CREATING A BASIS FOR THREE DIMENSIONAL SKETCHING

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ABSTRACT

The design process usually starts with rough doodles and sketches to create a basic visual representation of the solution to a problem. The processes from this conceptual stage to more detailed specifications has often been segmented between incompatible physical and virtual representations. This work explores digital 3D sketching using large touch panel displays and active pen technology for the use in the early stages of the design process. We focus on rendering high quality 3D curves in a free-form sketching environment. There are two major challenges we provide approaches for; transforming our low resolution input data to a resolution independent format, and rendering dense curve representations at high quality in real time.

BIOGRAPHICAL SKETCH

The author was born in Manhattan, New York on August 21st, 1991. Currently, he resides in Staten Island, New York. In 2009, he started undergrad at Cornell University. After graduating with a Computer Science degree, he entered the Program of Computer Graphics the following year.

I dedicate this thesis to my family and friends whose support helped make this possible.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The design process usually starts with rough doodles and sketches to create a basic visual representation of the solution to a problem. The processes from this conceptual stage to more detailed specifications has often been segmented between incompatible physical and virtual representations. Unfortunately, the answers to many important questions about the design are made during the conceptual stage without all of the information the designer needs, because getting this information requires a digital representation of the work that is currently too difficult to create during the rapid pace of the conceptual stage. Historically, there have been constraints to digitizing the conceptual design stage: displays were too small and the forced use of the mouse and keyboard were far more difficult to work with that the traditional methods of pen and paper. However, with the advent of large touch panel displays (e.g., the 55-inch Surface Hub Display), it is possible to implement a digital system that closely mimics a traditional conceptual design process.

In this work, we implement the basis of a sketching interface that allows the user to create drawings in three dimensions. The interface is capable of using modern input devices to approximate the act of real world sketching as closely as possible. These devices include a display capable of multi-touch input, as well as a special electronic pen which relays extra information not sent through regular touch input. For the sketch itself, we implement a spline-based data structure in order to store high quality, three dimensional strokes, that can be zoomed in without loss in quality. We also implement a three-dimensional line rendering library, as native line rendering implementations are poor quality.

When creating a three-dimensional model, much of the work is done on a computer using Computer-Aided Design (CAD) software specifically designed for the unique application. For example, in the architecture profession, Rhino and Revit are used to create building models. In the animation industry, Maya, Blender, and 3DSMax are used to create character models and complex scenery. In both cases however, the initial designs are still done using two-dimensional sketches, rough drawings not intended as the finished work. Sketches are generally not highly detailed works, as they intend to only capture the essentials of a final design. Through a number of rough sketches, a three-dimensional form can be implied through the representations of perspective and volume. This two-dimensional information is then used as a reference when designing the final three-dimensional model. Details of modern approaches to content creation on a computer are presented in Chapter 2.

Sketching is an old method of expressing ideas, and has a variety of techniques associated with the practice. Many professionals have been reluctant to use computer software, because the skills they have used and trained themselves in do not transfer to the digital medium. In recent years, technology has advanced to where the creation of specialized user input devices can allow better emulation of traditional sketching techniques. These devices are explored in Chapter 3.

Once we decide on what tools we will utilize for our system, we need to decide the interaction method. While there are a variety of approaches, we wanted an approach that mimics real world sketching. In our interface, a user sketches on a tablet device using an active pen. Displayed on the tablet is a three-dimensional scene that can be manipulated using touch and gesture in-

put. This scene contains geometry of some form that the user can sketch on.

While the solution appears to be simple, there are a number of challenges one must solve if one would like the end result to look good. A large challenge is the data we receive from the pen device is an approximation of the actual input stroke. While in traditional 2D computer sketching applications this would not be a problem, in 3D moving the camera causes the sketch to lose it's quality. In Chapters 4 and 5, we discuss how the rough, two dimensional user input is transformed into a high-quality, three-dimensional spline curve.

Once we have defined our three-dimensional curve, it is rendered using the OpenGL Library. However, the native support for displaying curves is limited, as many artifacts appear in the final curve when naively attempting to render them. Details on the approach we use to display our curves in high quality is discussed in Chapter 6.

CHAPTER 2

BACKGROUND / RELATED WORK

2.1 Two-Dimensional Image Representation on Computers

At it's most basic form, a sketch can be described as an image usually drawn on a planar two-dimensional surface. With computer displays, there are two standard methods for generating two dimensional images: raster graphics and vector graphics. The underlying data structures have a large impact on the types of tools that can be designed to create, modify, and display the resulting images.

2.1.1 Raster Graphics

Raster graphics is an image format that uses a two-dimensional grid to represent each pixel in the image. A raster image is characterized by its width and height in pixels and by its color depth, the number of bytes per pixel. The depth value specifies the color for each pixel, usually by identifying the magnitude of the pixel's RGB components. The reasoning behind representing images by this method is that today most computer monitors have bitmapped displays. Today, although there are many standard formats, almost all displays consist of rectangular arrays of square pixels, and the bandwidth from the display's memory is sufficient enough to dynamically render multi-megapixel images.

When creating and editing raster graphics images, the software directly manipulates pixel values, also known as pixel editing. This simplifies creating tools for editing raster graphics, since each tool can manually define how pixels are

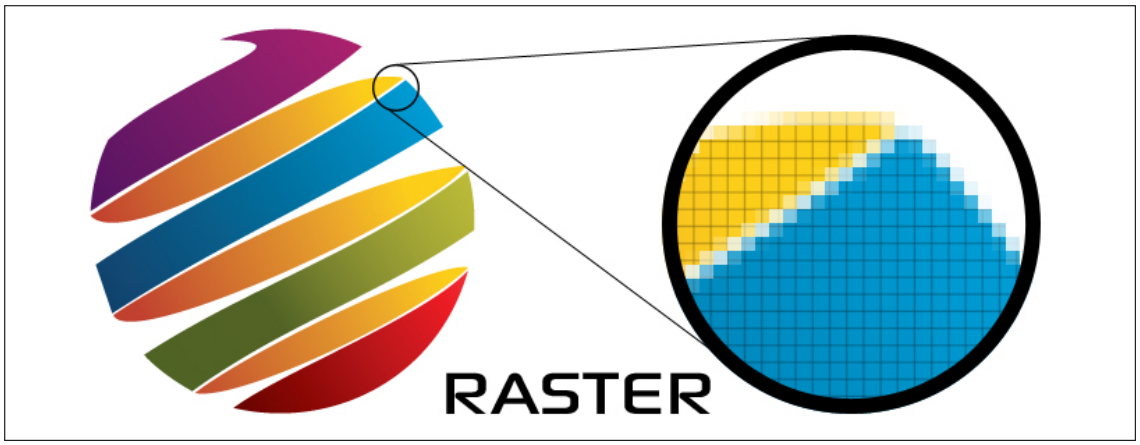


Figure 2.1: When we zoom in on a raster graphics image, we can see the image degradation that occurs from the pixel based storage format. [25]

effected based on where and how an input occurs. Unfortunately, the ultimate quality of an image based on raster graphics is limited by the fact that the picture is resolution dependent. The resolution of the image is independent of the resolution of the display, and it is possible for raster images for contain very large amounts of information, as can be seen from the Gigapixel Project [17]. However, even this still has it's limits. If you were to continuously zoom in on a raster image, eventually the image would eventually suffer from image degradation. This resolution dependency also means that raster images are not flexible for working with extremely detailed environments. It is possible for multiple small details to be contained inside of a single pixel. Since a pixel can only store one color, all of these small details are lost.

Examples of popular raster graphics software are Corel Painter [21], Adobe Photoshop [23], Microsoft's MSPaint [19], the open-source GIMP software [15], and Autodesk's Sketchbook [27].

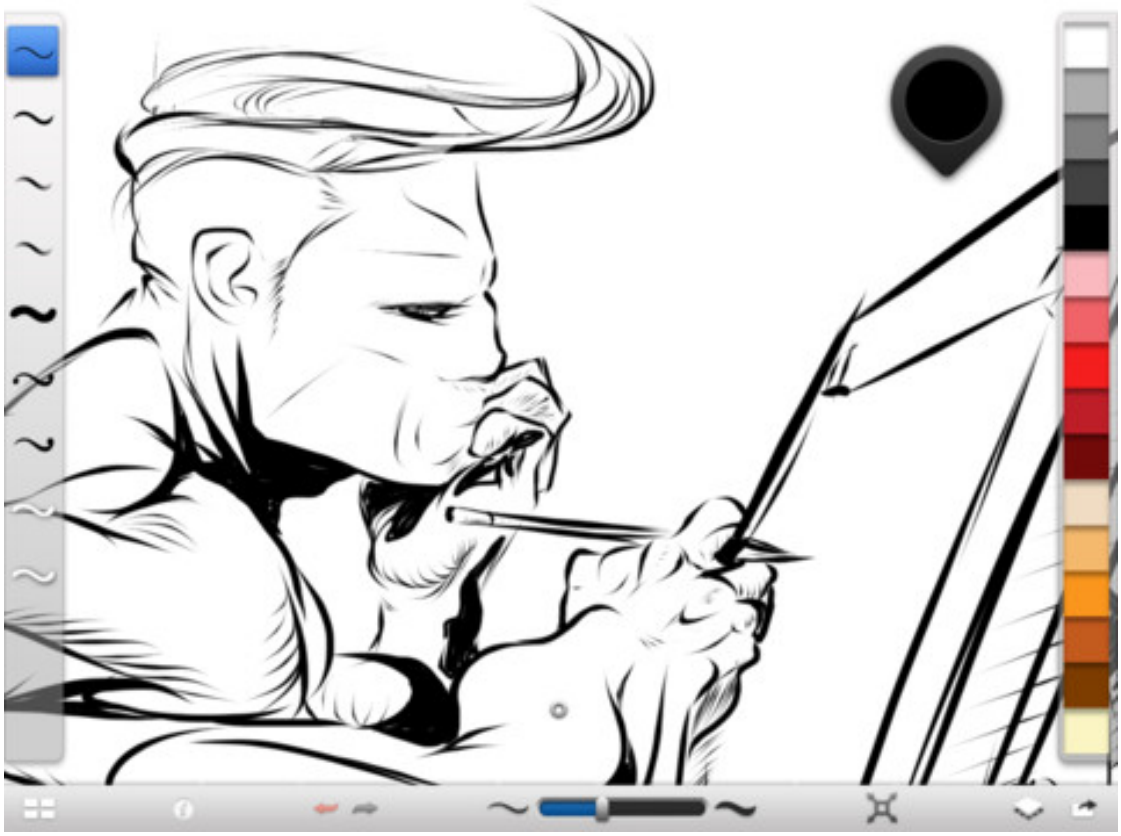


Figure 2.2: An artist creates a raster image using Sketchbook. The software comes with a variety of pen styles and tools to help simulate a physical art studio. [27]

2.1.2 Vector Graphics

Vector graphics software uses geometrical primitives such as points, lines, curves, shapes and polygons to represent an image. Each of these primitives has a defined geometric coordinate within the work space and determines the direction of the displayed vector. Vectors can also be assigned a variety of properties such as its color and thickness. Although the resolution is limited by the computer's numerical precision, it is independent of the actual display.

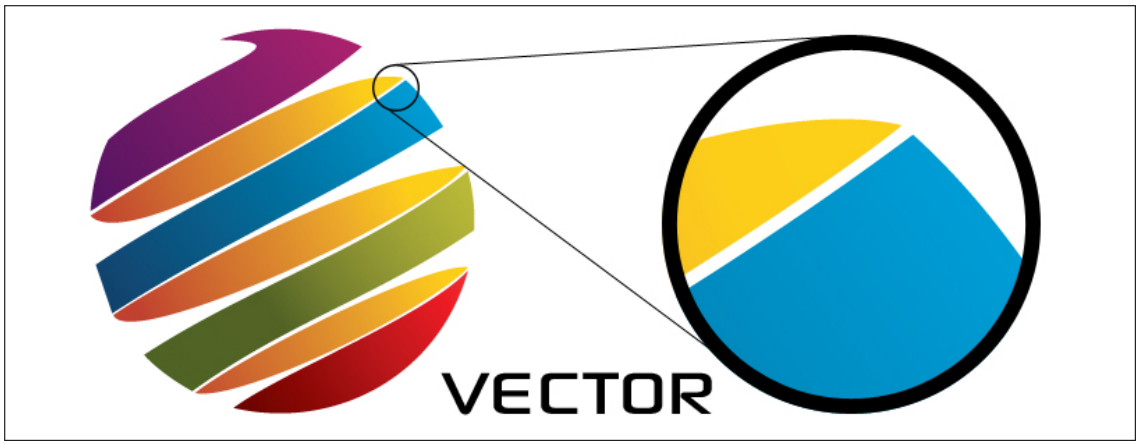


Figure 2.3: When we zoom in on a vector graphics image, we can see the lines remain smooth, unlike in a similar raster graphics image. (Figure 2.1.1) This is because of the underlying mathematical representation of the shapes in the image. [25]

Because of the mathematical nature of vector graphics, they are theoretically similar to three-dimensional computer graphics, but the term specifically refers to two-dimensional images; in part to distinguish them from raster graphics. Vector graphics are primarily used for line art, images drawn with distinct straight or curved lines. For example, early CAD systems mostly used calligraphic black and white displays and rendered images in vector graphics formats. However, today, data in vector graphics form is now converted to raster graphics formats when used outside of vector specific editing software.

Vector graphics data structures offer a number of advantages compared to raster approaches. First, they are based on mathematical expressions, which means they are resolution independent. Zooming in on the image does not cause image degradation as in raster graphics; the image will remain smooth. Second, objects made using vector graphics are independent from their visual representation. This allows for easy and accurate editing of primitives, pro-

vided they are contained in a vector graphics workspace. For example, assume we have an image of a circle covering a part of a square. In vector graphics, the circle can be moved without effecting the square beneath, because the data structure contains the information about both objects independently from their visual representation. This type of editing is not possible in a single raster graphics image, because the underlying pixel representation does not contain the definition of objects in the image.

Examples of popular vector graphics editing software are Adobe Illustrator [14], Corel Draw [8], and Inkscape [13].

2.1.3 Adaptively Sampled Distance Fields

In addition to the most commonly used data structures (raster and vector graphics), methods combining the capabilities of both approaches are beginning to emerge. An example of this is a new data structure called adaptively sampled distance fields [10] (ADFs). A distance field is a scalar field that specifies the minimum distance to a shape, where the distance may be signed to distinguish between the inside and outside of the shape. In ADFs, distance fields are sampled according to local detail and stored in a spatial hierarchy. ADFs are capable of representing a large class of forms, while reducing the storage size to a fraction of a traditional spatial data structure.

Mischief [9], a pseudo-vector graphics based drawing application. Although its underlying shape representations are mathematical, similar to those in other vector graphics applications, it does not allow for the precise editing of curves and shapes as seen in traditional vector graphics programs such as Adobe Il-

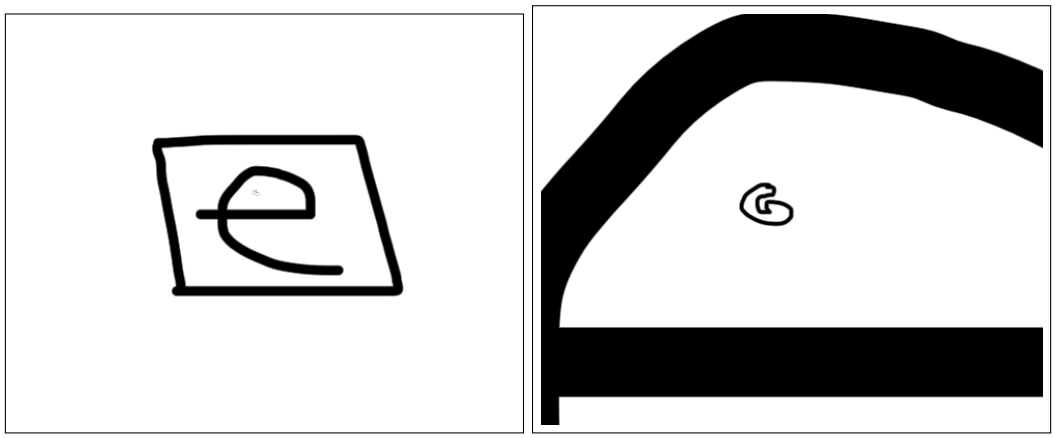


Figure 2.4: An example of the infinite canvas in Mischief. The work space can be continuously zoomed in upon without loss in quality.

lustrator. Instead it attempts to use vector graphics to simulate real world art techniques, similar to Sketchbook. This is made possible by using ADFs to store the complicated details and shapes of real world brushes. Mischief is also able to utilize the efficient storage capabilities of ADFs for the implementation of their ”infinite canvas”; their infinitely zoom-able, translatable workspace. This unique data structure allows for Mischief to achieve incredible detail and unlimited scale.

2.2 3-D Sketching in CAD

In order to overcome the limitations of 2D sketching, there have been many previous attempts to utilize 3-D sketching in the design process. In this section, we will describe some of the better recent examples others have previously either implemented or published. A common weakness in each of these methods is that to date none of them implement a way to generate geometry directly from the sketch.

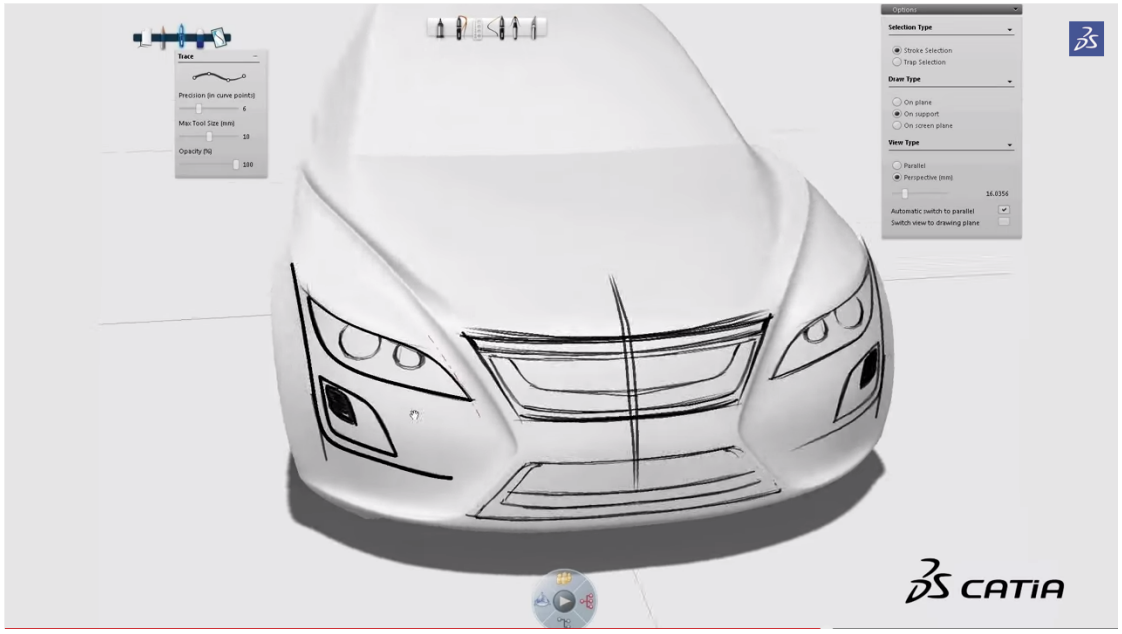
2.2.1 CATIA Natural Sketch

Natural Sketch is a feature inside of the CATIA modeling software[4]. Natural Sketch allows the user to draw on a virtual two-dimensional plane that can be manipulated around the 3-D environment, a surface of an arbitrary 3-D model, and a "clipping plane". It's sketching features include the ability to alter the pen style, to automatically change the camera view to align with the drawing plane if one is being used, and to copy and alter individual strokes.

