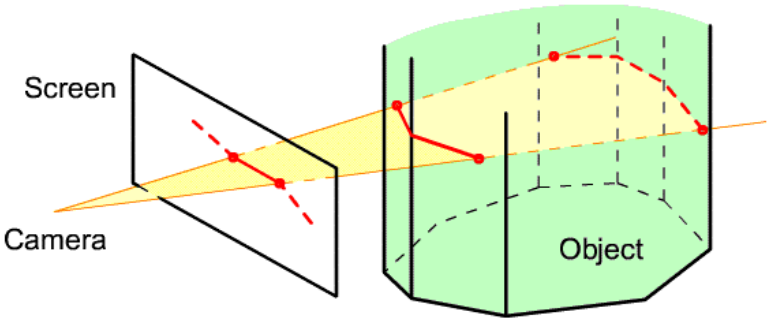


Figure 78. Cutting algorithm.

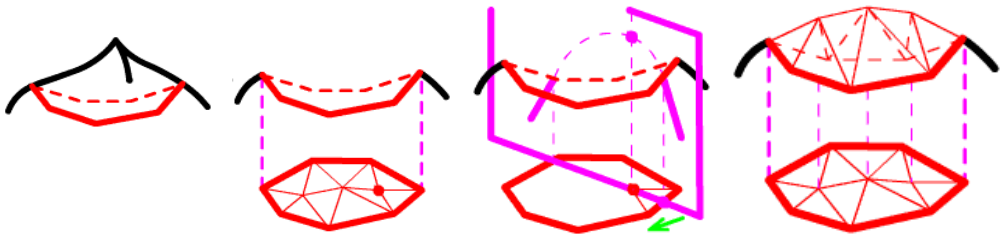
7.5.5. Smoothing

The smoothing operation deletes the polygons surrounded by the closed surface line (called a ring) and creates new polygons to cover the hole smoothly. First, the system

translates the objects into a coordinate system whose Z-axis is parallel to the normal of the ring. Next, the system creates a 2D polygon by projecting the ring onto the XY-plane in the newly created coordinate system, and triangulates the polygon (Figure 79b). (The current implementation fails if the area surrounded by the ring contains creases and is folded when projected on the XY-plane.) The triangulation is designed to create a good triangular mesh based on [118]: it first creates a constrained Delaunay triangulation and gradually refines the mesh by edge splitting and flipping; then each vertex is elevated along the Z-axis to create a smooth 3D surface (Figure 79d).

The algorithm for determining the Z-value of a vertex is as follows: For each edge of the ring, consider a plane that passes through the vertex and the midpoint of the edge and is parallel to the Z-axis. Then calculate the z-value of the vertex so that it lies on the 2D Bezier curve that smoothly interpolates both ends of the ring on the plane (Figure 79c). The final z-value of the vertex is the average of these z-values.

Finally, we apply a surface-fairing algorithm [138] to the newly created polygons to enhance smoothness.



a) before b) triangulation c) calculating Z-value d) result

Figure 79. Smoothing algorithm.

7.6. Implementation

Our prototype is implemented as a 13,000 line Java program. We tested a display-integrated tablet (Mutoh MVT-14, see Figure 1) and an electric whiteboard (Xerox Liveboard) in addition to a standard mouse. The mesh construction process is completely real-time, but causes a short pause (a few seconds) when the model becomes complicated. Teddy can export models in OBJ file format. Figure 2 shows some 3D models created with Teddy by an expert user and painted using a commercial texture-

map editor. Note that these models look quite different from 3D models created in other modeling systems, reflecting the hand-drawn nature of the shape.

