LEARNSTEM: An Interactive and Intuitive STEM Accessibility System

by

Rahul Kumar Namdev

Submitted to the Department of Electrical Engineering and Computer Science
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To my parents

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Abstract

I present an intuitive and interactive platform to make complex STEM (Science Technology Engineering and Mathematics) educational materials accessible to blind and visually impaired people using a mini-hyperBraille device with almost no loss of information as compared to printed materials.

I have come up with a novel way to increase the effective resolution of the Braille device by adding a mechanical XY gantry. Using this XY gantry enables us to create an ultra-high resolution, larger surface Braille device without paying the prohibitive price charged for the bigger hyper Braille displays available in the market. In addition to that, to further augment usability and intuitiveness of our system, we have integrated a Nod-ring, which is a tiny finger-worn device for supporting additional hand gestures such as zoom in and out.

Previous studies have shown that the use of zoom and pan can increase usability and improve the understanding of tactile graphics. Along with zooming and panning, our system uses vibrating patterns, rhythmic motions, synthetic voice and synchronized voiced-vibrations to convey information to blind users in an intuitive way. We also implemented a touch gesture recognition framework on our touch enabled Braille device. Using these touch gestures and a high quality synthetic voice, we have developed a highly responsive system for providing voice annotations of the graphics content.

An important contribution of this work is the implementation of a high-quality system for automatic transcription of STEM (including difficult math Nemeth translations) books into Braille. Learning resources for blind people are quite sparse and transcription of STEM material is a very expensive and time consuming process. Using our automated transcription platform it is easy, fast and inexpensive for publishers to transcribe STEM books into Braille books. The scope of this automated transcription platform is not only limited to STEM books but it can be used for transcription of any content/book/web-page available online.

Thesis Supervisor: Pattie Maes
Title: Prof. MIT Media Arts and Sciences

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Chapter 1

Introduction

Technology represents a crucial part of our current education system. We can't imagine the current education system without technology. From kinder-garden to graduate school, at every stage of education technology has given us lot resources to learn from. For example, the recent advent of online education systems such as MOOCS [1], Khan Academy [2], Coursera [3] provides students with free quick learning resources. These learning system do not restrict a student to be learn in in a physical class setting. Using video conferencing a student can sit in any part of the world while learning from a teacher teaching in a different part of the world.

The advent of education apps on Android and ipad devices also assist students to learn easily. For example the app VideoScience [4] which is a collection of 80 (and more are getting added every month) science demonstrations helps students to learn about various science experiments. In a similar fashion, SkyORB [5] is a fast lightweight ipad/Android astronomy app for teaching students about various planet positions around the sun. This app also warns, the user when a phenomenon occurs such as a lunar eclipse, full-moon etc. Using these tablet devices and educational apps, teachers can quickly learn about students' interests, provide more personalized content and assess their learning in real-time.

But unfortunately most of these technology based educational resources only benefit sighted students while people with vision disabilities are left behind. They either don't have access to these resources or can't use them. For example, most of the videos available on aforementioned on-line educational websites are not 'fully-accessible' for blind students. In a similar fashion, the educational apps described above are limited to sighted students. These apps can't help blind students in their learning because of their disabled vision.

In this thesis, we try to develop an end to end, low cost reliable, interactive and intuitive system to ease STEM learning for blind and visually impaired people. We are constantly improving our system to incorporate more difficult concepts and we are try to make our system more and more intuitive to make it easy to learn from.

1.1 Motivation and Related Literature

According to a survey done in 2010 by the World Health Organization, around 235 million people have visual impairments of whom roughly 39 million are blind. Most of these people live in developing countries where proper educational resources are either not available or are very expensive. Even in developed countries, the lack of proper educational materials have caused BVI (Blind and Visually Impaired) literacy to remain very low. For example, in the USA alone, where approximately 1.3 million people are legally blind, only 10% of the people can read braille. Moreover, only 1 in 100 blind people is able to learn high school mathematics and continue toward higher education.

Why is literacy so low among blind people? There are a couple of reasons which are given below.

1.1.1 Lack of Digital Educational Materials

Lack of digital educational materials including textbooks, standardized tests, and lack of proper tactile graphics devices causes blind students to be excluded from the Common Core curriculum. As mentioned in the previous section most of the digital educational apps developed for ipad/Android devices are not of any use to blind people. Figure 1-1 depicts snapshots of the skyORB app. In the left image an interactive description of different planets is given and in the right image a student can perform zoom-in and zoom-out and learn about moons of various planets. Clearly this is a great astronomy app for a sighed kid it doesn't aid blind students in their learning.

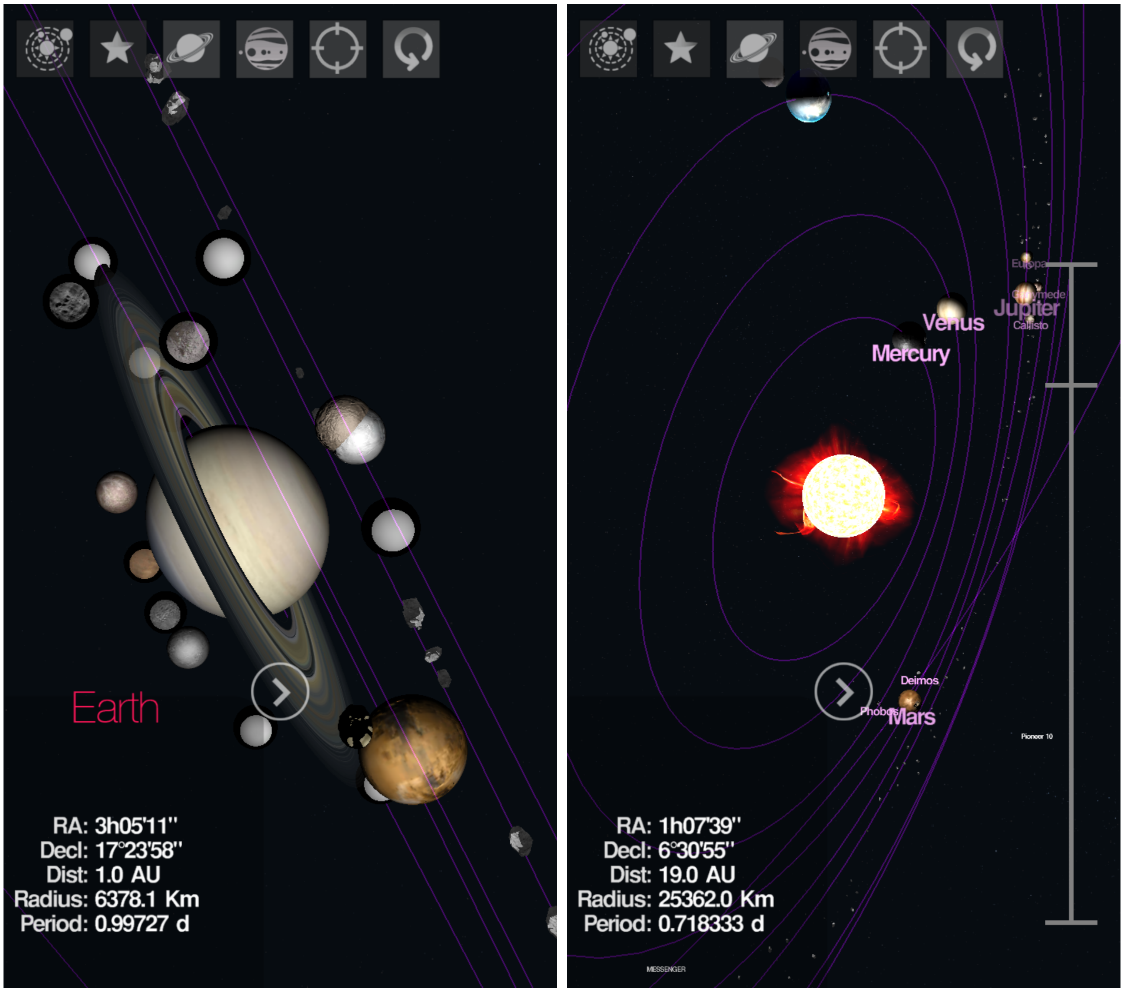

Figure 1-1: Snapshots of the skyORB app. In the left image we have an interactive description of various planets and there position with respect to the sun and earth and in the right image we have a description where the student can learn about the moons of various planets in our solar system. While providing a great learning aid for sighted people this app does not help much for blind students.

Figure 1-2: An image of the full page display of Metec-AG. This Braille device has 120X60 = 7200 piezoelectric pins. These piezoelectric pins can vibrate in real time providing for fast graphical renderings. This hyperBraille device can also accept touch inputs from user's fingertips. But the device costs 45,000 euros which is huge drawback.