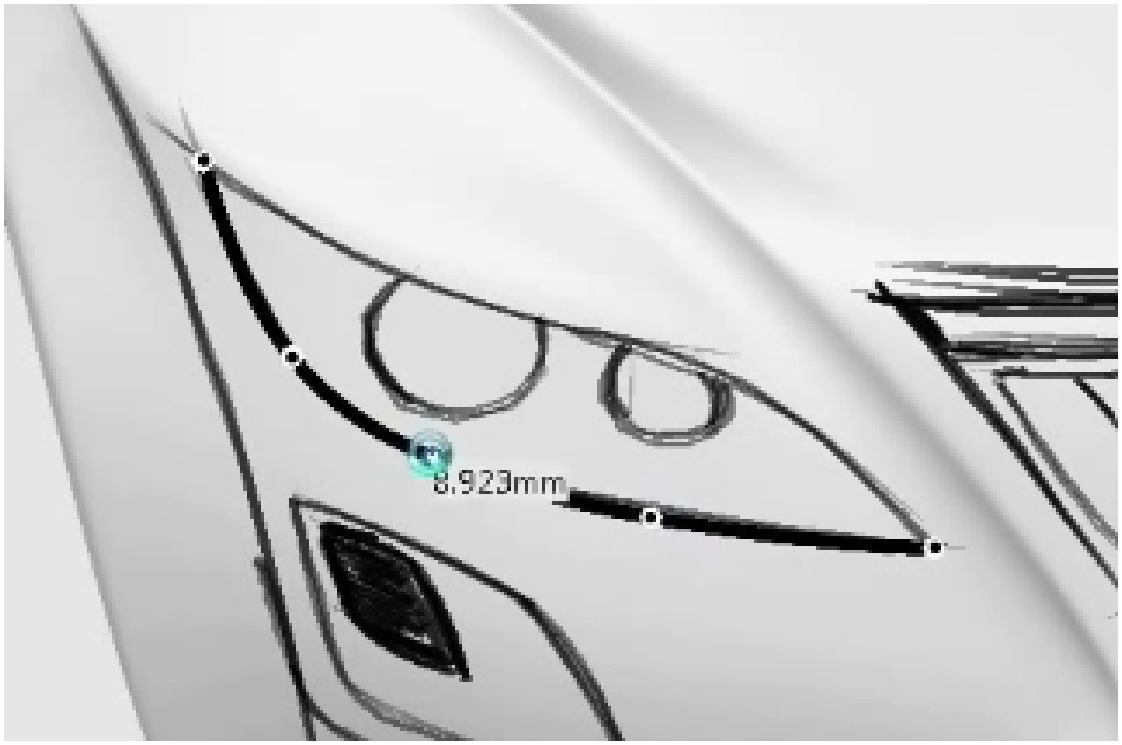
Natural Sketch uses a two-phase design system. First, the user creates a "rough sketch", where lines are rendered exactly as drawn. Afterwards, the user can trace over their already drawn lines to produce smooth curves from the initial sketch. As will be describer in Section 4.2, CATIA is based on spline technology, which allows for this smooth curve generation. These curves also contain a user defined number of editable geometric knots, which allow the user to alter the shape of the traced curve. While this system closely has the capabilities we would like to implement, it is currently only available in a solid modeling environment, making it incompatible with many tools most designers use to create early stage 3-D sketch models.

2.2.2 EverybodyLovesSketch

EverybodyLovesSketch [3] is a 3D curve sketching system from the University of Toronto's Dynamic Graphics Project Lab. It features a pen based gesture system, allowing the user to execute functions using rapid strokes, circles, and other predefined stroke patterns. Other features include dynamic sketch plane selection using previously drawn strokes, single view definition of arbitrary ex-



(a) Details are added to a base model.



(b) A rough sketch can be traced with editable spline curves.

Figure 2.5: (a) An example of using Natural Sketch to add detailing on the curved surfaces of an existing car model. (b) The rough sketch can then be emulated with Catmull-Clark splines. [5]

trusion vectors, multiple extruded surface sketching, copy-and-project of 3D curves, free-form surface sketching, and an interactive perspective grid. EverybodyLovesSketch is based off of previous work by the same lab, ILoveSketch, which contains the base 3D sketching functionality.

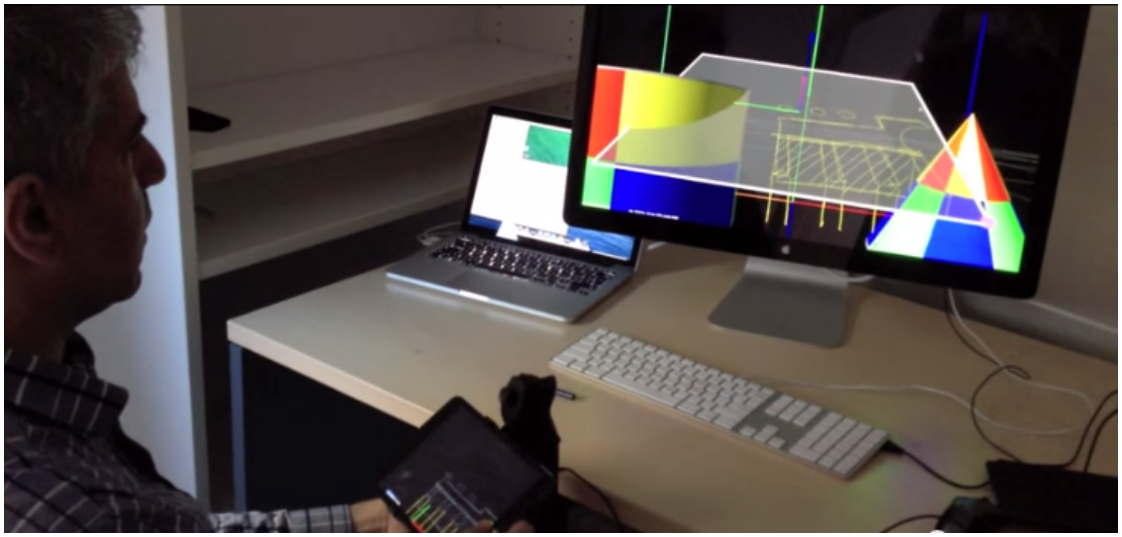
2.2.3 Hyve3D

Hyve3D [7] is an infinite virtual sketching environment from the University of Montreal. It uses two screens; a computer monitor to show the 3-D environment, and an iPad for the drawing surface. The sketching plane represented by the iPad is shown in the virtual environment, and is manipulated by moving and rotating the iPad in the real world. The user then ”pins” the sketch plane in place and proceeds to draw at leisure. The advantage of this system is that it combines real world manipulation with virtual representation, eliminating the need for complex user interfaces and gestures. The disadvantage is that this kind of movement has no one-to-one feedback between the real world and the virtual world, meaning that it is difficult to judge how your movements of the iPad effect the exact positioning of the drawing plane without confirming it visually.

2.3 3-D Sketching in 3-D

3-D content creation on a traditional computer screen is implicitly constrained. Any type of input or user interface is limited by the fact that one dimension of the workspace will always be inferred due to the two dimensional output.

(a) A user using an iPad to sketch on a plane inside of the virtual environment.



(b) Manipulating the drawing plane by manipulating the iPad

Figure 2.6: (a) An example of using Hyve3D to draw inside of a virtual environment. (b) The user utilizes an iPad as both the physical sketching surface and the tool to position the virtual sketch surface. [7]

Figure 2.7: Augmented reality sketching using the Gravity tablet and headset. The tablet is used to define the location of the sketch plane in the ”virtual” workspace, which can then be drawn upon. [22]

Work in this space explores alternative devices that work with methods of three dimensional input. The result has been leveraging a number of emerging technologies that deal with input and output that is experienced in three dimensions. While the output for the methods described in this section is either virtual or physical, the input is provided in the same way; a user physically moves a device in three-space to create content.

2.3.1 Virtual Reality / Augmented Reality

Recently, there have been two key technologies developed with the intention to immerse the user in a virtual environment or combine virtual images with real environment, termed augmented reality. Both of these involve head-mounted

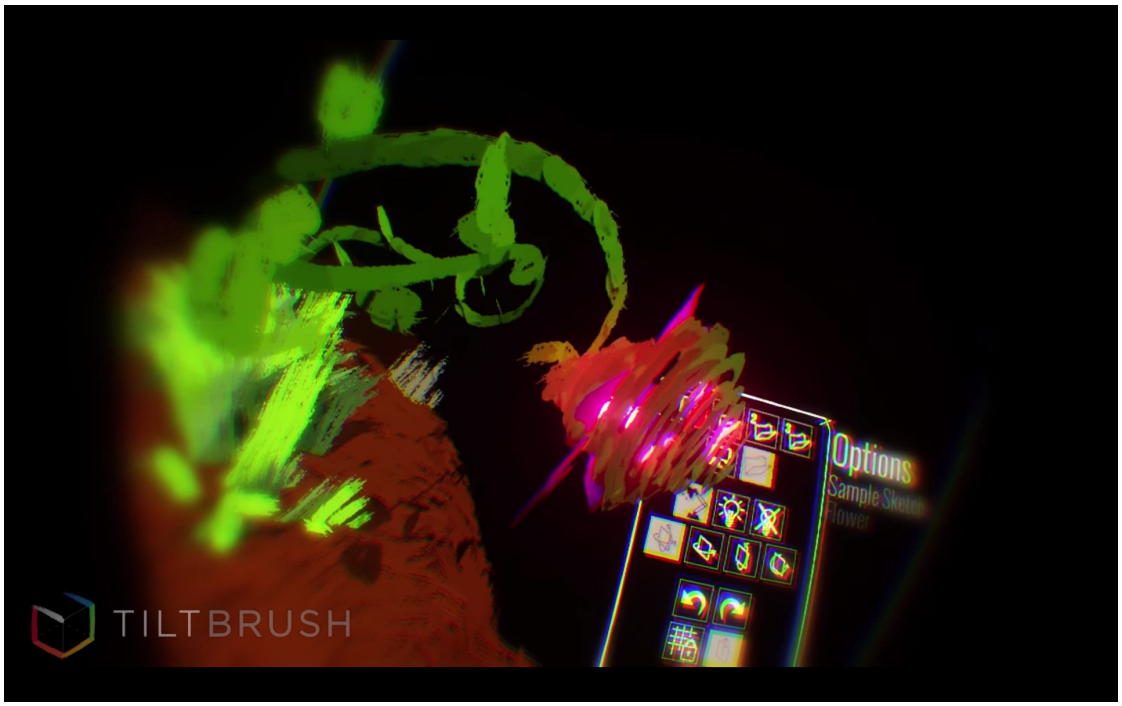


Figure 2.8: Virtual reality sketching using Tilt Brush. The user can sketch in a virtual environment in a manner similar to light painting.

displays (HMDs) that display two two-dimensional stereo images. Despite the images being flat, the system takes advantage of how humans see, such that the user feels the presence of actually being inside of the virtual or augmented reality environments. The advantage to using these virtual systems is the parallax from the stereo images allows the user to fully be immersed in the space they are working in. Unfortunately for input tasks, the downside of these systems is that their input methods are essentially drawing in midair; there is no tactile feedback similar to a pen pushing against a piece of paper. An example of an augmented reality approach to 3-D sketching is Gravity Sketch [22], and one of a virtual reality approach is Tilt Brush [28]. Gravity sketch uses a tablet as a sketching surface as well as a tool to manipulate the sketching environment. Tilt Brush uses a game controller to draw in the air in a manner similar to light

Figure 2.9: 3-D drawing using a 3-D printing pen. [24]

painting.

2.3.2 3-D Printing

So far, we have implied 3-D sketching is only possible in virtual environments, due to using the inherent two dimensional techniques artists have developed for centuries. However, groups have experimented with using 3-D printing to create pens that can sketch simple 3-D models; examples being the Polyes Q1 Pen [24] and the 3Doodler [1]. These pens work similarly to hot glue guns, except instead of glue, the pens secrete ABS plastic that quickly hardens as it exits the tip of the pen. Like the digital approaches, these pens lack tactile feedback, and rely purely on the user's sight to sketch. Unfortunately, between the apparent structural instability of even small models created by the pen, as well as the

lack of flexibility in the way the pen can be used, it appears that this route is impractical for creating the types of large and intricate structures seen in modern design.

CHAPTER 3

INPUT TECHNOLOGIES AND HUMAN COMPUTER INTERACTION

An important goal for any user interface is to have the human-computer interaction be as intuitive and natural as possible. Natural interaction is critical for a sketching interface; while younger, more technologically willing professionals flock to digitized content creation software, those classically trained prefer to stick to physical methods. In order to convince the latter to adapt to a new system, the transition process must be as smooth as possible, so as many of the techniques utilized in the physical system should be emulated as closely as technology allows in the digital system.

A key element for bridging the gap between physical and digital tools are input devices, computer hardware used to control electronic devices. For a long time, the most common input devices for digital environments have been the mouse and keyboard, which provide rather unintuitive ways to move and control the computer. However, in recent years there have been a number of advancements in the human-computer interaction field, which has produced a wide array of input devices. In this chapter, we will discuss human-computer interaction principles used to decide how to best utilize input devices, as well as discuss the particular devices needed to create a good sketching system.

3.1 Input Classifications

3.1.1 Modality

In human computer interaction, a modality is a channel of sensory input/output between the human and the computer. Modalities can be split into two general types: human-computer, and computer-human modalities.

Human-computer modalities describe the ways humans input information to the computer. These modalities are devices and sensors attached to the computer. Common input device modalities are keyboards, pointing devices, and touch screens, while more complex modalities are computer vision, speech recognition, gesture recognition, and orientation. In sketching, the equivalent of a human-computer modality is the sketch implement. Whether the tool is a pen, pencil, charcoal, or something else, the artist provides "data" to the sketching surface through his strokes by sending information like position, angle, and pressure.

Computer-human modalities describe the ways the computer outputs information to communicate with humans. This requires stimulation of one of the human senses: sight, hearing, taste, smell, touch, balance, temperature, and pain. Of these, modern input devices generally communicate using sight and hearing, because they are capable of sending information at much higher speeds and larger bandwidths, as well as being the more common ways humans communicate with each other. There are also small uses of haptics, general vibrations or other movement, to provide feedback, but generally they are accompanied by visual and auditory cues.

While working on this project, it became apparent that professionals are very sensitive to a complex combination of input and output modalities, some of which are not reflected well by current hardware capabilities. For example, an architect commented while drawing on the large display that he felt uncomfortable because the digital pen pressing against the display didn't feel like a physical pencil brushing against a piece of paper. The difference in friction and materials meant that he was unsure of how things like pressure and angles effected his drawing. This problem is a result of both the limitations of the input device, as well not providing proper feedback for his actions. On this project, we focus more on the input modalities, but for a truly realistic sketching system, specialized hardware must be utilized in order to closely emulate these intricacies.

3.1.2 Direct and Indirect

Direct and indirect input refer to how the input space corresponds to the display space. With direct input, the two are directly correlated. For example, on a touch screen, where you touch is where the input is recorded. With indirect input devices, the input value is only relative to the input space. Moving a mouse three inches can correspond to movement of any kind on the computer screen. For example, in desktop settings, moving the mouse to the left three inches can correspond to a variety of moments on the computer screen. In a three-dimensional application it can cause the user to move left, or turn left.

Indirect input devices have the advantage of being more application independent. However, this comes at the cost of accessibility. A mouse can do many

things, but the user must learn what it does in the current context. Direct input methods tend to be intuitive while limited in scope. The user knows touching a screen at a spot causes an action at that spot.

As will be described later, when physically sketching, most if not all interactions are direct. There are minute indirect details such as different drawing implements which can produce different strokes with the same input, but on a high level there is a one-to-one spatial correlation between actions and results. Therefore, for this project, it is important to minimize any indirect interaction between the user and the system. For any indirect interaction, we should try to minimize the complexity of the difference between the input and output spaces.

3.2 Input Devices

3.2.1 Keyboard

A keyboard is an indirect input device using an arrangement of buttons or keys, acting as mechanical levels or electronic switches. Common keyboards are typewriter style devices, with many buttons representing alphanumeric characters as well as a small number of additional function keys. Desktop keyboards usually have from 100 to 105 keys, while laptop and other small device keyboards contain less. All standard keyboards have a typing area used for letters of the alphabet, numbers, punctuation, and other basic characters. However, there are also composite devices that have keyboard like features, such as video game controllers. Game controller buttons offer contextual and situational functionality depending on the application in use.

There are certainly auxiliary areas in good sketching software where a keyboard of some kind should see use; for example, saving files, but for the core of the application, the user should never use one. Many design applications such as Maya use a combination of function and character keys to perform actions, bringing a significant learning curve in order to use these applications effectively. This results in an interface that is unnatural, and requires application specific skill-sets. For this project, we try to avoid use of the keyboard as much as possible.

3.2.2 Pointing Devices

A pointing device is a device that more easily allows a user to input spacial data to a computer. Many common input devices fall under this classification. CAD systems and graphical user interfaces allow the user to control and provide data to the computer using physical motion. These movements are then echoed on the screen in some way, whether it be by an on-screen cursor, or some change in the visual output. Pointing devices are usually controlled by either physical movement of an object, or touching a surface. Examples of devices based on motion are the mouse, trackball, and joystick, and those based on touch are the graphics tablet, stylus, touchpad, and touch screen.

Mouse

A mouse is a small, hand-held device that is pushed over a flat, horizontal surface. Older mice used a physical ball at the base of the device, combined with sensors to detect when the ball rotates. When the mouse moves and rotation is

sensed, the distance and directional information is sent from the mouse to the computer. A more modern approach is the optical mouse, which uses infrared light instead of a roller to detect changes in position.

The mouse is the oldest pointing device, and used with every desktop computer. The mouse works in an indirect space as the position of the mouse and that of the cursor on screen are completely unrelated. When a mouse is moved ten inches to the left, the movement of the mouse cursor on screen is not ten inches, but some function with ten inches as input. As discussed previously, we would like to eliminate indirect input where ever possible. While it will be possible to use the mouse with our application, it should be seen as legacy functionality.

Tablet

A graphics or digitizing tablet is a special tablet that is similar to a touchpad. However, it is controlled with a digital pen or stylus that is held and used like a normal pen. An alternative control device for tablets is called a puck. This is a mouse-like device that can detect absolute position and rotation. Professional pucks used for detailed CAD work have a reticle which allows the user to see the exact point on the tablet's surface targeted by the puck. Graphics tablets are commonly used to create 2D computer graphics because of their input similarities to traditional drawing techniques. Tablets are very commonly used for digital sketching applications. However, many graphics tablets are used in combination with a screen, meaning there is still a visual and physical disconnect between the sketch and the output.