7.7. User Experience

The applet version of Teddy has undergone limited distribution, and has been used (mainly by computer graphics researchers and students) to create different 3D models. Feedback from these users indicates that Teddy is quite intuitive and encourages them to explore various 3D designs. Figure 80 shows some 3D models create by novice users. Note the users had no experience with traditional 3D modeling systems and they created these models within several minutes. In addition, we have started close observation of how first-time users (mainly graduate students in computer science) learn Teddy. We start with a detailed tutorial and then show some stuffed animals, asking the users to create them using Teddy. Generally, the users begin to create their own models fluently within 10 minutes: five minutes of tutorial and five minutes of guided practice. After that, it takes a few minutes for them to create a stuffed animal such as those in Figure 60 (excluding the texture).

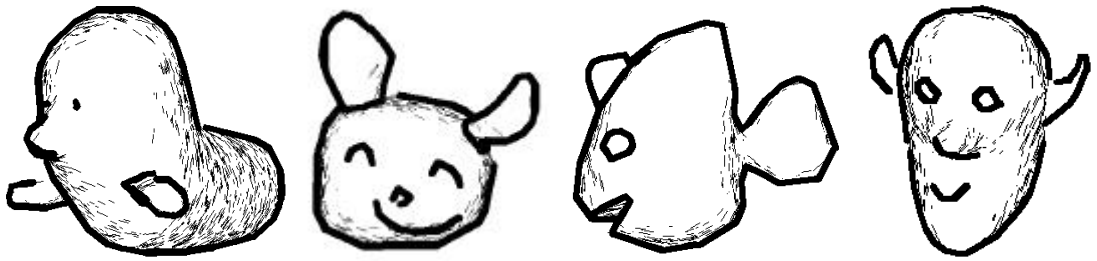


Figure 80. 3D models created by novice users in Teddy.

7.8. Future Work

Our current algorithms and implementation are robust and efficient enough for experimental use. However, they can fail or generate unintuitive results when the user draws unexpected strokes. We must devise more robust and flexible algorithms to handle a variety of user inputs. In particular, we plan to enhance the extrusion algorithm to allow more detailed control of surfaces. We are also considering using implicit surface construction techniques.

Another important research direction is to develop additional modeling operations to support a wider variety of shapes with arbitrary topology, and to allow more precise control of the shape. Possible operations are creating creases, twisting the model, and specifying the constraints between the separate parts for animation systems [103]. While we are satisfied with the simplicity of the current set of gestural operations, these extended operations will inevitably complicate the interface, and careful interface design will be required.

7.9. Summary

We introduced a sketching interface for freeform design, and described our current algorithm and the Teddy system implementation. Unlike other sketch-based modelers, our target is rotund, freeform models such as stuffed animals. The user specifies the silhouette of the intended model interactively using freeform strokes, and the system constructs a natural 3D model automatically. The user interface is significantly simple and easy to use, and our implementation achieves real-time construction of polygonal mesh based on 2D strokes. Our user experience has so far shown that first-time users could create various organic models within minutes using the system.

Chapter 8

Freeform User Interfaces Revisited

This chapter revisits the concept of the Freeform User Interface. While Chapter 3 explained the basic idea behind Freeform UI and defined it according to three basic properties, this chapter analyzes its characteristics and limitations based on our experience with the preceding four example systems. We also provide several design guidelines for refining Freeform UI systems.

8.1. Analyzing Freeform User Interface Systems

We now review the example systems described in the preceding chapters and other pen-based research systems for graphical applications from the perspective of Freeform User Interfaces. In the Figure 81, we rate the previous systems in terms of the three properties of Freeform UI: freeform strokes as input, perceptual processing, and informal presentation. The goal of these ratings is to clarify the idea of Freeform UI in the context of various research activities, rather than to evaluate each research project. The first five systems are two-dimensional, and the last four systems are three-dimensional.

System	Freeform strokes as input	Perceptual processing	Informal presentation
SILK [73]	△	—	○
Music Notepad [39]	△	—	—
Baudel's [6]	○	△	—

PerSketch [127]	○	△	○
Pegasus	△	◎	○
Path-drawing	○	○	△
SKETCH [161]	△	◎	◎
3D curves [22]	○	○	○
Teddy	○	◎	◎

Legend: Low High

—	△	○	◎

Figure 81. Interface systems with Freeform UI property ratings.