In addition, the hyperBraille devices which are available in the market are either quite expensive or are not adequate for fast graphical renderings. For example, while a full page hyperbraille (figure 1-2) device from Metec-AG [6] costs around 45,000 euros, [11, 15, 34, 35, 38, 39, 41, 42] lacks in refresh rate. Similarly, other devices such as the Braille Notetaker (figure 1-3) [7] and [29] lack the high spatial resolution needed for interpretation of tactile graphics.

1.1.2 Fundamental Problems with Braille

Braille was fundamentally created for representing text and characters which are linear in nature. It was not made for representations of any mathematical symbols or mathematical equations which are non-linear in nature. For example in figure 1-4, we have a representation of a derivative matrix in math and its corresponding representation in braille. Braille conversion of mathematical equations generally involves Nemeth codes [30]. As the Nemeth representations are quite long and complicated,

Figure 1-3: An image of Braille Notetaker device. This device has 32, 8-dot Braille cells for reading braille characters. This device can also act as keyboard for interacting with a PC. The cost of this device is $5,495.00.

learning these Nemeth representations sometimes becomes quite onerous for blind students. Similarly any static representation of simple chemical formulae such as shown in figure 1-5 are quite complicated to understand from their braille representation.

1.1.3 Static Braille Books

All the Braille books available to blind people are static in nature. According to some previous studies on static tactile graphics (Tactile graphics which are printed in Braille books using a Braille embosser and are not interactive) such as [20, 21, 24, 28], blind people tend to recognize only about 10% of the raised line tactile drawings, which on the other hand can be trivially recognized visually. For example, even for very simple everyday objects such as a key-chain, a triangle or an apple it is very hard for blind people to recognize the object from a line drawing. This is because touch perception has a restricted field of view and limited spatio-temporal resolution [23, 27] as compared to vision. This sometimes causes interpretation of these static raised line drawings to be very difficult and complicated to BVI users. In addition, most often with static tactile graphics, information must be gathered in strictly sequential manner in order to interpret the whole structure of the tactile graphic. Deviating from this sequential manner could lead to severe misinterpretations and hence incorrect recognition of the underlying object.

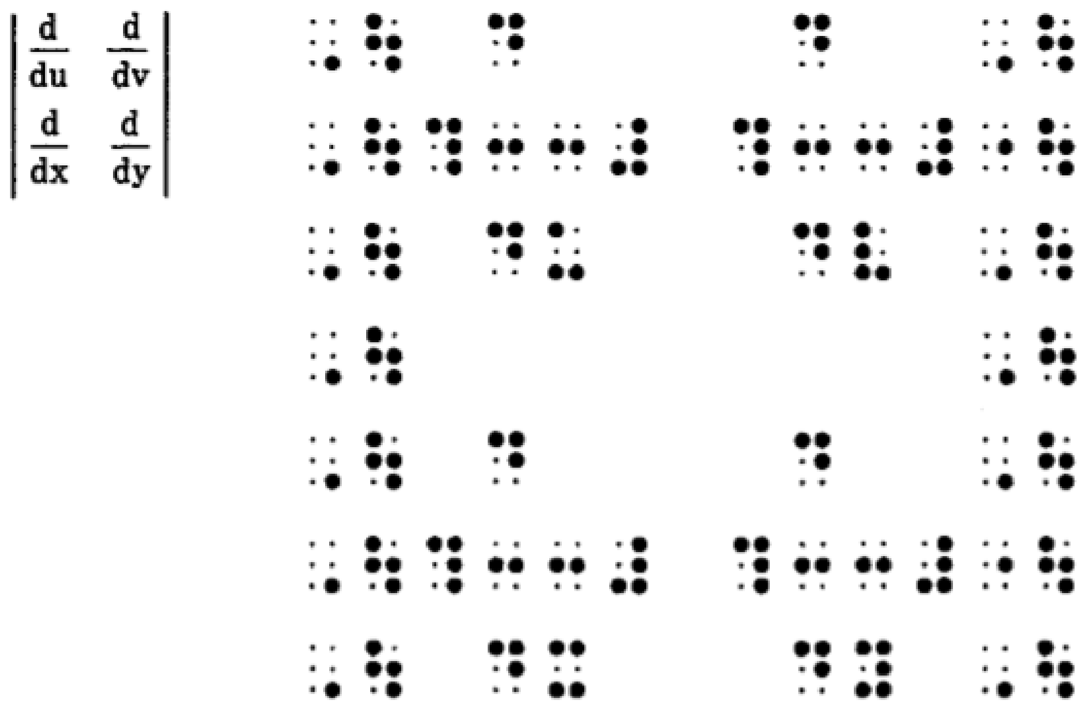

Figure 1-4: Representation of a derivative matrix equation in simple math and the corresponding representation in Braille. It can be seen that the representation in Braille of a derivative matrix requires much more space due to the linear nature of Braille.

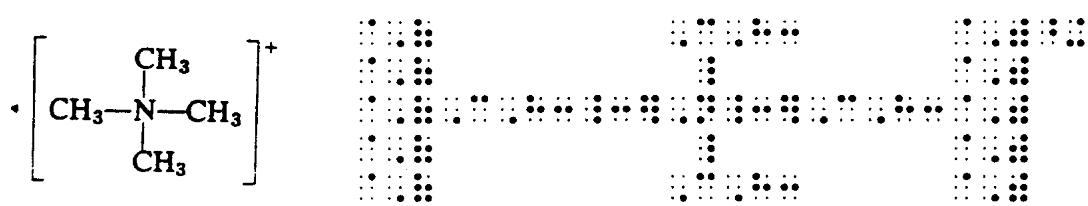

Figure 1-5: Representation of a simple chemical molecule in Braille. Again here due to linear nature of Braille, a simple chemical formula needs a higher resolution of Braille dots. A small device similar to the Braille Notetaker device cannot represent this kind of chemical formula.

1.1.4 Existing Interactive Systems

Given the previous studies about static tactile graphics, it is clear that static graphics are unable to convey important and essential information to blind users and we should develop a novel intuitive and interactive dynamic tactile platform that can effectively convey crucial STEM (Science, Technology, Engineering and Mathematics) educational information. Our STEM accessibility system is indeed such an intuitive and interactive system. We will provide an overview of our STEM accessibility system in in next chapters, but before we present our system and its advantages, we briefly describe previous attempts to convey dynamic graphics. In later sections, we also argue how our system is a significant improvement upon these previous efforts.

Although there have been several attempts to build dynamic tactile graphics devices, most have either not been successful or are not widely available. Among these, the Optacon (OPtical to TActile CONverter) device shown in figure 1-8 has been the most successful. It allows a user to control the threshold for conversion of a gray image or a color image into the corresponding tactile graphics. Optacon was primarily designed for reading text letter-by-letter. When using Optacon, a user moves the camera on some printed text and an image of the text is sent to the display on the tactile array. The tactile array has 24X6 tiny pins which can vibrate independently with a piezoelectric connected to it. Wherever the text image is black (black text on white paper) pins corresponding to that part are vibrated. As the user moves the camera to scan a text line, corresponding text/letters are represented on the tactile array.

Recognition of letters with Optacon is quite high: some users are able to achieve recognition of 80% [14] while others are able to achieve a reading speed of 100 words per minute [13, 19] with acceptable recognition rate. But it can take up to a couple of years to achieve this speed [13, 27].