Pen

As mentioned above, touch panels can be used with rigid styli to simulate the experience of writing. However, the pen itself can also be computerized to capture additional information for various applications. An active pen is an input device that includes electronic components and allows users to write directly onto the display surface of a computing device. The active pen's electronic components generate wireless signals that are picked up by a built-in digitizer and transmitted to its dedicated controller, providing data on pen location, pressure and other functionalities. Additional features enabled by the active pen's electronics include *palm rejection* to prevent unintended touch inputs, and *hover*, which allows the computer to track the pen's location when it is held near, but not touching the screen. Most active pens feature one or more function buttons (e.g. eraser and right-click) that can be used in place of a mouse or keyboard.

3.2.3 Touch Screen Devices

A touch screen can be considered as an input device layered on top of a display. Users provide input by touching the screen with one or more fingers, or with a special stylus/pen. This method of input allows users to directly interact with what is displayed, as opposed to using an indirect input device such as a mouse or touchpad.

One major advantage touch screens offer over other input devices is ease of use. While frequent computer users are familiar with using a mouse and keyboard, touching icons on a screen is intuitive even for those with limited to no computer experience. This ease of use can reduce the learning curve and

increase productivity when using these types of user interfaces. Touchscreens are also faster to use than traditional input methods. When a user interacts with a computer using a mouse and keyboard, there are many small adjustments the user needs to make; they need to locate the pointer, and adjust for the mouse acceleration. Direct interaction allows for users to interact with the computer without worrying about correlating the interaction space to the virtual space.

There are many ways to build a touch screen. The key points in any implementation are to recognize one or more input points touching a display, to interpret the command these touches represent, and to communicate with an application. The three main types of touch sensing technologies are resistive sensing, surface acoustic wave sensing, and capacitive sensing.

Resistive Sensing

Resistive touch panels are composed of two thin, flexible sheets coated with a resistive material and separated by a small gap. A resistive touch monitor features a simple internal structure: a resistive panel is placed on top of a glass screen, with a polyester film screen on top of the panel used as the contact surface. Pressing the surface of the film screen causes the electrode-covered sheets between the film and glass panels to come into contact, resulting in the flow of electrical current. The point of contact is identified by detecting this change in voltage. (Figure 3.1)

Resistive technology is low cost due to the simple structure of the touch screen and controller circuit. Analog sensors have high resolution, the most common being 4096 by 4096 dots-per-inch (DPI), as well as high accuracy, while

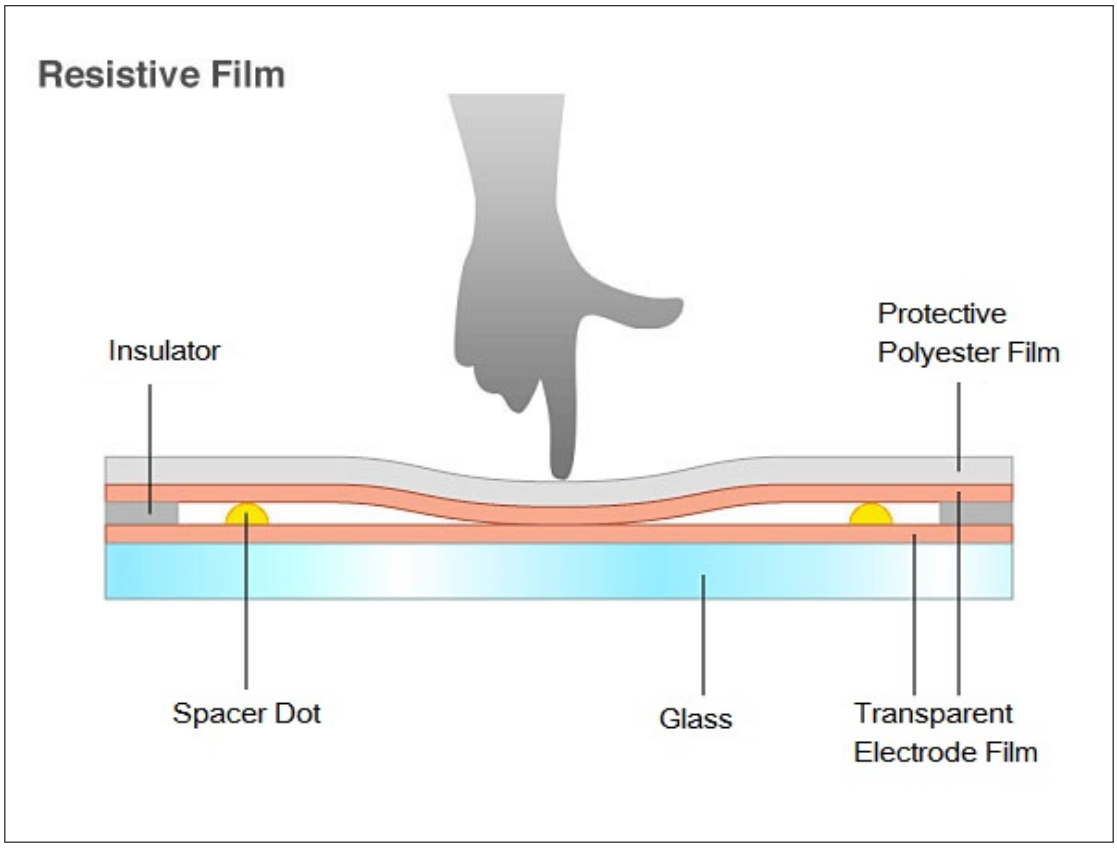


Figure 3.1: When a user interacts with a resistive touch panel, they press against a protective polyester film. At the touch point, two sheets of electrode covered film press against each other, causing an electric current. [12]

consuming low amounts of power during operation. This DPI refers to the number of sensing dots-per-inch, and is uncorrelated to the display DPI. Resistive touch screens can be used with any object that can provide a pressure point, since the system only requires contact. This allows for users to use pens and gloves to interact with a device. Disadvantages include it's poor responsiveness compared to other developed sensing methods, generally requiring harder presses, providing lower light transmittance causing a reduction in screen quality, and a decrease in accuracy with large screen sizes (>24 inches). While high

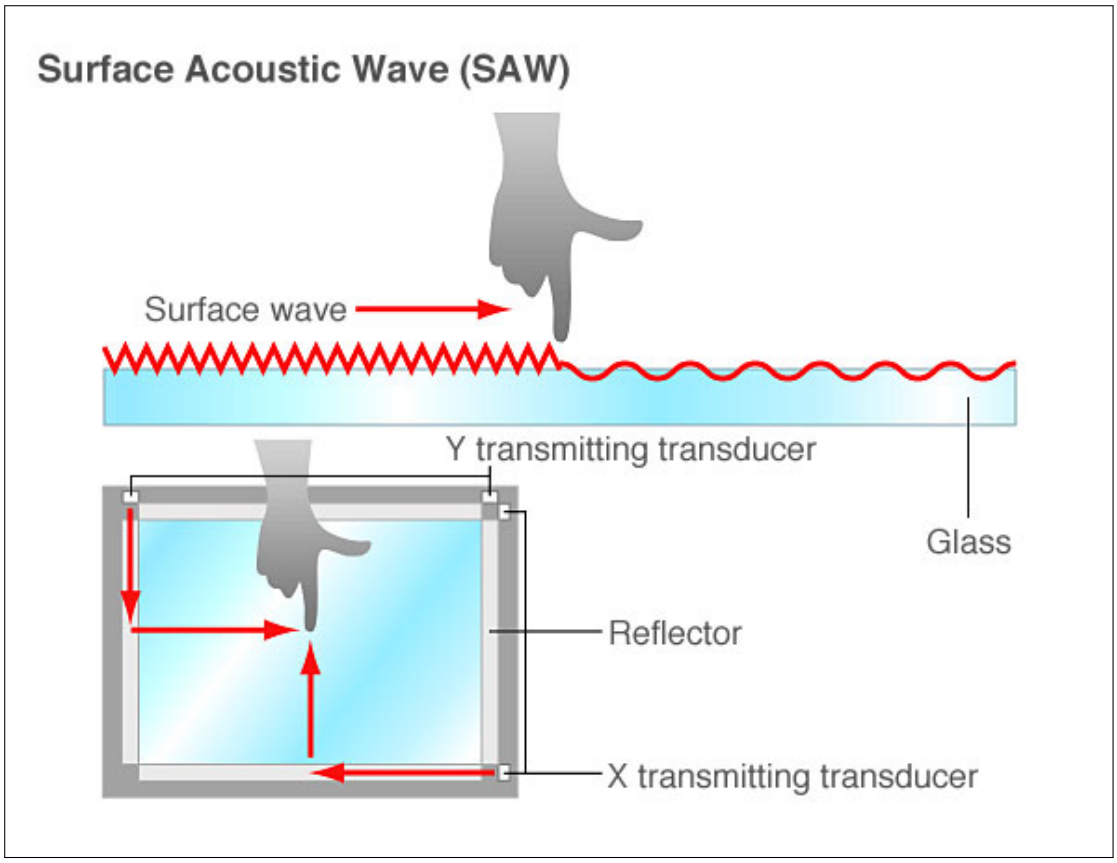


Figure 3.2: A surface acoustic wave sensor transmits vibrations across the surface of a glass screen. When the screen is touched, the vibrations are absorbed and attenuated by the touch object. [12]

resolutions would allow for more accurate and more detailed sketching, the poor responsiveness would make resistive panels a poor substitute for traditional drawing media.

Surface Acoustic Wave (SAW) Sensing

Surface acoustic wave (SAW) technology was developed to achieve bright touch panels displays with high levels of visibility; mainly to address the drawbacks of low light transmittance in resistive film touch panels. These are also called surface wave or acoustic wave touch panels. Aside from standalone LCD monitors, these are widely used in public spaces in devices like point-of-sale terminals, ATMs, and electronic kiosks.

These panels detect the screen position where contact occurs with a finger or other object using the attenuation in ultrasound elastic waves on the surface. The internal structure of these panels is designed so that multiple piezoelectric transducers arranged in the corners of a glass substrate transmit ultrasound surface elastic waves as vibrations in the panel surface, which are received by transducers installed opposite the transmitting ones. When the screen is touched, ultrasound waves are absorbed and attenuated by the finger or other object. The location is identified by detecting these changes. (Figure 3.2)

The strengths of this type of touch panel include high light transmittance and superior visibility, since the structure requires no film or transparent electrodes on the screen. Structurally, this type of panel ensures high stability and long service life, free of changes over time or deviations in position. Even if the surface does somehow become scratched, the panel remains sensitive to touch. Weak points include compatibility with only fingers and soft objects (such as gloves) that absorb ultrasound surface elastic waves. These panels require special-purpose styluses and may react to substances like water drops or small insects on the panel. This sensing method, like resistive sensing, is more suitable for public displays that see heavy use. While high quality displays are

desirable, the relative inflexibility of input capabilities limit SAW powered displays for use in sketching applications.

Capacitive Sensing

Capacitive touch panels use the natural flow of electricity through the human body, also called body capacitance, as the input signal. They are most commonly used in consumer level hardware such smart phones, tablets, and LCD monitors. They are constructed from a wide variety of materials, such as copper, Indium tin oxide (ITO), and printed ink. Unlike resistive film touch panels, capacitive touch panels do not respond to touch by clothing or standard styli. They feature strong resistance to dust and water drops and high durability and scratch resistance. In addition, their light transmittance is higher, as compared to resistive film touch panels allowing for higher quality displays. There are two types of capacitive technology; surface capacitive and projected capacitive systems.

Surface Capacitive Sensing is often used for larger sized displays (over 14 inches) that are used by the general public because of their high durability and high screen quality. Surface capacitive displays can be seen on ATM machines, ticket kiosks, arcade games, automation devices in factories and offices, and in the medical industry.

A surface capacitive panel is constructed using a glass sheet. A transparent conductive coating is placed over the sheet, and a glass protective coating is

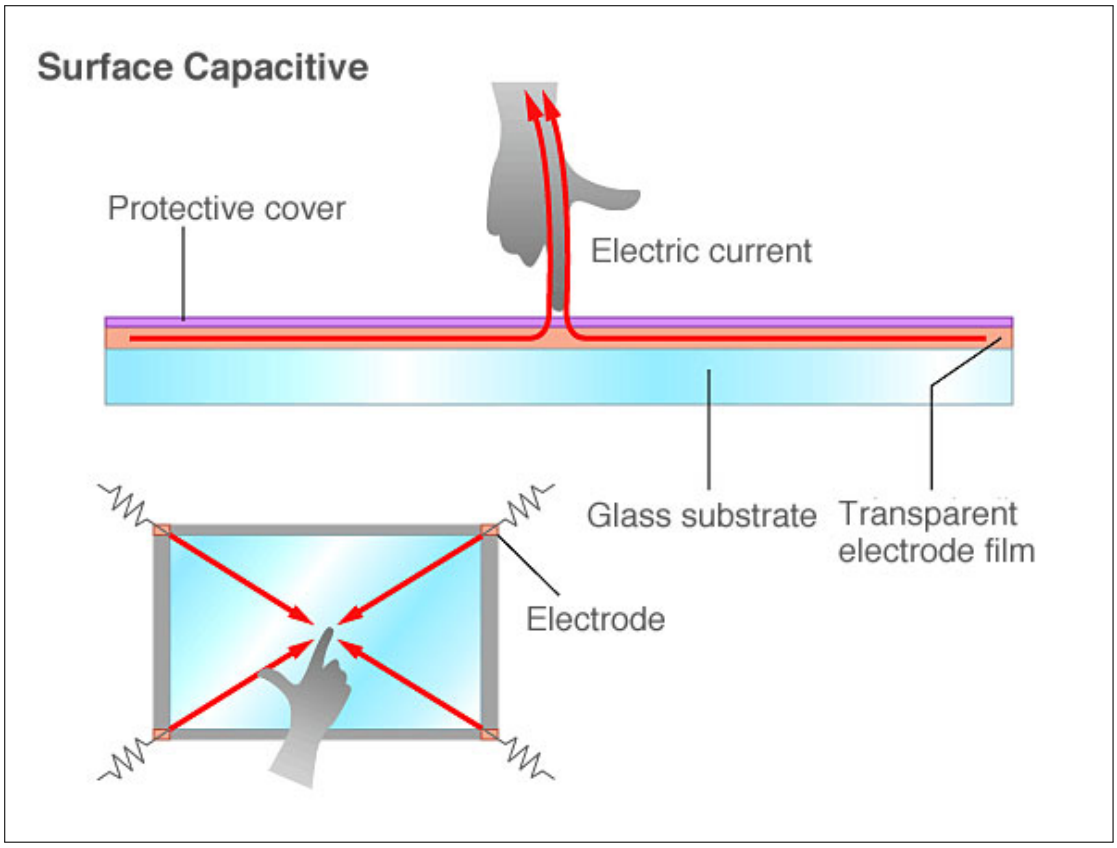


Figure 3.3: In a surface capacitive sensor, a uniform electric field is generated over a glass panel from electrodes on the panel's four corners. When a user touches the panel, current flows from each of the corners through the finger. [12]

placed above that. Electrodes are placed on the four corners of the panel.

If the same phase voltage is imposed to the electrodes on the four corners, then a uniform electric field will be formed over the panel. When a finger touches the panel, electrical current flows from each of the four corners through the finger. The ratio of the electrical currents flowing from each of the four corners is measured to detect the touched point. The measured current values will be inversely proportional to the distance between the touched point and each of the four corners. (Figure 3.3)

A surface capacitive touch panel has a simpler structure than a projected capacitive touch panel (see below). This allows for lower cost in production, high durability, and high visibility due to the main structure being a single glass layer. However, it's simplistic structure also means it is structurally difficult to detect two or more contact points simultaneously. Surface capacitive can usually only detect bare finger touches, although some may detect touches through a thin pair of gloves. Surface scratches can cause touch signals to get interrupted. Some surface capacitive displays support pen writing, but not simultaneous pen and touch.

Projected Capacitive Sensing is often used for smaller screen sizes than surface capacitive touch panels. They've attracted significant attention in mobile devices. The iPhone, iPod Touch, and iPad all use this method to achieve high-precision multi-touch functionality and high response speed. However, the technology is also now being used for large display devices such as Microsoft's Surface Hub, a 55-inch projected capacitive display.

The internal structure of these touch panels consists of a substrate incorporating an IC chip for processing computations, over which is a layer of numerous transparent electrodes positioned in specific patterns. The surface is covered with an insulating glass or plastic cover. When a finger approaches the surface, electrostatic capacity among multiple electrodes changes simultaneously, and the position where contact occurs can be identified precisely by measuring the ratios between these electrical currents. (Figure 3.4)

A unique characteristic of a projected capacitive touch panel is the fact that the large number of electrodes enables accurate detection of contact at multiple

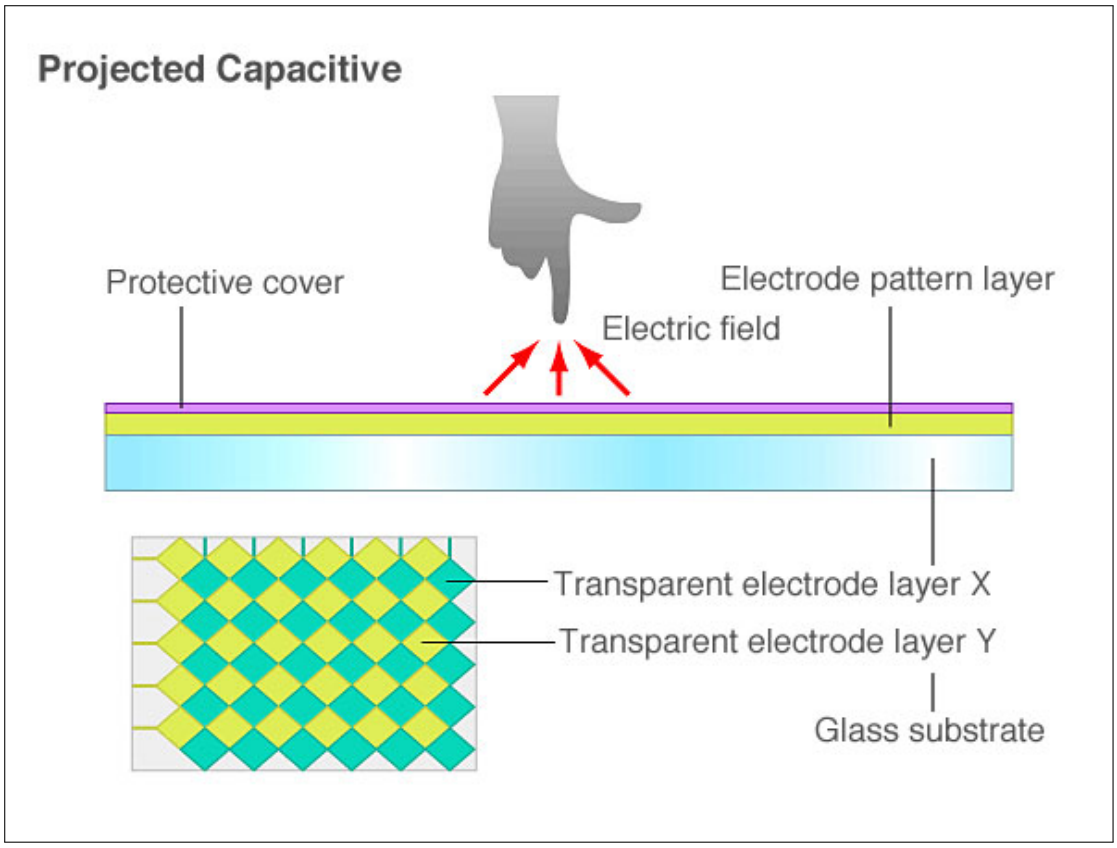


Figure 3.4: In a projected capacitive sensor, the display is covered by a layer of numerous transparent electrodes positioned in specific patterns. When a finger approaches the surface, electrostatic capacity among multiple electrodes changes simultaneously. [12]

points (multi-touch). Smaller projected capacitive multi-touch panels, such as those found in smart phones and tablets, are made with indium-tin-oxide. However, the methods used to make small panels are poorly suited for use in large screens, since increased screen size results in a slower transmission of electrical currents across the panel, increasing the amount of error and noise in detecting the points touched. Instead, larger touch panels use center-wire projected capacitive touch panels in which very thin electrical wires are laid out in a grid as a

transparent electrode layer. While lower resistance makes center-wire projected capacitive touch panels highly sensitive, they are less suited to mass production than ITO etching.

