M.Sc. Engg. Thesis

A Low-cost Reading Tool For Economically Less-privileged Visually-impaired People Exploiting Ink-based Braille System

by

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Dedicated to my loving parents

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The thesis titled "A Low-cost Reading Tool For Economically Less-privileged Visually-impaired People Exploiting Ink-based Braille System", submitted by Tusher Chakraborty, Student ID **1015052038F**, Session October 2015, to the Department of Computer Science & Engineering, Bangladesh University of Engineering & Technology, has been accepted as satisfactory in partial fulfilment of the requirements for the degree of Master of Science in Computer Science & Engineering and approved as to its style and contents. Examination held on October 28, 2017.

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Candidate's Declaration

This is hereby declared that the work titled "A Low-cost Reading Tool For Economically Less-privileged Visually-impaired People Exploiting Ink-based Braille System", is the outcome of research carried out by me under the supervision of Dr. A. B. M. Alim Al Islam, in the Department of Computer Science & Engineering, Bangladesh University of Engineering & Technology, Dhaka 1000. It is also declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Abstract

People with visual impairment use Braille as a medium of textual representation having palpable dots. While the more privileged among us use OCR based text readers as preferential alternative, the lesser privileged ones are still bundling with conventional Braille tools. Our endeavor in this thesis is to develop a low-cost and easy-to-use solution for less-privileged people. Here, we propose *EyePen*, a system that enables less-privileged visually-impaired people reading Braille characters, printed using conventional ink-jet and laser printers. The use of printed Braille characters using ink-jet printers offers a cost-effective alternative in place of the more expensively printed conventional palpable Braille dots. Besides, *EyePen* demands a very short learning period and offers a smooth learning experience ensuring ease-of-use while being in operation. We conduct a participatory design and iterative evaluation involving five visually-impaired children in Bangladesh for more than 18 months. Our user evaluation reveals that *EyePen* is easy-to-use, and exhibits a potential low-cost solution for economically less-privileged visually-impaired people. The user evaluation results show that the accuracy of reading printed Braille characters using *EyePen* converges to 100% within a very short period of time for all users. Finally, we present a potential writing aid that can facilitate low-cost and easy writing of Braille characters on normal paper exploiting our system.

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Chapter 1

Introduction

In this thesis, we design and develop a low-cost and easy-to-use reading system for economically less-privileged visually-impaired people. In the following sections, we discuss the motivations and contributions of our work in this affair.

1.1 Motivations of Our Work

Access to printed text is always a challenge for people having visual impairments. According to WHO, there are approximately 285 million visually-impaired people worldwide, and 90% of them live in low-income settings [1]. While technological advancements have reaped benefits to the sighted peers, challenges involved in reading and writing by visually-impaired people still remain an open problem. Recent development in smart phones and computer vision algorithms have paved paths to new solutions. However, these solutions are expensive which make them unfeasible for economically less-privileged people.

Braille is conventionally a written form of tiny palpable bumps embossed on a paper or surface that exploits the haptic senses of a visually-impaired person. It requires printing papers using embossed printers which are generally expensive, typically starting from $1,800 to $5,000. While reading follows conventional practice from left to right, Braille is written by embossing dots from right to left on the other side of the paper. This is a matter of practice; visually-impaired children are encouraged to learn Braille in the early age. However, the trend of using Braille in the later stages of a visually-impaired person's life is low. The palpable dot based conventional Braille system has been perceived as a difficult and arduous process because of the effort necessary to learn Braille [2]. Children from the privileged community are exposed to high penetration of smartphone and gadget based applications. Consequently, the popularity and literacy rate of Braille is low [3, 4]. On the other hand, the low-income groups cannot afford such applications and gadgets.

It is important to understand why Braille is failing and why it is still important. School budget constraints, lack of skilled Braille teachers, and massive influx of printed text-based readers are primary reasons behind the decreasing popularity of Braille. This is more intense in low-income countries. However, research studies such as [5, 6] have already pointed out a subtle relationship between Braille literacy and employment rate. They showed that visually-impaired adults having prior Braille literacy exhibit 44% unemployment rate compared to 77% unemployment rate observed for individuals habituated with printed texts. Besides, Brawand and Johnson summarized Braille as one of the most effective mediums for conveying mathematical instructions to visually-impaired people [7]. Therefore, a comprehensive reading system for Braille is imperative. Moreover, a report from the US Department of Education [8] states that youth with visual impairment are more likely to attend post-secondary school than those with other disabilities. Since this group shows more inclination towards education, a number of research studies have been conducted to solve their reading problems.

The particular design problem and challenge is two-fold. First, designing for visually-impaired people, and second, making practical use of it for low-income settings. There is a thriving need for assistive devices among visually-impaired and blind community; however, they do not necessarily accept tools that introduce personal and social discomfort [2]. Considering the influence of environment, the social model of disability is often hard to perceive. As a result, researchers and practitioners often find it difficult to design systems and tools that address such social model of disability, yet achieving a low-cost status.

There are attempts to ease reading process in both smart phone and wearable form-factor [9, 10, 11]. Computer vision and OCR based algorithms have solved plain text based reading problems. Previous work in this area has attempted to revitalize Braille by developing refreshable Braille displays, finger actuators and vibrators, and providing tactile cues using additional supporting display frames. While these efforts have shown benefits, researchers and practitioners ponder upon their practical utility for low-income settings. For example, the cost of refreshable Braille displays range from \$3,500 to \$15,000 depending upon the number of characters displayed [12]. Moreover, they often come bundled with additional computational support as a processing unit, thereby questioning the portability and personal usability among low-income groups. Even though smart phones provide alternative solutions to reading problems, it is far from ideal for economically less-privileged people to afford smart phones [13].

Since smart phones and gadgets alone cannot solve this problem, we attempt to investigate whether reviving Braille can help. There are two arguments why Braille is still important. First, Braille has a relationship with employment as discussed before. Second, a study reveals that non-visual free-form handwriting by the visually-impaired is often messy and space inefficient, because, they lack necessary spatial feedback and shape awareness [14]. Our work is motivated by understanding the limitations of state-of-the-art research, the challenges in designing systems for visually-impaired people, and a practical field work and engagement with focus groups living in low-income settings.

1.2 Our Contributions

In this thesis, we attempt to overcome the problems of Braille reading and writing by visually-impaired people in low-resource constraints, involve them in a participatory iterative design process, and we put forward a novel low-cost solution (< $4). To the best of our knowledge, we are the first to come up with such system. We name our solution as *EyePen*, specifically targeting people in low-income settings. It enables people with visual impairment in reading Braille characters printed using conventional ink-jet or laser printers available in our homes, offices, street stationeries, etc. *EyePen* comes as a bundle containing a pen that aids in reading printed Braille characters and a trajectory guide board that guides the pen. The underlying mechanism of *EyePen* relies on the classical reflection model of light.

Based on our work, we make the following set of contributions in this thesis:

1. In this study, we undertake a participatory design and iterative evaluation process involving five visually-impaired children for more than 18 months.

2. We design and develop a novel pen-shaped device that aids less-privileged visually-impaired people in reading Braille characters printed using conventional ink-jet printers.

