

COMPUTER ASSISTED LEARNING OF JAPANESE KANJI

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ABSTRACT

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Adam D. Horne

The purpose of the program described in this problem report is to assist learners of Japanese kanji in remembering the order, direction, and number of strokes for a given kanji. Using OpenGL and the Open Haptics toolkit, the program allows the user to both see and feel the kanji. Using a PHANTOM haptic device, the user can trace the different strokes using a height map of the kanji or following arrows that show the direction and order of strokes.

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TABLE OF CONTENTS

ABSTRACT	II
ACKNOWLEDGEMENTS	III
TABLE OF CONTENTS	IV
CHAPTER 1: INTRODUCTION	1
The PHANTOM device.....	1
CHAPTER 2: USING HEIGHT MAPS WITH HAPTICS	4
Explanation of Height Maps.....	4
Previous Use of Height Maps in Haptic Programs	5
Alternatives to Height Maps.....	6
CHAPTER 3: EXPLANATION OF JAPANESE KANJI.....	8
Why Use Kanji?.....	8
Techniques for Learning Kanji	10
Important Concepts in Writing Kanji.....	11
CHAPTER 4: THE HAPTIC HEIGHT MAP PROJECT.....	14
Scope.....	14
Definitions	15
Programming Environment.....	15
An Explanation of OpenGL.....	16
Design of Data Structures and Classes	17
<i>HeightMap</i> Class	17
<i>StrokeOrder</i> Class.....	19
Programming the OpenGL.....	20
Problems with the Viewing Volume.....	21
<i>render</i> Function in the <i>HeightMap</i> Class.....	22
<i>render</i> Function in the <i>StrokeOrder</i> Class	23
End Result of the OpenGL Code	24

Programming the OpenHL.....	25
Comparison of Haptic Programming Platforms.....	25
Converting Existing OpenGL Code for use with OpenHL.....	27
<i>render</i> Function in the <i>HeightMap</i> Class.....	28
<i>render</i> Function in the <i>StrokeOrder</i> Class.....	29
End Result of the OpenHL Code.....	29
Creating the Data Files	30
Creating the Height Maps.....	30
Creating the Stroke Order Files	31
CHAPTER 5: CONCLUSION	32
Testing on a 600 MHz Pentium	32
Testing on a 3.2 GHz Pentium.....	33
Suggested Improvements.....	34
Uses in Other Programs	36
BIBLIOGRAPHY	39
APPENDIX A: SOURCE CODE	40
Header Files	40
HeightMap.h.....	40
Point.h.....	42
Stroke.h.....	42
StrokeOrder.h	43
Source Files	44
HeightMap.cpp	44
Main.cpp.....	47
Stroke.cpp.....	61
StrokeOrder.cpp.....	64

Chapter 1: Introduction

The idea for the Haptic Height Map program came from a toy for children to help learn the letters of the alphabet. The toy was a wooden block with the shapes of all the letters of the alphabet carved into the surface. A child could use a stylus to trace the shapes of the letters and learn how to write the letters through repetition. The English alphabet only has twenty-six characters, so it is possible to fit the entire alphabet on one reasonably sized wooden tablet.

The toy was a good tool for children to practice writing. The Haptic Height Map program was written to simulate the writing toy in a virtual environment. Japanese students are expected to learn eighty kanji during their first year of school and almost two thousand by the time they graduate from high school. It would be very impractical to produce a physical tool like the alphabet toy for that many kanji. The Haptic Height Map program creates a virtual representation of a kanji character through the use of height maps that a user can feel and trace with a PHANTOM device.

The PHANTOM device

The PHANTOM is a computer peripheral that allows a computer user to touch and feel virtual objects simulated by the computer. Haptic Height

Map was programmed and tested with a PHANTOM Omni using the Open Haptics toolkit. The Open Haptics Library (OpenHL) integrates with the Open Graphics Library (OpenGL), so most programs that can be written in OpenGL can be modified to add a haptic interface.



Figure 1: The PHANTOM Omni

The PHANTOM is a force feedback device that allows the user to touch and interact with virtual environments. It is comprised of a stylus attached to a base by an arm. It offers six degrees of freedom and a wide range of motion. The Open Haptics toolkit provides functionality to assign material properties and forces such as friction and magnetic attraction and repulsion to objects that are being modeled. The toolkit handles all force

effects so the programmer does not have to perform complex calculations for physical properties. This allows the PHANTOM to simulate a realistic haptic experience.

Chapter 2: Using Height Maps with Haptics

Height maps are used primarily to store height information for large areas. They are used extensively in geographic simulations because they can store a large amount of information in a compact way. Height maps have been used in other haptic programs to simulate the creation of paintings[1].

Explanation of Height Maps

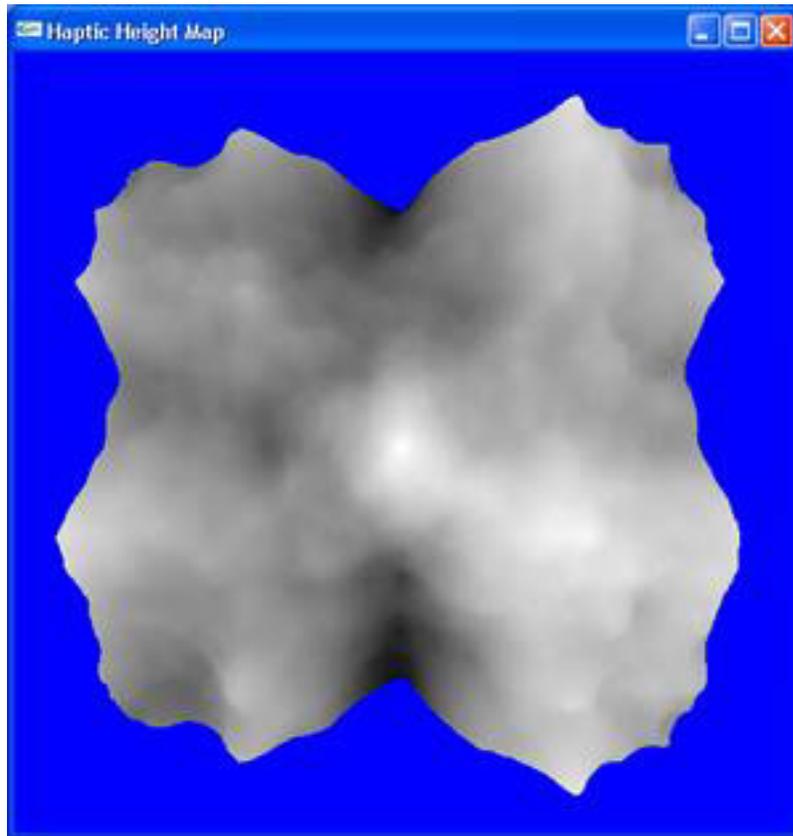


Figure 2: Height Map

Height maps are a storage device to hold height information for points over a large area. Figure 2 shows an example of a height map with a wide range of values. Height maps are normally stored as grayscale images. The images have a set resolution on the x and y axes, and each point in the image corresponding to an (x, y) coordinate has a value ranging from 0 to 255. This value is the height value for that position in the image[2]. It is also used to provide a color for that point, with 0 being black and 255 being white.

Previous Use of Height Maps in Haptic Programs

Height maps have been used in haptic programs to simulate the way that paint is applied to canvas. A program called IMPaSTo was created by a group of researchers at the University of North Carolina at Chapel Hill that uses a PHANTOM device to simulate the art of painting[1]. The program uses the PHANTOM as a virtual brush and physically models the flow of paint from the brush to a virtual canvas.

IMPaSTo uses multiple height maps to keep track of the depths of different layers of paints that have been applied to the canvas. The height map allows for two different states for the paint, wet and dry. If the top layer of paint is wet, then paint from the canvas will interact with paint on

the brush to change the color. If the top layer is dry, then paint is applied on top of the highest dry layer and creates a new height map for the wet layer.

Using multiple height maps allows the program to keep track of the different layers of paint color and how this will affect the way the painting looks[1]. Height maps are efficient for this type of application because for any given point (x, y) , only one value has to be stored for each layer to record the depth of the paint. This can improve the efficiency in both processing time and memory usage.

Alternatives to Height Maps

A program to simulate the haptic display of mathematical functions was written by a group of researchers at the Virtual Environments Laboratory at West Virginia University. It used a similar concept of carving the shape of the function into a virtual object that allowed a user to feel the mathematical function.