3.2.4 Summary of Input Technologies

In Table 3.2.4, we provide an overview of the touch technologies discussed in the previous sections. For a pure 2-D sketching interface, comparing the capabilities indicates that a resistive panel would likely be the best input device. It's high accuracy and resolution are very desirable traits for creating high quality, accurate sketches. However, our system intends to use multi-touch gestures to navigate the three-dimensional sketching environment. Therefore, we require multi-touch capabilities that a resistive panel lacks. As a result, we design our application around capacitive displays, as they have the best touch functionality. Their poor stylus support can be augmented by the use of active pen technology specially designed for capacitive displays. In particular, we use Microsoft's Surface Hub technology, which has a basic pen capability, upwards of 4K resolution, and support for up to a hundred touch points.

3.3 Advanced User Interaction: Input using Gesture

A gesture is a form of communication where visible body action communicate particular messages. Common gestures are usually performed by hand and arm movements. Other forms of physical non-verbal communication, such as purely expressive display, proxemics, and joint attention differ from gestures, which

Method	Resistive	Capacitive	SAW
Light Transmittance	Poor	Good	Good
Finger Touch	Excellent	Excellent	Excellent
Gloved Touch	Excellent	None	Good
Stylus Touch	Excellent	Poor	Good
Maximum Single User Touch Points	One	Ten	Two
Accuracy	Excellent	Good	Good
Durability	Poor	Excellent	Excellent
Water Resistance	Excellent	Excellent	Poor
Cost	Reasonable	Not reasonable	Not reasonable

Table 3.1: A comparison of touch technology.

communicate specific messages. While some gestures are ubiquitous, such as pointing, which differs little in intent from one application to another, many do not have universal meanings and are defined differently in different disciplines.

3.3.1 Types of Gestures

In *Gestures* [18], Morris describes two main types of gestures: primary and incidental.

Primary gestures are voluntary movements that a person uses with intent of communicating a message. There are three main types:

1. Emblems: These are gestures that have a direct verbal equivalent. For example, a waving of a hand upon an encounter means hello. Emblems tend to form in situations where speech is challenging or impossible. For example, airport controllers on runways communicate with gestures because the planes make it impossible to hear.

2. Illustrators: These gestures are closely linked with speech, and serve to clarify, or add to the content of the message. Illustrators are made by hand movements. A common example of an illustrator is pointing.
3. Reinforcers: There are gestures that help regulate the flow of conversation. For example, a head nod during conversation can mean that the current speaker should continue, or an upwards point might mean to wait to continue speaking.

Secondary, or incidental gestures are unintentional, but despite their lack of a direct message, are still important in conversation. Gestures such as grooming the hair, fidgeting, looking down or away, or looking at a clock are all examples of involuntary gestures. While they do not directly communicate, secondary gestures can still send information about the current state of their user. This is called leakage, when true feelings or attitudes are revealed despite what the overt signals are communicating. For example, a man in a rush might say, "Yeah, I can talk" while looking at a watch. Secondary gestures are not important for Human Computer Interaction, however care must be taken so involuntary gestures are not accidentally used as input.

Human computer interaction further distinguishes between types of gestures, splitting them into two major categories.

1. Offline: These gestures are processed after the user interaction with the object. For example, drawing a circle activates a menu.
2. Online: These gestures directly manipulate an object. A common example is taking two fingers and spreading them while touching an object to zoom in on the object.

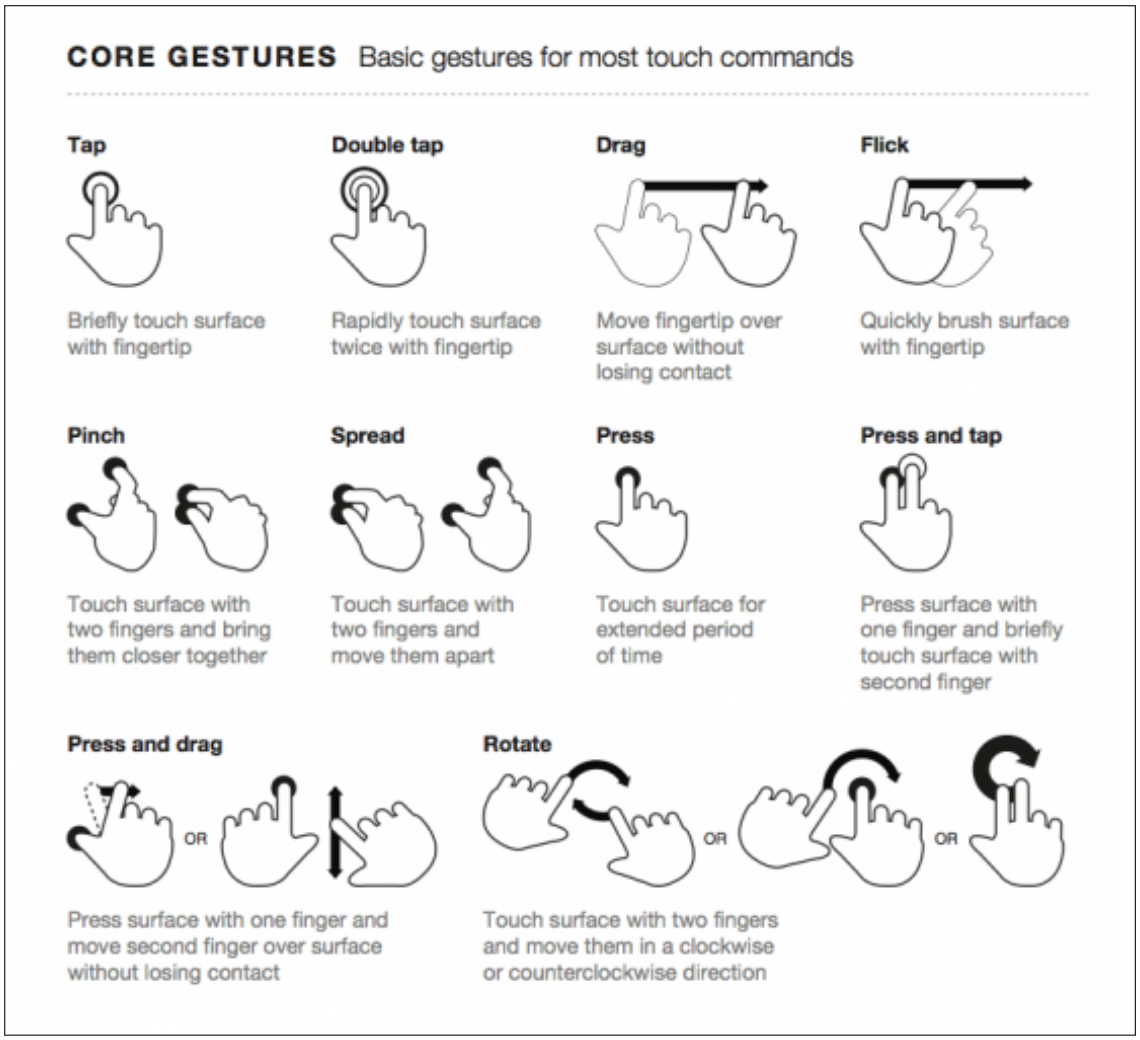


Figure 3.5: A visual representation of the core set of touch gestures. [29]

3.3.2 Multi Touch Gestures

Multi-touch gestures are predefined motions used to interact with multi-touch devices. Many modern consumer electronics like smart-phones, tablets, laptops, or desktop computers feature functions triggered by multi-touch gestures. They tend to be direct input methods with simple to understand functionality heavily based on the gesture used, allowing non-technical people to quickly

configure and navigate multi-touch applications. This section will only discuss core multi-touch gestures, and not the many subsets of unique gestures that combinations of this set of core gestures can create. Visual representations of how these gestures are performed can be seen in Figure 3.5

Tap

Taps are performed by quickly pressing and releasing a screen with a fingertip. Most systems differentiate between single and double taps, performed by tapping the screen once or twice respectively. Taps are generally used for selecting items, with single and double taps offering different types of selection. Taps are both online and offline gestures, since the number of taps need to be processed, but directly interact with objects being tapped.

Drag

Drags are performed by moving a fingertip over a surface without losing contact. An alternative type of drag is the flick, which is performed by the same method as the drag, only faster. Drags are generally used to move elements, making them online gestures.

Pinch and Spread

Pinches are performed by taking any number of fingertips and enclosing them towards a point. Spread gestures are the inverse action. Generally these online gestures are used for magnification.

Rotate

Rotate gestures are performed by moving two or more fingertips in a circular pattern around a point. The rotation point is used as the input location. Rotation is an online gesture.

Press

Presses are performed by touching a screen for an extended period of time. Presses can be combined with other touch gestures to allow for a deeper level of user interaction. Presses are offline gestures, since the duration of the press must be processed. This action usually results in context menus which are used for enhancing information about the object.

3.3.3 Pen Gestures

Pen gestures recognize certain shapes, not as handwriting, but as an indicator of a special command. For example, a pig-tail shape (used often as a proofreader's mark) would indicate a delete operation. Depending on the implementation, what is deleted might be the object or text where the mark was made, or the stylus can be used as a pointing device to select what it is that should be deleted. These types of gestures are offline. Pen gestures tend to be abstract, with functionality not necessarily representative of the shape formed by the gesture. (Figure 3.6)

Pens can be used to perform many of the multi-touch gestures, but the pen is just treated as a finger in these scenarios. In order for our project to incorporate

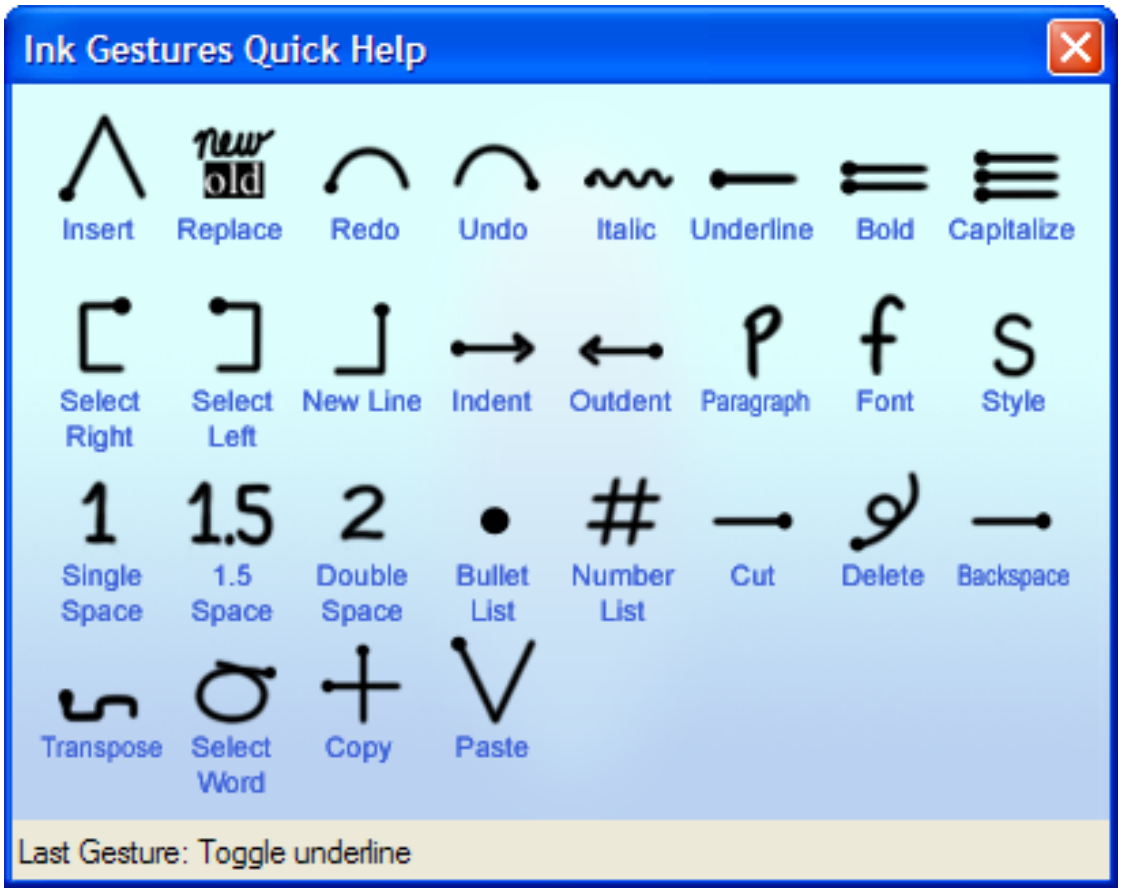


Figure 3.6: Examples of pen gestures and their associated functions. Note that many gestures have shapes unrelated to their functionality. [2]

pen gestures, the pen input would need to be preprocessed before it is projected into 3-D space. While pen gestures are a useful tool, in a free-form sketching environment it can be unclear if the user intends to make a stroke or a gesture, even if using the same symbol. This can potentially confuse the user. We can use touch gestures to accomplish similar results, and thus did not incorporate pen gestures in our application.

3.3.4 Three Dimensional Gesture Recognition

While older forms of gesture recognition attempt to translate physical interaction with an input device in order to form gesture based commands, more modern approaches directly interpret motions of the human body. This is accomplished using computer vision techniques, as well as different types of cameras and sensors used to capture and understand a three dimensional environment. Once this information is captured a variety of techniques can be used to analyze the scene and detect gestural information. While 3-D gesture recognition is an emerging area, and is beginning to see common use in a number of modern user interfaces, it's use for 3-D sketching is left to future work. Possible applications are using 3-D gestures to manipulate the environment in conjunction with 2-D gestures.

3.4 Summary

In this chapter we discussed how users interact with digital technology, an overview of common and project related input devices, and why certain interaction methods are preferable for 3-D sketching. For our application, we chose to support a subset of these techniques and devices in order to mimic real world sketching as closely as possible. We use a capacitive touch display, which supports a very large number of touch input points as well as an active pen device. From the active pen, we leverage the capability to detect sub-pixel input position, as well as the ability to detect how hard the user presses on the screen with the pen.

CHAPTER 4

CREATING A SKETCH

The most basic operation in any sketch-based modeling system is, of course, obtaining a sketch from the user. The key characteristic of a sketch-capable input device is that it allows freehand input. While a mouse is capable of this form of input, devices that more closely mimic the feel of freehand drawing using a pen, such as a digitizing tablet, are better for users to maximize their ability to draw. Devices that serve as both an input device and a display device are particularly suited to this, because it most closely mimics traditional artist creation methods by allowing direct interaction with the sketch space, as opposed to tablets where the space between the input device and the display surface is relative. Because of this direct interaction method, it is important that our system accurately translated the user's sketch to the 3-D virtual space. In this chapter we will discuss how we take the sketch input and create a smooth stroke that is independent of the resolution of the input device.

4.1 Representation of a Sketch

At the bare minimum, an input device should provide positional information in some two dimensional coordinate system, usually one based on the interaction window. For sketch input, the representation must at least approximate continuous movement (Figure 4.1). Sampling rates vary from one device to the next. The samples themselves may also be spaced irregularly, with sample points closer as users draw slowly or carefully, or further apart if the user draws quickly.

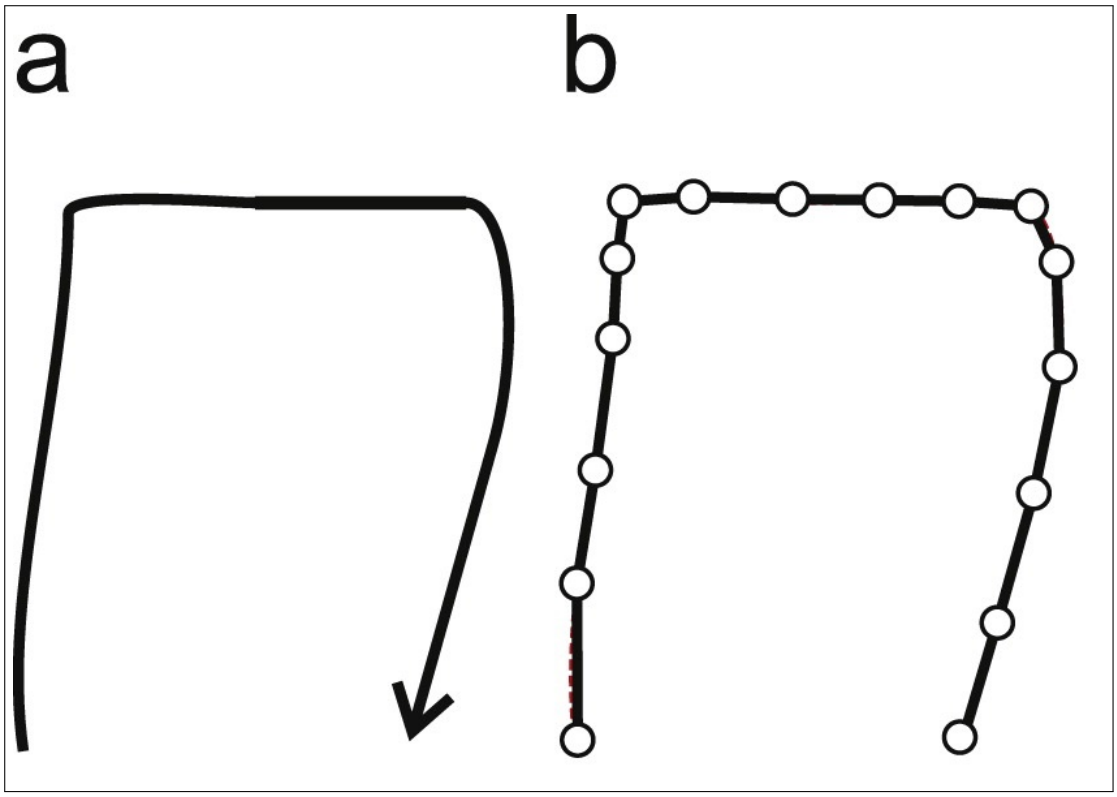
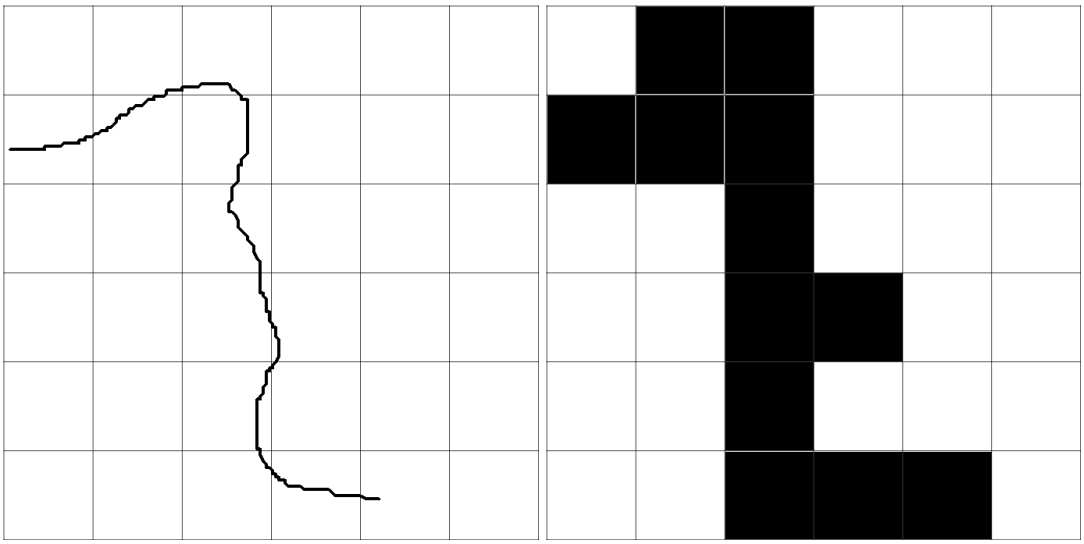


Figure 4.1: In an ideal scenario, an input stroke (a) is provided to the application as (b) a sequence of point samples.