SILK [73] and Music Notepad [39] are gesture-based systems. The user's stroke must conform to a predefined gesture, and arbitrary shapes are not recognized. This falls short of the freeform stroking property. The system associates the stroke with an appropriate symbol using a simple-pattern-matching algorithm. This is, again, in contrast to the perceptual processing property, which aims to extract high-level implicit information from strokes. One important contribution of SILK is its use of a sketchy appearance. The recognized widgets are displayed in the form of freeform strokes without being replaced by cleaned-up graphics. The authors reported that the informal appearance facilitated the exploratory design activities.

Baudel's mark-based technique for editing spline curves [6] is a good example of stroking as a primary input. The user specifies a desired curve shape using a freeform stroke, and the system modifies the curve appropriately. The PerSketch system [127] is important in that it emphasizes the importance of perceptual structure in freeform drawings. However, it is basically a simple scribbling system and does not perform any high-level processing other than flexible grouping of line segments.

Current implementation of Pegasus does not sufficiently exhibit Freeform UI properties in that it supports only straight line segments. It is our future work to support curves and make Pegasus a complete Freeform UI. Pegasus's context-aware beautification and prediction are good examples of perceptual processing in that the system automatically

infers high-level structures the user might perceive in the diagram. Pegasus intentionally uses exceptionally thick line segments for displaying beautified segments in order to prevent users from drawing too-complicated diagrams and expecting excessive precision.

Path-drawing for 3D navigation exhibits Freeform UI properties to a reasonable extent. It uses arbitrary freeform strokes as input, and finds the desired path considering the structure of virtual 3D space. The painted path is presented in wide polyline in 3D scenes.

The Sketch system [161] uses simple gestures for placing 3D objects in the scene. Some gestures involve freeform strokes, but most consist of short straight line segments representing characteristic edges of geometric primitives. The system calculates the placement of objects in a 3D scene based on 2D input, considering the structure of the 3D scene and the user's natural expectation that an object must rest on top of another object. The authors introduced sketchy representation of 3D scenes, which was followed by many similar efforts in the computer graphics research community [81]. Like the SKETCH system, the sketch-based technique for 3D curves [22] infers the 3D shapes of curves based on simple relationships between lines and shadows.

Teddy is a strong embodiment of Freeform UI. It introduced a fluent, natural interface designed around stroke-based input for a task that has been considered significantly complicated and difficult. It automatically infers the 3D shape of an object from a 2D silhouette drawn by the user based on the assumption that typical freeform objects can be represented by rotund surface. Teddy uses special pen-and-ink renderings for displaying resulting 3D objects to facilitate exploratory activity and keep users from worrying about details too much.

8.2. Limitations

Freeform UI achieves fluent interaction that is not possible with traditional GUI, but several difficulties are inherent in it. This section discusses three major difficulties (ambiguity, imprecision and learning), and the next section proposes possible solutions to mitigate the problems.

Freeform UI is characterized by its *indirect* interaction style. Traditional command-based interfaces accept explicit command input and perform the command directly without any hidden processing. In contrast, Freeform UI accepts highly ambiguous freeform strokes as input, and performs complicated processing internally to infer the user's intention from the strokes. This *indirectness* enables simple and intuitive interaction, but at the same time the result of computation can be contrary to the user's own expectation and can cause frustration. The indirect operation is inherently associated with the problem of *ambiguity*. It is difficult to infer appropriate interpretation from the user's ambiguous freeform strokes, and the behavior of perceptual processing can be seen as ambiguous from the user's perspective.

Imprecision is another problem inherent in Freeform UI. While mouse-based careful manipulation of each control point in traditional GUI is suitable for editing precise diagrams, handwritten freeform strokes are not good at precise control. Perceptual processing and informal presentation are also incompatible with precise manipulation.