Some systems use tactile graphics devices with touch input [18] and support zooming and scrolling. Other systems such as [26, 33, 43] have also developed zooming and scrolling. These systems suggest that being able to zoom and pan increases the under-

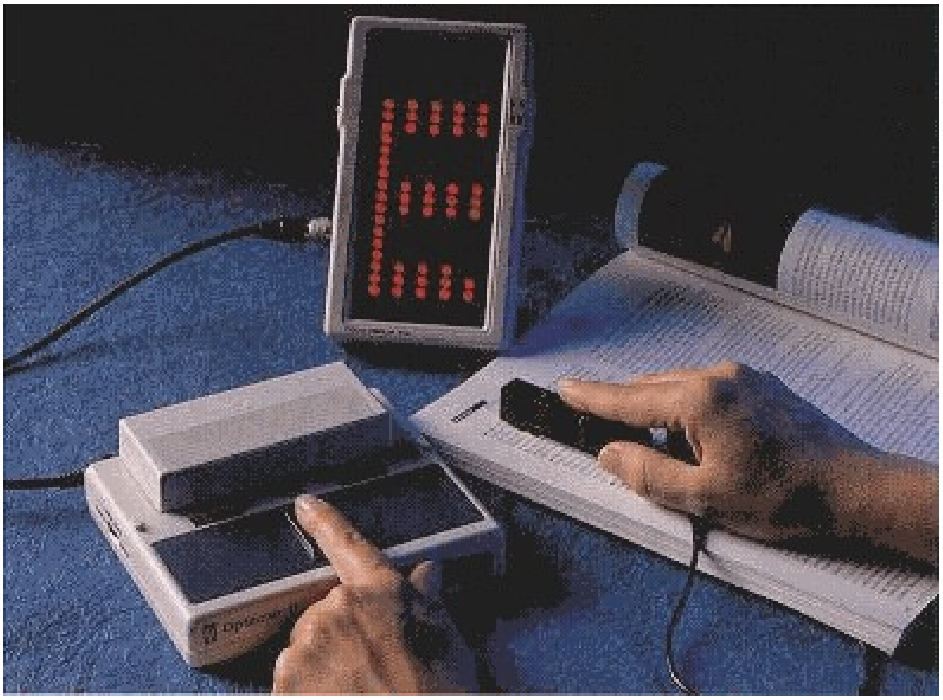

Figure 1-6: An image of Optacon device. This device was designed for reading letter-by-letter text. An Optacon has a camera which captures images of text/letter. Optacon has 24X6 vibrating pins and as a user moves the camera to scan a line, corresponding character are represented in Braille on the tactile array.

standing of tactile graphics. Some tactile graphics devices have used auditory feedback using audio cues to increase the understanding of simple tactile graphics [17,22,31,32].

Recently, there have been a plethora of special effect devices such as Relief displays and Feel displays. Instead of using vibrotactile vibration most of these devices such as [12, 25, 40] use varying friction in between fingertip of the user and touch surface of the tactile device in order to provide a haptic sensation.

Fujitsu has also recently developed a tactile device which uses the ultrasonic vibrations to convey tactile information by varying friction between user's fingertips and the surface of the tactile device. This mobile tablet can rapidly change between high and low friction in response to touch on the surface of the touch screen and the underlying image. This tablet surface can provide a feeling of bump, rough and slippery nature of the content based on the underlying image to provide adequate tactile illusion.

Senseg Tixel tablet is a similar kind of tablet developed by Senseg. This tablet

Figure 1-7: An image of Fujitsu Sensory Haptic Tablet Device. This tablet uses ultrasonic vibrations to convey tactile information by changing the friction between fingertips of a user and touch panel.

uses electrostatic field to create an attractive force between the touch panel and the fingertip of the user. By modulating these attractive forces this device creates various touch sensations corresponding to varying textures, edges etc. They also provides a full android based software development kit which includes an API to enable developers to integrate tactile sensations in their projects.

In addition, there have been attempts to develop interactive 3D displays which provide a 3D sensation in the air [36, 37]. All these 3D/2D relief, feel and 3D-air displays are quite fascinating options but none of these displays have focused on teaching aspects. In addition some of these displays are quite huge and some others are quite expensive.

In this thesis, I present an interactive system to teach BVI people STEM educational materials in a fast, intuitive and efficient way. The system uses zooming, panning, a high-quality synthetic voice, synchronized vibrations, rhythmic motions and touch gestures after an intuitive experience. As an example, consider a student who is trying to learn about the geometric concept of a triangle. As soon as the student initiates the tutorial for a triangle, our system will output a synthetic voice stating the following, “A triangle is a basic shape in geometry. A triangle has three

Figure 1-8: An image of the Senseg Tablet. This tablet uses an electrostatic field to create an attractive force between the touch-screen surface and the user's fingertips. By modulating this attractive force, the device provides various touch illusions.

edges, three vertices and three angles. All the angles of a triangle sum up to 180 degrees. As an example, on the Braille device, consider a triangle ABC with line**AB**, line**BC** and line**CA**". As soon as synthetic voice says lineAB –in the previous sentence – only lineAB on the Braille device will vibrate. All the pins corresponding to lineAB will quickly go up and down periodically 5 times and everything else will remain stationary. Similarly, as soon as the synthetic voice says lineBC, only lineBC will vibrate and everything else remains stationary. By using similar rhythmic patterns we display lineCA. This way a blind student is able to learn about different properties –how many sides a triangle has, what it looks like and how we name its sides– quickly and effectively.

Once the blind student is able to learn and understand these properties of a triangle, if she is interested in learning specific properties of some element of a triangle, say the length of a line or value of an angle, she can perform a touch gesture on the Braille device and the corresponding information will be revealed to her by the synthetic voice. For example, a 'single-tap' on a side reveals its name and a 'double-

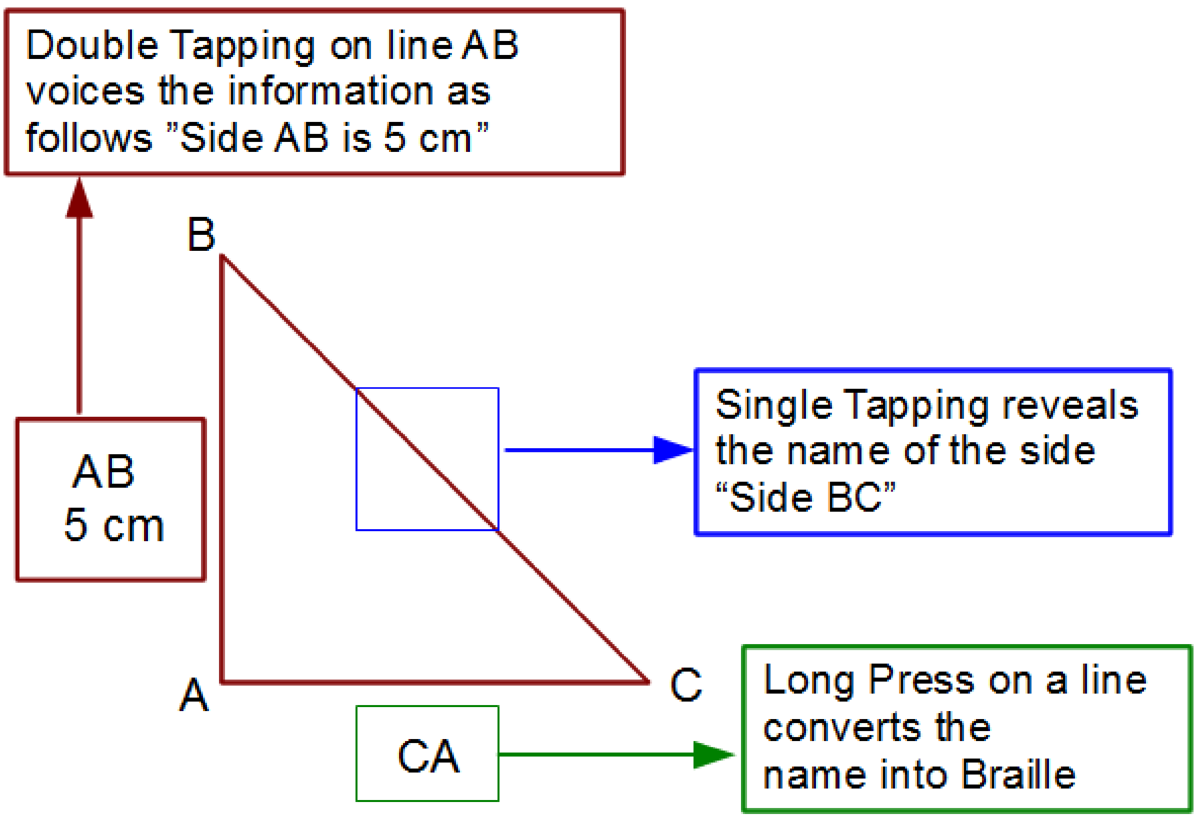

Figure 1-9: This figure portrays touch gesture responsive feedback capability of our interactive system. Single tap on any element (line of angle) of the triangle reveals its name. Double-tap reveals its length/value. Long press converts name into corresponding Braille characters.

tap' reveals its length. Figure 1-9 depicts an example.

We also use rhythmic motions and animated patterns to make it easier to learn difficult concepts. As an example, for teaching about projectile motion, we depict the trajectory of the projectile by animating points following the trajectory of the projectile.

1.2 Contributions

Some of the contributions of this work are listed below.

- We use a custom made version of a hyperBraille device. This custom version of has 360 pins (24X15) pins. As this device is much smaller and has fewer piezoelectric pins this device is much cheaper than the big full-page hyperBraille device from Metec AG.

- In order to increase the effective resolution of this Braille device, we have added a mechanical XY gantry equipped with high precision encoders to our system. As a result, the effective resolution of this small custom made device is larger than full page hyperBraille display.