We will refer to this sampled sequence of points as a stroke. Strokes are stored as a list of points, objects containing coordinates from the sample space, sorted by time. A sketch is comprised of a large number of these stroke objects. We also support a simple layer system that can be used to segment a sketch by allowing strokes to be contained in the active layer.

4.1.1 Understanding the Stroke Space

Before we discuss how to create smooth strokes, we need to understand how the stroke input gets sent to the application. When the pen touches the screen, it's



(a) The intended complicated stroke input onto a sensing grid.

(b) A potential raw input detected by the sensor.

Figure 4.2: When sketching, the user's input is rasterized according to the resolution of the sensor. This makes complicated sketch input (a), difficult to understand from the limited resolution of the input (b).

position is detected by the touch panel. This detected position is not necessarily exactly the same as the real world positions of the pen. This is because the input is rasterized according to the resolution of the sampling device. For example, assume we are working with integer sample data, and we receive that the pen is at pixel position (148, 148). The pen could actually be at (147.6, 148.2), or (148.2, 147.6), or any other position that samples to (148, 148) (Figure 4.1.1). This is an issue because in our sketching application, we would like to be able to zoom in to any surface. This means that small errors in sampling data, and as a result, errors in spline generation, will be magnified. While the former isn't really an issue, the latter is.

4.2 Spline Curves

The input data represents an approximation of the stroke input from the user since it is dependent on the sample resolution of the input device, and by extension, the resolution of the display. Although this would work decently well assuming we are working with a static raster image, three dimensional sketching allows the user to move the camera. Moving the camera eventually results in poor quality sketches using the stored stroke data due to the lack of sub-sample information that accurately reflects the intent of the original stroke. To remedy this, a mathematical representation of the curve is needed such that the "sampling rate" of the stroke is independent from the resolution of the input device. In computer graphics, this is commonly accomplished with spline curves.

A spline is a collection of polynomial segments. These segments can be linear, cubic, or a polynomial function of any degree. Splines are a common solution for modeling smooth curves from a small number of points. For this project, we use a Bézier curve function for the spline pieces. A Bézier curve is a parametric curve commonly used in computer graphics to model infinitely scaling, smooth curves. The curve is defined by control points P_0, P_1, ..., P_n, and is explicitly evaluated as follows:

$$\mathbf{B}(t) = \sum_{i=0}^{n} \binom{n}{i} (1-t)^{n-i} t^i \mathbf{P}_i \tag{4.1}$$

$$= (1-t)^n \mathbf{P}_0 + \binom{n}{1} (1-t)^{n-1} t \mathbf{P}_1 + \cdots \tag{4.2}$$

$$\cdots + \binom{n}{n-1} (1-t) t^{n-1} \mathbf{P}_{n-1} + t^n \mathbf{P}_n, \quad 0 \le t \le 1 \tag{4.3}$$

where $\binom{n}{i}$ are the binomial coefficients, defined as

$$\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k} \quad \text{for all integers } n, k : 1 \le k \le n-1 \tag{4.4}$$

with initial values

$$\binom{n}{0} = \binom{n}{n} = 1 \quad \text{for all integers } n \geq 0 \tag{4.5}$$

The curve can also be evaluated recursively, by

$$\mathbf{B}_{\mathbf{P}_0}(t) = \mathbf{P}_0 \tag{4.6}$$

$$\mathbf{B}(t) = \mathbf{B}_{\mathbf{P}_0\mathbf{P}_1\ldots\mathbf{P}_n}(t) = (1-t)\mathbf{B}_{\mathbf{P}_0\mathbf{P}_1\ldots\mathbf{P}_{n-1}}(t) + t\mathbf{B}_{\mathbf{P}_1\mathbf{P}_2\ldots\mathbf{P}_n}(t) \tag{4.7}$$

What this equation means is that a Bézier spline of order n can be defined by linear interpolation between two splines of order $n-1$. For this project, we will use a cubic Bézier function for the spline segments.

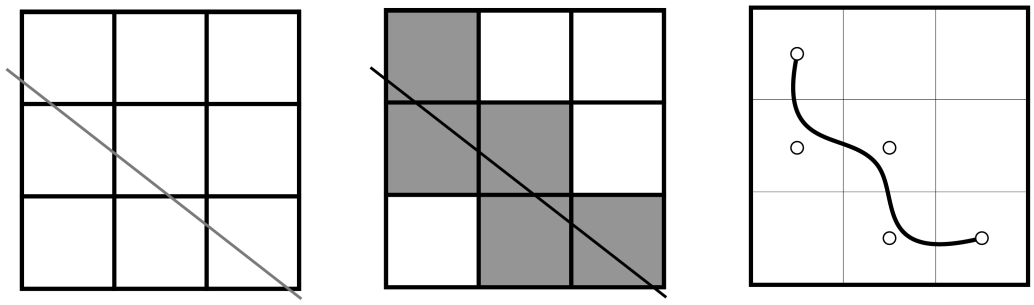
We must now determine a method for transforming our point sample data to a spline curve. A naive approach would be to generate a spline curve that passes through the all of our sample points in the sequential order in which they were generated. Any series of any four distinct points can easily be converted to a cubic Bézier curve that goes through all four points in the same order. While this method guarantees that the generated curve passes through all of the input sample points, it is not guaranteed to generate a curve that represents the intent of the original stroke.

4.2.1 Generating Splines From the Sample Data

In theory, creating splines that are accurate to the original stroke would involve generating a curve that passes through each of the sample points. However in practice, generating a curve in this fashion is not as necessary as one would think. As discussed in Section 4.1.1, the input data that we get is not necessarily

accurate to the actual shape of the sketch. Therefore, even if we were to create a curve that perfectly passed through all of the input points, it is possible that the output curve would still be unsatisfactory. One common example of this is a user sketching a line diagonally through a screen. Perfect sample data produces input in a staircase pattern, which would result in a wavy curve not representative of the intent of the original diagonal line (Figure 4.3). Additionally, because the sample distance between points is not consistent, it is possible to produce a curve with artifacts that appear unnatural upon magnification (Figure 4.4). What we should actually try to accomplish with our curve generation is to match the intent of the stroke.

The approach we take is using the input samples as control points to generate a piecewise spline curve. This method is better at dealing with extreme changes in sample rates because the produced curve contains less convex and concave changes. The curve generated will still not pass through the sampled points, but if the sample rate is high, it will ultimately converge or be very close. Thus using the input data as control points results in smooth reasonable curves even when the control points are far apart. Additionally, to avoid any "staircase" sampling issues (Figure 4.3(b)), we include a euclidean distance constraint between the sample data based on the resolution of the input. By manipulating the sample data this way, we are able to create curves that reasonably match the intent of the user.



(a) (b) (c)

Figure 4.3: When a diagonal is drawn (a), the input gets rasterized into a staircase pattern of input (b). This input produces curves that do not adequately represent the intent of the original stroke (c). While this effect would be unnoticeable when the diagonal is originally drawn, zooming in onto the curve would reveal the error.

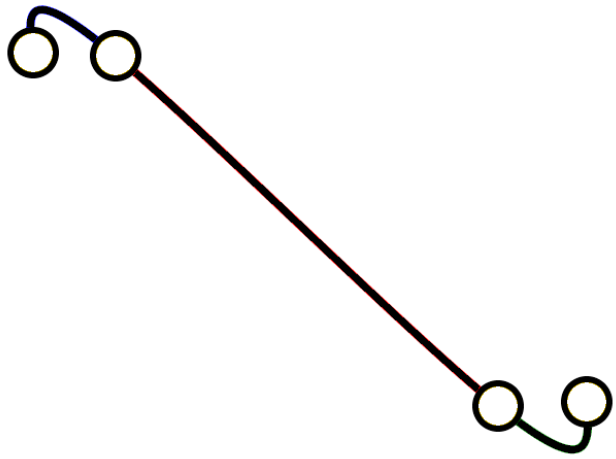


Figure 4.4: Using sample data as geometric knots can result in oddities in the curve generation if the knots have unusual spacing between them. This is very possible because no guarantee is made in the spacing between sampled points.

4.2.2 Algorithm

We begin with a list of control points, numbered from 0 to $N-1$. Segment i of the curve is influenced by control points $i-1$, i, $i+1$, and $i+2$. Using this definition we can generate $N-3$ segments from the N control points without falling off the ends of the sequence.

Since we can't render a spline, we need to approximate the curve by subdividing it into small line segments. We're going to divide each Bézier curve into a set of connected linear components, with the intent that a large enough number will look sufficiently smooth. To accomplish this, we use a de Casteljau construction, which "splits" a Bézier curve into two smaller Bézier curves. Subdivision of these segments occurs as follows:

1. Begin with points $\{P_0, P_1, P_2, P_3\}$, which define a Bézier curve.
2. Define $P_4 = (P_0 + P_1) * 0.5$, $P_5 = (P_1 + P_2) * 0.5$, and $P_6 = (P_2 + P_3) * 0.5$ (Figure 4.5(a))
3. Define $P_7 = (P_4 + P_5) * 0.5$, and $P_8 = (P_5 + P_6) * 0.5$ (Figure 4.5(b))
4. Define $P_9 = (P_7 + P_8) * 0.5$ (Figure 4.5(c))
5. Create two new Bézier curves using $\{P_0, P_4, P_7, P_9\}$ and $\{P_9, P_8, P_6, P_3\}$ (Figure 4.5(d))
6. Repeat steps 2 through 5 until a termination criteria is met. Possible criteria include distance between control points, and distance between control points P_1 and P_2 and the line between P_0 and P_3.

If the termination criteria is small enough, then the curve will appear very smooth, even when zooming in to the curve. Our termination criteria checks the

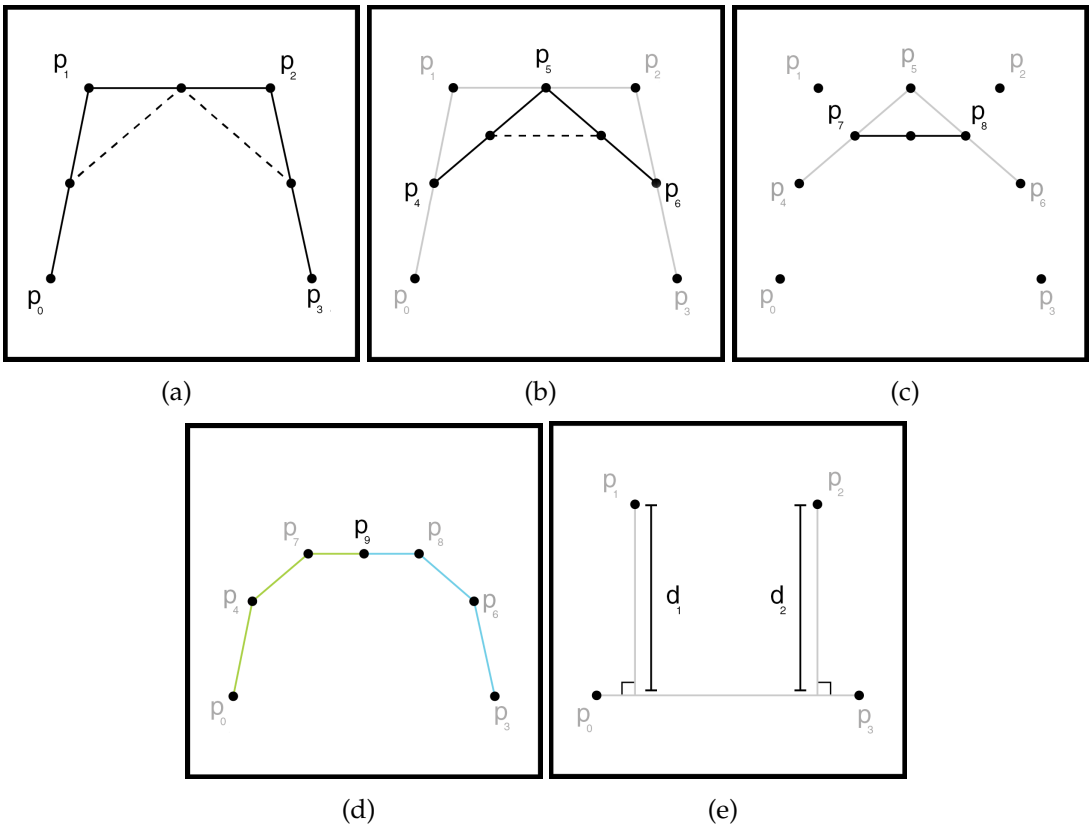


Figure 4.5: We begin with four points representing our spline: P_0, P_1, P_2, and P_3. Three points are generated by taking the midpoints of each adjacent segment of the control polygon (a). This process is repeated using the newly created set of points until only one point is generated (b) (c). From the points created through these calculations, two new sets of four points each are created (d). This process is repeated until a termination criteria is reached. We check that the perpendicular distance between two of the control points, P_1 and P_2, and the line between P_0 and P_3 is below a certain amount.

perpendicular distance between points P_1 and P_2 and the line the goes through points P_0 and P_3. (Figure 4.5(e)) If both of the distances are below a threshold, the subdivision terminates. This algorithm produces a smooth B-spline curve starting at control point 0 and ending at $N - 1$.

4.3 Summary

In this section, we described how we convert user input over a set of pixel coordinates into a curve approximating the intent of the stroke. We believe intent is more important than perfect accuracy since in practice, replicating curves that perfectly match input data results in poor quality curves. This is because of the finite resolution of a pixel grid, where as in real world sketching, the concept of 'input resolution' does not exist. Using a B-spline algorithm with cubic Bézier components, we can calculate a smooth spline curve for our stroke input.

CHAPTER 5

SKETCHING IN 3D

In a typical 2-D sketching application on a graphical tablet, a user draws on a two dimensional plane that mirrors the surface of the input device. However, in a 3-D sketching application, the user draws on arbitrary three dimensional planes and surfaces. The most basic example is a simple plane: a user can orient a plane in three dimensional space, and the draw on the tablet. The strokes on the tablet are then projected onto the plane, thereby creating a 3-D stroke.

The goal is to be able to perform real-time 3D sketching. We assume that our model environment has been "polygonalized" into triangles. The constraint is that we need to draw on the image plane with the true perspective image as seen from the observer's position. Using a perspective image, as opposed to an orthographic image, would give the best understanding of the drawing environment, allowing us to mimic drawing in 3D space.

The difficulty is achieving this at interactive rates, at least as fast as a person draws; roughly 30 frames per second. This is hard! We rely on techniques implemented in rendering algorithms, specifically the ray casting methods utilized in ray tracing. To obtain the speed, it is necessary to reduce the large number (N) of ray-triangle intersections for complex environments. Note that N is large due to the decomposition into many small triangles. We utilize a spatial tree data-structure containing a hierarchical bounding-box scheme to reduce the computation time. We have been able to achieve this acceleration as shown in Chapter 7.

In this chapter we provide detailed definitions of:

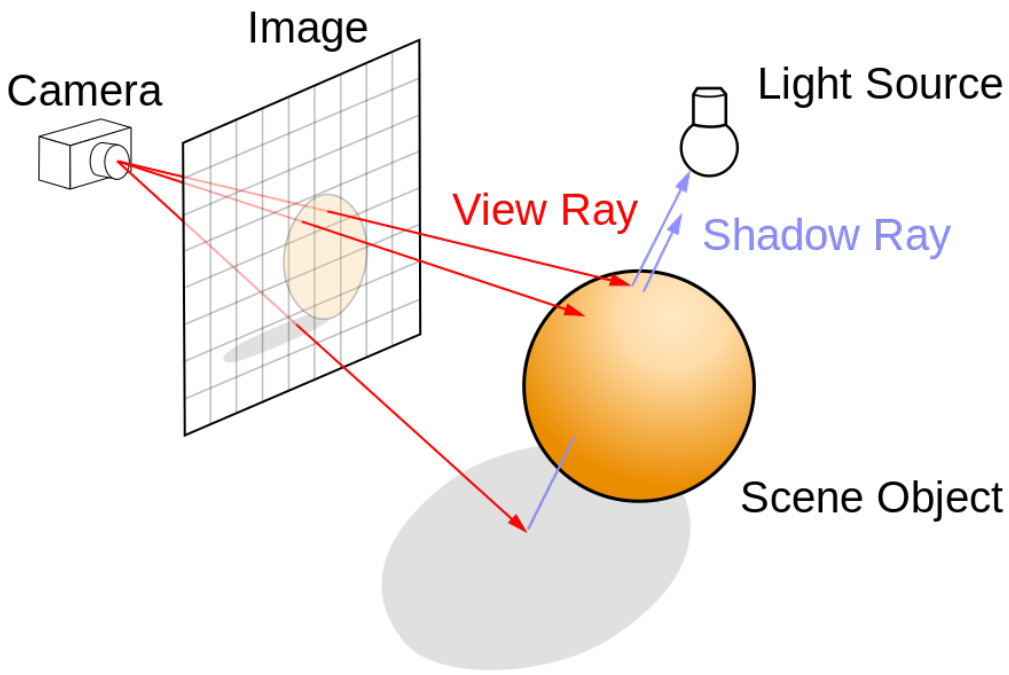


Figure 5.1: Ray Tracing in Computer Graphics

- The ray casting approach
- The method for ray-triangle intersections
- The hierarchical box and tree data structures:
- The heuristic Surface Area subdivision

We use all of the above to efficiently project two dimensional user input onto a three dimensional sketching environment.