3. We design a trajectory guide board bundled with the pen. This board guides tip of the pen and helps it to glide over the paper by maintaining alignment while reading.

4. We perform user evaluation of *EyePen* with five visually-impaired participants representing less-privileged community. Our results show that the accuracy of reading using *EyePen* converges to 100% within a short period of time. Besides, we perform a *semi-structured interview* of the participants and confirm the usability and acceptance of *EyePen*.

1.3 Outline of Our Thesis

This is how the rest of this book is organized. In Chapter 2, we elaborate on state-of-the-art studies and analyze this problem from different viewpoints highlighting related works in each cases. After that, in Chapter 3, we present the research context and introduce the existing educational infrastructure of visually-impaired people in this research context. Next to that, we we introduce *EyePen* through a comprehensive collaboration with focus groups and experiments in our laboratory in Chapter 4. In Chapter 5, we delineate our intuition driven preliminary prototype and feedbacks from our participants after using this prototype. The first deployment helped us understand to focus on a better design principle. On the basis of the feedbacks from our participants, we modified our initial prototype in Chapter 5.2. We conducted a second deployment after modifying the preliminary design. We delineate the results of our second deployment in Chapter 6. We also perform a usability survey over the participants to grasp an idea of the acceptability of *EyePen* in Chapter 7. We summarize the potential future work of our study in Chapter 8. Finally, we draw our conclusion in Chapter 9.

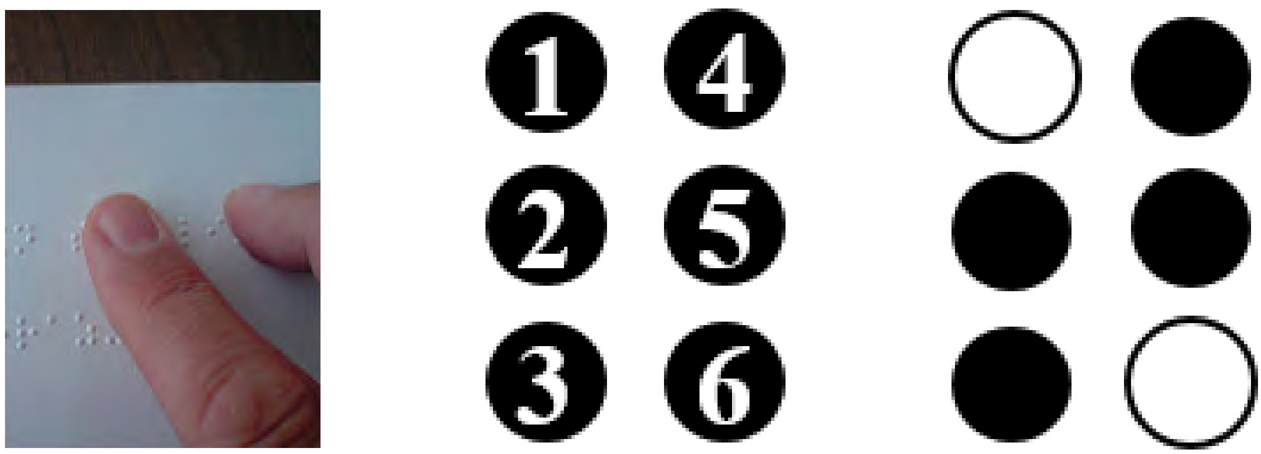
Chapter 2

Background and Related Work

We introduce two matters of importance at this stage to the reader for simplicity of exposition.

Visual Impairment: WHO comprehensively defines visual impairment according to the International Classification of Diseases [1]. According to this classification, moderate visual impairment and severe visual impairment are grouped under 'low vision'. Blindness is referred to as complete vision loss. Low vision and blindness represents all visual impairment. In this paper too, we shall generally refer blindness and low vision as visual impairments.

Braille: Braille is a written form and medium widely adopted by visually-impaired people. It consists of



(a) Conventional Braille dots (b) Ordering of dots (c) Letter 'T'

Figure 2.1: Conventional Braille dots and character

tiny palpable bumps or raised dots embossed on a paper or a surface. Braille is particularly a code that represents each alphanumeric character through a combination of six raised dots. Each Braille character has three rows and two columns, which in combination is called a *Braille cell*. Figure 2.1a shows a conventional Braille reading method where Braille characters are embossed on a surface. Figure 2.1b shows the relative ordering of the dots in a Braille cell. Figure 2.1c represents the letter ‘T’.

A number of research studies have been carried out in both academia and industry to devise solutions for visually-impaired people. Here, we discuss various research efforts that are pertinent to reading and writing by visually-impaired people.

2.1 Reading Aids and Techniques

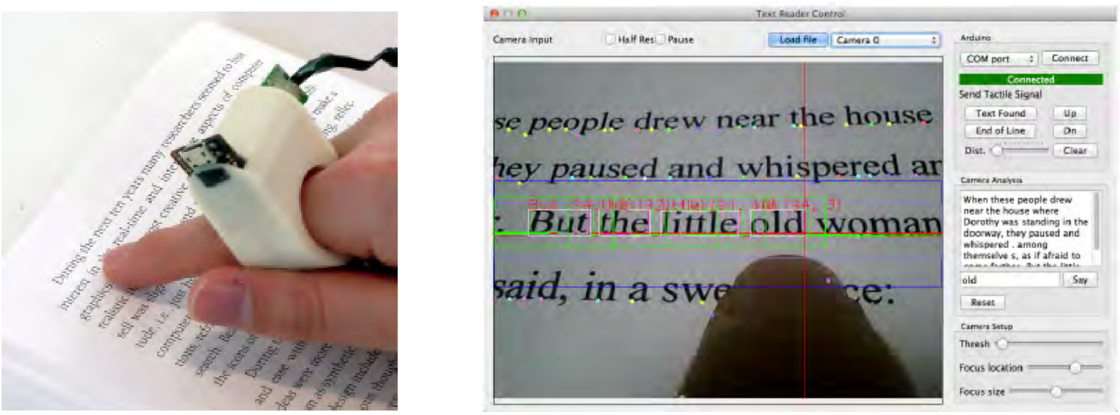
Reading devices and techniques vary in the nature of interaction with the users and the modality of their usage. However, we categorize them based on the later.

Figure 2.2: VBraille representation of a Braille character

2.1.1 Mobile Applications

The era of smart phones helped researchers to quickly develop applications that provide audio feedback to the users. Coughlan et al., [15] describes a prototype smart phone application that reads printed texts. They propose a prototype smartphone system that finds printed text in cluttered scenes, segments out the text from video images acquired by the smartphone for processing by OCR, and reads aloud the text read by OCR using TTS. ZoomText [16], SayText [17], Text Detective [18], KNFB Reader [19], etc., are similar examples of text-based readers. ZoomText has three versions available and works as an amalgamation of magnifier and TTS. Contrary to these applications, VBraille [20] exploits haptic Braille perception using smart phones by dividing the screen into six zones corresponding to six dots. The average time it takes for a visually-impaired participant to read a VBraille character ranged between 4.2 and 26.6 seconds. Figure 2.1 depicts the VBraille representation of the alphanumeric character ‘p’.