- We use in-air gestures using a Nod-ring to increase the intuitiveness of our system. This Nod-ring has motion sensors and this ring communicates with the PC using a Bluetooth module. We use this ring for zoom-in and zoom-out, raising the ring in vertically upward direction performs a zoom-in and moving the ring vertically downward performs a zoom-out.

- We have developed a Microsoft word like, Latex and SVG editor. We call this MLatex editor. This editor takes Latex and SVG scripts as inputs and provides corresponding text and graphics in Braille and raised line drawings. This editor uses Liblouis [10] a high accuracy Braille translation framework for translating from English to Braille. We will be making this editor open-source so that all the Braille book publishers and blind community can benefit from it.

- We demo efficiency, interactivity and intuitiveness of our system in user studies done with blind people. So, far we have tested our system with 10 blind people and a couple of sighted teacher of blind kids. According to their feedback this system will definitely help blind people learn STEM materials faster.

- We are currently developing an automatic teaching framework for blind people. This automatic teaching system will teach about real life objects such as an apple, an arm-chair or a banana to blind people. This teaching system will display raised line drawing of these real life objects on a Braille like device and the blind person will first observe the full raised line drawings. Once the blind person has gone through the full tactile graphic, our automatic teaching system will ask the blind person to draw the same shape on a different touch device. Using machine learning algorithms our teaching system will automatically detect if the shape drawn is correct or not and will provide corresponding feedback to blind user.

1.3 Thesis Layout

This thesis is loosely organized into the following chapters.

- Motivation and related literature
- Hardware components of our system
- Software components of our system
- Automatic Teaching Framework
- User testing and future work

Starting with a brief description of various statistics about Braille literacy, section 1.1 mostly provided an overview of recent related work on Braille literacy. In this section we also compared previous works to our system and we argued that our system is more efficient, more interactive and intuitive and less costly. In chapter 2, we provide a description of all the hardware components of our system. In chapter 3, we provide description of software components of our system. In chapter 4, we provide a description of our automatic teaching system that can teach something to a blind person without need for a human teacher. In chapter 5 we provide results of user testing. In addition to that, this chapter also provide future directions and concludes this thesis.

Chapter 2

System Overview - Hardware Components

In this chapter we present an overview of all the hardware components of our system.

2.1 Our Braille Device

We use a mini, high-speed refreshable hyerBraille tactile display in our project. This display is custom modified version of the bigger full page hyperBraille display [6] from Metec. The display uses mechanical piezoelectric binary pins. These pins can rise and sink vis-a-vis the base of the Braille device. The device is also embedded with capacitive touch, which enables the device to detect touch inputs from the fingertips of a user. This allows us to dynamically update the content on the Braille device based on the user's interaction with the device. We have implemented a touch gesture recognition framework including 'single-tap', 'double-tap', and swipe gestures using this touch capability. Based on these touch gestures, our system provides responsive feedback to the user, by either updating output displayed on the Braille device or by synthetic voice stating/revealing some relevant information.

Figure 2-1 depicts an image of this mini hyperBraille device. Unlike the big hyperBraille display [6] which has 7200 pins (60 rows with 120 pins in each row), this mini-hyperBraille display only has 360 pins (15 rows of 24 pins in each row).

Figure 2-1: This figure depicts an image of the mini refreshable hyperBraille device. This device has piezoelectric vibrating pins which can go up/down at a very high refresh-rate. An image of some part of a triangle is being shown on the Braille device. This device also has the capability to perceive touch input from the user's fingertips.

One important reason for using this custom modified display in our project, is the prohibitive cost of a big, full page hyperBraille display. The full page hyperBraille display costs more than 45,000 euros whereas the mini-hyperBraille display costs only around 3,500 euros. The lower price of this mini hyperBraille display, comes with trade off for resolution. With only 360 pins available arranged in a 15X24 matrix, this display offers limited resolution for most of the graphical renderings. To overcome this resolution and cost problem, we have integrated our mini-hyperBraille device with a mechanical 2D XY-gantry.

2.2 Mechanical XY gantry

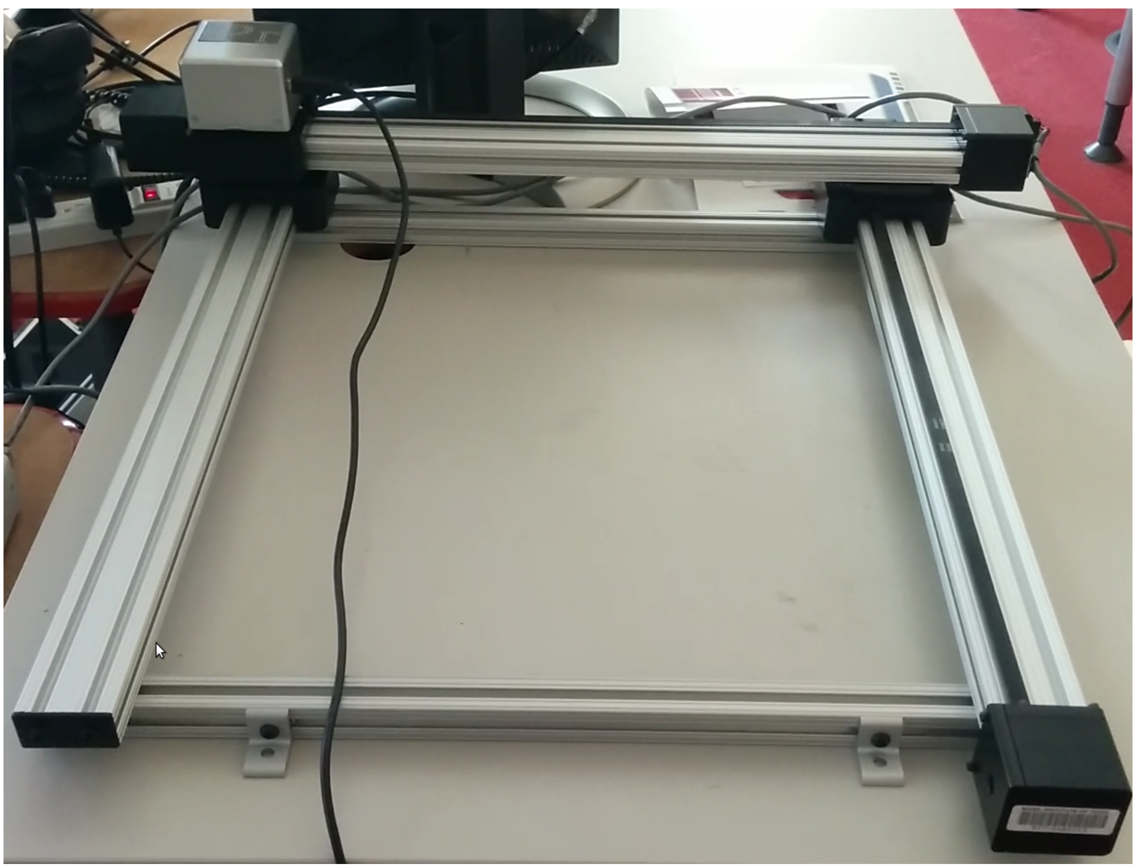

Figure 2-2: Snapshot of XY slider. This Mechanical XY-slider is equipped with high precision encoder providing for exact location of central movable stage.

We use a 2D XY gantry [8] to increase the overall tactile spatial resolution of our system. This XY gantry has a hand-movable platform which can be moved smoothly along the X and Y axis. This XY gantry is equipped with high precision encoders which provide for coordinates of X, Y locations of the movable platform up to sub-millimetre accuracy. We mount the Braille device on this movable platform. Now, as a user moves this movable platform (with Braille device mounted on the top of this platform), the XY-gantry sends the X,Y location of the platform to computer and based on the X,Y location computer updates the position of a rectangular cursor on the computer screen.