This program was written using strips of triangles by computing the y values of points for a given x value. Instead of reading information stored in a height map, all the values to be displayed are computed while the program is running. The (x, y) coordinates are used to create a V-shaped groove in the surface of the object with a set of eight triangles for each vertical strip on the surface[4].

The method described in the use of the program to display mathematical functions is not ideal for displaying kanji. Many kanji have strokes that are completely vertical or have more than one stroke that intersects a given vertical strip. The functionality used to display mathematical functions is not able to handle more than one intersection for a given vertical strip. The algorithm can not handle more than one mathematical function due to this constraint[3]. It would also not be able to render most kanji.

Chapter 3: Explanation of Japanese Kanji

The Japanese writing system uses two different character sets for phonetic spelling: hiragana and katakana. Hiragana and katakana are syllabaries with each character corresponding to one of the seventy-two syllables of the Japanese language. Hiragana is used for spelling Japanese words, and katakana is used mainly for spelling words borrowed from other languages or adding emphasis to a word. Any Japanese word can be written in hiragana and katakana. In addition to the two phonetic syllabaries, Japanese also uses kanji, which are characters borrowed from the Chinese writing system. Each character corresponds to one word, specific concept, or general idea.

Why Use Kanji?

Since Japanese has two syllabaries that could be used to write with, why is there a need for kanji? The reason is due to the way that Japanese sentences are written. The Japanese language does not have the same sentence structure or punctuation as English. English uses a sentence structure in the pattern “subject verb object” whereas Japanese uses a sentence structure of “subject object verb.” The English sentence, “I drink water,” becomes, “I water drink,” in Japanese.

In Japanese, the function of a word is determined by the particle that comes after it. The subject is usually followed by the particles “wa” or “ga,” while the object is usually followed by “o” or sometimes “ga.” There are other particles to denote possession, spatial relationships, where an action takes place, and when an action takes place. The verb is usually the last word in a sentence, so it does not need a particle to mark its function. It can be difficult to determine when one of these syllables is a particle, because these syllables can also be a part of words in the sentence.

A good example of where kanji can clear up confusion in a sentence is, “Mom went to the dentist.” Table 1 shows this sentence written in English and several different ways it could be written in Japanese.

	Subject	Part.	Destination	Part.	Verb
English	Mom		dentist	to	went.
Romaji	Haha	wa	haisha	e	ikimashita.
Hiragana	はは	は	はいしゃ	へ	いきました。
Hiragana and kanji	母	は	歯医者	へ	行きました。

Table 1: Example: Mom went to the dentist.

Spelled out in Romaji, a script to spell Japanese words using English letters, it looks like, “Haha wa haisha e ikimashita.” This is not confusing in Romaji because it uses the basic English punctuation of putting a space between the words and particles. When written in hiragana, it looks like,

「ははははいしゃへいきました。」 This is confusing because the

particle “wa” is also the same character as “ha,” so the same character is repeated four times, and the sentence is very hard to understand without a context for the conversation in which it is used. The same sentence written using hiragana and kanji looks like, 「母は歯医者へ行きました。」 The use of kanji clears up any ambiguity caused due to the lack of punctuation, so this is a good example of why kanji is so important for understanding the Japanese writing system.

Techniques for Learning Kanji

The primary technique for learning Japanese kanji is repeatedly writing the kanji in order to memorize it. The number of times a Japanese student will write a kanji varies depending on how hard the kanji is to learn. Simple kanji may only need to be written twenty times to be remembered. Difficult kanji may need to be written as many as a hundred times or more. Since the average Japanese student is expected to learn almost two thousand kanji before graduating from high school, most students can expect to write a hundred thousand or more kanji.

There are several shortcomings inherent in this form of learning. First, the student needs to use either a brush or pen and have paper to write on. Over the course of a student’s schooling, much paper is going to be wasted,

especially considering the huge number of kanji the student is going to write. The student must also use a reference book with the stroke orders. The act of looking from the paper the kanji is being written on to the book where the stroke order is illustrated can cause distraction that makes it harder to remember the kanji.

Important Concepts in Writing Kanji

There are several important concepts that should be considered when learning and writing kanji. Kanji are comprised of a number of different strokes, and the number of strokes in any given kanji can range from one to eighty or more. Two things to consider when writing kanji are what type of stroke to use and what order in which to write the strokes.

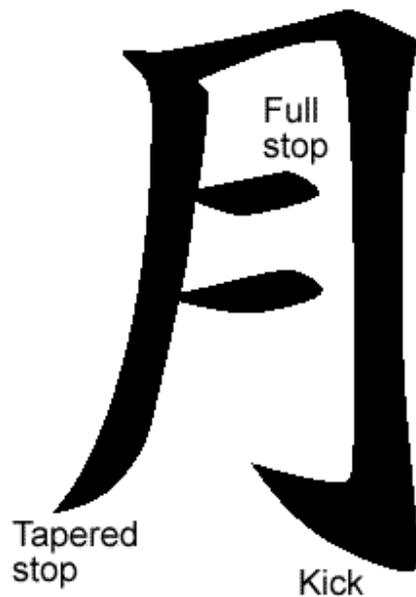


Figure 3: Example of Stops

The types of strokes are characterized by how the stroke ends. Kanji are traditionally written with a brush, so there are several ways that a stroke can be ended. The brush can be brought to a full stop and lifted to give a blunt end to the stroke, or the brush can be lifted while still moving at the end of the stroke to give a tapered end. Also, instead of lifting straight up after a full stop, the brush can be moved slightly to the side to give the stroke a little tail, called a “kick.” The different types of stops are illustrated in Figure 3. When writing with a pen, there is no way to make a distinction between a tapered and full stop, but the difference between a stop and a kick should still be emphasized.

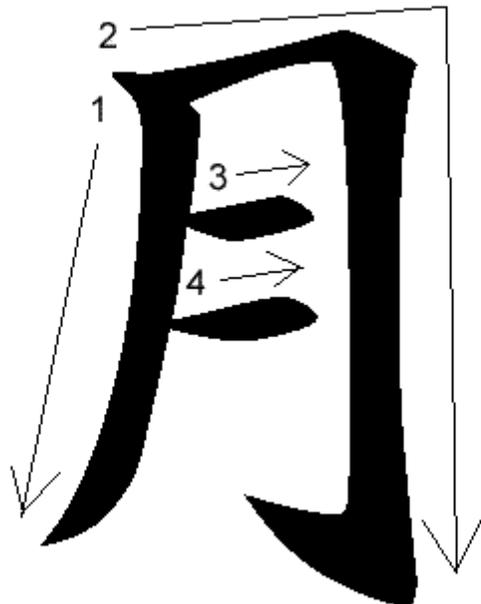


Figure 4: Example of Stroke Order

The other important concept that should be remembered when learning and writing kanji is the order in which the strokes are written. Each kanji has a defined order in which its strokes should be written. This order is important because some kanji are made by combining two or more kanji together. Learning the correct stroke order for a given kanji can make it easier to learn other kanji when the basic kanji is used as part of the new kanji.

Chapter 4: The Haptic Height Map Project

The goal of the Haptic Height Map project was to create a program using height maps to display kanji with real-time visual and tactile feedback that a student of Japanese kanji could use to learn kanji. By repeatedly writing kanji, a student is training the hand and mind to recognize the shape of the kanji and the feeling of writing it. This chapter will discuss how the Haptic Height Map program is implemented and what functionality is included to reach the goal of real-time visual and tactile feedback.

Scope

The Haptic Height Map program simulates an object that represents a carving of a Japanese kanji like the alphabet toy used to learn English letters. A user can see a representation of the kanji on the monitor and use a PHANTOM device to trace the shape of the kanji. The program simulates the act of writing the kanji with real-time visual and tactile feedback. Data files to represent the eighty kanji that Japanese students learn in first grade have been created and tested with the Haptic Height Map program.

Definitions

Following are definitions for concepts that should be known to understand how the Haptic Height Map program works:

1. Kanji – A written character borrowed from the Chinese writing system that corresponds to one word, specific concept, or general idea.
2. Stroke – Corresponds to one continuous motion of the brush when writing from the point when the brush first touches to when it leaves the writing surface. Strokes are not necessarily straight lines.
3. Stroke order – The order in which strokes should be written when writing a kanji.
4. Haptic_HM – The Haptic Height Map program.
5. OpenGL – The Open Graphics Library is a toolkit to implement the graphics of the program.
6. OpenHL – The Open Haptics Library is a toolkit provided by SensAble to implement the haptics of the program. OpenHL is modeled after OpenGL.