The indirect nature of Freeform UI also requires a *learning* process by the novice user. Because a simple stroke can transform to a variety of results, the user has to try many strokes and accumulate experience to master the operation. In other words, Freeform UI imposes certain implicit rules to infer complicated information from simple strokes, and the user has to learn the implicit rules through experience. The additional difficulty is that it is difficult to describe the operations of Freeform UI in a textual manual. However, once novice users understand the basic behavior of the operations, they can perform a variety of complicated tasks using a few operations. In contrast, it is relatively easy to learn a single command operation in traditional command-based interfaces, but the user has to learn many commands, and their combinations, to perform practical tasks.

8.3. Guidelines to Mitigate the Limitations

Based on our implementation and user study experience, we found several techniques and design guidelines to mitigate the these problems. Although it is impossible to remove these difficulties entirely because they are strongly associated with the essential nature of Freeform UI, the following tips work as basic guidelines to design a good Freeform UI system.

First, it is important to give users an appropriate impression that the system is not designed for precise, detailed editing; this will help prevent frustration over ambiguous, imprecise operation. We have already discussed that informal presentation is essential to arousing appropriate expectations about the system's behavior and to hide imprecise details. In addition, a designer can install similar tricks in many places, such as in the introduction to the system, in the system's feedback messages and in the user manuals.

From a technical point of view, construction of multiple alternatives is an effective way to mitigate ambiguity. This strategy is commonly used in Japanese text input systems to type thousands of Chinese characters using a limited alphabet. Pegasus constructs multiple alternatives as a result of beautification and prediction; this feature turned out to be essential to making beautification and prediction perform practically. Construction of multiple alternatives is definitely an important feature one should consider when developing a system based on Freeform UI.

As for the problems of learning and ambiguity, it is important to make the interface quick-responding and to ensure that changes can be easily undone so as to encourage trial-and-error experience. It would be considerably frustrating if a user had to input a lot of commands and wait a long time to see the result of computation for each operation. In order to assure comfortable interaction with ambiguous Freeform UI systems, the internal processing should return the result of computation instantly, and the interface should allow lightweight interaction. Sometimes, it is necessary to sacrifice the quality of computation to assure this quick response, which is in contrast to the fact that traditional command-based systems frequently keep the user waiting during complicated computations. For example, Teddy uses relatively simple algorithms to calculate geometry quickly sacrificing surface quality, instead of using more advanced, time-consuming algorithms.

Finally, it is necessary to give explanatory feedback for each operation so that the user can easily understand why the system returned the unexpected result. This kind of *informative feedback* is not very important in traditional command-based interfaces because the system response is always predictable. However, well-designed informative feedback is a crucial feature to prevent frustration and to facilitate the learning process in Freeform UI. For example, Pegasus displays small marks indicating what kinds of geometric constraints are satisfied by the beautified segment. In Teddy, many users

reported that the sound effect was very important to understand the system's behavior. We believe that informative feedback can allow the user to learn how to use the system without having to read manuals or tutorials beforehand; it is our future work to test this idea through practical implementation and user study.

8.4. Summary

This chapter discussed the concept of Freeform UI from various directions. To clarify the concept of Freeform UI, several interface systems were reviewed in the context of three Freeform UI properties. We pointed out that ambiguity, imprecision, and requirement for learning were the inherent difficulties of Freeform UI. Finally, the following design guidelines were proposed to mitigate the problem: Informal presentation of contents, generation of multiple alternatives, quickly responding, easily undoable system, and informative feedback.

Chapter 9

Conclusion

In this dissertation, we have addressed the problem of communicating informal graphical ideas to computers. This chapter briefly summarizes the work, and discusses some possibilities for future work.

9.1. Summary

Currently predominant WIMP-style GUI is not sufficient as the user interface design paradigm to meet emerging needs for computing outside of office applications running on desktop computers. Nielsen generalized these next-generation user interfaces as non-command user interfaces [100], which allow the user to accomplish various tasks on computers without having to give explicit commands. The goal of this dissertation is to propose a non-command user interface framework for exploratory activities in the domain of graphical computing.