Figure 2.3: A visually-impaired person wearing OrCam glass



(a) Prototype of FingerReader

(b) Software in midst of plaintext reading

Figure 2.4: Prototype and software of FingerReader

2.1.2 Wearable Solutions

Wearable solutions here are mostly accompanied by a camera to assist in vision, and generates either haptic or audio output, or in some cases both. OrCam [10](price $2,500 [21]) is a smart wearable eye glass designed to assist visually-impaired people in reading printed texts. OrCam makes a small gizmo that hooks onto a pair of glasses and tells the wearer what’s in front of the person. It can read the text of a document aloud (Figure 2.3), or announce the names of friends and family members around. FingerReader [11] is a smart finger-worn device (Figure 2.4a) that helps blind users with reading. It subsumes a novel concept for text reading for the blind, utilizing a local-sequential scan that enables continuous feedback and non-linear text skimming 2.4b. However, FingerReader may not work under poor lighting condition. HandSight [22] addresses this problem

Figure 2.5: Finger-mounted camera in HandSight

by introducing a self-illuminating finger-worn device (Figure 2.5). This study also presents empirical results comparing audio and haptic directional finger guidance for a reading task in terms of user performance and subjective response. Besides, [23] is a handheld device with text based acquisition using a camera coupled with a control unit and vocal output unit. Studies such as [24][25][26] design applications and algorithms that assist people with vision problem with reading signages and printed texts.

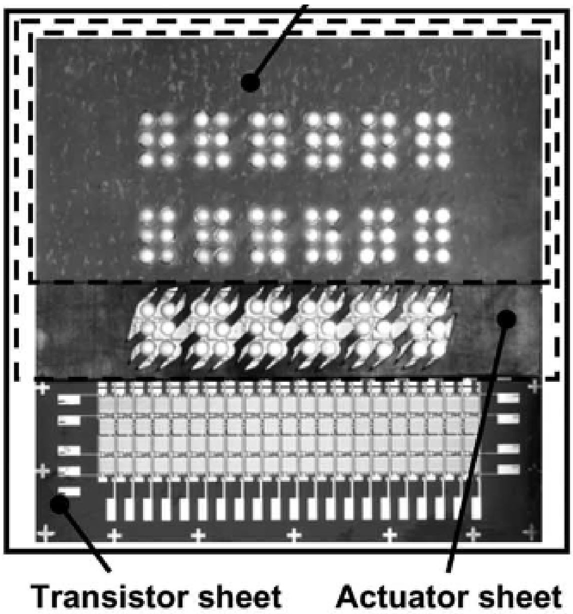


Figure 2.6: Braille sheet display

Figure 2.7: UbiBraille - Braille-reading vibrotactile prototype

2.1.3 Braille Based Devices

Conventional Braille reading utilizes haptic senses of the readers. In refreshable Braille displays, the dots of a Braille cell are formed by pins independently controlled by actuators [27, 28, 29]. A picture of a Braille sheet display in plan view is shown in the Figure 2.6. A different approach from refreshable Braille display is providing tactile cues of Braille characters using photo-active materials [30]. UbiBraille [31] is a vibration based Braille reading device that actuates the six fingers mapped with six dots of a Braille character. As shown in the Figure 2.7, this approach draws inspiration from the traditional Braille writing mechanism where finger chords are used to input 6-dot codes.

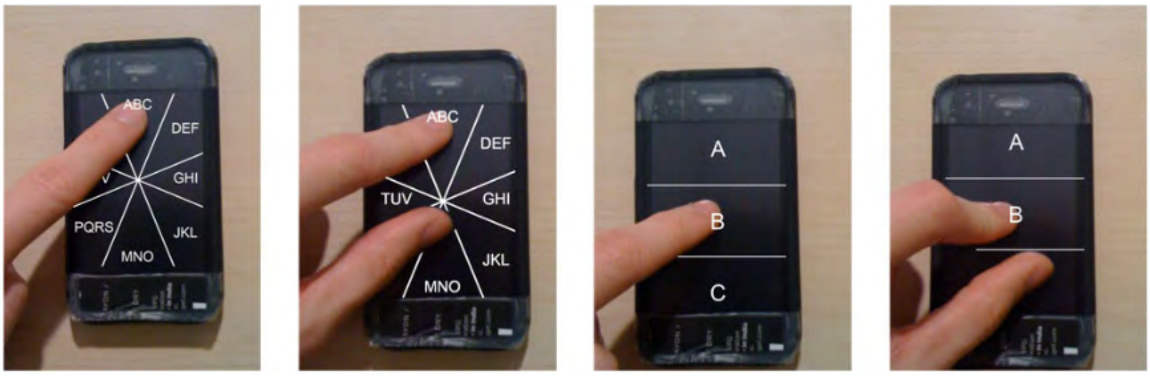


Figure 2.8: Entering a character using No-Look Notes

2.2 Writing Aids and Techniques

We explain here state-of-the-art applications and techniques that help visually-impaired people in writing. McSig [14] explores non-visual free-form hand writing by visually-impaired students. No-Look Notes [32] is a pioneering work on the first multi-touch enabled phone screens, which revealed that arranging characters in 8-segment pie menu is less erroneous and more faster than speech based input. Figure 2.8 depicts the flow diagram of entering a character using No-Look Notes. Similarly, MTITK [33] is a mobile keyboard where users

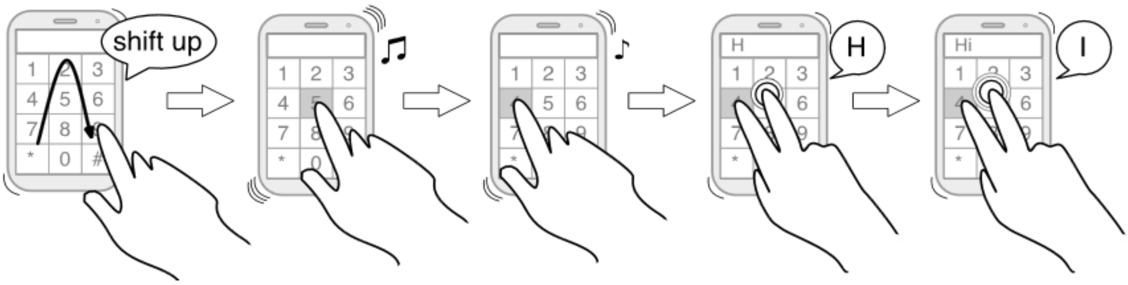


Figure 2.9: An example of how a user can enter the word “HI” in MTITK

Figure 2.10: QWERTY keyboard touchplates in different materials

tap to enter a text, and gesture to edit it. MTITK has four interaction modes: finger multi-touch via the screen for input, speech, audio, and tactile vibrations for output and feedback. Figure 2.9 depicts the flow diagram of entering “HI” in MTITK. Touchplates [34] (Figure 2.10) is a low-cost acrylic board overlay on a touchscreen providing tactile cues to the soft keyboard displayed underneath.

Among the Braille based inputs, BrailleTouch [35] is no different than VBraille. TypeInBraille [36] also receives Braille as input using gestures to demarcate raised and unraised dots. Azenkot et al., [37] mapped fingers with Braille dots, and experimented with single hand input versus both hands input. Another work [38] explored speech input by blind people. Their study revealed that participants were satisfied with speech input, however, they spent an average of 80.3% of their time editing the texts.