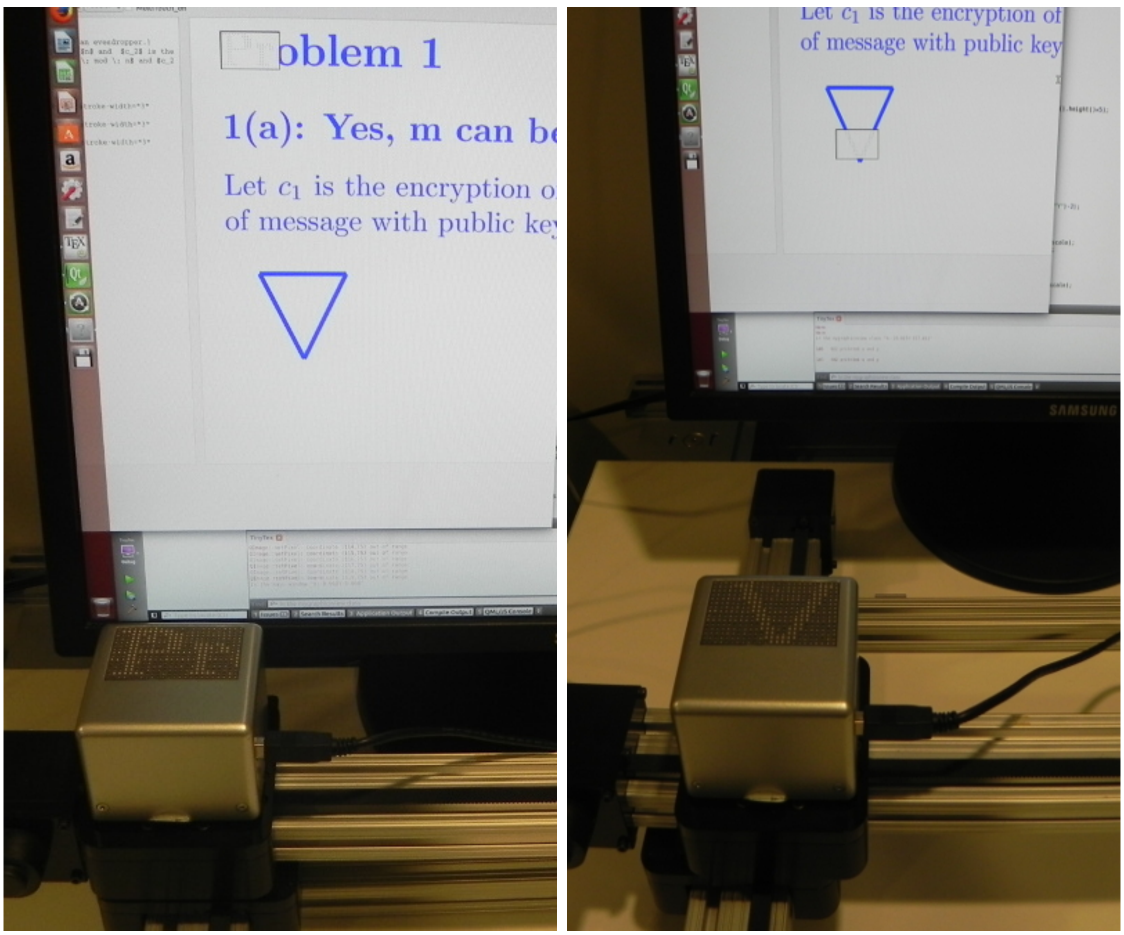

Figure 2-3: Snapshots of the XY slider with movable platform at two different positions. In the first position the X,Y slider is at a location such that the cursor overlaps with some text. This same text is also rendered on the Braille device in raised line drawings. In the second position the XY slider is at a location where the cursor overlaps with a triangle. On the Braille device we have raised line drawing of the same part of the triangle.

This rectangular cursor scans image on the computer screen enclosed with in its rectangular boundaries and then displays that image on the Braille device. A demo of this is shown in the figure 2-3. The left image shows an instance where the xy slider is close to (0,0) position and it can be seen that the rectangular cursor is on characters **Pr** from the word 'Problem'. The same **Pr** characters are also displayed on the Braille device. Similarly, in the right image the xy slider is moved such that the rectangular cursor overlaps with the lower part of a triangle, which is replicated on the Braille device.

The main advantage of using a XY gantry is that it provides a very high effective spatial resolution. The movable platform of this gantry can move 50 centimetres in each direction. This results in an effective resolution of at-least 200X200 vibrating pins. The approximate cost of such a hyperBraille device with 200X200 vibraing pins would be more than 250,000 euros, but our entire system (Mini-hyperBraille device, XY-gantry, Nod ring 2.3) costs less than 6,750 euros.

2.3 The Nod Ring

To further increase the usability of our system, we have integrated it with a Nod-ring [9]. This ring is equipped with motion sensors, a blue-tooth 4.0 antenna and an in-built pair of processors. This ring is lightweight, seamless and its battery lasts for almost a full day. We use this ring for performing zoom in and out of any text/tactile graphics displayed on the Braille device. The ring is meant to worn on the less dominant hand so the user can zoon in and out while still touching the display with their dominant hand. Raising the ring (hand) in vertically upward direction performs zoom-in of the tactile graphics and moving the ring (hand) in vertical downward direction performs zoom-out. Figure 2-4 depicts snapshots of the Nod-ring.

At this point one may ask why are we not using pinch gesture on the Braille device similar to an iphone or an Android to perform zoom-in/zoom-out? This is because of two reasons. First, the touch input resolution of the Braille device is very limited to adequately implement pinch gesture. Second, tactile graphics perception by blind

Figure 2-4: Snapshots of the Nod-ring. This Nod ring can be worn on fingers of a blind user and is very lightweight. This ring has motion sensors which can track its movement in XYZ directions. We have developed touch gestures such that vertical up movement of finger performs zoom-in of any tactile graphics on the Braille Device and vertical down movement of the Nod-ring performs zoom-out.

people is highly sequential and performing a pinch gesture by the hand will definitely break the sequentiality in perception.

Chapter 3

System Overview - Software Components

In this chapter we describe the software components of our system.

3.1 The SVG Latex editor

As learning resources for blind people are quite sparse and transcription of educational material especially STEM material into Braille is a cost exorbitant affair, we are developing a high-quality Latex like (Latex is a high-quality typesetting system which includes features designed for the production of technical and scientific documentation) like typesetting system –**SVG Latex editor**– for automatic transcription of Latex files and Scalable Vector Graphics (SVG) graphics into Braille. Scalable Vector Graphics (SVG) is a very popular XML-based vector image format for two-dimensional graphics. Creating SVG images is very easy and almost all the photo editing software has an option to save/create SVG images.

We will make our SVG Latex editor open-source. This editor system will enable publishers to transcribe any STEM books into Braille quickly, inexpensively and free of human errors (typically made by blind people as they are the ones who do transcriptions and error checking).

This SVG Latex editor provides two main options. First, it can convert any text

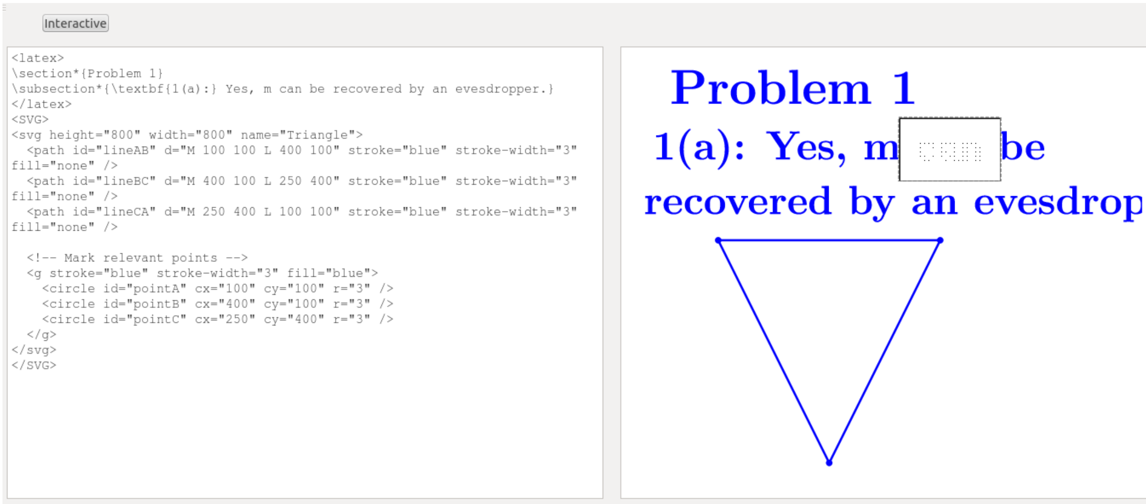

Figure 3-1: This figure portrays a snapshot of our SVG Latex editor. In the left we have an editable area in which we write Latex + SVG and on the right we have output either in Braille or in the form of raised line tactile graphics for text and graphical figures.

into Braille, so that blind people can read in Braille. Second, it provides for conversion of normal text into a raised dotted pattern as shown in figure 3-1 where the word **can** is converted into raised dots for people who need to use tactile device. These are the people who are partially visually impaired but not completely blind. This feature of the system may also benefit kids with dyslexia.