5.1 Ray Casting

Ray casting is the use of rays, a line with an endpoint and a direction, to test for intersections with surface geometry. These computations are the fundamentals

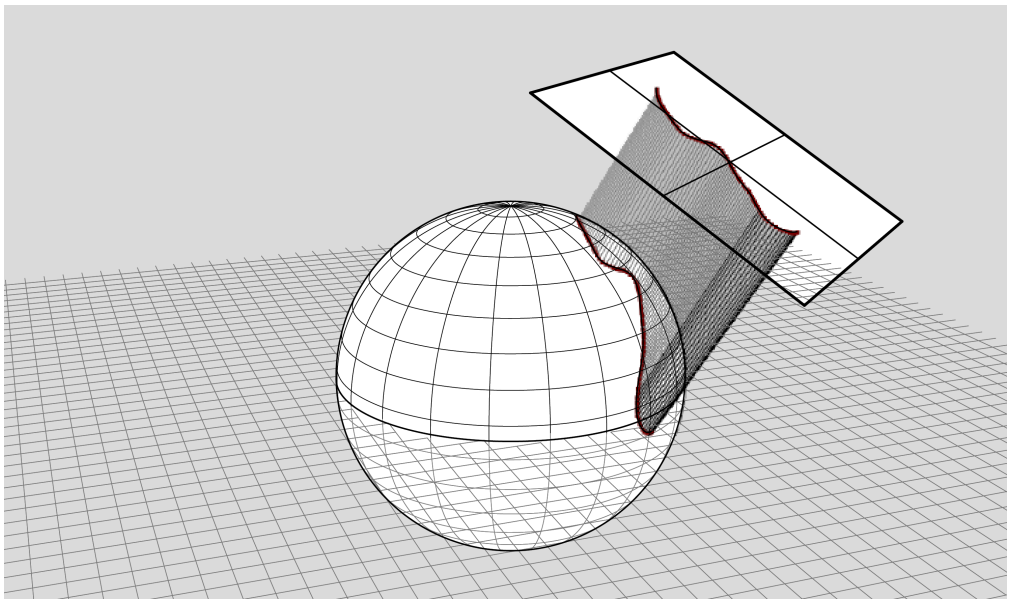


Figure 5.2: When a user creates a stroke on the screen, the resulting curve is projected onto the sketching surface.

of ray tracing computer graphics algorithms, used to solve a variety of problems.

Ray casting is commonly used for object selection in interactive 3-D applications. A pointing device provides user input on pixel (i, j), and the "picked" object is whatever is "seen" though the pixel. Using ray casting, a ray is created and sent in the virtual viewing direction. The origin of the ray is the position of the camera in the virtual environment, and the direction of the ray is based on the location of the user input. This is further explained in Section 5.1.1. If the ray intersects with a surface, that surface is used as the drawing plane. We can use a similar approach to project our strokes from the screen onto the surfaces of objects. The ray casting algorithm is utilized as follows:

1. The user draws a stroke on a 2-D plane, giving a set of sample points
2. An imaginary plane is created in the virtual space representing the image

plane.

3. Rays are cast into the three dimensional scene from the imaginary plane based on the sample positions.
4. The intersections with the scene geometry represent the new 3-D positions of the stroke.

Once we intersect all of the sample points with the scene geometry, we can use the spline techniques described in the previous chapter to create a 3-D curve approximating the appearance of the projected 2D stroke.

5.1.1 Generating the Ray

OpenGL uses a projection matrix to project the 3D scene to the 2D computer monitor. First, the matrix transforms points from view space to clip space, the space that defines whether points are visible to the user. Then the matrix transforms these points to normalized device coordinates (NDC), which causes any visible point to be contained in a box with lower bound (-1,-1,-1) and upper bound (1,1,1). (Figure 5.1.1) We want to create rays that match this behavior of OpenGL perfectly, otherwise the user will not be able to draw properly on the surfaces of objects. The easiest way to accomplish this is to invert the calculations OpenGL uses in order to calculate two points in world space that we can use to generate the view ray.

When the user clicks on the screen, we take the screen point and normalize to a point between (-1,-1) and (1,1). This represents the X-Y position of the screen point in NDC. We then create two 3D points p_0 and p_1 with the XY values of

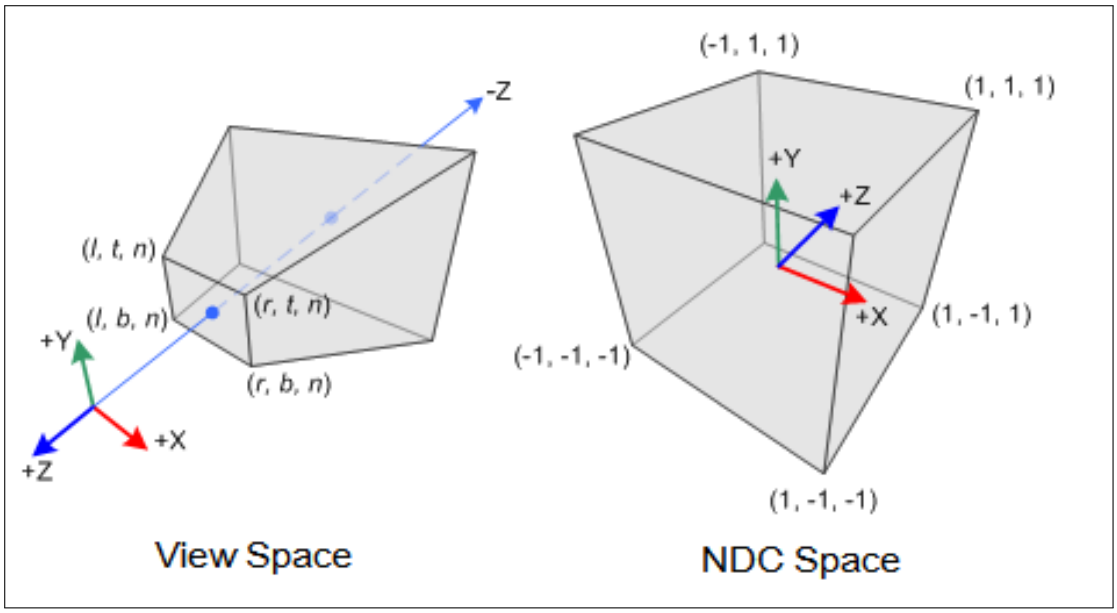


Figure 5.3: First, the projection matrix transforms points from view space to clip space, the space that defines whether points are visible to the user. Then the matrix transforms these points to normalized device coordinates (NDC), which causes any visible point to be contained in a box with lower bound (-1,-1,-1) and upper bound (1,1,1).

the NDC screen point and z values -1 and 1 respectively to represent the upper and lower bounds of the clip space. By multiplying these two points by the inverse of the view-projection matrix, we can obtain two points in world space (Figure 5.1.1). p_0, the point with original z value -1, is the origin of the ray, and the ray direction is equal to $p_1 - p_0$.

5.1.2 Ray-Triangle Intersection

Given a ray $\mathbf{e} + t\mathbf{d}$, where $\mathbf{e}$ is the origin of the ray and $\mathbf{d}$ is the ray direction, we want to find the first intersection with any object where $t > 0$. In this section,

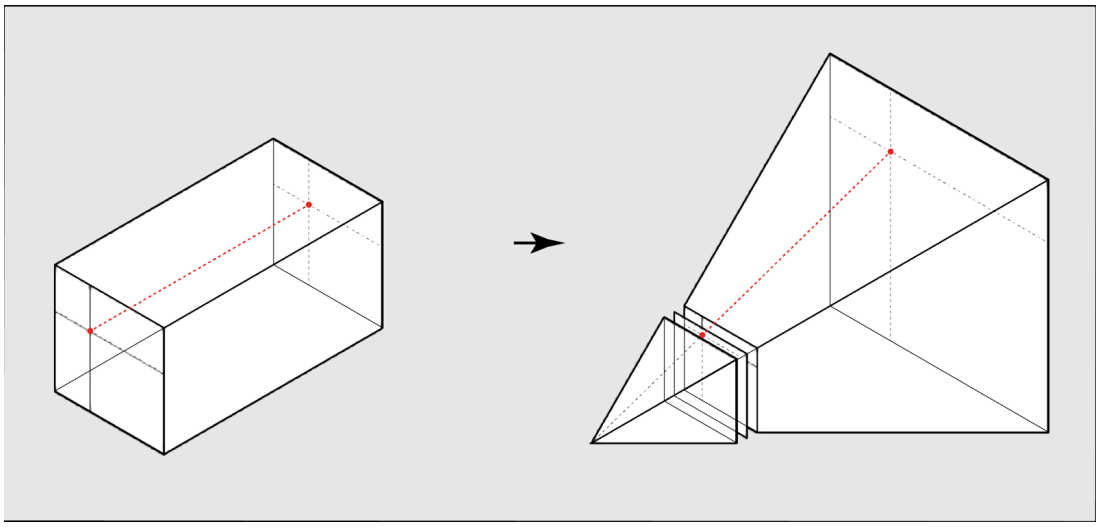


Figure 5.4: Using a known point on a 2D screen, we can create a ray in NDC space using the xy point and the z bounds of the space (-1 and 1). Transforming these two points from NDC space to world spaces gives us a line segment that represents what the pixel ”sees” in the environment.

the intersection with the most basic computer graphics primitive, the triangle, is discussed. The use of triangles is prevalent for two primary reasons. The first is that in order to compute the actual ray-polygon intersection point, one must ensure that it lies within the boundaries of the polygon. By using triangles, one avoids the computational cost required for re-entrant polygons (polygons with interior angles greater than 180 degrees). This simplifies the algorithm and allows for hardware implementations. The second reason is that all surfaces, including spheres or arbitrary parametric surfaces, can be easily approximated using triangles. Thus, being able to rapidly intersect triangles will allow 3D sketching on any object used for the application.

To demonstrate the algorithm utilized, we will intersect a ray with a parametric plane that contains the triangle. Once intersected, we use barycentric

coordinates to check if the intersection point is contained within the boundaries of the triangle. Note we could eliminate this check if we want to draw on an infinite intersection plane.

To intersect a ray with a parametric surface, a system of equations is created where the Cartesian coordinates all match:

$$x_o + tx_d = f(u, v) \tag{5.1}$$

$$y_o + ty_d = g(u, v) \tag{5.2}$$

$$z_o + tz_d = h(u, v) \tag{5.3}$$

These three equations contain the three unknowns (t, u, and v). When the parametric surface is a parametric plane, the parametric equation can be written in vector form. If the vertices of the triangle are **a**, **b**, and **c**, then the intersection occurs when

$$\mathbf{e} + t\mathbf{d} = \mathbf{a} + \beta(\mathbf{c} - \mathbf{a}) + \gamma(\mathbf{c} - \mathbf{a}). \tag{5.4}$$

β and γ are two of the three barycentric coordinates of the triangle. If $\beta > 0, \gamma > 0$, and $\beta + \gamma < 1$, then the intersection point lies inside of the triangle; otherwise it hits the plane outside the triangle. If there are no solutions, then either the triangle is degenerate or the ray is parallel to the parametric plane.

To solve for t, β, and γ, Equation 5.4 is expanded from the vector form to equations for each of the three coordinate planes.

$$x_o + tx_d = x_a + \beta(x_b - x_a) + \gamma(x_c - x_a) \tag{5.5}$$

$$y_o + ty_d = y_a + \beta(y_b - y_a) + \gamma(y_c - y_a) \tag{5.6}$$

$$z_o + tz_d = z_a + \beta(z_b - z_a) + \gamma(z_c - z_a) \tag{5.7}$$

This can be rewritten into a standard linear equation of the form $Ax = b$:

$$\begin{bmatrix} x_a - x_b & x_a - x_c & x_d \\ y_a - y_b & y_a - y_c & y_d \\ z_a - z_b & z_a - z_c & z_d \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \\ t \end{bmatrix} = \begin{bmatrix} x_a - x_o \\ y_a - y_o \\ z_a - z_o \end{bmatrix} \tag{5.8}$$

This can be solved using Cramer's rule: given a system of n linear equations for n unknowns, represented as $Ax = b$, where the $n \times n$ matrix A has a nonzero determinant, and the vector $x = (x_1, \ldots, x_n)^{\mathrm{T}}$ is the column vector of the variables, the system has a unique solution. This solution is given by

$$x_i = \frac{\det(A_i)}{\det(A)} \qquad i = 1, \ldots, n \tag{5.9}$$

where A_i is the matrix formed by replacing the i-th column of A by the column vector b. Solving gives the solutions:

$$\beta = \frac{\begin{vmatrix} x_a - x_o & x_a - x_c & x_d \\ y_a - y_o & y_a - y_c & y_d \\ z_a - z_o & z_a - z_c & z_d \end{vmatrix}}{|A|} \tag{5.10}$$

$$\gamma = \frac{\begin{vmatrix} x_a - x_b & x_a - x_o & x_d \\ y_a - y_b & y_a - y_o & y_d \\ z_a - z_b & z_a - z_o & z_d \end{vmatrix}}{|A|} \tag{5.11}$$

$$t = \frac{\begin{vmatrix} x_a - x_b & x_a - x_c & x_a - x_o \\ y_a - y_b & y_a - y_c & y_a - y_o \\ z_a - z_b & z_a - z_c & z_a - z_o \end{vmatrix}}{|A|} \tag{5.12}$$

where A is given in Equation 5.8, and $|A|$ denotes the determinant of A.

5.2 Acceleration Structures

An acceleration structure must be used in order to give sub-linear time for ray object intersection for complex objects. In a naive implementation, the ray caster would iterate over all triangles in the scene to check for intersections, giving $O(N)$ performance. For sufficiently large values of N, this would be very slow; thus a "divide and conquer" algorithmic approach is used, creating an ordered data structure to speed up the intersection process.

While many approaches exist, we implement a simple bounding volume hierarchy (BVH) tree [26].

5.2.1 Bounding Boxes

A bounding box for a point set S in three dimensions is the box with the smallest measure (volume) within which all the points lie. For this project, we use axis-alligned bounding boxes (AABBs), which are constrained so their edges lie parallel to the Cartesian coordinate axes (Figure 5.2.1). A key operation in any intersection acceleration structure is computing the intersection of a ray and a bounding box. Since we are interested in the actual ray-surface intersection, it is not necessary to calculate where the ray hits the box, only if it is hit at all, as the box itself is not an actual piece of geometry.

One of the fastest current methods for intersecting a ray with an AABB is the slab method [20]. The idea is to treat the bounding box as the space contained inside of N pairs of parallel planes. For each pair of planes, two pairs of t values, t_{min} and t_{max} are solved for the segment that is between the two planes. If

the largest t_{min} is smaller than the smallest t_{max}, then some portion of the ray is contained within all three planes.

5.2.2 BVH Tree

Normally, for intersecting a ray with a scene, one needs to check for the ray's intersection on every piece of geometry. To reduce this rather costly computation time, we utilize a bounding volume hierarchy (BVH). This is a binary tree data structure superimposed on a set of geometric objects.

There are two main components to the BVH; the nodes, which make up the structure of the tree, and the leaves, which sit at the bottom of the tree. The leaves of the tree are sets of geometry of a predetermined maximum size. Ideally, the objects contained in the leaves are very spatially close to each other. Each node in the tree represents an axis-aligned bounding box in the 3D world. The node's shape is defined as the minimum sized bounding box that contains all of the node's children. This parental grouping occurs recursively until there is a single bounding volume at the root of the tree. (Figure 5.6)

The algorithm used to construct a BVH can be basically described as follows. First, we decide on a cost function that will check the quality of the object division. Then, a bounding box is created for the current node. At the beginning of the algorithm, this is the root of the tree containing all of our scene geometry. We sort along all three axes and find the axis with the least cost according to our chosen cost function. We then find a position along the cheapest axis that will be used as the center of subdivision. Finally, the objects are divided based on the chosen center into two sub-groups. Two child nodes are created from these

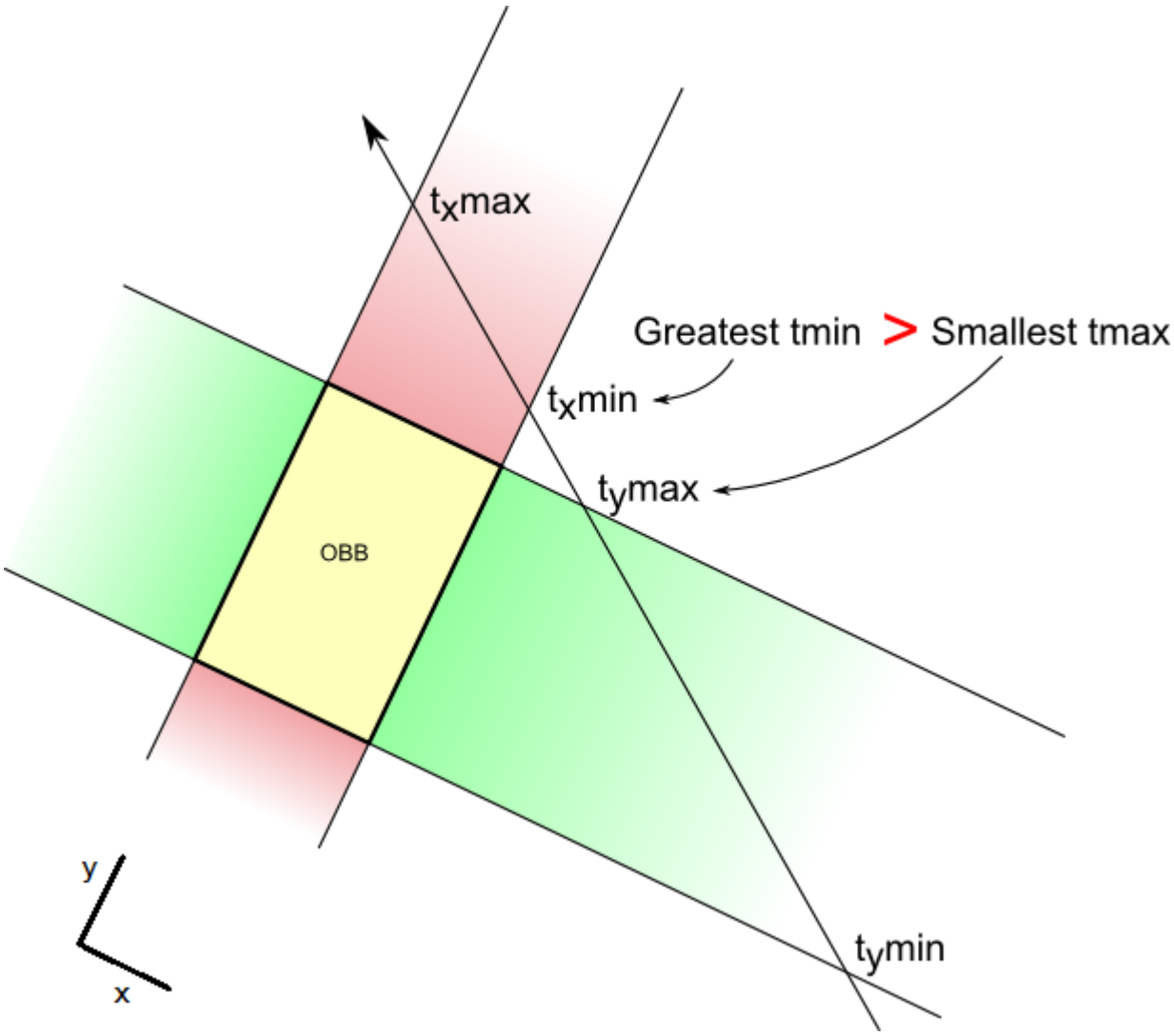


Figure 5.5: For 3D geometries, when checking if a ray intersects a bounding box, the ray is intersected through three pairs of parallel planes defined by the upper and lower bounds of the bounding box. After calculating the pairs of intersection values, the largest of the smaller number of the pairs is compared to the smallest of the larger number. If the largest min is greater than the smallest max, the ray intersects the box. For simplicity, the figure is shown in two dimensions.