Approach	**Demand for high-end devices**	**Promote Braille proficiency**	**Consider low-resource settings**	**Aid in paper context**
VBraille [20]	Yes	Yes	No	No
OrCam [10]	Yes	No	No	Yes
FingerReader [11]	Yes	No	No	Yes
HandSight [22]	Yes	No	No	Yes
UbiBraille [31]	Yes	Yes	No	No
ZoomText [16]	Yes	No	No	No
SayText [17]	Yes	No	No	No
Refreshable Braille displays [27, 28, 29]	Yes	Yes	No	No
Peterson et al., [30]	Yes	Yes	No	No
EyePen	No	Yes	Yes	Yes

Table 2.1: Comparison of our approach with existing studies

2.3 Any Reading Plus Writing Solution?

Most state-of-the-art studies have independently focused on either reading or writing problems of visually-impaired people. Reading aids here are mostly smart phone based utilizing state-of-the-art OCR algorithms. On the other hand, existing solutions for writing present greater involvement of Braille based inputs since text-based solutions have been proved to be difficult. Thus there is a void in research studies attempting to solve both reading and writing problems.

2.4 What is There for the Less-Privileged?

We argue here why state-of-the-art literature is less likely to aid less-privileged people. Can less-privileged people afford a smart phone? Medhi et al., [13] showed that more than half of the existing mobile phone subscribers live in low-income countries, and most of them are subscribers of low-cost feature phones. Consequently, it is far from ideal for people having low per capita income (for example $1045 [39]) to afford smart phones. Moreover, apart from standalone devices, some solutions (e.g., FingerReader, HandSight) come with companion computing devices. While assistive devices demand portability [2], these devices are less portable.

Next, we present a comparison with the recent state-of-the-art approaches in Table 2.1. Here, we encapsulates the comparison on the basis of four crucial context-aware design attributes that we are looking forward.

Chapter 3

Research Context

Our current study was conducted at a school for disabled in Dhaka, Bangladesh. This is a government run school which facilitates children with several forms of disabilities including visual impairment. Here, we review the key findings of our more than 15 months long ethnography conducted in the school.

The National Institute for Disabled at Mirpur, Dhaka is an institute for children with different disabilities. We worked very closely with the teachers and students of the 'School for Visually Impaired'. This school has only 48 children as of May 2016, comprising 30 boys and 18 girls. Students of Class 5 are considered as seniors of the school. Soon after they graduate from Class 5, some of them dropout, while some still pursue education in some private schools for disabled. The school consists of ten teachers; five of them have different forms of visual impairment and are quite fluent in Braille. The rest have normal vision. We chose this school as it suited best to our purposes comprising facilities and problems of low-resource settings. The monthly tuition fee varies by classes, therefore we report here the average $3.75 per students. All students reside at the on campus dormitory. Apart from getting helped by the caretakers for some of the daily chores, the visually-impaired children live on their own.

Visually-impaired children in this school are taught Braille in the early age. Teachers reported that students who are congenitally blind[1] grab Braille faster, compared to those who lost their sight partially or wholly at some stage in their life. We report a similar findings empirically during user evaluation later in this paper.

(a) A Braille book

(b) Plain print book

Figure 3.1: English language book for Class 5 in Bangladesh

	Braille print	**Plain print**
Dimension (l×w×h) cm	27×24×4	25×21×0.7
Number of pages	203	104
Cost (USD)	50	0.76

Table 3.1: Comparison between Braille and plain text books

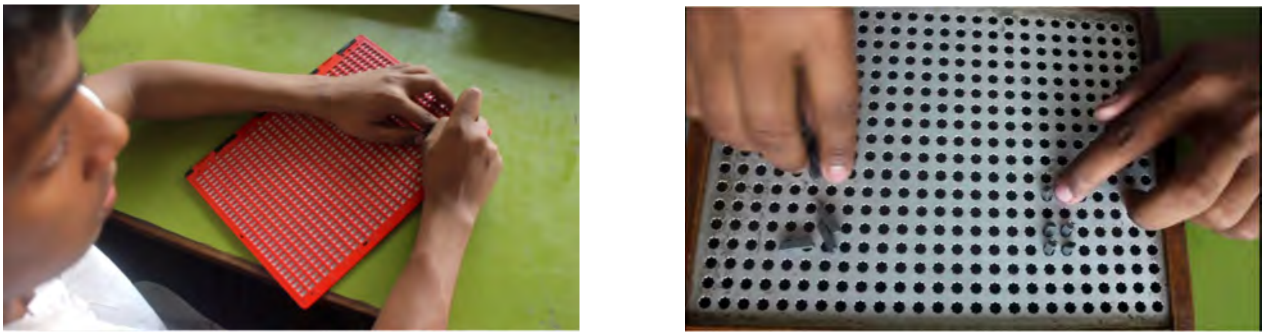
3.1 Books in Braille

Braille embossers are expensive [40]. There is only one government run Braille printing press in Bangladesh. Figure 3.1a shows a Braille printed English book under the national curriculum of Bangladesh. Figure 3.1b shows the corresponding print for sighted peers. Table 3.1 demonstrates a comparison between these two books as an example. Here, considering only printing cost, Braille book is 65× costlier than plain print book. Although students in this school receive Braille books free of cost from the government, our primary concern here is the massive cost involvement in printing Braille books. Moreover, the only Braille press struggles to supply academic books in time. Students once spent at least half of their academic year without books [41].

3.2 Supplementary tools

Visually-impaired children use a slate or frame as support while writing. Figure 3.2a shows a student writing in Braille. Writing in Braille involves arduous effort and mental concentration since writing is not straight forward. Students flip the paper, attach it beneath the frame, and use the stylus in appropriate notches to emboss holes from *right to left*. In order to read the same, (s)he has to flip it back again and read from left to right in usual manner. While practice shapes them up, however, teachers and guardians believe that writing involves surplus

[1]Congenitally blind are those who are born with visual impairment.



(a) Braille writing support frame

(b) Tools for general arithmetic

Figure 3.2: Supplementary tools for visually-impaired children

amount of mental and physical efforts in this system. Figure 3.2b shows necessary tools for general arithmetic purposes, for example, addition, subtraction, multiplication, and division. Small lead bars are inserted inside the notches of the frame in different orientation to enumerate different numbers. The tip of these lead bars are jagged, taking advantage of their haptic senses. However, frequent use corrodes and smooths the tip. A significant caveat is that, these lead bars are seldom available in Bangladesh, and often arrive from India on demand.

3.3 Use of Technology

The study in [42] suggested that people in low-income countries struggle with complex hierarchical information navigation in smartphones. Hence, use of smartphones in regions belonging to low-income groups tend to be low. Our practical experience from visiting this school also reflected a similar view. Since students resided at the on-campus dormitory, they were allowed to keep mobile phones with them. While conducting this study, none of the students were a user of a smartphone. We observed that they were more comfortable with low-cost feature phones. Frequently used feature was the voice call. Another commonly used feature was the radio service.