Programming Environment

The language used to program Haptic_HM is C++. This language was chosen for its ease of integration with both OpenGL and OpenHL. There are implementations of graphics libraries like OpenGL for other

programming languages such as Java, but OpenHL has only been implemented for the C and C++ programming languages. Haptic_HM was programmed in Microsoft Visual Studio 6, and all project documents, source code, and kanji data are available for use in Visual Studio.

An Explanation of OpenGL

OpenGL and the GLUT library are used in Haptic_HM to control the graphics, so following is a brief explanation of how they work. OpenGL is a library that handles all aspects of graphics display. OpenGL takes care of lighting, material properties, transformations, and determining what to display on the screen. GLUT is a library that simplifies the runtime aspects of the program such as refreshing the graphics, creating windows, and handling keyboard commands.

At the start of the program there is an initialization of the window. GLUT creates a window for the graphics to be displayed in and initializes the necessary components of OpenGL. After the program has been initialized it enters a display loop. The program will execute commands in the display loop and respond to keyboard commands from the user. GLUT handles any input from the keyboard and calls the display function anytime the system is idle. This means the display is constantly updated to reflect

any changes made by the user. The program will not exit the display loop until forced to do so by the user.

Design of Data Structures and Classes

There are two main classes required to display the kanji and stroke order: *HeightMap* and *StrokeOrder*.

***HeightMap* Class**

The *HeightMap* class holds all the information necessary to display the kanji. The height maps are stored as pictures in the RAW format. The RAW file is a grayscale image that only holds the data for the height values of the kanji[2]. Other formats for image storage could be used, but the RAW format was chosen because it is a simple format that is compact and easy to use.

To display the height map of the kanji, a RAW file must first be loaded into memory. First create an instance of the *HeightMap* class and call the *loadHeightMap* function with the name and size of the file to use. It is necessary to specify the size of the RAW file because the RAW format does not store this information in the file. The standard size for a RAW file to be loaded into Haptic_HM is 128 by 128 pixels. Due to the display properties of the object that is created, files of different sizes may not be

displayed properly if loaded into the program. The *loadHeightMap* function will prompt the user when the file is done loading or if there is a problem loading the file.

After the height map is loaded, it can be displayed by OpenGL. Before displaying the height map, a scale should be set for the height values by calling the *setScale* function. This scale determines how much to scale the height values of the height map. This scale should be based on the size of the RAW file. Since Haptic_HM uses data files that are 128 by 128, a small scale value is required. Haptic_HM sets the scale value to five percent of the base value. This means that while the height map is displayed over a 128 by 128 area, the depth of the height map will be a value between 0 and 12.8. When the kanji is displayed, this creates a shallow indentation in the surface that the haptic device can fall into.

In order to display the kanji that has been loaded, the instance of the *HeightMap* class should call its *render* function. This will display the kanji in the position specified by the program. It will display the points from the height map in a grid of triangle strips with their x and y values being the point in the data file and the z value being the value read from the height map file for that (x, y) position. It will also use the value from the file to

determine the color of the point, with a value of 255 being white and on the front surface and a value of 0 being black and on the back surface.

The *HeightMap* class offers functionality to load and unload height map data. It also allows the user to set the value of the height map for any given (x, y) coordinate. Functionality provided in the *HeightMap* class could be used to expand the program to show other kinds of information such as mathematical functions.

StrokeOrder Class

The *StrokeOrder* class holds all the information necessary to display the stroke orders of the kanji. The *StrokeOrder* class uses a vector to store information for the individual strokes in the kanji. The *Stroke* class holds information about the points that comprise a single stroke. In order to display the stroke order, all the points must be loaded into their strokes, and then those strokes must be stored in order in the instance of the *StrokeOrder* class.

There are two ways to load information into the instance of the *StrokeOrder* class. The first way to load information is to hard code the individual points into strokes and add them into the instance of *StrokeOrder*. Once a *StrokeOrder* has been created, it can be saved to a binary data file by calling the *saveFile* function with the name of the file to save. The second

way to load information is to call the *loadFile* function with the name of a data file that has already been created with the stroke order information.

After the information has been loaded into the instance of the *StrokeOrder* class, it can be viewed by calling its *render* function with the number of the stroke to render. If the number passed into the *render* function is a number between one and the total number of strokes in the kanji, then only that stroke will be shown. If the number passed into the function is zero, then all the strokes will be shown.

A Boolean value can also be passed into the *render* function that determines whether to draw arrowheads on the ends of the lines. If the value passed in is true, then the strokes will be drawn with arrowheads indicating which direction the stroke is to be written. Arrowheads are used when drawing the graphics so the user can see the direction of the stroke. Arrowheads are not used for the haptic portion of the program since the user only wants to feel the lines of the stroke itself.

Programming the OpenGL

Writing the portion of the program with OpenGL to display the height map was relatively straight-forward. There are relatively few commands to initialize OpenGL for the program. There are no textures or lighting involved in the program, so that functionality has been disabled. Culling has

been enabled so that polygons that are not in view will not be rendered.

There have been times when the PHANTOM device will push through the height map with no resistance. It is possible that turning on culling could cause polygons in the height map to not be rendered and allow the PHANTOM device to fall through cracks because the polygons are missing. Testing with culling both on and off was inconclusive, so it is unclear whether culling causes this problem. It is believed the PHANTOM device will push through the object if too much force is applied to protect the device from breaking.

Problems with the Viewing Volume

Initially the camera was set to have a large viewing volume with the near clipping plane set very close to the camera and the far clipping plane set a long way in the distance. This made programming the *render* function for the *HeightMap* class easier as there was no need to scale the height map. This became a problem later when integrating the PHANTOM device due to the fact that the arm of the PHANTOM has only a limited range of motion. After several trials with manipulating the viewing area, it was found to be easiest to use the standard viewing volume used in example programs written by SensAble for the PHANTOM device and adapt the *render*

function in the *HeightMap* class so that the height map fit into the smaller viewing volume.

***render* Function in the *HeightMap* Class**

The *render* function for the *HeightMap* class cycles through the height values read in from the data file and makes calls to OpenGL to draw the height map. The points in the file are drawn using a triangle strip. A triangle strip takes a list of points and draws polygons between the points in a more efficient way than drawing the triangles individually. There was a problem initially in the order the points were being input into the *render* function. When the triangles were being drawn, the front face was away from the camera, so nothing was being drawn. After turning off culling, it became apparent what was happening, and the problem was corrected by swapping the order that points were being added to the object. This resulted in the front faces of the polygons to be facing the camera, and culling could be turned on.

Another problem encountered while writing the *render* function was that the height map was being shown upside down. This was due to the way that the RAW data file was written when it was saved by the image editing software. It was necessary to subtract the y value of the point from the size of the RAW file in order for the height map to be rendered correctly.

***render* Function in the *StrokeOrder* Class**

The *render* function for the *StrokeOrder* class draws arrows to show the direction and placement of strokes in the kanji. If passed a value of zero, it draws all the strokes. If passed the value of a specific stroke, it draws only that stroke. It also accepts a Boolean value to determine whether it should draw arrows at the endpoints to indicate direction.

Like the height map, the strokes were originally being displayed upside-down, so they also have their y values subtracted from the size of the RAW file in order to appear correctly on the screen. The z value for the arrows is set to be one above the maximum height of the height map before scaling. This is to make sure that the arrows will always be slightly above the height map and visible.

The only difficult part about drawing the strokes is drawing arrowheads at each of the endpoints. In order to draw the arrowheads, it is necessary to calculate a two-dimensional vector between the end point and the point before it. The vector is then normalized to determine the x and y components of the vector. These components are multiplied with a rotation matrix twice (once with a positive angle and once with a negative angle) in order to obtain new x and y coordinates for the two tips of the arrowheads. These coordinates are then added to the x and y of the original end point to

obtain the world coordinates for the tips of the arrowhead. The line is then drawn through each of these points and returns back to the end point, where it can go on to the next point in the stroke.

End Result of the OpenGL Code



Figure 5: OpenGL Screen Capture

Figure 5 shows a screen capture of the program displaying a kanji with all the strokes of the stroke order displayed. The program is written so the user is looking down on the height map. The white area of the image is closer to the user than the black area. The arrows of the stroke order are drawn in red and are slightly raised above the surface of the height map.

Figure 5 shows that it is possible to render the kanji and stroke order in a way that looks natural.

Programming the OpenHL

The haptic portion of the program was written after the graphics were written and tested. Writing the portion of the project to interface with the haptics was relatively easy because many of the bugs were worked out while programming the OpenGL portion of the program. OpenHL was written to interface easily with OpenGL and recognizes many of the function calls used in OpenGL.