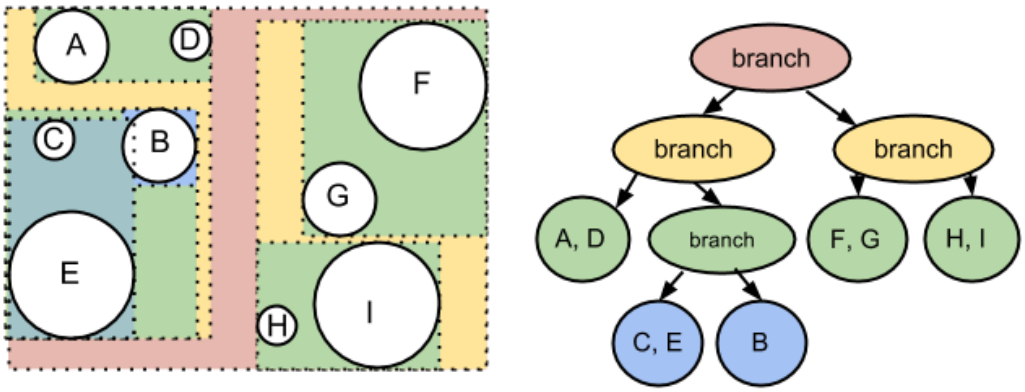


Figure 5.6: An example of a Bounding Volume Hierarchy (BVH). At each node, if the contained number of objects is higher than our predetermined maximum (in this example, two), the node branches into two. For simplicity, the figure is shown in two dimensions. [11]

sub-groups, and the algorithm repeats. When a small enough number of objects are in each node, the algorithm terminates.

By using this data structure, we only need to traverse a small portion of the total scene. For example, if the ray does not intersect the root bounding box of the scene, we know that the ray does not intersect any of our scene geometry. This reduces the computational complexity of a ray intersecting a scene from linear time $O(N)$ to logarithmic time $O(log(N))$.

A good BVH tree has the following properties:

- The nodes in a given sub tree should be close to each other. The lower down the tree, the closer the nodes should be.
- Each node in the BVH should be of minimum volume.

- The sum of all bounding volumes should be minimized.
- The volume of overlap of sibling nodes should be minimized.
- The BVH should be balanced with respect to both its node structure and its content. Balancing allows as much of the BVH to be pruned when not traversed.

The quality of a BVH tree is mostly determined by how the objects are subdivided between child nodes. One of most commonly used splitting heuristics is the Surface Area Heuristic (SAH) [16]. The idea behind SAH is to balance both the number of objects contained in a bounding volume while minimizing the surface area of the volume itself. This is an exceptionally slow heuristic when constructing the tree, but currently provides the fastest solution at runtime. Thus the construction cost should be considered for use in real time applications. For our application, we decided to sacrifice the construction costs in order to allow for higher polygonal complexity.

5.3 Summary

Using the algorithms described in this chapter, we have been able to project our sketch strokes from the two dimensional input surface to the three dimensional model environment. The acceleration structures allow the use of highly complex models with high polygonal counts while maintaining a relatively fast runtime. Using the above algorithm, we have been able to sketch on complex three dimensional objects at interactive rates.

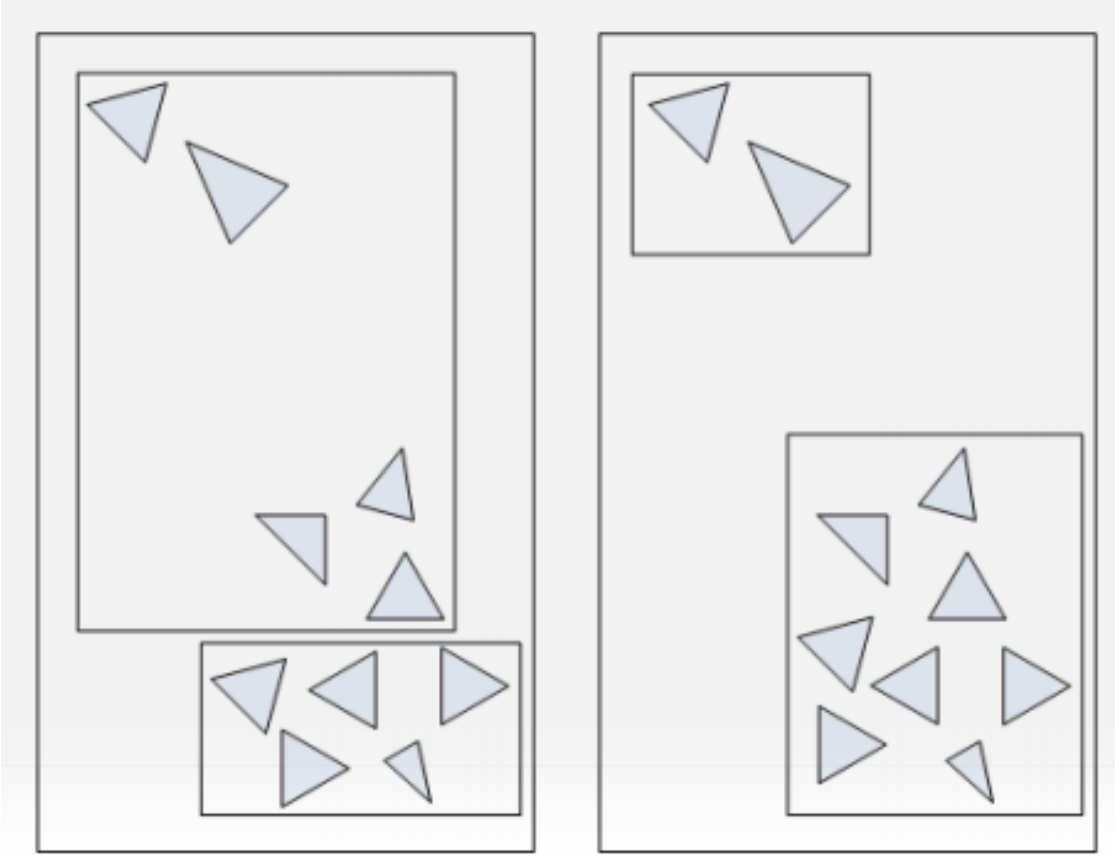


Figure 5.7: A comparison between the bounding volumes of a node using a naive heuristic(left) and a surface area heuristic (right). Note that for SAH, the total area of the child bounding boxes is much smaller than that of the naive approach. For simplicity, the algorithm is shown in two dimensions.

CHAPTER 6

CURVE RENDERING

As a sketching application, it is important for curves to be rendered with high quality. While graphics hardware has support for line rendering, it's implementation is only suitable for line segments, with significant issues when trying to render curves. In this chapter, we discuss a new system which we implemented for curve rendering.

6.1 Problems with Native Curve Rendering

OpenGL has support for a variety of line primitives: lines, line strips, and lines with adjacency data. However, these primitives are not suited for rendering curves at high quality. This is because OpenGL uses a rectangle between the two segment points to render line segments. While this method is well-suited for common uses of lines in 3D applications, for example wire frame images, it does not extend to curve rendering because of the gaps that appear between segments (Figure 6.1). It is reasonable to assume that if we use a curve that is subdivided to a fine enough degree, then the gaps will be sufficiently small that they would not be visible. However, in practice, in many cases even finely subdivided lines have visible gaps around any curve (Figure 6.1).

To eliminate these artifacts, our project implements a custom line renderer that constructs a triangle mesh from the line definition. Constructing a mesh for the line allow allows the implementation of a wide variety of stroke types, including strokes with various end caps or variable widths based on stroke direction. Additionally, OpenGL lines have inconsistent support for anti-aliasing

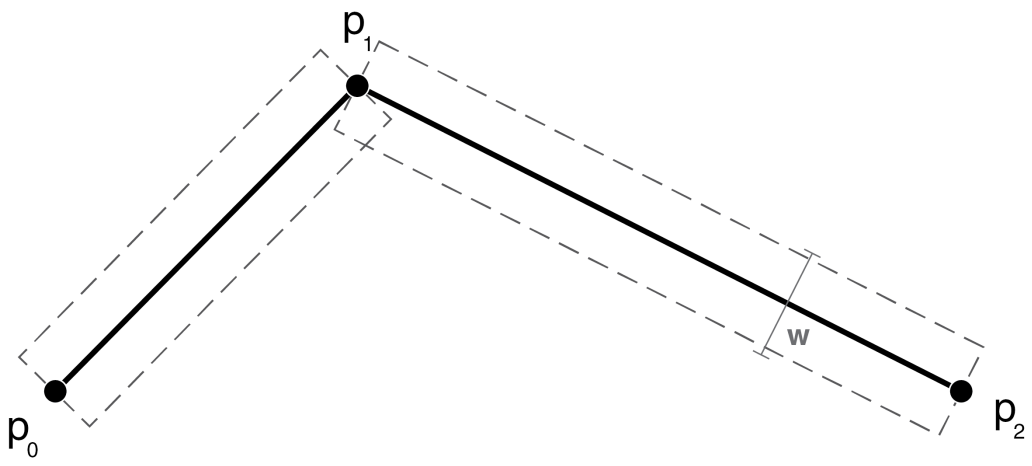


Figure 6.1: Two line segments connected together, as displayed by the default GL_LINES implementation. The dotted lines represent the geometry created from the line definitions. Note the visible artifact at their intersection.

across all hardware. By switching to a triangle mesh, we leverage the native anti-aliasing support for triangles without worrying about consistency. As we can see in the above image, without anti-aliasing rendered lines can appear jagged and of poor quality. In order for our system to be visibly appealing in sketch mode, it is important to render the highest quality lines as possible.

6.2 Creating Joins From the Curve Definition

To improve the appearance of our curved lines relative to the native OpenGL implementation, it is necessary to compute better methods for rendering the

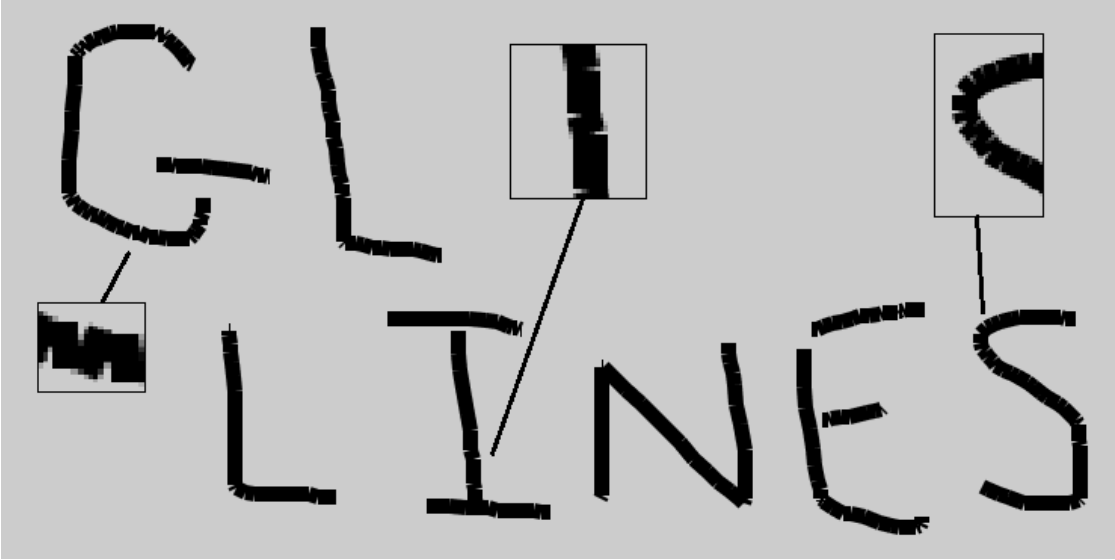


Figure 6.2: An example of the flaws of using native line rendering in OpenGL with GL_LINES for rendering our sketch data. The cause of the holes is the artifact in Figure 6.1.

Symbol	Description
p_n	Ordered point on line in the range $[0, 2]$
w	The width of the rectangular line segments
$\vec{n_{xy}}$	The normal to the line segment (p_x, p_y)
$\vec{t_x}$	Vector from p_1 along n_{x1} with length $w/2$

Table 6.1: Section Variables

intersections between each of our line segments. For this project, we implement three types of ”joins”: round, miter, and bevel. Miter and bevel joins are used in conjunction with each other, while round joins are used alone.

A round join (Figure 6.3) is formed by rounding out the gap such that a smooth curve is created. If both of our line segments have the same thickness, then the join calculated by forming a circle whose center is located at p_1, with a radius of $w/2$. The total angle that needs to be filled can be calculated by $\vec{t_0} \cdot \vec{t_2}$,

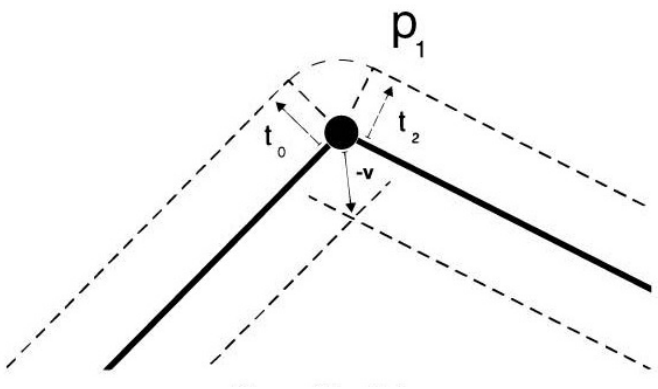


Figure 6.3: Diagram of a round join with parameter labels. The smooth curve is approximated with a triangularization.

and can be filled by rotating either $\vec{t_0}$ or $\vec{t_2}$ about p_1.

Miter joins are formed by extending the lines in the line geometry parallel to the original segment. The join is formed where these extended lines intersect, as can be seen in Figure 6.4. To calculate this, we take the vectors defined by $(p_0 + \vec{t_0}, p_1 + \vec{t_0})$ and $(p_2 + \vec{t_2}, p_1 + \vec{t_2})$ and compute their intersection. We call the vector from p_1 to this intersection $\vec{v}$. We can then compute a polygon between p_1, $p_1 + \vec{t_0}$, $p_1 + \vec{t_2}$, and $p_1 + \vec{v}$, which creates the miter join.

Miter joins have the particular issue that artifacts can arise from exceptionally sharp points in the line segments. We can detect these cases by checking to see if v is larger than a certain length. If so, we use a bevel join instead. The bevel join is formed by simply creating a triangle between p_1, $p_1 + \vec{t_0}$, and $p_1 + \vec{t_2}$ (Figure 6.5).

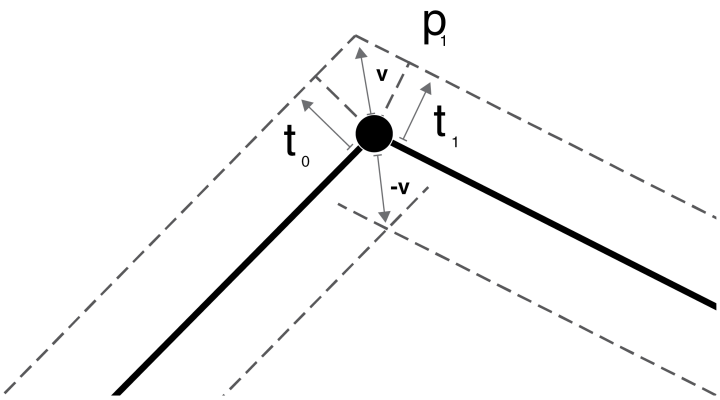


Figure 6.4: Diagram of a miter join with parameter labels

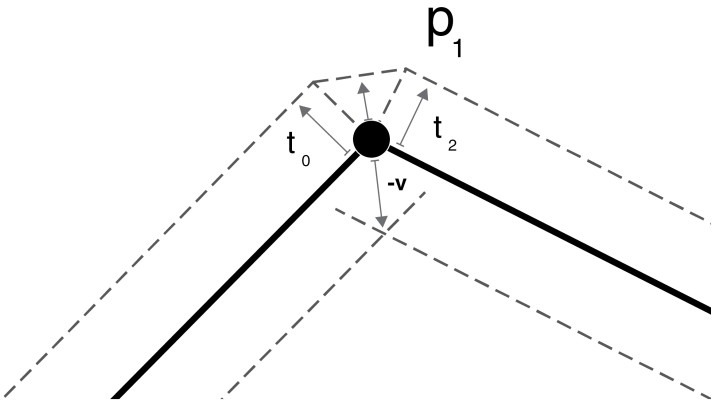


Figure 6.5: Diagram of a bevel join with parameter labels

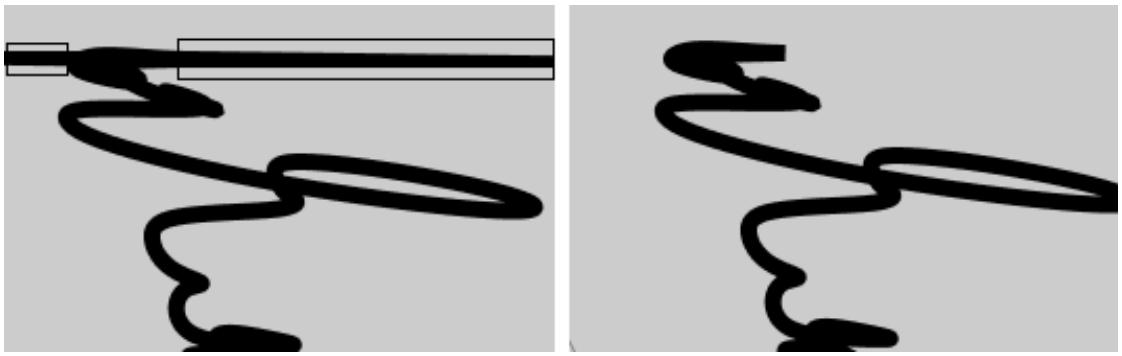


Figure 6.6: Left: An example of a miter join artifact from a sharp curve. The boxed regions show the artifact. Right: The artifact is detected by calculating the length of the miter join. If detected, the join is replaced with a bevel join.