Considering the socio-economic condition of Bangladesh, it is undeniably true that economic factor plays a major role in the choice of mobile phones. Nevertheless, we also believe that the physical keyboard of non-smartphones has to do with the choice of mobile phones. Physical keyboards provide necessary spatial and tactile awareness to the user, which is very crucial for visually-impaired users. There was only one desktop computer in the school inside the office of the headmaster. We visited students' on-campus resident hall a number of times while conducting this study. We asked the officer in-charge whether the students have provision to keep personal computer or gadgets with them. The answer was negative, and a conversation on their family income also revealed that they could hardly afford personal computer and gadgets.

In this age of technological advancements, the current state is appalling. Clearly Braille is important, as mentioned in Chapter 1. However, as discussed in Chapter 2, technological benefits has not reaped benefits to this more demanding community.

Chapter 4

Our Proposed Solution

In this chapter, we delineate our proposed solution to address the challenges mentioned in the earlier chapters through a comprehensive collaboration with focus groups and experiments in our laboratory.

4.1 Focus Group and Design Goals

Participant	**Category**	**Initial Braille learning period**	**Age (years)**	**Writing hand**
P1	Blind	1.5 months	8	Left
P2	Blind	4 months	9	Right
P3	Blind	1 months	10	Right
P4	Low vision	5 month	10	Right
P5	Low vision	1.5 months	11	Right

Table 4.1: Demography of participants

We targeted one primary group and two secondary groups as focus group participants. The primary group consisted of five children from the school. We collaborated directly with the primary focus group to study the usability of our developed system and received feedback for further improvement. The two secondary focus groups consisted of school teachers and two visually-impaired undergraduate students from University of Dhaka (DU). These groups participated in design discussions, idea generation, and also provided feedback. Table 4.1 shows a demography of primary focus group participants. Following the classification provided by WHO [1], we group moderate and severe visual impairment under 'low vision', and complete vision loss under 'blindness'. Conforming with WHO standard, we refer low vision and blindness together under the umbrella term 'visual impairment'.

To summarize our findings from the previous chapter, and supporting these findings through a number of empirical data presented in Chapter 1 and Chapter 2, the limitations and inconveniences present in the current systems are -

1. Palpable Braille printing is *expensive*. Apart from some private organizations, government support and subsidies are limited in low-income countries.

2. Braille writing is cumbersome. It takes significant effort from the writer, to write the same thing from right to left, that (s)he reads from left to right.

3. Wide dissemination of education is limited in current settings. This is mostly because students are heavily dependent on academic books only, while non-academic books are beyond their reach.

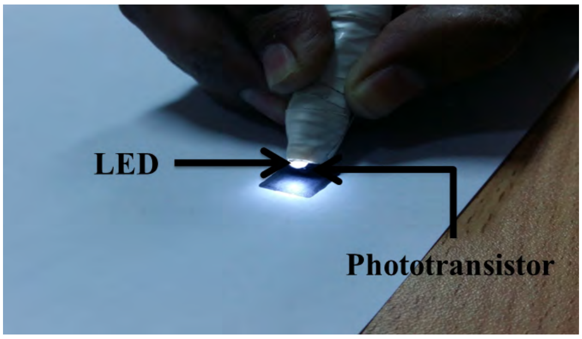
The first design challenge is to think beyond haptic modality. Embossed Braille characters are taught to the visually-impaired in the first place because they can exploit their haptic senses to compensate for the sight loss. The second design challenge is to come up with a solution that is affordable and demands low-resource.

The journey through the design process ultimately flourished in a bottom up manner. Our initial endeavor was to find an affordable solution for the marginalized community. There is a wide dissemination of regular black and white laser/ink-jet printers in our homes, offices, street stationaries, etc. This is affordable; organizations and individuals can easily purchase such printer at low cost and run for at least 2-3 years. Moreover, if they can not purchase it, they can get it printed from street stationaries at a reasonable price. Can we print Braille using regular printers? Yes, we can. However, if Braille dots are not embossed on the paper, then how can visually-impaired people make any sense of this?

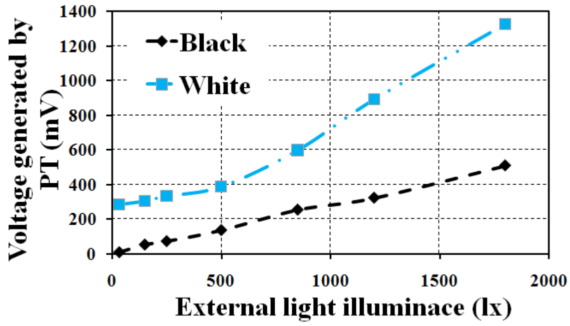
This led us to the first design challenge, thinking beyond haptic modality. The idea of printing Braille using regular printers seemed puzzling to the focus groups. They were able to hypothesize that their haptic senses and fingers would be of no good in this case. Although they were expecting an OCR based approach, however, they knew that OCR based techniques were expensive and not easily affordable.

4.2 The Physics Underneath

If we think of each Braille dots as a filled square printed in black ink on a white paper, we need to find an alternative to haptic feedbacks using which visually-impaired people can make sense of the dots. We use the classical reflective property of light and build a custom off-the-shelf device based on this theoretical model.



(a) Experimental setup



(b) Experimental results

Figure 4.1: Experiment to confirm the theoretical model

We conduct a testbed experiment using (1) A white paper with printed black colored region on it, (2) A pair of LED and phototransistor [43], (3) An Arduino board [44]. Figure 4.1a presents a snapshot of the experimental setup. A phototransistor (PT) is placed on a paper and an LED emits white light to illuminate the region beneath the PT. The PT generates analog voltage according to the reflected light incident upon it after being reflected from the paper. An Arduino board coupled with the PT converts analog voltage generated by the PT into digital value and logs that digital value into a PC.

We perform our experiment in different lighting condition through varying the illuminance of an external light source. We put the PT both on white and black colored region of the paper. Figure 4.1b shows change in digital values representing voltage generated by the PT for black and white colored region of the paper. This figure confirms that there is a significant gap between the voltages for the two different colored regions. This infers that we can interpret black colored dots from the white surface of the paper.

4.3 Working Principle

Here we discuss about the overall design of our proposed solution. Figure 4.2 represents a printed single Braille cell with all six dots. Figure 4.3 represents a simplified block diagram of our proposed solution. The system