Comparison of Haptic Programming Platforms

Previous Phantom devices were programmed with the GHOST SDK. This SDK had its own functions to create geometries that had both visual and tactile components. GHOST was relatively easy to use as it was similar to OpenGL. It had good support for commonly used primitive three-dimensional shapes such as spheres, cones, and cubes. GHOST was not as useful for two-dimensional objects. For two-dimensional object, triangular meshes were required, and they were not nearly as easy to implement as similar programming options in OpenGL like triangle strips.

The Open Haptics Library is the new SDK for programming the PHANTOM Omni. OpenHL was designed to intercept OpenGL commands and translate them into a form that the PHANTOM can utilize. OpenHL can understand most OpenGL commands that are used to create geometric objects. This means that just about anything that can be represented visually with OpenGL can, with a little bit of modification, be felt using the PHANTOM and OpenHL. OpenHL can use the commands that were used by OpenGL to create the triangle strips to create the exact same geometry to be felt with the PHANTOM device.

The way that OpenHL creates geometries that the PHANTOM can feel is by capturing calls to OpenGL and rendering them in the haptic environment instead of the visual environment. Because it recognizes OpenGL commands instead of requiring the user to make separate calls to special haptic functions, it is possible to convert programs written in OpenGL to be used with the PHANTOM device. For this reason, the OpenGL portions of Haptic_HM were written and tested before adding the OpenHL portions. The only special changes that must be made are to the viewing volume. Because the PHANTOM has a limited field of motion, the viewing volume must be set up to a certain size to accommodate the PHANTOM. This means that the user is constrained in the area that is in the

field of vision, and it is easier to have a fixed viewing area and move objects into that viewing volume. This was the reason that changes had to be made to the *render* function of the *HeightMap* class.

Converting Existing OpenGL Code for use with OpenHL

The easiest way to program the haptics is to isolate all OpenGL calls that are used to create geometric shapes in their own function. When designing the *render* functions for the *HeightMap* and *StrokeOrder* classes, all the calls to functions that create the geometry of these objects were isolated inside their respective *render* functions.

In the display function, there are calls to two similar functions, *drawSceneGraphics* and *drawSceneHaptics*. At the beginning of the functions will be calls to set up the scene. For the graphics, this may be calls to change the colors, lighting, or material properties of the object. For the haptics, this will be calls to manipulate forces like friction on the object, whether there is an attraction associated with the object, and how hard it is to pull the Phantom away from the object. In each function, after the initial setup, the calls can be made to the *render* functions of the objects to be drawn. Simplified versions of the functions would look like the functions in Table 2.

<pre>void drawSceneGraphics() { // function calls to set up lighting, etc. hMap.render(); // function calls to set up lighting, etc. strokeOrder.render(); }</pre>	<pre>void drawSceneHaptics() { // function calls to set up forces, etc. hMap.render(); // function calls to set up forces, etc. strokeOrder.render(); }</pre>
--	---

Table 2: Simplified Functions

The way that OpenHL knows to capture OpenGL commands and render them as haptics is by creating a shape id and making a call to *hlBeginShape* with this shape id. This forces any later commands to be rendered in the haptic context until there is a call to *hlEndShape*. Two objects with the same shape id will share the same haptic properties. This is not desirable in most situations, so it is important to have separate ids for each object that is being rendered.

***render* Function in the *HeightMap* Class**

The haptic context for the *HeightMap* class has to be set up to allow the user to feel the height map when it is rendered. Calls are made to the *hlMaterialf* function to set up material properties of the surface such as friction and stiffness. Finally, the touch model has to be initialized so the PHANTOM can react when it gets near and touches the surface. The height map is set up as a contact surface so that it can be felt by the PHANTOM but will not apply any other forces.

***render* Function in the *StrokeOrder* Class**

The haptic context of the *StrokeOrder* class is set up in the same way as the *HeightMap* class. The *StrokeOrder* class has two different ways of functioning depending on the user's preferences. If the user does not want the PHANTOM to snap to the lines of the strokes, then the strokes are not rendered in the haptic context. If the user wants the PHANTOM to snap to the lines of the strokes, then constraints are turned on, and the lines are rendered without the arrowheads.

Constraints cause the PHANTOM to force itself to be pulled towards the object when it gets within a certain bounding distance of the object. With constraints turned on, the PHANTOM will snap onto the lines of the stroke order and be forced to follow along those lines. It is possible to pull the PHANTOM away from the line by applying enough force to overcome the limit set in the constraints. This allows the user to move from one stroke to another.

End Result of the OpenHL Code

After implementing the OpenHL code, there are two different ways to feel the shape of a kanji. The user can feel the shape of the height map and follow the grooves that are created to trace the shape of the kanji. Alternately, the user could turn on the constraints to force the PHANTOM to

snap to the lines of the stroke order. The user can either display all of the strokes and move the PHANTOM between strokes or display the strokes individually and cycle through them to trace them in order.

Creating the Data Files

In order to test the program, it was necessary to create data files for a range of kanji. Data files were created for all the eighty kanji that Japanese students learn in the first grade. This provided enough kanji to test the PHANTOM over the entire surface area of the height map. The height maps were created first and displayed in the program to assist in defining the values for the stroke orders.

Creating the Height Maps

The RAW data files for the height maps were created using Adobe Photoshop and a Wacom tablet. The Wacom tablet is a peripheral input device with a large, dynamic surface. It works along with Photoshop to allow the user to write or draw in a more natural fashion than using a mouse. The tablet recognizes the amount of pressure exerted by the user and adjusts the thickness of lines that are drawn according to this pressure. This makes it easier to simulate the difference between strokes ending with tapers, stops, and kicks. Each kanji was written by hand in Photoshop and saved as a

RAW data file. This gives the kanji a more authentic look when displayed in Haptic_HM.

Creating the Stroke Order Files

The stroke order data files were created in the Haptic_HM program. The RAW data files were loaded into Photoshop, and key points in the strokes of the kanji were recorded in the Haptic_HM program. This included the starting point, end point, any points needed in the middle of a stroke that was not straight, and a point for the kick at the end of some strokes. Each of the strokes was then tested to make sure it corresponded with the actual location and looked correct when displayed over the height map. When all the strokes were in the correct places, the stroke order was saved so that it could be loaded later without having to reenter each point.

Chapter 5: Conclusion

The Haptic Height Map program was tested on two different machines at various times during its development. The main problem with using the PHANTOM Omni device and programming with the Open Haptics Library is the requirement to have a special license file on each computer. The license file has to be requested from SensAble, and it took some time to receive a reply with the new license file when the PHANTOM was moved to a new testing environment. This would make it hard to test the program in several different environments.

Testing on a 600 MHz Pentium

The Haptic_HM program was mainly written on a 600 MHz Pentium machine with 16 megabytes of video RAM. The only part of the program not tested on this machine was constraining the PHANTOM to the lines of the strokes. All other portions of the program were designed and tested on this machine.

The results on this machine were poor. The program ran, but there was a notable difference in how the graphics were being displayed and the feedback from the PHANTOM. Users would move the PHANTOM along a stroke, and the arm of the PHANTOM would stop because it had hit the end

of the stroke, but the graphics on the screen showed that the cursor where the PHANTOM should be located was only halfway through the stroke. This was disorienting for some users and was not a desirable result. The main problem with this testing machine appeared to be the video card, as it was not powerful enough to display the graphics so that they synchronized with the PHANTOM device. After determining that this test computer was not powerful enough to run the program, it was decided to test the program on a newer, more powerful computer.

Testing on a 3.2 GHz Pentium

After transferring the license for the PHANTOM, it was possible to test the Haptic_HM program on a 3.2 GHz Pentium with 128 megabytes of video RAM. All parts of the program that had been tested on the original machine were tested on the new machine along with the new functionality of constraining the PHANTOM to the lines of the stroke orders.

The results on this machine were much better than the original test machine. There was no longer any disconnection between where the graphics showed the cursor to be and what the user felt with the PHANTOM. Users were no longer disoriented by the experience and could follow the strokes in the height map easily.

The addition of the ability to constrain the motion of the PHANTOM to the lines of the strokes gave the user another option for tracing and learning the strokes of the kanji. The program ran in real time and users found the interaction between the PHANTOM and the graphics to be more intuitive. The results show that it is feasible to practice writing and learning kanji through the use of a haptic device such as the PHANTOM.