We proposed an interface design framework for graphical computing based on pen-based input, and named it Freeform UI. It uses freeform handwriting strokes as input, allowing the user to convey graphical ideas to computers intuitively and fluently. The system then recognizes the configuration of the strokes and performs appropriate actions, freeing the users from tedious command operations. Finally, the system presents the result of computation using informal rendering, which facilitates creative thinking. Freeform UI is different from typical pen-based systems in that it analyzes the perceptual structure of the drawings instead of using simple pattern-matching. We described the following four example user interface systems as our basis for clarifying the strengths and limitations of Freeform UI.

Pegasus is a 2D drawing program based on interactive beautification and prediction.

The system infers possible geometric constraints in the user's freeform stroke input, and automatically beautifies the stroke satisfying the constraints. It generates multiple alternatives as the result of beautification, as a way to overcome the inherent ambiguity in freeform strokes. The system also predicts the user's next drawings from the surrounding context. Using beautification and prediction, the user can construct precise 2D geometric illustrations without using complicated editing commands. A brief user study showed that users can draw simple 2D diagrams more precisely and rapidly using interactive beautification than with traditional CAD and drawing programs.

Path-drawing is a pen-based interaction technique for navigating through virtual 3D environments fluently. The user draws the desired path on the 2D screen using a freeform stroke, and the camera and avatar move along the projected path on the walking surface. This technique frees the user from constant control caused by the driving technique, and provides richer control than the simple click-and-jump technique. Path-drawing navigation showed comparable performance and user satisfaction in our user study.

Flatland is an experimental electronic office whiteboard system. It was designed to support concurrent and continuous activities on personal office whiteboards as opposed to task-specific short-term activities in meetings. We introduced an efficient screen real estate management mechanism, pluggable application behaviors working on the surface and an efficient history management mechanism. The system works as an infrastructure for running various stroke-based applications including Pegasus and Teddy.

Teddy is a sketch-based 3D freeform modeling system. The user draws 2D freeform strokes interactively, and the system automatically constructs a reasonable 3D geometry. The system is unique in that it is designed for rotund, freeform models such as stuffed animals, which have been prohibitively difficult for the novice user to create with traditional 3D modelers. The system uses interactive non-photorealistic rendering to prevent the user from worrying about the details and to encourage exploration.

Based on these implementation efforts and user experiences, we observed that ambiguity, imprecision and the requirement for learning are the inherent difficulties of Freeform UI. We then proposed several design guidelines to mitigate the problems. For example, informal presentation of contents gives an appropriate expectation in the

user's mind, and the generation of multiple alternatives can address the problem of ambiguity to some extent.

9.2. Future Directions

The basic idea behind Freeform UI is to leverage the user's drawing ability in computing environments. The four experimental systems described in this dissertation are only a small sample of the broad possibilities. This section discusses some future directions to explore further possibilities of drawing-based interfaces.

Various 3D input devices and active force feedback devices [107,111] are already on the market. The idea of Freeform UI can lead to more-effective use of these devices than is current the case. In general, research efforts on 3D devices and force feedback devices focus on simulating the interaction style of the physical world in the virtual world. This is only a first step, which corresponds to scribbling programs for 2D pen-based systems. The next step should be to infer an advanced perceptual structure in the 3D trajectory and to achieve fluent interaction beyond simple scribbling. One inherent difficulty with these 3D devices is that people are not familiar with drawing strokes in a 3D empty space. Drawing on a 3D surface using force feedback devices is expected to be better than drawing freely in an empty space.

Motion can be represented as a freeform path with temporal information, and it might be possible to use freeform sketching for specifying character animation. The question is how to specify temporal information using freeform strokes. The temporal information is not included in physical sketching, and it is not clear what kind of interface metaphor works well for general users. It might be possible to use the movement of pen during drawing operation, but it can be unintuitive because people are not used to controlling temporal parameters during drawing.