6.2.1 Curved Lines with Variable Width

Up until this point, we have worked under the assumption that the width of the curved line is constant. However, we would like to support the ability to draw curved lines that have variable width. To achieve this, each point on the curve is given an independent width variable, w_i. Assuming we work with three points, we must also define new vectors t_0, t_{01}, t_{12}, and t_2 based on the normals of the line segments and the widths at each of the curve points. Same adjustments need to be made in the join calculations to account for this. The miter calculation needs to take the new t vectors into account, turning $(p_0 + \vec{t_0}, p_1 + \vec{t_0})$ and $(p_2 + \vec{t_2}, p_1 + \vec{t_2})$ into $(p_0 + \vec{t_0}, p_1 + \vec{t_{01}})$ and $(p_2 + \vec{t_2}, p_1 + \vec{t_{12}})$. For a round join, a linear interpolation is used to calculate the radius at the points of triangularization. The bevel join has no changes in calculation. The final triangulations also change accordingly.

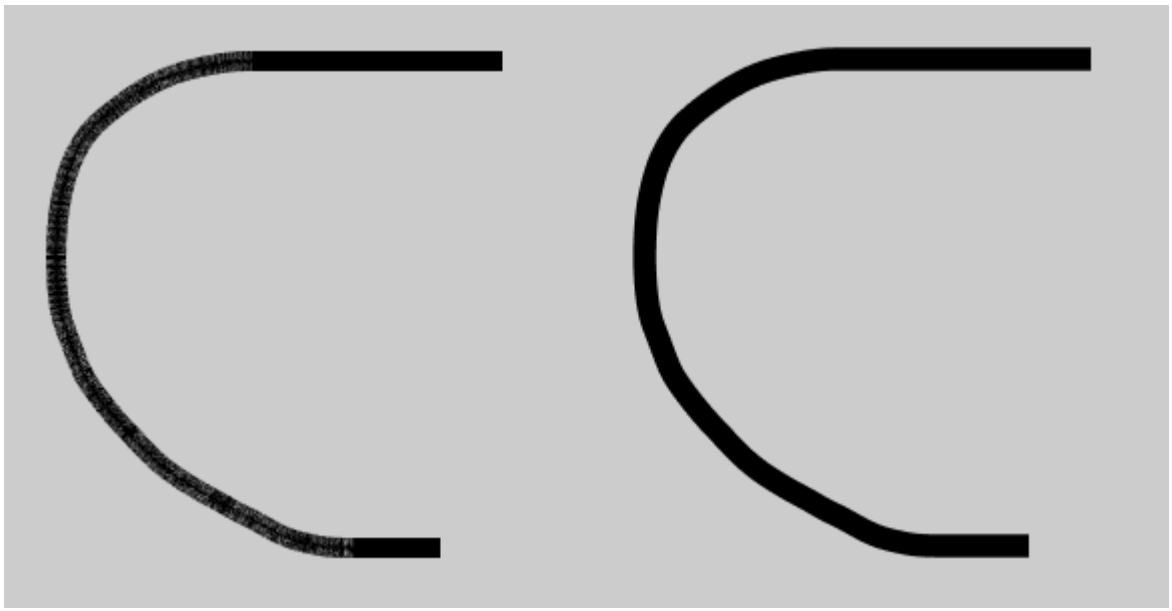


Figure 6.7: Left: A curve using default GL_LINES. Right: Implemented system

6.3 Implementation

Creating this representation geometry can rapidly increase the size of the data, especially as more and more lines are drawn. A simple polygonalization for a robust miter and bevel join implementation can create as many as six polygons for each pair of points on the curve. This does not take into account round joins, as smooth circle approximations require an even larger number of small polygons. By combining this characteristic with spline subdivision, we run the risk of running into bandwith problems when transferring polygon data between the GPU and the CPU for very large or complex strokes. To solve for this, we implement these algorithms in a geometry shader using a line adjacency data structure input (Figure 6.8). In order to reduce the number of branch operations, we polygonalize each line segment in halves, taking care of the join calculation

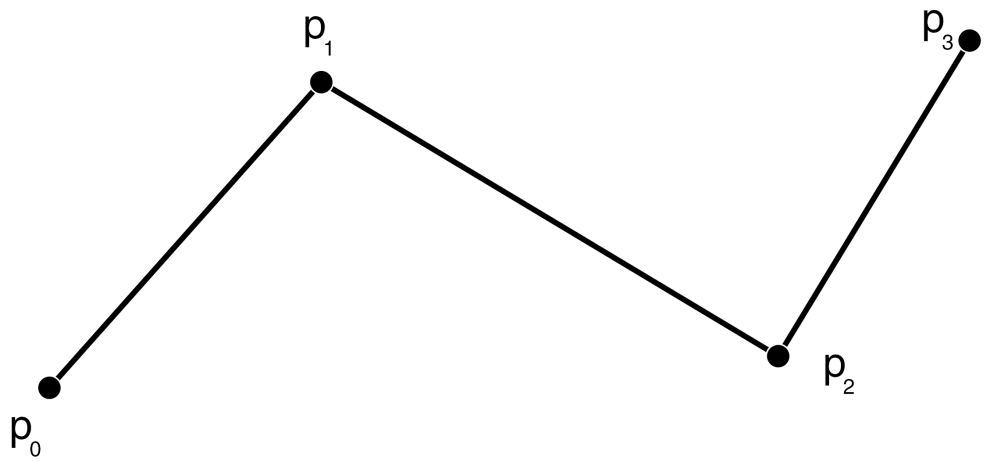


Figure 6.8: Our geometry shader makes use of the line adjacency data structure to generate the curve geometry. Each instance of the geometry shader uses a set of four ordered points (p_0, p_1, p_2, p_3) to generate geometry for the line segment (p_1, p_2)

for each side separately. An example of a polygonalized line segment can be seen in Figure 6.9.

Using the routines described above, the system can now display polygonalized, three dimensional lines efficiently. However, we still need to decide in what plane we create the line geometry. The approach CATIA [4] takes is creating the line geometry on the screen and projecting it onto scene objects. With this approach, lines only exist on the plane they are drawn on. As a result, it is possible to turn the camera such that the camera is perpendicular to the drawing plane and not see already drawn strokes. This approach is only suitable for applications where a base geometry is already supplied, and therefore not suitable for early stage design applications. Other shortcomings include the re-

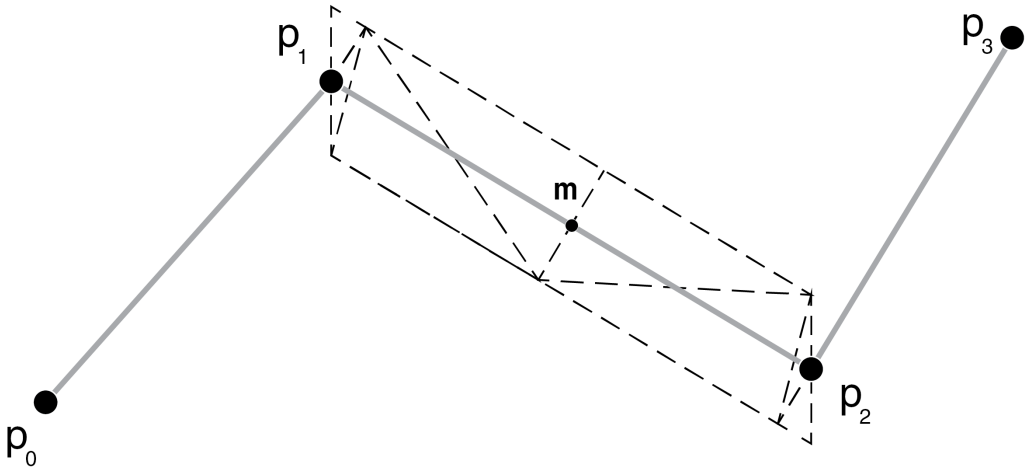


Figure 6.9: Since geometry is only created for the line segment (p_1, p_2), we need to polygonalize our geometry in such a way that the entire line is rendered correctly. We do this by polygonalizing half of the join for each line segment.

quirement of a large number of ray cast operations for each line created. Each segment of the polygonalized curve requires a ray cast operation per polygon vertex. This puts too much work on the CPU for a real time application.

We would like to allow for lines to be viewed from any direction, while still retaining their original line width and quality. The approach our application takes is to perform all of the calculations from creating line geometry in the distorted image space, the space defined after the model is transformed by the model, view, and projection matrices. By working in the distorted image space, we can guarantee the geometry is always expanded in a plane parallel to the

view plane. The reason we work in the distorted image space as opposed to view space, the space before the projection matrix is applied, is we would like our lines to have a consistent width regardless of depth. This is because if we were to combine depth altering width with variable sketching width the sense of depth quickly becomes confusing. This choice is a design decision made after speaking to various architects about the importance of being able to draw lines with different widths.

Algorithm 1: Line Rendering Algorithm

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for Line Adjacency data set $\{p_0, \cdots, p_3\}$ **do**

Convert world space line points $\{p_0, \cdots, p_3\}$ to the distorted image space points $\{p_{0s}, \cdots, p_{3s}\}$.

Compute normals for each of the line segments $(p_{ns}, p_{(n+1)s})$. Normals are enforced to be pointing towards the outer arcs of segment pairs.

Compute join parameters using image space variables and a defined line width.

Triangulate for the line segment (p_1, p_2)

end for

6.4 Color

One might have noticed that all of the sketches shown so far have been done in black ink. Unfortunately, colored ink is not possible in our current system.

Before talking about the 3D case, we should talk about the representation of color in a vector 2D graphics environment. For example, assume we have

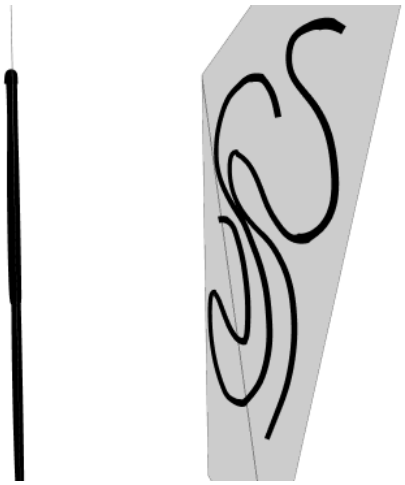

Figure 6.10: Even when rotating the drawing plane such that it is no longer visible, our lines remain visible.

a vector image with two circles of different color overlapping each other. The visibility of the circles is determined by their draw order. However, if we were to look at this in anther way, what is happening is the circles are given a hidden depth value outside the 2D image plane that is related to the draw order. This ”depth” allows for an easy way to determine visibility of colors in vector environments. (Figure 6.11)

However, in a 3D sketching environment, this ”depth” cannot be used to accomplish the same result, as in a 3D environment, depth is already defined. In our system, when two strokes intersect on the same surface, the 3D coordinates are identical. In graphics hardware, the z-coordinate of a point in NDC space determines visibility. When two transformed polygons have the same xyz coordinates, we encounter an issue known as Z-fighting, where the two pieces of geometry ”fight” over which one is visible. This manifests as flickering and bizarre appearing geometry at intersections. When all of the strokes are the same color, the artifacts exist but are not visible. Because of this, we cannot

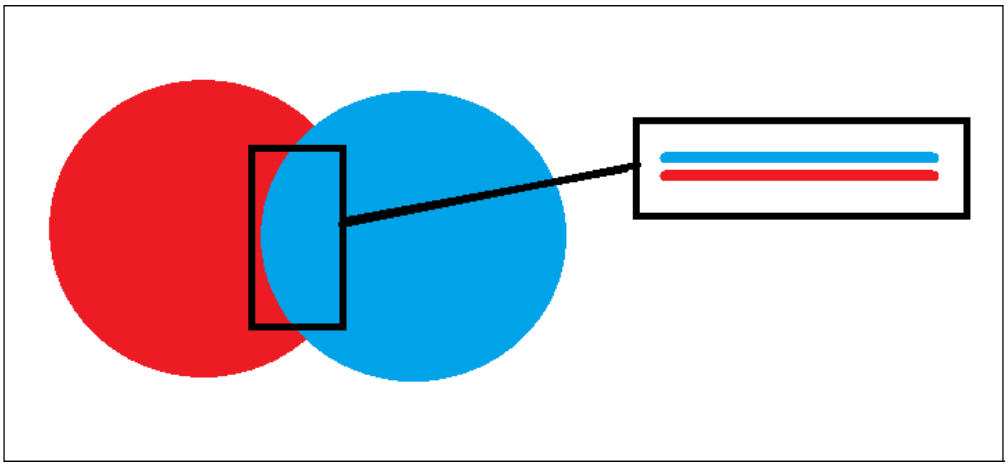

Figure 6.11: When objects of two different colors overlap in a vector graphics environment, a hidden depth value is used to determine visibility.

sketch in multiple colors without including Z-fighting artifacts.

6.5 Summary

In this chapter we have described a method for creating geometry from a sketched line defined by its input sample points. We have also described how we create it's representation as a 2-D geometry such that the representation is visible from any 3-D direction. By creating our geometry exclusively on the GPU, we minimize the bandwidth needed to transfer data from the CPU to the GPU, allowing extremely detailed curves using our subdivided spline calculations.

CHAPTER 7

CONCLUSION

In the architecture world, more focus is being put on 3D digital representations of buildings. However, the design phase remains in two dimensions. The focus of this thesis was to create the foundation of a user interface for simple three dimensional sketching. This includes utilizing different input devices, converting the sketch data from 2D to 3D, and rendering high quality 3D curves. In this final chapter, I will review the progress made towards this goal as well as places the research can go from here.

While there are other modern input devices that provide richer ways for interacting with 3D space, we decided that the best approach was to incorporate sketching on a two dimensional screen, as this most closely mimics current techniques. We also choose to incorporate touch technology, as it provides us with a second modality of user input when combined with pen. The benefits of this approach is direct interaction with the workspace, whereas in virtual reality the interaction methods are more indirect.

In Chapter 4, we discussed the conversion of our pixelized input to resolution independent spline curves, as well as techniques to generate curves that matched the intent of the original input over the raw data. In Chapter 5, we showed how to move from the 2D screen space to a 3D environment using ray casting, and how to use acceleration structures to speed up the process on complex environments. In Chapter 6, we provided a technique to render high quality curves free of common artifacts in native graphics libraries. Our rendering solution also allows for view independent curves that maintain a hand-drawn quality.

Overall, this research creates a basis for creating a specialized user interface for 3D sketching. While the current implementation is very bare bones, a new user interface can easily be made as all of the tools have been provided.

7.1 Implementation Details

The project was implemented in C++ using the QT library. An extension was written to allow pen and touch input on Windows devices. For testing, a 55-inch perspective pixel touch screen was mounted onto a harness for use as a digital drafting table. The attached computer used a 6th generation Intel processor with a NVIDIA Titan graphics card.

The system runs in real time at at least 30 frames a second until about 1,000,000 curve points are stored. A complex curve of reasonable length can have between 400 to 1000 points stored, while straighter curves are very cheap to store (around 10 to 100). This number becomes smaller is the sketching surface is using more complex geometry, but for these tests, a simple plane was used. In testing, this was proven to be sufficient for small to medium complexity sketches, but insufficient for very large, complex sketches. These numbers can improve with better hardware, as they are GPU limitations

7.2 Extensions

This thesis lays the groundwork for 3D sketching. There are some natural extensions that would improve the current results.

7.2.1 Color

In 6.4, we discussed how it is not possible to use colored stokes in our system because of Z-fighting artifacts. Being able to sketch in color without worrying about z-fighting would involve a four dimensional representation of the sketch space, where the forth dimension represents draw order.

One possible approach is to create a voxel structure in the sketch space, and store the sketch in that. The voxels can store the color that is on "top". Work would need to be done in order to use a voxel grid with high resolution at interactive rates.

7.2.2 Improving Sketching on Non-Planar Geometry

Thus far, we have shown sketching on planar surfaces and relatively smooth geometry. However, our system has issues with sketching around hard corners. This is because of both the input system as well as our spline interpolation.

First, we will discuss the input related issues. Assume we have two planes intersecting at a 90 degree angle, with the angle facing away from the camera. In this scenario, drawing a straight line across the two planes results in a series of ray intersection points on the two planes, with none of them lying close to the intersection. Using these points to calculate a spline will result in a section of the curve passing through the sketch geometry at the area of the planes' intersection.

These issues are a result of where we choose to interpolate the spline. Currently, we calculate the spline after we have intersected our input with the scene

geometry. Calculating the spline in 2D space and then projecting it onto the sketch geometry Would handle many of these artifacts. However, this exponentially increases the number of ray cast options. On complex, high polygonal environments where these types of issues would likely arise, the performance of our application drops. Improving the performance of the ray intersection algorithm will allow for the spline to be calculated before the ray cast.

An alternate approach would be to ”push” the stroke onto the surface geometry using collision detection. However, major performance improvements would be necessary for working with complex models.

7.3 Future Work

This thesis provides a groundwork on which future projects in 3D sketching can be built upon. There are a number of areas for future work on this topic.

7.3.1 Reducing Complexity

Currently, when sketching, each curve is stored in its entirety, even when curves are overlapping. For small sketches this is fine, but for larger sketches, removing redundant curves would make it possible for more complex sketches.

7.3.2 Generating Geometry

In Chapter 1, we discussed the segmentation in the design process, as early sketches are created using physical methods and then used as references to create a 3D model. While in this work, we have presented an approach to digitizing the early phase design process, we have not presented a method of easing the transition between these two stages. Doing this would require generating a 3D model from the sketch. As a first step, perhaps we can generate polygon data from a single plane of sketching. Other sketching modes can also be implemented to create simple geometry, such as a mode designed to sketch polygons instead of curves using closed splines, where the first and last point of the spline are connected.

7.3.3 Simulating Physical Sketching

Currently, actually using our application to a sketch is not comparable to a traditional drafting environment. Aside from the complexities of transitioning from 2D space to 3D space, many architects claimed that their were uneasy sketching with our application because drawing with an active pen lacked the tactical feedback provided by using a traditional sketching implement on a piece of paper. Work has been done in using haptic feedback to simulate the friction of writing on surfaces [6]. However, the current toolkit is for an arc ball input device. A first step could be extending the work to planar surfaces, with haptic technology integrated into the active pen.

7.4 Summary of Contributions

This research contributed to the field of computer graphics by creating a basic toolset to do three dimensional sketching. This is a new area that has begun to emerge due to new input devices allowing different methods of interacting with a computer.

In summary, the work described in this thesis made the following contributions:

- **Explored methods of converting rasterized input data to high-quality, resolution independent Bezier curves.** Due to the varying speeds a user can sketch, our algorithm needs to be able to handle input data of unknown spacing. As a result, we use our user input as control points to generate the spline. We have found that even though this might produce curves slightly different from the original input, users are pleased with the results.
- **Created an interface to convert 2D pen and touch data to 3D sketches.** We use a modified version of the QT library for our user interface framework. Our version fixes the broken touch and pen support in the native QT library, allowing our interface to be used with any Windows device. We utilize modern ray tracing algorithms and data structures to project our 2D sketch onto a 3D environment.
- **Provided a low overhead solution to rendering high quality 3D curves.** This solves common issues with using OpenGL to render curves as opposed to line polygons.

These contributions provide a basis for creating a 3D sketching environment for architectural design.

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