Suggested Improvements

Haptic_HM has shown a proof of concept that the PHANTOM can be used as a tool to learn kanji, but there are several improvements that could be implemented in the program to make it easier to use and also more powerful as a learning tool. Due to time constraints, it was not possible to implement all the functionality to make Haptic_HM a polished, professional product.

The program only allows kanji and stroke orders to be loaded by hard coding them into the main part of the program. A user interface that allowed for dynamically changing the data files that are loaded into the program would be a good improvement. The *HeightMap* and *StrokeOrder* classes already offer some of the functionality to allow the user to unload the current kanji and load information for a different kanji.

At the moment there are no visual indications of the order of the strokes other than cycling through the strokes in the stroke order. It would look better and be a better tool if the numbers of the strokes were displayed at the beginning of the stroke. There are several options available in OpenGL that would make this possible. OpenGL offers special functions to handle the display of text. Another possibility would be to billboard a texture of the stroke number next to the beginning of the stroke.

Another consideration for how well the program performs is how well the goal of helping a user to remember kanji is accomplished. The program can be used to trace kanji and learn the stroke order, but there is other information that is useful to know about the kanji. Each kanji has its own pronunciation or set of pronunciations for the kanji compounds in which it is used. It would be very useful for a person learning kanji if the information about the kanji were displayed along with the height map and stroke order. This information would be the pronunciations, names of radicals in the kanji, and examples of kanji compounds in which it is used. All this information is available in reference materials, but if the user looks away from the screen to get this information, then this is the same disconnect as when the student is writing on paper and has to look away to check the stroke order.

It would be best if all this information were displayed on the screen along with the kanji. The same functions that can be used to display the stroke numbers could be used to display this text around the area where the height map is displayed. Having all this information on the screen at one time would allow the user to learn all the necessary information without having to look at other reference materials.

Uses in Other Programs

The *HeightMap* class that was created to display the kanji could have uses for displaying other types of information. One area of interest currently being explored is adapting the program to work with mathematical functions.

One problem with the algorithm originally used to display mathematical data described by Van Scoy et al. was the difficulty of displaying multiple functions at the same time. In order to display multiple functions in the algorithm described, a model must be built involving triangulation with the values of the functions and extruding the shape in the Z-axis[3].

The HeightMap class has functionality to take care of building a mathematical function. The height value at a given (x, y) coordinate can be modified easily when constructing a function. Multiple functions could be applied to the values in the height map with no need to triangulate between

the different functions. Members of the Virtual Environments Laboratory at West Virginia University will be exploring how to adapt the Haptic Height Map for use in displaying mathematical functions.



Figure 6: Asymptotes in the Function $y=\tan x$

One of the main problems with the display of mathematical functions occurs when there are asymptotes like in the function $y=\tan x$. The previous approach uses TriPolyMeshes and results in extraneous grooves in the function as shown in Figure 6. Another problem is the non-uniform size of the groove when the magnitude of the slope of curve is different. This leads to very small grooves when the slope is approaches being vertical[4].

One approach to solve this problem was to construct circles around the points along the curve. Using these circles, the triangles of the groove

could be computed to make the groove a more uniform width. This approach is very processor intensive and hard to implement.

The Haptic Height Map program can be adapted to show mathematical functions without some of the problems associated with the previous version of the software. The first solution would be to create RAW data files that are drawings of the mathematical function to be studied. This would require a picture of each mathematical function to be constructed before it could be felt using the program.

With the addition of a parser to interpret mathematical functions, the program could also be adapted to create a height map during run-time. The Haptic Height Map program already has the functionality to change values in the height map. This would allow the display of any mathematical function without having to construct the RAW data file in advance.

Bibliography

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4. Van Scoy, Frances L., Takamitsu Kawai, Angela Fullmer, Kevin Stamper, Iwona Wojciechowska, Addis Perez, Jesir Vargas, Shelma Martinez. "The Sound and Touch of Mathematics: a Prototype System." *Proceedings of the Sixth PHANTOM Users Group Workshop*, pages 27-30, October 2001.

Appendix A: Source Code

Following is all the source code for the Haptic Height Map program. The source code, Visual Studio project files, and data files for the first eighty kanji can also be found at

https://etd.wvu.edu/etd/controller.jsp?moduleName=documentdata&jsp_etdId=3917

Header Files

HeightMap.h

```
#ifndef _HEIGHTMAP_H_
#define _HEIGHTMAP_H_

#include <stdlib.h>

struct HEIGHT_DATA
{
    unsigned char* data;    //the height data
    int size;              //the height size (restricted to powers of 2)
};

// Class: HeightMap
// The HeightMap class stores information for the height map.
class HeightMap
{
protected:
    HEIGHT_DATA heightData; // structure to store the information

    float heightScale; // value to scale the height of the height map by

public:
    HeightMap() {}
    ~HeightMap() {}

    int size; // holds the size of the RAW file
};
```

```

    bool loadHeightMap(char* filename, int filesize); // loads in height
map information
    bool unloadHeightMap(); // unloads height map information
    void render(); // render the height map graphics

// Function: inline void setScale(float scale)
// Sets the scale for the height map.
inline void setScale(float scale)
{
    heightScale = scale;
}

// Function: inline float getScale()
// Returns the scale of the height map.
inline float getScale()
{
    return heightScale;
}

// Function: inline void SetHeightAtPoint(unsigned char height, int x,
int y)
// Sets the height value at the given (x, y) coordinate.
inline void SetHeightAtPoint(unsigned char height, int x, int y)
{
    heightData.data[(y * size) + x]= height;
}

// Function: inline unsigned char getTrueHeightAtPoint(int x, int y)
// Returns the actual height value at the given (x, y) coordinate.
inline unsigned char getTrueHeightAtPoint(int x, int y)
{
    return (heightData.data[(y * size) + x]);
}

// Function: inline float getScaledHeightAtPoint(int x, int y)
// Returns the scaled height value at the given (x, y) coordinate.
inline float getScaledHeightAtPoint(int x, int y)
{
    return ((float)(heightData.data[(y * size) + x]) * heightScale);
}

```

```

    }
};

#endif // _HEIGHTMAP_H_

```

Point.h

```

#ifndef _POINT_H_
#define _POINT_H_

// Class: Point
// This class holds information for individual points for the strokes.
class Point
{
private:
    int x; // x coordinate
    int y; // y coordinate

public:
    Point() { x = y = 0; } // Constructor
    Point(int inX, int inY) { x = inX; y = inY; } // Constructor - sets (x, y)
coordinate

    int X() { return x; } // Returns value of x
    int Y() { return y; } // Returns value of y
    void X(int temp) { x = temp; } // Sets value of x
    void Y(int temp) { y = temp; } // Sets value of y
};

#endif // _POINT_H_

```

Stroke.h

```

#ifndef _STROKE_H_
#define _STROKE_H_

#include "Point.h"
#include <Vector>

```

```

using namespace std;

// Class: Stroke
// Holds the information for one kanji stroke.
class Stroke
{
private:
    vector<Point> points;    // vector to store the individual points of the
stroke
    float scaleFactor;    // amount to scale the stroke when it is rendered

public:
    Stroke(float scale) { scaleFactor = scale; }    // Constructor
    void render(bool arrows);    // Renders the stroke
    void addPoint(Point* temp);    // Adds a point at the end of the stroke
    Point pointAt(int num) { return points[num]; }    // Returns the
stroke at num
    int size() { return points.size(); }    // Returns the
number of points in the vector
};

#endif // _STROKE_H_

```

StrokeOrder.h

```

#ifndef _STROKEORDER_H_
#define _STROKEORDER_H_

#include "Stroke.h"
#include <Vector>

using namespace std;

// Class: StrokeOrder
// Stores all the strokes of the stroke order for a given kanji.
class StrokeOrder
{
private:

```

```

        vector<Stroke> strokes;           // vector to hold the strokes
        float scaleFactor;               // amount to scale the strokes when
they are rendered

public:
    StrokeOrder(float scale) { scaleFactor = scale; } // Constructor
    void setScale(float scale) { scaleFactor = scale; } // Sets the scale
factor
    void render(int num, bool arrows); // Renders the stroke order
    void addStroke(Stroke* temp);     // Adds a stroke to the end of
the stroke order

    int totalStrokes(void) { return strokes.size(); } // Returns the total
number of strokes in the stroke order

    void saveFile(char* filename); // Saves the stroke order to a file
    void loadFile(char* filename); // Loads in the stroke order from a file
};

#endif // _STROKEORDER_H_