Freeform strokes can be used to find similar drawings in a large picture database. Stroke-based information retrieval is discussed in the Electronic Cocktail Napkin project [49,50], but those designers use the configuration of simple primitives as the basis for calculating similarity. Their system can find drawings consisting of simple primitives such as a circle inside a rectangle, but it cannot find arbitrary freeform drawings such as a cat's silhouette. Geometric shape analysis methods, such as those

used in Teddy [113] can be a powerful tool for these shape-retrieval systems.

A natural extension of Pegasus and Teddy is to combine them. The idea is to integrate beautification and prediction into 3D drawing interfaces such as Teddy and SKETCH. Basic geometric constraints such as connection and symmetry are commonly seen in typical 3D objects, and it will be significantly helpful to satisfy these constraints automatically. One possible problem is that it is difficult to visualize multiple possibilities in a 3D space because they will inevitably overlap each other. It is also unclear how to let the user select one of several overlapping candidates.

As we have discussed in Chapter 7, the important challenge of Freeform UI is the design of informative feedback or situated exploratory helps. In command-based UI, it is relatively easy to describe the system's behavior to novice users because the system's reaction to each command is well defined and obvious. However, the relationship between the user's freeform stroke input and the system's reaction to it is complicated in Freeform UI, and informative feedback to each user's input stroke is necessary to make the user understand this complicated relationship without a manual and a tutorial. Although we have addressed this problem a little in Pegasus, nothing has been done along these lines in Teddy. It is in our future work to find a general framework for designing good informative feedback through implementation efforts and user study.

Adaptation and customization remain unexplored in this dissertation, but these mechanisms are critical to improving the productivity of Freeform UI systems. Perceptual processing is inherently ambiguous and arbitrary. Automatic adaptation and/or explicit customization are required to make perceptual processing produce appropriate results expected by individual users. It is relatively easy if the system generates multiple candidates. The system can learn the user's preference from what candidate the user selects. In the case of Pegasus, it is possible to learn what kinds of constraints the user prefers. A more complicated technique is to infer the user's preferences from the sequence of undo-and-retry operations. If the user dislikes a result of an initial stroke, redraws a similar stroke and is satisfied by the new result, the system can learn that it should generate the second result from the original stroke.

All systems introduced in this dissertation are research prototypes. The real evaluation and contribution of these ideas will come from the deployment of real products based on Freeform UI. Many issues must be addressed to make Freeform UI into successful

commercial products, including robust algorithms, intensive user studies, refined system design, and carefully designed manuals, tutorials, and informative feedback. We suspect that significant amounts of resources and trial-and-error processes will be required to develop these new kinds of application programs, but only such efforts can open new frontiers in computing.

9.3. Concluding Remarks

I was fascinated by pen-based computing when I saw the Xerox LiveBoard in 1995. I spent all day drawing various illustrations on the LiveBoard using Microsoft's paint program. It was fun, but I noticed that the system did not make the most of pen-based input, because the entire interface (Windows for Pen Computing) was designed for operation with a mouse. It was really frustrating to push buttons, select menus, and drag handles using a pen. In addition, the drawing activity in the paint program was essentially nothing more than drawing using a plain pen and paper. Handwriting character recognition and gesture recognition were commonly used, but I thought that something more could be possible with pen computers. This experience led me to explore various pen-based interaction techniques beyond mouse-oriented GUI and physical pen-and-paper drawings, and that in turn led me to come up with the concept of Freeform UI.

It is often the case that people simply apply traditional GUI to a new input device, or they simply import the device's physical interaction style into a computer, without considering the essential nature of the input device. For example, early voice recognition systems used a voice to select an item in a menu, and another typical program was just to record the voice without any processing. Another good example of poor application is an attempt to use an eye-tracking system to replace pressing buttons on a screen. These approaches may be useful to a certain extent, but ultimately, the most effective use of a new input device can only be possible by designing an appropriate interaction technique for the device. The biggest message of this dissertation is that one can design a powerful interaction technique by considering the essential strength of a new input device, instead of naïvely applying existing interface framework to the device.

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