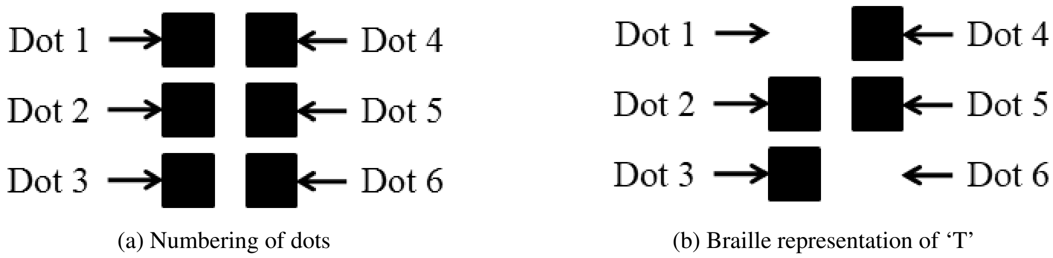


Figure 4.2: Printed single Braille cell proposed in our solution

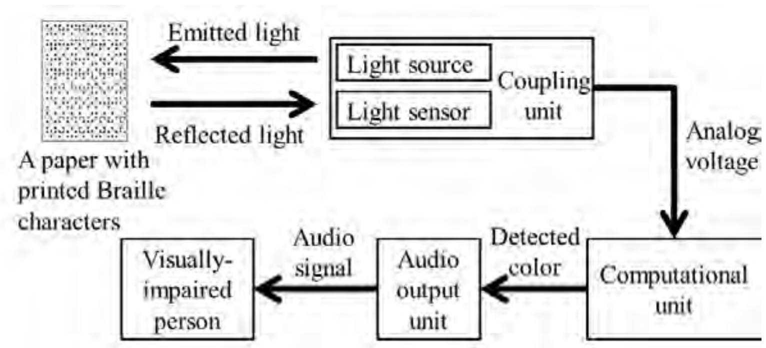


Figure 4.3: Overview of how our proposed solution is designed to work

consists of four units: (1) A paper with printed Braille characters, (2) A Coupling unit, (3) A Computational unit, and (4) An Audio output unit.

The Braille characters are printed on a paper using a conventional ink-jet or laser printer. The rest three parts of the system together helps in the detection of dots of printed Braille characters. We however, defer the explanation of reading process.

The Coupling unit contains a pair of light source (i.e., LED) and light sensor (i.e., PT), oriented in the same direction. The LED emits light on the paper. The sensor generates analog voltage according to the level of illuminance of light incident upon it after being reflected from the paper. As the illuminance of reflected light varies depending on the colors of the reflector regions of the paper, the analog voltage generated by the sensor also get varied.

The Computational unit (a micro-controller) processes these analog voltage for detecting presences of black colored dot(s) on the paper over which the Coupling unit operates. Figure 4.4 represents a simplified flow chart of our algorithm for detecting black colored dots. We set a threshold value for distinguishing black colored region from white colored region. The Audio output unit generates audio output when this value is less than this threshold. Our earlier observation from Figure 4.1b is that there is a substantial difference between the sensor

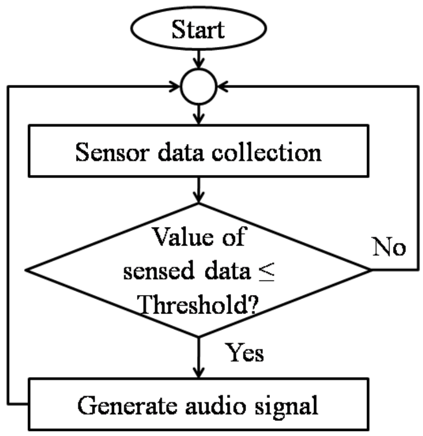


Figure 4.4: Flow chart of Braille dot detection algorithm

voltages generated for black colored region and white region of a paper at a certain environmental lighting condition. Consequently, we consider a threshold value that demarcates the black colored region from the white color. Note that, this threshold value maintains a sufficient margin from the values pertinent to the two different colored regions. To summarize, the Audio output unit generates a beep only when there is a black colored region.

Chapter 5

Evolution of EyePen

We undertake participatory design process and iterative evolution in the way of devising *EyePen*. In this chapter, we delineate the evolution of *EyePen* through a comprehensive user participation.

5.1 Preliminary Design

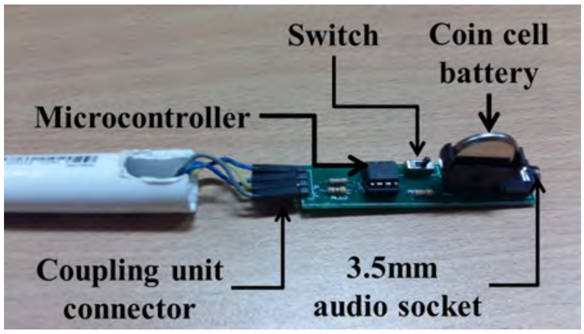
The initial design presented in our prior work was mostly intuition driven. In this section, we summarize here our first design followed by the user feedback.

5.1.1 The Pen

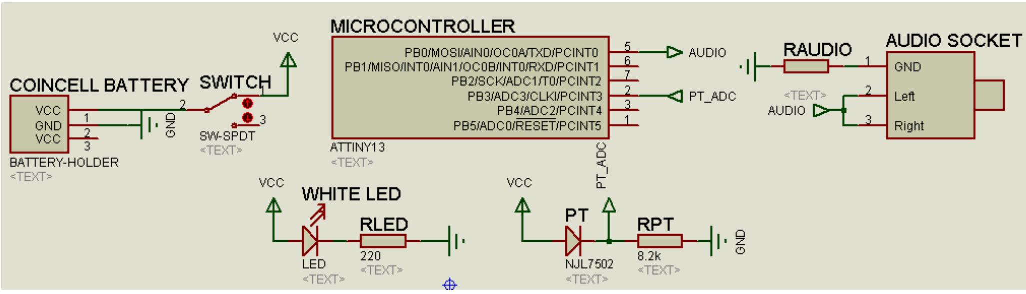
Levesque [2] discussed about assistive devices for blinds from a strategic point of view. His findings summarizes that, although there is a clear demand for assistive devices among visually-impaired people, they are not desperate for them and do not embrace any technology however useful they are. They are less likely to accept or wear a device that draws unnecessary attention of the people and marginalize them as a separate entity. Consequently, a certain design principle that helps them achieve their goal, yet upholds their integration in the society is needed here.

To this point, we contemplate at objects that are pervasive and ubiquitous to a wider range of audiences. The acceptance of an assistive device depends on, among other factors, portability, ease-of-use, comfort, and availability. Elements that combine to work and confirm the theoretical principle based on which *EyePen* is working are simple and straight-forward. Consequently, we were able to design a COTS pen-shaped body. Figure 5.1a shows outlook of this pen. The internal circuitry is shown in Figure 5.1b and 5.1c. Whereas haptic modality is generally used to provide feedback to a visually-impaired, our design process evolved with audio

(a) Pen-shaped body



(b) Circuit inside the pen



(c) Schematic

Figure 5.1: Outlook and internal circuit of the pen-shaped body

signal feedback. This is because, as discussed in [2], audio signals are well interpreted by visually-impaired people. However, audio feedback is one possibility among different other output modalities; providing audio feedback is useless for deaf-blind, nevertheless, other output modalities are beyond the scope of this paper. Earphones are not expensive; and are available in many different qualities for less than \$1.5. The entire system runs on a coin-cell battery, which is affordable as well.

There is yet another motivation that derived the iterative design process of this pen. Since our central motivation is to design and develop a low-cost low-resource device that could read and write Braille; the pen-shaped body confirms the goodness in design that proved to be natural and intuitive while writing.

5.1.2 Usability Analysis

We conducted a field level usability analysis to interpret the expectations of focus group members and the reaction after using the preliminary prototype of *EyePen*. We went to the school and invited the children to use *EyePen*. Note that, since this analysis was focused on usability only, we conducted informal training sessions to help them get used to it.