```

Source Files

HeightMap.cpp

```

#include <stdio.h>
#include <math.h>

#ifdef WIN32
#include <windows.h>
#endif

#include <GL/gl.h>
#include <GL/glut.h>

#include "HeightMap.h"

// Function: bool HeightMap::loadHeightMap(char* filename, int filesize)

```

```

// This function loads in information for the height map.
// It reports an error if the file does not load properly.
bool HeightMap::loadHeightMap(char* filename, int filesize)
{
    FILE* tempFile;

    // if data is currently loaded, unload that information
    if(heightData.data)
        this->unloadHeightMap();

    // open the RAW data file for reading
    tempFile = fopen(filename, "rb");
    // report an error if the file is not loaded
    if(tempFile == NULL)
    {
        // bad filename
        fprintf(stdout, "An error occured while loading height map
information.\n");
        return false;
    }

    // create an array to hold the height data
    heightData.data = new unsigned char [(filesize * filesize)];

    // report an error if memory is not allocated
    if(heightData.data == NULL)
    {
        //failed to allocate memory
        fprintf(stdout, "Could not allocate memory to load the file.");
        return false;
    }

    // read in the height map data
    fread(heightData.data, 1, (filesize * filesize), tempFile);

    // close the file
    fclose(tempFile);

    // set the m_iSize data
    this->size = filesize;
}

```

```

    // report that the file has been read successfully
    fprintf(stdout, "Height map data has been loaded.\n");
    return true;
}

// Function: bool HeightMap::unloadHeightMap()
// This function unloads the height map from memory.
bool HeightMap::unloadHeightMap()
{
    // if there is data then unload it
    if(heightData.data)
    {
        // delete the data
        delete[] heightData.data;

        // reset the size
        size= 0;
    }

    // report that the height map has been unloaded
    fprintf(stdout, "Height map data unloaded.");
    return true;
}

// Function: void HeightMap::render()
// This function renders the height map in both the graphics and the haptics.
void HeightMap::render()
{
    unsigned char color;    // used to set the color value for vertices
    int Y;    // counter to loop through the Y values of the height map
    int X;    // counter to loop through the X values of the height map

    // enable culling to get rid of unnecessary polygons
    glEnable(GL_CULL_FACE);

    // loop through Y values
    for (Y = 0; Y < (size - 1); Y++)
    {
        // begin drawing a triangle strip for this Y value

```

```

glBegin(GL_TRIANGLE_STRIP);

    // loop through X values
    for(X=0; X<size-1; X++)
    {
        // set the color based on the height
        color = this->getTrueHeightAtPoint(X, Y);
        glColor3ub(color, color, color);

        // render the point
        glVertex3f((float)X, (float)(size - Y), this-
>getScaledHeightAtPoint(X, Y));

        // set the color based on the height
        color= this->getTrueHeightAtPoint(X, Y+1);
        glColor3ub(color, color, color);

        // render the point
        glVertex3f((float)X, (float)(size - (Y+1)), this-
>getScaledHeightAtPoint(X, Y+1));
    }

    // end the triangle strip
    glEnd( ); // GL_TRIANGLE_STRIP
}
}

```

Main.cpp

```

#include <stdio.h>
#include <stdlib.h>
#include <fstream>

#ifdef WIN32
#include <windows.h>
#endif

#include <vector>
#include <GL/gl.h>

```

```
#include <GL/glut.h>
#include "HeightMap.h"
#include "Point.h"
#include "Stroke.h"
#include "StrokeOrder.h"

#include <HL/hl.h>
#include <HDU/hduMatrix.h>
#include <HDU/hduError.h>

#include <HLU/hlu.h>

using namespace std;

static HHD hHD = HD_INVALID_HANDLE;
static HHLRC hHLRC = 0;

HLuint heightMapShapeId;
HLuint strokeShapeId;

#define CURSOR_SIZE_PIXELS 20
static double gCursorScale;
static GLuint gCursorDisplayList = 0;
static double gHapticsSnapDistance = 0.0;

bool drawCube = false;
bool drawStroke = false;
bool forceSnap = false;

HeightMap hMap;

StrokeOrder strokeOrder(0);

int currentStroke = 0;

void init();
void initGL();
void initHL();
void reshape(int w, int h);
void display();
```

```

void idle(void);
void heightMapTransform();
void drawSceneGraphics();
void drawSceneHaptics();
void drawCursor();
void updateWorkspace();
void exitHandler(void);
void renderStroke();
void keyboard(unsigned char key, int x, int y);

// Function: void init()
// Initializes the graphic and haptic context to prepare for display.
void init()
{
    initGL();
    initHL();
}

// Function: void initGL()
// Initializes states for the graphics engine.
void initGL()
{
    glClearColor(0.0f, 0.0f, 1.0f, 0.0f); // set the background color to blue
    glDisable(GL_TEXTURE_2D); // disable two dimensional textures
    glDisable(GL_LIGHTING); // disable lighting
    glDisable(GL_BLEND); // disable blending
    glEnable(GL_DEPTH_TEST); // enable depth testing

    glCullFace(GL_BACK); // set culling for back faces
    glEnable(GL_CULL_FACE); // enable culling

    glShadeModel(GL_SMOOTH); // set smooth shading
    glClearDepth(1.0); // depth buffer setup
    glDepthFunc(GL_LEQUAL); // type of depth testing
    glHint(GL_PERSPECTIVE_CORRECTION_HINT, GL_NICEST);
    // the nicest perspective look
}

// Function: void initHL()

```

```

// Initializes states for the haptics engine.
void initHL()
{
    HDErrorInfo error;

    // Initialize the device and report any errors.
    // Exit if there is an error with the device.
    hHD = hdInitDevice(HD_DEFAULT_DEVICE);
    if (HD_DEVICE_ERROR(error = hdGetError()))
    {
        hduPrintError(stderr, &error, "Failed to initialize haptic device");
        fprintf(stderr, "Press any key to exit");
        getchar();
        exit(-1);
    }

    hHLRC = hlCreateContext(hHD);
    hlMakeCurrent(hHLRC);

    // Enable optimization of the viewing parameters when rendering
    // geometry for OpenHaptics
    hlEnable(HL_HAPTIC_CAMERA_VIEW);

    // generate id's for the shapes
    heightMapShapeId = hlGenShapes(1);
    strokeShapeId = hlGenShapes(1);

    // set the stiffness to use with the device
    HDdouble kStiffness;
    hdGetDoublev(HD_NOMINAL_MAX_STIFFNESS, &kStiffness);

    // set the distance at which the device will snap to objects
    gHapticsSnapDistance = 5.0 / kStiffness;
}

// Function: void exitHandler()
// Deletes references to objects when the program is shut down.
void exitHandler()
{
    // delete all the shape IDs

```

```

hlDeleteShapes(heightMapShapeId, 1);
    hlDeleteShapes(strokeShapeId, 1);

// free haptic context
hlMakeCurrent(NULL);
if (hHLRC != NULL)
{
    hlDeleteContext(hHLRC);
}

// free haptic device
if (hHD != HD_INVALID_HANDLE)
{
    hdDisableDevice(hHD);
}
}

// Function: void updateWorkspace()
// Updates the haptic context when the workspace size changes.
void updateWorkspace()
{
    GLdouble modelview[16];
    GLdouble projection[16];
    GLint viewport[4];

    // obtain information about the scene
    glGetDoublev(GL_MODELVIEW_MATRIX, modelview);
    glGetDoublev(GL_PROJECTION_MATRIX, projection);
    glGetIntegerv(GL_VIEWPORT, viewport);

    // reset the haptic context
    hlMatrixMode(HL_TOUCHWORKSPACE);
    hlLoadIdentity();

    // fit haptic workspace to view volume
    hluFitWorkspace(projection);

    // compute cursor scale
    gCursorScale = hluScreenToModelScale(modelview, projection,
viewport);
}

```

```

    gCursorScale *= CURSOR_SIZE_PIXELS;
}

// Function: void reshape(int width, int height)
// Handles changes to the graphic and haptic context when the window is
// resized.
// Borrowed from examples that came from SensAble.
void reshape(int width, int height)
{
    static const double kPI = 3.1415926535897932384626433832795;
    static const double kFovY = 40;

    double nearDist, farDist, aspect;

    glViewport(0, 0, width, height);

    /* Compute the viewing parameters based on a fixed fov and viewing
    * a canonical box centered at the origin */

    nearDist = 1.0 / tan((kFovY / 2.0) * kPI / 180.0);
    farDist = nearDist + 2.0;
    aspect = (double) width / height;

    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluPerspective(kFovY, aspect, nearDist, farDist);

    /* Place the camera down the Z axis looking at the origin */
    glMatrixMode(GL_MODELVIEW);
    glLoadIdentity();
    gluLookAt(0, 0, nearDist + 1.0,
              0, 0, 0,
              0, 1, 0);

    updateWorkspace();
}

// Function: void display()
// Is called during the display loop. Contains all calls to objects
// that should be displayed.