3.2 STEM Tutorials

As of now, we have included tutorials for some basic Mathematical and simple Physics concepts in our STEM accessibility system. These tutorials include introductions to the concepts of triangle, quadrilateral, poly-lines, circle, ellipse, projectile motion and more. All of these tutorials are highly intuitive and use dynamic renderings as depicted in figure 3-2.

To create these dynamic renderings(tutorials) we have used the 'rich XML' nature of SVG. We associate appropriate meta-data with each element of tactile graphics using this XML nature of SVG. We have added bi-directional XML links in SVG files corresponding to all the elements of tactile graphics. For example, what information

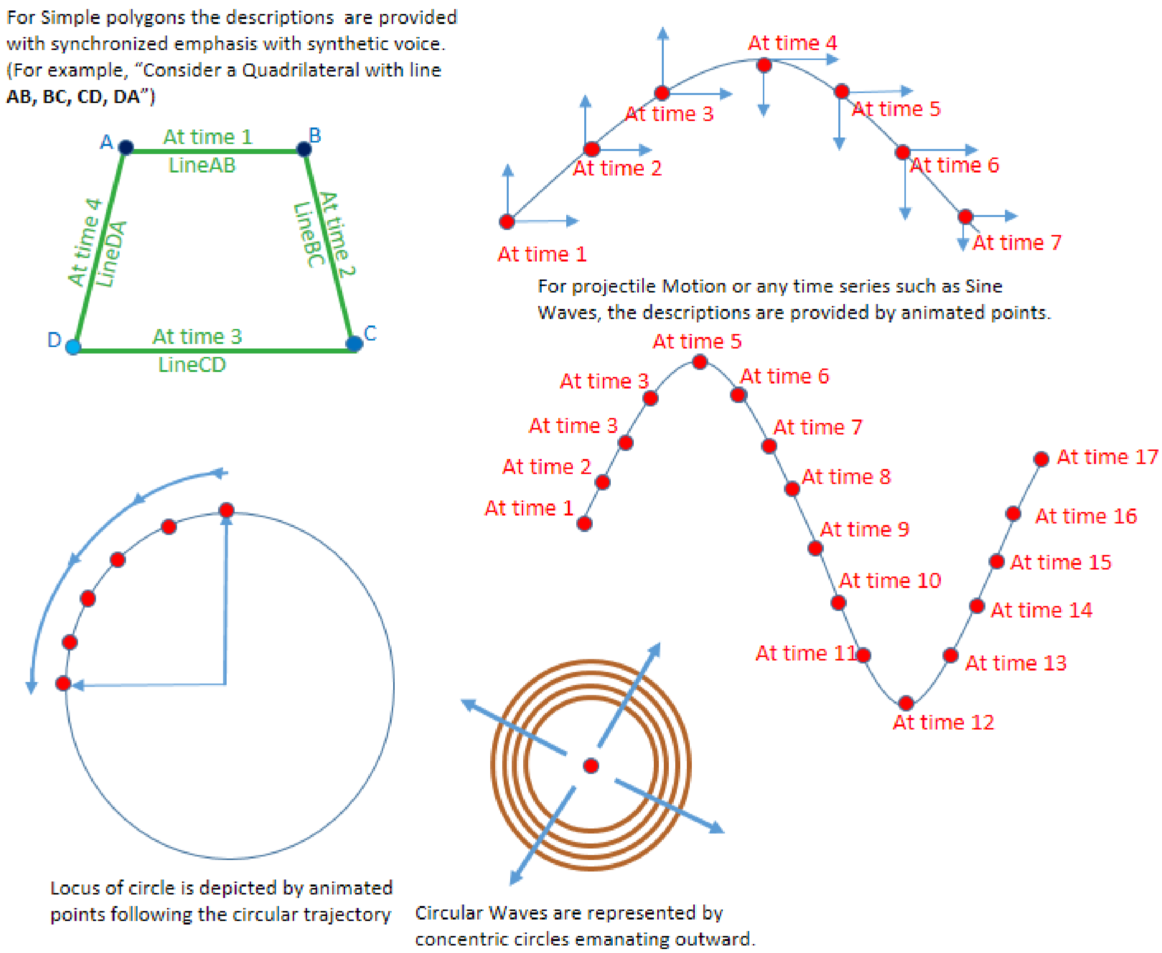

Figure 3-2: A depiction of interactive content about various STEM concepts. A simple polygon is displayed by synchronized vibrations (emphasis) on various sides of the polygon. A circle, sinusoidal wave, projectile motion is depicted by animated points depicted their trajectory and locus. Circular waves can be depicted by concentric circles emanating outwards.

should be revealed when a user performs a single-tap/double-tap/long-press on one of the sides of a triangle **(An example of this is shown in figure 1-9)**, is included with the SVG code defining that side. We have also used the 'rich XML' nature of SVG to implement the non-uniform zoom framework described in section 3.4. The information contained in the SVG file and in the bi-directional links is also responsible for deciding what vibrations/motion patterns to use for different STEM concepts.

In addition to that, our SVG file includes what information is to be spoken when giving a tutorial on some concept. For example in the case of circle, the information which is spoken is the following '*Let us learn about a circle. If a point A moves such that its distance from some other point B, remains constant over time, then the trajectory of the point A is called a circle. Moreover, the distance between A and B is called the radius of the circle*'.

The power of using SVG files and these bi-directional links is that any non-technical person can modify the information to be spoken when giving a tutorial or the information to be revealed in response to a touch-gesture. This capability will allow publishers, school teachers, and parents to modify the content of the tutorial at their inclination.

For creating all the tutorials currently included in our system, we first created the "Rich" source material, an XML database corresponding to all the mathematical and physical concepts/geometric shape currently included for tutorials in the system using an SVG authoring tool available online. Then we created bi-directional XML links between each pictorial element of a mathematical shape and its semantic and audio information. To do this we used different tag's properties of XML. For example, we used **id** tag to store the name of the triangle and **text** tag to store what audio information is to be revealed when an element with the **id** is single-tapped or double tapped. We use a high quality Microsoft Windows voice to produce the synthetic voice in our system.

In our XML file we also encode information corresponding to what kind of vibrations will be performed corresponding to a particular mathematical/physical concept. For example, in the case of a triangle we store the following information ' *Vibrationtype*

= *blink, Frequency = 4 Hz numberofblinks = 5'*. This information corresponds to 5 times blinking (all the pins corresponding to edges go up and down in periodic manner) of the edges of triangle with each blink occurring in .25 seconds (4 Hz).

Similarly, in case of the projectile motion tutorial we store the following information *' Vibrationtype = Animate, Frequency = 12 Hz', XVelocity = 20 m/s, YVelocity = 20 m/s'*. This information corresponds to animation occurring on the Braille device with a frequency of 12 Hz and following the trajectory of an oblique projectile having velocity in x direction as 20 m/s and velocity in y direction as 20 m/s.

We can extend our system to include different vibrations corresponding to different physical concepts. For example for depicting circular waves we can use concentric circles emanating outward from a center point. In a similar fashion we can display plain waves going from one end to the other undulating with a certain frequency.

3.3 The Braille Translator

The Braille translator is an integral part of SVG Latex editor. It handles the task of accurate translation of simple English sentences and Mathematical equations into Braille. This translator converts English character/words into six-dot-braille. This conversion uses integration of Braille fonts in latex. We use open-source Braille translator Liblouis [10] to make our system capable of translating simple text as well as difficult mathematical equations into equivalent Braille and Nemeth representations.

The reason why we use the Liblouis Braille translator in our system is because it is a highly accurate Braille translator. It is written in C and as I have written my entire code in C/C++ and it was very easy to use. In addition, Liblouis has also been used in various screen readers such NVDA and ORCA. Also, Liblouis has its base in BRLTTY which is a highly used screen reader for the Linux environment.

3.4 Modified Non-Standard Zoom-in and Zoom-out

A key-part of our system is a non-uniform zoom-in/zoom-out capability. For example, if we are looking for zooming in of a triangle then the system should only scale the length of sides and internal area of the triangle. In this non-uniform zoom-in/zoom-out the vertices should remain constant in size with zoom. Width of lines and text size should also remain constant in size with zoom-in/zoom-out. We achieve this behaviour using various properties of SVG such as 'Non-Scaling strokes'.

Chapter 4

Automatic Teaching System

One crucial factor contributing to low literacy among blind people is the lack of good teachers. To address this issue, we are currently developing an automated teaching system. After the tutorials of our STEM accessibility system, we will ask a blind student to draw shape of some concept which he learned (say a parabola) on an ipad. Using some machine learning algorithms we will verify if the shape which the student has drawn is correct of not.