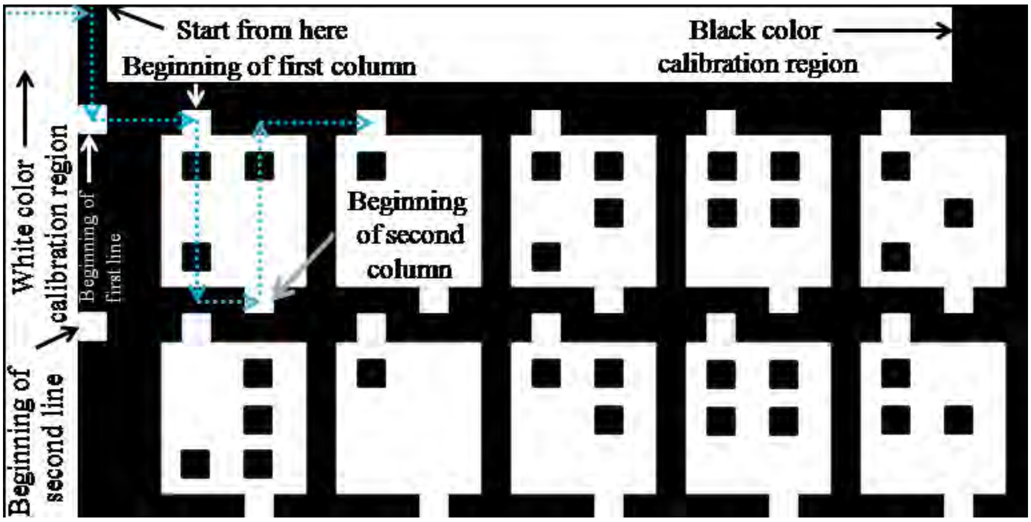


Figure 5.2: The upper part of a printed Braille paper

Reading Braille Using EyePen

Figure 5.2 shows the upper part of a paper containing printed Braille characters. The following factors influenced the design of this page- (1) recall from Section 4.3 that the sensor values are influenced by external illuminance. Consequently, a calibration phrase is needed, (2) it is difficult to drag the pen on a paper by a visually-impaired person. Consequently, a spatial frame of reference is needed to perceive the information from this paper.

To start off with calibration, the visually-impaired person places the tip of the pen at the top-right corner of the paper for black color calibration, as shown in the Figure 5.2. For a pre-defined amount of time, the system monitors the sensor value and keeps an average value for black colored region. After that, the system generates an audible beep. Then the visually-impaired person places the tip of pen at the top-left corner of the paper for white color calibration. At the end, the system decides a threshold value.

Now that the person and the pen are ready to read Braille, and following the need for a spatial frame of reference, the conventions followed in reading procedure are: (1) A line starts with a white region, (2) The first column of each Braille character begins with a white region and implies a vertically downward movement, and (3) The second column of each Braille character begins with a white region and implies a vertically upward movement.

Figure 5.2 illustrates the reading procedure and the path of movement of the pen for scanning the dots of the first character. The path starts from the top-left corner of the paper. Since it is strenuous for a visually-impaired person to lift the pen and re-position at the beginning of subsequent characters on the same line, we define the movement by a continuous train of ‘U’ shaped path. As a result, the visually-impaired person no longer needs to lift the pen. The path itself leads them to subsequent Braille characters. An important step while scanning these characters is to successfully interpret the relative position of where a beep is generated. Therefore, after completion of scanning the first character, the visually-impaired person recognizes presence of the dots at ‘1’, ‘3’, and ‘4’, and thus (s)he finds the character to be ‘M’. Following the same procedure, the visually-impaired person can continue reading subsequent Braille characters.

We developed a software module for formatting and precisely printing this page. The software takes a file containing conventional alphanumeric characters as input and converts them to Braille characters with a specific formatting, as shown in Figure 5.2. We printed this page using our laboratory ink-jet printer.

Experiences and Feedbacks

We gathered mixed feelings following the first deployment of *EyePen*. According to their feedbacks, we outline some crucial aspects of the system.

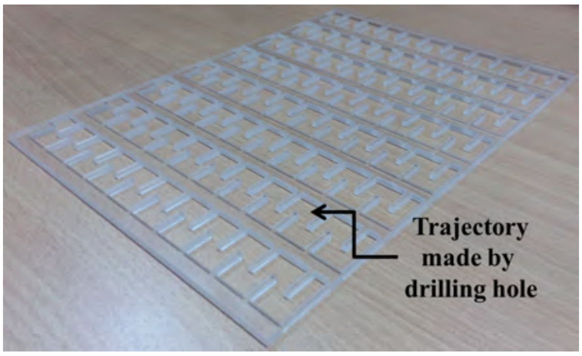
- We found that it was strenuous and near-to-impossible for a visually-impaired person to drag the tip of pen-shaped body horizontally or vertically along a straight line in a perfect manner. Whenever (s)he missed the defined track once, it was difficult to get back on the right track again.
- The number of Braille characters per line was not satisfactory (five lines, each having five characters only).
- Another shortcoming of the system was the calibration process. It appeared as a surplus burden in reading procedure.
- Nonetheless, the threshold was dependent on the environmental lighting condition which could change for various reasons such as power-failure, switching the room light on/off, etc., while reading.

5.2 Modified Design

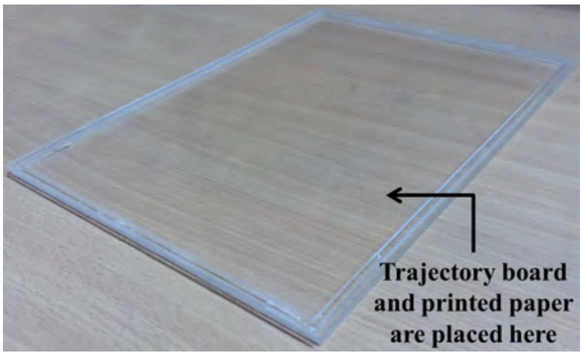
The first deployment helped us understand to focus on a better design principle. We received important feedbacks regarding spatial frame of reference as an aid to read and keep alignment.

5.2.1 Trajectory Guide Board

During a focus group discussion session, one visually-impaired children expressed his opinion about using a frame board for spatial awareness and control, similar to the one in Figure 3.2a. This was an important lead for us while going back to our laboratory and modify the system so that it becomes usable.