```

```

void display()
{
    //glLoadIdentity();
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

    drawSceneHaptics();
    drawSceneGraphics();

    // force OpenGL to redisplay
    glFlush();
    glutSwapBuffers();
}

// Function: void heightMapTransform()
// All transformations to the HeightMap object should be contained here.
// Is used to move and scale the height map in order to be visible on the
screen.
void heightMapTransform()
{
    //  glLoadIdentity();
    float scaleFactor = 2.0/(128.0 - 4.0);
    glTranslatef(-1.0, -1.0, -0.5);
    glScalef(scaleFactor, scaleFactor, scaleFactor);
    //  glRotatef(20.0, 1.0, 0.0, 0.0);
}

// Function: void drawSceneGraphics()
// Contains all calls that will display graphics.
void drawSceneGraphics()
{
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

    drawCursor();
    //glMatrixMode(GL_MODELVIEW); //select the modelview matrix

    glPushMatrix();
        heightMapTransform();

        // If desired, draw a cube at the bottom, left corner of the height
map.

```

```

        if (drawCube)
        {
            glColor3f(0.0, 1.0, 0.0);
            glutSolidCube(1.0);
        }

        // render the height map
        hMap.render();

        // if strokes are turned on, draw the current stroke
        if (drawStroke)
            strokeOrder.render(currentStroke, true);
        glPopMatrix();
    }

// Function: void drawSceneHaptics()
// Contains all calls that will display haptics.
void drawSceneHaptics()
{
    // begin haptic frame - required to draw in the haptic context
    hlBeginFrame();

    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

    glPushMatrix();

        // set up parameters for the height map
        heightMapTransform();
        hlBeginShape(HL_SHAPE_FEEDBACK_BUFFER,
heightMapShapeId);
        // make the height map so it can be touched but doesn't force the
cursor to snap to it
        hlTouchModel(HL_CONTACT);
        // set up physical forces for the height map
        hlMaterialf(HL_FRONT_AND_BACK, HL_STIFFNESS, 0.8);
        hlMaterialf(HL_FRONT, HL_STATIC_FRICTION, 0);
        hlMaterialf(HL_FRONT, HL_DYNAMIC_FRICTION, 0);

        // If desired, draw a cube at the bottom, left corner of the height
map.

```

```

if (drawCube)
{
    glColor3f(0.0, 1.0, 0.0);
    glutSolidCube(1.0);
}

// render the height map
hMap.render();
hlEndShape(); // heightMapShapeId

// if strokes are turned on, draw the current stroke
if (drawStroke)
{
    // set up parameters for the stroke order
    hlBeginShape(HL_SHAPE_FEEDBACK_BUFFER,
strokeShapeId);
    // only render the strokes in the haptics if we want to snap
to them
    if (forceSnap)
    {
        // set the strokes so you are forced to follow along
the lines
        hlTouchModel(HL_CONSTRAINT);
        hlTouchModelf(HL_SNAP_DISTANCE,
gHapticsSnapDistance);
        // set up physical forces for the stroke order
        hlMaterialf(HL_FRONT, HL_STIFFNESS, 0.2);
        hlMaterialf(HL_FRONT,
HL_STATIC_FRICTION, 0);
        hlMaterialf(HL_FRONT,
HL_DYNAMIC_FRICTION, 0);

        // render the stroke order without arrowheads
        strokeOrder.render(currentStroke, false);
    }
    hlEndShape(); // strokeShapeId
}
glPopMatrix();

// end the haptic frame

```

```

    hEndFrame();
}

// Function: void idle(void)
// This function is called whenever the system is not performing calculations.
// This function handles refreshing the graphics and haptics.
void idle(void)
{
    glutPostRedisplay();
    //display();
}

// Function: void createStroke(char* filename)
// This function is used to create a stroke order for the stroke.
void createStroke(char* filename)
{
    // first stroke
    Stroke* temp = new Stroke(hMap.getScale());
    Point* start = new Point(50, 21);
    // Point* middle = new Point(40, 39);
    Point* end = new Point(19, 53);
    temp->addPoint(start);
    // temp->addPoint(middle);
    temp->addPoint(end);
    strokeOrder.addStroke(temp);

    // second stroke
    Stroke* temp2 = new Stroke(hMap.getScale());
    Point* startb = new Point(40, 40);
    // Point* middleb1 = new Point(79, 37);
    // Point* middleb2 = new Point(87, 110);
    // Point* middleb3 = new Point(89, 95);
    Point* endb = new Point(38, 99);
    temp2->addPoint(startb);
    // temp2->addPoint(middleb1);
    // temp2->addPoint(middleb2);
    // temp2->addPoint(middleb3);
    temp2->addPoint(endb);
    strokeOrder.addStroke(temp2);
}

```

```
// third stroke
Stroke* temp3 = new Stroke(hMap.getScale());
Point* startc = new Point(63, 32);
// Point* middlec1 = new Point(58, 63);
Point* endc = new Point(109, 31);
temp3->addPoint(startc);
// temp3->addPoint(middlec1);
temp3->addPoint(endc);
strokeOrder.addStroke(temp3);

// forth stroke
Stroke* temp4 = new Stroke(hMap.getScale());
Point* startd = new Point(85, 20);
// Point* middled1 = new Point(86, 68);
Point* endd = new Point(86, 97);
temp4->addPoint(startd);
// temp4->addPoint(middled1);
temp4->addPoint(endd);
strokeOrder.addStroke(temp4);

// fifth stroke
Stroke* temp5 = new Stroke(hMap.getScale());
Point* starte = new Point(83, 41);
Point* middlee1 = new Point(72, 59);
Point* ende = new Point(57, 74);
temp5->addPoint(starte);
temp5->addPoint(middlee1);
temp5->addPoint(ende);
strokeOrder.addStroke(temp5);

// sixth stroke
Stroke* temp6 = new Stroke(hMap.getScale());
Point* startf = new Point(90, 41);
Point* middlef1 = new Point(103, 58);
Point* endf = new Point(125, 70);
temp6->addPoint(startf);
temp6->addPoint(middlef1);
temp6->addPoint(endf);
strokeOrder.addStroke(temp6);
/*
```

```

// seventh stroke
Stroke* temp7 = new Stroke(hMap.getScale());
Point* startg = new Point(80, 91);
Point* endg = new Point(68, 107);
temp7->addPoint(startg);
temp7->addPoint(endg);
strokeOrder.addStroke(temp7);

// eighth stroke
Stroke* temp8 = new Stroke(hMap.getScale());
Point* starth = new Point(39, 110);
Point* endh = new Point(88, 108);
temp8->addPoint(starth);
temp8->addPoint(endh);
strokeOrder.addStroke(temp8);

*/
strokeOrder.saveFile(filename);
}

int main(int argc, char *argv[])
{
// information about the files to load in
char* file = "data\\0018.RAW";
char* strokefile = "data\\0018.str";

// load in the height map and set up information for it
hMap.loadHeightMap(file, 128);
hMap.setScale(0.05f);

// set up the stroke order based on the scale of the height map
strokeOrder.setScale(hMap.getScale());

// call createStroke() if there is no stroke data
// createStroke(strokefile);
// load stroke order data if it exists
strokeOrder.loadFile(strokefile);

// set up glut to handle the window, display, and keyboard
glutInit(&argc,argv);

```

```

    glutInitWindowSize(600,600);
    glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB |
GLUT_DEPTH);
    glutCreateWindow("Haptic Height Map");
    glutReshapeFunc(reshape);
    glutDisplayFunc(display);
    glutIdleFunc(idle);
    glutKeyboardFunc(keyboard);

    // call the initialize function
    init();
    // go into the main display loop
    glutMainLoop();

    return 0;
}

// Function: void keyboard(unsigned char key, int x, int y)
// This function handles when the user pushes a key on the keyboard.
void keyboard(unsigned char key, int x, int y)
{
    switch (key)
    {
        // move to the next stroke
        case '!':
            // if on the last stroke, change to 0 and show all strokes
            if (currentStroke == strokeOrder.totalStrokes())
                currentStroke = 0;
            // if not on the last stroke go to the next stroke
            else
                currentStroke++;
            break;
        // move to the previous stroke
        case ',':
            // if showing all strokes, change to the last stroke
            if (currentStroke == 0)
                currentStroke = strokeOrder.totalStrokes();
            // if not showing all strokes, show the previous stroke
            else
                currentStroke--;
    }
}