The realm of this automatic teaching system will not just be limited to teach and test students learning STEM. We can also use it to teach about real life objects, such as the shape of an apple, a banana or an arm-chair. A depiction of this concept is shown in figure 4-1. Using the large SVG sketch database introduced in [16], we will first show various object sketches (converted from SVG into tactile graphics) to blind people. Then, using the multi-class support vector machines based machine learning algorithm from the same paper, we will verify if the object drawn by the blind person is accurate or not.

The dataset provided in [16] has 20,000 unique sketches of real life objects with varying orientation, alignment and view. These 20,000 objects sketches are from fixed pre-decided 250 categories such as apple, banana, ant, angel and arm-chair. The authors of [16] implemented a bag-of-features based multi-class support vector machine technique to classify the sketches into their respective classes. Their recognition method was able to classify 56% results accurately. We are currently implementing the same system for blind people to act as our automatic teaching framework.

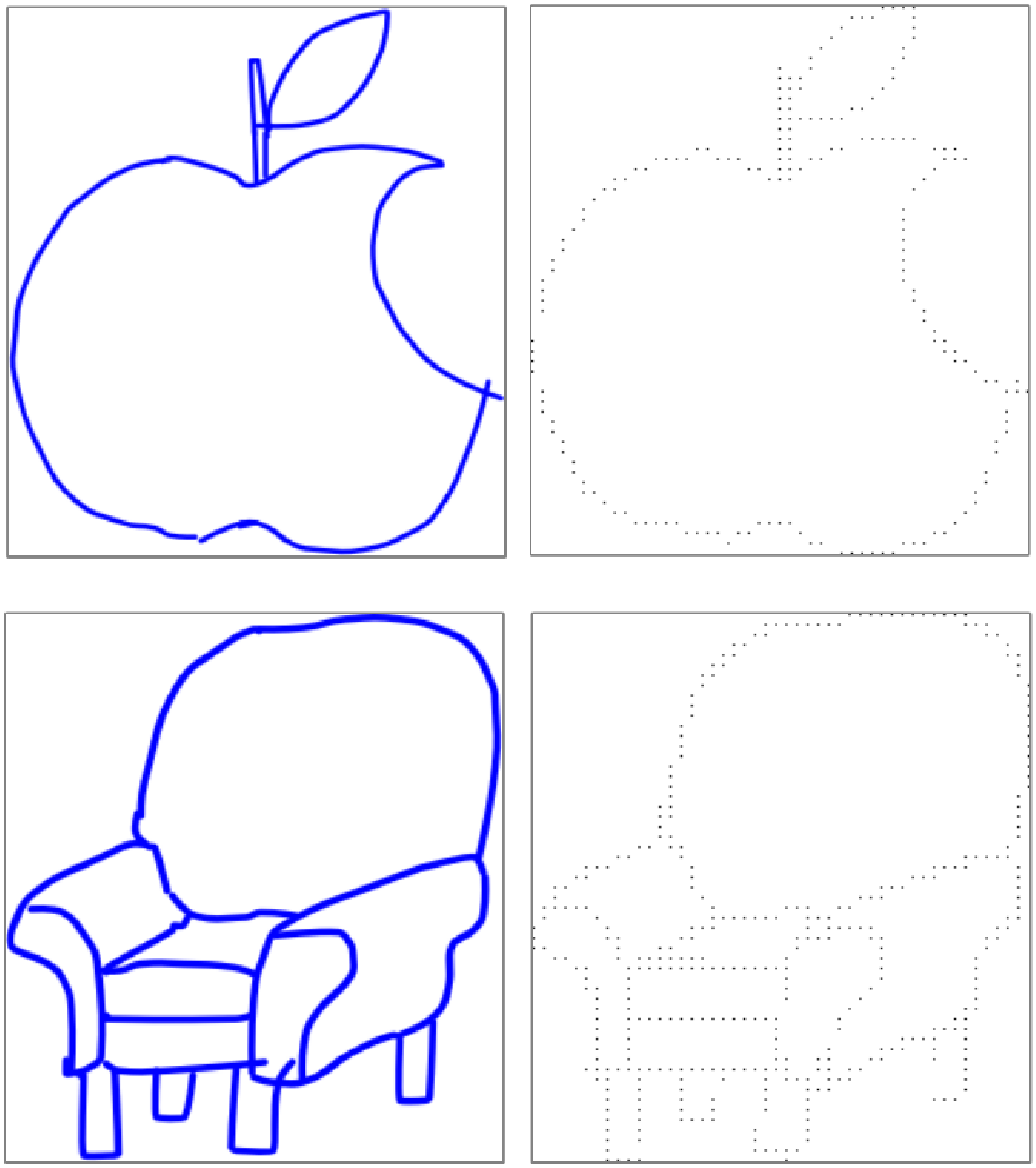

Figure 4-1: A depiction of SVG image of a real life object an apple, an arm-chair and their corresponding raised line representations. The raised line representation would be shown to blind person and once the blind person is sure of his/her learning we will ask the blind person to draw the same object on touch device (while they will be able to check their drawing on the Braille device) and would automatically detect if the blind person has correctly drawn the shape.

Chapter 5

User Testing and Discussion

We have tested our STEM accessibility system with 10 blind people. While testing our system with blind users we used following sequence of experiments to show them our work and ask for their feedback.

First, on the Braille device, we showed blind people the demo of a triangle with synthetic voice and vibrations. First the synthetic voice talks about what a triangle is and then vibrations on three edges synchronized with the synthetic voice are shown. No touch gestures are shown at first.

Next, we enable the touch gestures on the Braille Device and we ask the blind person to perform either single, double or long tap gestures and ask for their feedback about these touch gestures and the usability of these touch gestures.

Then, we show the demo of Projectile Motion to our blind test users. In this demo first there is a synthetic voice describing what projectile motion is followed by animated patterns on the Braille device depicting the trajectory of the projectile.

Finally, we show them the XY slider and ask them to scan long lines of text as well as some big tactile graphics which cannot be displayed on the Braille device alone due to its lower resolution.

After going through this sequence of experiments, the question we ask blind people is 'would a young kid be able to learn these concepts faster using our system as compared to traditional raised line drawing books?'

In response to the demo of the triangle, most of the blind users told that they are able to understand the concept of triangle and its properties pretty easily and according to them if the same concepts is shown to blind kid who is learning about a triangle for the first time would definitely learn faster and efficiently with our STEM accessibility system as compared to static Braille books.

After going through the touch gestures, feedback from most of the users was that at first it takes time to figure out where the line/edge/side on the Braille device is but once they are able to figure out where the side/edge is then they can easily perform single/double tap actions to know properties of different elements of the triangle. This help them learn about length and name of different sides of the triangle. But at the same time sometimes performing single/double/long tap doesn't reveal proper information or any information at all. This was due to the limited touch resolution of Braille device. In our hyperBraille device we have 24 X 15 = 360 piezoelectric output pins which can go up and down. For every set of 5 X 2 output pins for these piezoelectric pins, we have one touch input, i.e touch input resolution of our device is far more limited as compared to output pins resolution.

In response to the demonstration of projectile motion, most blind users felt that it is futuristic way to teach blind kid about different physics and math concepts which might be harder to learn for them using traditional Braille books.

Blind users gave mixed reviews about the use of the XY slider . For scanning long lines of text most users felt that the XY slider is good. For scanning tactile graphics some users felt that using XY slider works well while others felt that the XY slider sometimes does not help much as moving the XY slider breaks the continuity in perceiving the tactile graphics.

In addition, I have constantly solicited feedback from blind users who are quite good in Braille literacy. For example, even though we are using Liblouis Braille Translator system which is a highly accurate English (and from many other languages) to Braille translator, but it is not 100% accurate especially when it translates mathematical symbols. Lindsay Yazzolini, a blind woman who graduated from Brown University, and who has been affiliated with MIT's Brain Computer science department helped me in verifying the accuracy of the Braille translator. She gave me constant feedback on errors in the translations from Liblouis Braille. One specific example is the translation of simple straight line equation like $y_b = m_1 x_1 + b_2 + b$ from math to Braille was represented as $y^b = m^1 x^1 + b^2 + b$ because subscript was getting incorrectly translated as super script in Nemeth Braille translation. In a similar fashion at one instance vector b (i.e $\overrightarrow{b}$) was wrongly represented by b. With iterations of feedback and corrections from Lindsay, I was able to improve the accuracy of our Braille translator.

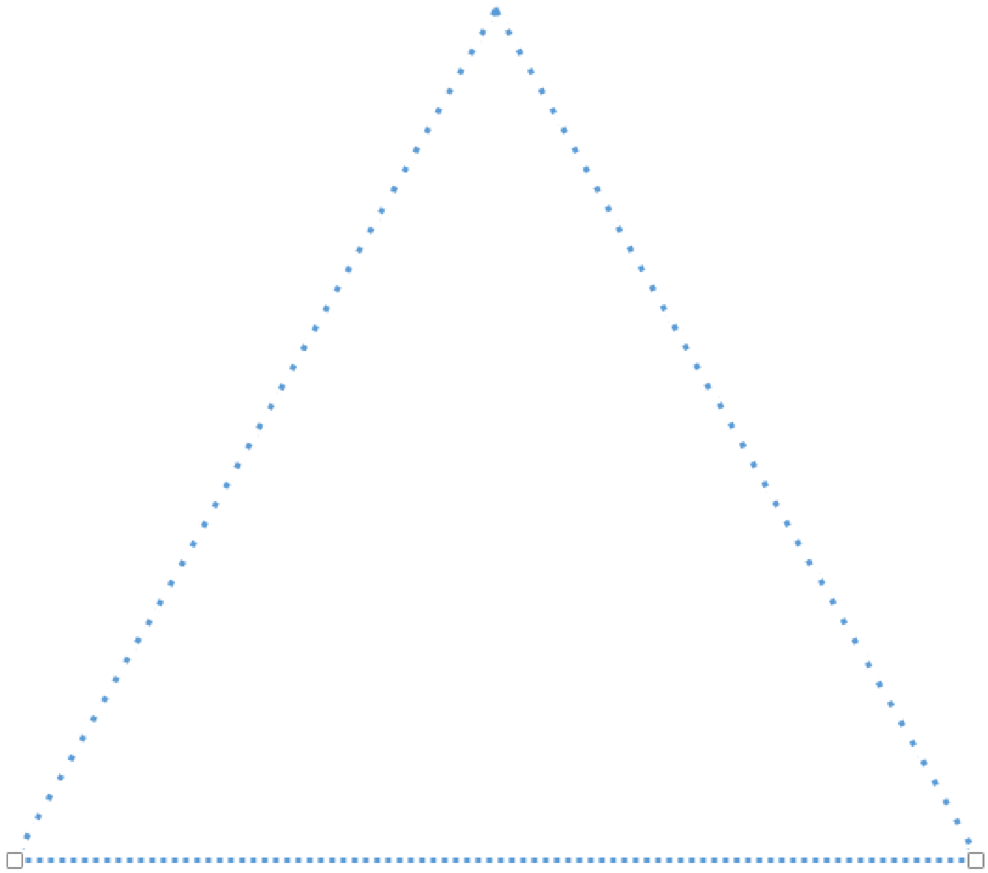

Figure 5-1: A depiction of the different resolutions in horizontal side of a triangle versus the non-horizontal sides. This happens because distance between two dots on the non-horizontal side is equal to $\sqrt{2}$ times the distance between the dots on horizontal side.

In a similar fashion, Jeffery Drucker who is a blind client from the MIT PPAT class provided a lot of good feedback. For example he observed that when we display a triangle on the Braille device, then the resolution of the horizontal side is higher than non-horizontal side. Because of this a blind kid might wrongly assume that having different resolution on different sides is a specific property of a triangle.

This is currently a limitation of our system. To overcome this limitation we need to have very high special resolution (The Braille pins need to be very close to each other) in the Braille device. This is currently not possible in any of the Braille device available in the market.

In addition, blind people from National Braille Press helped me figure out limitations of our XY gantry. I showed them bar-graphs, a circle and a ellipse demo. They also reported that the XY slider works great for scanning long lines of text and simple connected figures like a triangle. But it fails where there is a break in the continuity. For example when a blind person scans a bar-graph there is break in the continuity and lines appear and disappear constantly on the Braille device as we move the XY slider over the bar-graph. This is shown in the figure below.

Similarly, blind subjects were not able to distinguish between the shape of a circle and the shape of an ellipse. This is because as they move the XY slider along the locus of a circle or along the locus of an ellipse they feel that they are moving into similar circular path.

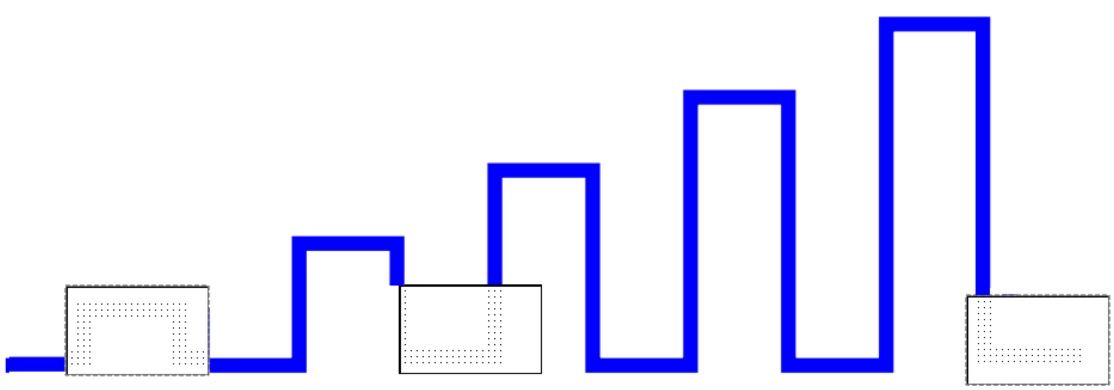

Figure 5-2: A depiction of continuity problem when scanning a bar-graph using XY slider. In this figure the XY slider moves from left to mid to rightmost location.

Finally, people from National Braille Press also mentioned that sometimes XY slider is too smooth and easy to move. At a lot of places they wanted to observe some tactile graphics and wanted the XY slider to not move at all. But as the XY slider was very smooth they faced difficulty in observing the tactile graphics.

The aforementioned three difficulties are the limitations of our system. When using traditional static books to perceive the raised line drawing of big a figure blind people try to perceive it in a highly continuous manner. But when the central stage of the XY slider moves this continuity breaks and they lose track. To overcome this limitation in the next version of the system we will replace XY slider with a big touch panel. As soon as the blind person would touch (with one hand) some location on the touch panel the corresponding content will be shown below the fingertips of the other hand of the blind user on the Braille device. As the blind person would move his first hand slightly left or right the content on the Braille device would change accordingly. I believe this improvement will remove some of the problem of XY slider but we still have to test this revised setup to confirm.

In addition, we have received constant feedback about the poor quality of synthetic voice previously used. Initially, we were using espeak, and flight synthetic voice engines from Linux but owing to constant comments about poor voice quality we have recently integrated our system with high quality Microsoft Windows synthetic voice.

In addition some blind users pointed out that even though we are able to reduce the cost of our system, the current system is still very expensive, non-portable and very heavy. To overcome this issue we are planing to test and integrate feel effect devices (such as Senseg Tablet mentioned in Introduction chapter) in our system.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In this thesis, we presented a low cost highly interactive STEM accessibility system for teaching STEM content to BVI users in a intuitive and interactive way. We verify the effectiveness of our system by user testing. Other than showing this work to blind people we have also shown it to the president of the National Braille Press, Mr. Brian Mac Donald, two teachers of blind children and three parents of blind children. According to all of them, the system offers an opportunity to transform the way blind people learn STEM and system will definitely expedite the STEM learning process for blind people. We believe that it is the first system to use touch gestures, synthetic voice, rhythmic motions all in conjunction to develop a system to enable blind people to learn fast and efficiently. Moreover, this system offers huge reduction in cost while still being able to provide a high effective resolution of high speed vibrating piezoelectric pins. Finally, the automatic transcription system for STEM books (and any content available on-line) is another distinct advantage of this work.

6.2 Future work

One possible extension of our work which we are currently working on, is to make artistic paintings such as MonaLisa, the Last Supper as well as any photographs more accessible to blind and visually impaired people. Using computer vision algorithms we will first obtain dominant edges from the image. A raised line version of these dominant edges would be displayed on the Braille device in raised line drawing form. We can also use integrate relief and feel displays to extend the intuitiveness. In addition to that we will be turn images of paintings into a music. While feeling the raised line drawings (or feeling pictures on a relief display) blind person would also hear music generated based on colors, textures, and light/dark values corresponding to where their fingers are currently touching the picture. Colours and light/dark values, and more, could correspond to instruments and pitch, etc. We will come up with mapping of visual space to musical elements space that results in a pleasant and intuitive response.

In addition to that we are planning to 3D gantry in our system to be able to represent 3D sketches on the Braille device. We are also working on coming up with more intuitive techniques for teaching blind people about highly difficult concepts such as Newton's laws of motion, rotational motion equations, chemical equations involving organic and in-organic compounds, thermodynamics, heat-transfer and more.

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