```

```

        break;
    // toggle whether to snap to the strokes
    case 'f':
    case 'F':
        forceSnap = !forceSnap;
        break;
    // exit the program
    case 'q':
    case 'Q':
        exit(0);
        break;
    // toggle whether to show the strokes
    case 's':
    case 'S':
        drawStroke = !drawStroke;
        break;
    }
}

// Function: void drawCursor()
// This function draws a cursor at the point where the haptic device is.
// This was borrowed from an example from SensAble.
void drawCursor()
{
    static const double kCursorRadius = 0.5;
    static const double kCursorHeight = 1.5;
    static const int kCursorTess = 15;
    HLdouble proxyxform[16];

    GLUquadricObj *qobj = 0;

    glPushAttrib(GL_CURRENT_BIT | GL_ENABLE_BIT |
GL_LIGHTING_BIT);
    glPushMatrix();

    if (!gCursorDisplayList)
    {
        gCursorDisplayList = glGenLists(1);
        glNewList(gCursorDisplayList, GL_COMPILE);
        qobj = gluNewQuadric();
    }
}

```

```

    gluCylinder(qobj, 0.0, kCursorRadius, kCursorHeight,
               kCursorTess, kCursorTess);
    glTranslated(0.0, 0.0, kCursorHeight);
    gluCylinder(qobj, kCursorRadius, 0.0, kCursorHeight / 5.0,
               kCursorTess, kCursorTess);

    gluDeleteQuadric(qobj);
    glEndList();
}

/* Get the proxy transform in world coordinates */
hlGetDoublev(HL_PROXY_TRANSFORM, proxyxform);
glMultMatrixd(proxyxform);

/* Apply the local cursor scale factor. */
glScaled(gCursorScale, gCursorScale, gCursorScale);

glDisable(GL_LIGHTING);
glEnable(GL_COLOR_MATERIAL);
glColor3f(0.0, 1.0, 0.0);

glCallList(gCursorDisplayList);

glPopMatrix();
glPopAttrib();
}

```

Stroke.cpp

```

#include <stdio.h>
#include <math.h>

#ifdef WIN32
#include <windows.h>
#endif

#include <GL/gl.h>
#include <GL/glut.h>

```

```

#include "Stroke.h"

// Function: void Stroke::render(bool arrows)
// This function renders the stroke as an arrow.
// If arrows is true, heads are drawn on the arrows.
void Stroke::render(bool arrows)
{
    // set up the OpenGL settings for drawing the lines
    glLineWidth(2.0);
    glDisable(GL_LIGHTING);
    glColor3f(1.0, 0.0, 0.0);

    // begin drawing the lines
    glBegin(GL_LINE_STRIP);
    // draw the first point
    glVertex3f(points[0].X(), (128 - points[0].Y()), ((256 + 1) *
scaleFactor));

    float xfac, yfac; // the part of the vector in the x and y directions
    float length;    // length between two points in the line
    float tempx, tempy; // used to create the points for the
arrowheads

    // loop through the rest of the points in the line
    for(int index = 1; index < points.size(); index++)
    {
        // draw the point
        glVertex3f(points[index].X(), (128 - points[index].Y()),
((256 + 1) * scaleFactor));

        // if arrowheads are desired, draw the arrowheads
        if (arrows)
        {
            // compute a vector from the point to the previous
point

            xfac = points[index].X() - points[(index - 1)].X();
            yfac = points[index].Y() - points[(index - 1)].Y();
            length = sqrt(xfac * xfac + yfac * yfac);

            // normalize the vector

```

```

        xfac = (xfac / length) * 5;
        yfac = (yfac / length) * 5;

        float angle = 35.0;        // the angle to rotate the
points to make the heads

        // rotate the normalized vector
tempx = ((xfac * cos(angle)) - (yfac * sin(angle)))
+ points[index].X();
tempy = ((xfac * sin(angle)) + (yfac * cos(angle)))
+ points[index].Y();

        // create the first point of the arrowhead
glVertex3f(tempx, (128 - tempy), ((256 + 1) *
scaleFactor));

        // rotate the normalized vector in the other
direction
tempx = ((xfac * cos(-angle)) - (yfac * sin(-angle)))
+ points[index].X();
tempy = ((xfac * sin(-angle)) + (yfac * cos(-angle)))
+ points[index].Y();

        // create the second point of the arrowhead
glVertex3f(tempx, (128 - tempy), ((256 + 1) *
scaleFactor));

        // go back to the original point so it can go on to
// the next point in the stroke
glVertex3f(points[index].X(), (128 -
points[index].Y()), ((256 + 1) * scaleFactor));
    }
}
// end the line strip
glEnd(); // GL_LINE_STRIP
}

// Function: void Stroke::addPoint(Point* temp)
// This function adds a point to the vector at the end of the stroke.

```

```
void Stroke::addPoint(Point* temp)
{
    points.push_back(*temp);
}
```

StrokeOrder.cpp

```
#include "StrokeOrder.h"
#include <fstream>
#include <stdio.h>
#include <stdlib.h>

// Function: void StrokeOrder::render(int num, bool arrows)
// This function renders the strokes in the stroke order.
void StrokeOrder::render(int num, bool arrows)
{
    // if the number is greater than the total number of strokes
    // then set it to 0 to render all strokes
    if (num > this->strokes.size())
        num = 0;
    // render all the strokes if the number is 0
    if (num == 0)
    {
        for (int i = 0; i < strokes.size(); i++)
        {
            strokes[i].render(arrows);
        }
    }
    // render only one stroke if the number is a stroke
    else
    {
        strokes[num - 1].render(arrows);
    }
}

// Function: void StrokeOrder::addStroke(Stroke* temp)
// This function adds a stroke at the end of the vector of strokes.
void StrokeOrder::addStroke(Stroke* temp)
{
```

```

    strokes.push_back(*temp);
}

// Function: void StrokeOrder::saveFile(char* filename)
// This function saves the stroke order out to the specified file.
void StrokeOrder::saveFile(char* filename)
{
    // open an output stream for writing in binary format
    ofstream fout(filename, ios::binary);

    // report an error if the file could not be created
    if (!fout)
    {
        fprintf(stdout, "Unable to open stroke order file.\nUnable to
save stroke order information.\n");
    }

    // first write the total number of strokes
    // this is used to know how many strokes there are when the file is
loaded
    int totalStrokes = strokes.size();
    fout.write((char*) &totalStrokes, sizeof(int));

    // now write out all the strokes
    for (int i = 0; i < totalStrokes; i++)
    {
        // write the total number of points in the strokes
        // this is used to know how many points there are when the file
is loaded
        int totalPoints = strokes[i].size();
        fout.write((char*) &totalPoints, sizeof(int));

        // write the (x, y) coordinate for each point in the stroke order
        Point temp;
        for (int j = 0; j < totalPoints; j++)
        {
            int x = strokes[i].pointAt(j).X();
            int y = strokes[i].pointAt(j).Y();
            fout.write((char*) &x, sizeof(int));
            fout.write((char*) &y, sizeof(int));
        }
    }
}

```

```

        }
    }

    // close the file
    fout.close();
}

// Function: void StrokeOrder::loadFile(char* filename)
// This function is used to load information from a file into the stroke order.
void StrokeOrder::loadFile(char* filename)
{
    // open the file for binary data reading
    ifstream fin(filename, ios::binary);

    // if the file does not exist, report an error
    if (!fin)
    {
        fprintf(stdout, "Unable to open stroke order file.\nUnable to
load stroke order information.\n");
    }

    // read in the total number of strokes contained in the file
    int totalStrokes;
    fin.read((char*) &totalStrokes, sizeof(int));

    // loop through the strokes and read in all the points for each stroke
    for (int i = 0; i < totalStrokes; i++)
    {
        // read in the total number of points for the stroke
        Stroke* tempStroke = new Stroke(this->scaleFactor);
        int totalPoints;
        fin.read((char*) &totalPoints, sizeof(int));

        // read in the (x, y) coordinates of each point and add the point
to the stroke
        for (int j = 0; j < totalPoints; j++)
        {
            int x, y;
            fin.read((char*) &x, sizeof(int));
            fin.read((char*) &y, sizeof(int));

```

```
        Point* tempPoint = new Point(x, y);
        tempStroke->addPoint(tempPoint);
    }

    // add the stroke to the stroke order
    this->addStroke(tempStroke);
}
}
```