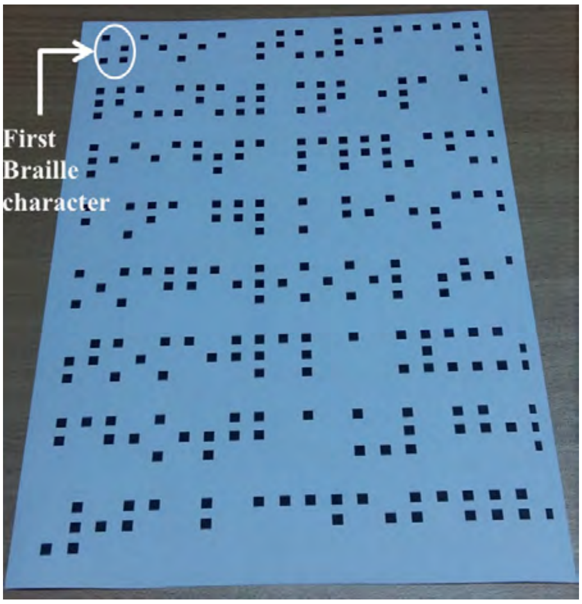


(a) Trajectory guide board



(b) Cage

Figure 5.3: Trajectory guide board and cage



(a) Paper containing printed Braille characters

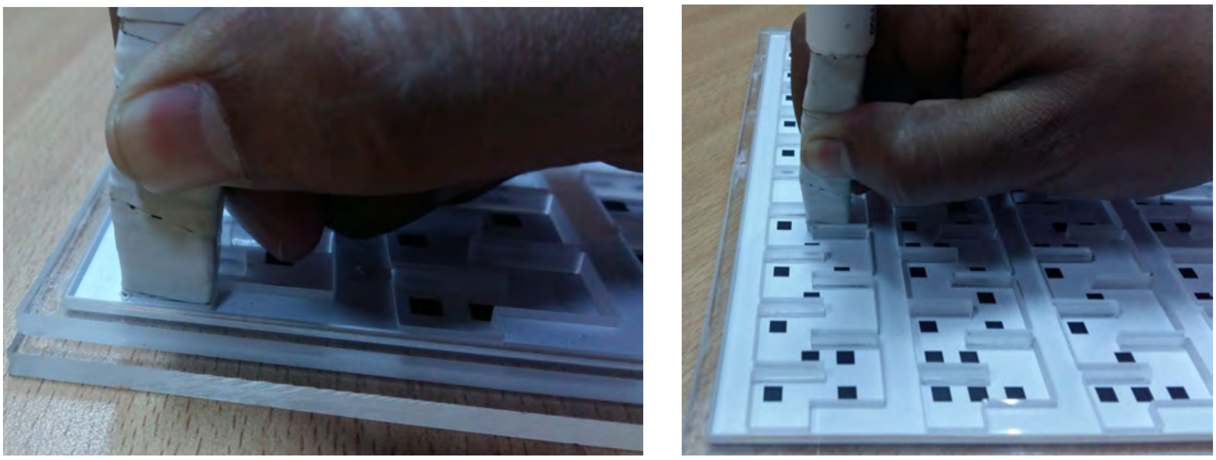
(b) A printed paper attached beneath a trajectory board

Figure 5.4: Modified printed page and trajectory guide board

We came up with the idea of using a trajectory guide board that can help visually-impaired people with spatial awareness while reading. The tactile nature of the board allowed them to feel intuitively the path to follow while reading. Figure 5.3a shows a snapshot of the trajectory guide board. A trajectory on board is made by drilling hole through top to bottom faces along the thickness of the board. The board is set over an A4 size paper that contains printed Braille characters. Figure 5.3b shows a cage for fitting the paper and the trajectory guide board in it. Figure 5.4a shows the snapshot of a paper (of A4 size) containing Braille characters printed using conventional ink-jet printer. Figure 5.4b shows a snapshot of a trajectory guide board attached over the paper. The trajectory defines the path of movement of the tip over the attached paper. The path of movement is defined in such a way that the six dots of a printed Braille character remain at certain relative positions over the path.

(a) The modified pen (b) Tip

Figure 5.5: Modified pen with its tip

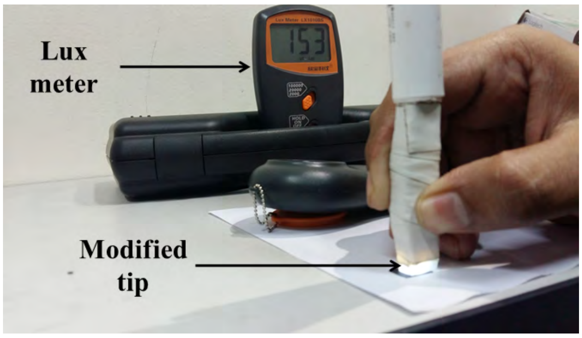


(a) Starting point (b) Midway while reading

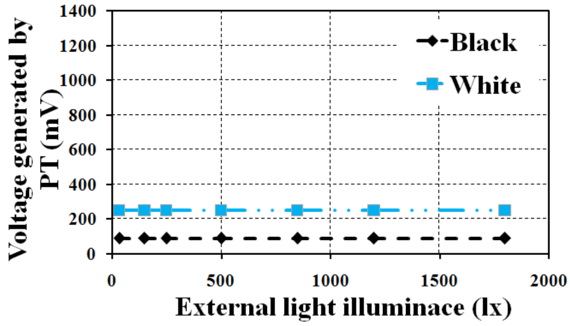
Figure 5.6: Tip fits the drilled hole of trajectory guide board

Figure 5.5a shows a snapshot of the pen with modified tip. Here, the only change is the structure of its tip. Figure 5.5b shows the newly designed pen tip which is rectangular (12mm×7mm) in shape. An acrylic opaque wall is built around the Coupling unit. Nonetheless, LED and phototransistor are placed at a slight height (3mm as shown in Figure 5.5a) from the lower border of the tip so that they do not touch the paper while tip is dragged over the paper. The hole on trajectory board and the tip are shaped in such a way that the hole fits the tip (as shown in Figure 5.6). Moreover, the tip can glide through the trajectory hole as well as over the paper.

Solving the calibration problem: The modified design of the tip inherently solves the calibration problem stated in the previous chapter. The opaque wall acts as a shielding to the Coupling unit from external lighting condition. To confirm this action, we perform testbed experiment again for the modified design of tip similar to the experiment in Figure 4.1. Figure 5.7a shows the experimental setup and Figure 5.7b presents the results.



(a) Experimental setup



(b) Experimental results

Figure 5.7: Experimental evaluation with modified tip

Here, the voltage generated by the phototransistor is independent of environmental lighting condition.

5.2.2 Reading Procedure

Figure 5.8: Modified reading procedure

Figure 5.8 illustrates the reading procedure after the aforementioned modifications. While reading, first, a visually-impaired person places tip of the pen at the top-left corner of the board. Then, the tip is glided towards the right, i.e., point **a**, following the trajectory. Here, the point **a** is the topmost point of the first vertical part of the trajectory. When the tip reaches point **a**, the system detects a black colored region and generates an audible beep. The visually-impaired person hears the beep and recognizes the presence of dot ‘1’ in the first Braille character. Then, the tip is glided down following the trajectory and reaches at the middle point of the first vertical part of the trajectory, i.e., point **b**. Since there is no dot at **b**, the system does not generate a beep.

Thus, the visually-impaired person recognizes the absence of dot ‘2’ in the first Braille character. Then, the tip is continued to glide down following the trajectory and reaches at the bottom point of the first vertical part of the trajectory, i.e., the point **c**. Here, point **c** contains a dot and the system generates a beep accordingly. Next, the tip is glided towards right following the trajectory and reaches at point **d**, which is the bottom point of the second vertical part of the trajectory. Since point **d** contains a dot, the system generates a beep here. Thus, the visually-impaired person recognizes the presence of dot ‘6’ in the first Braille character. Then, the tip is glided up following the trajectory and reaches at point **e** followed by point **f**, which are dots ‘5’ and ‘4’ respectively. In a similar manner, the visually-impaired person recognizes the presence of dot ‘5’ and the absence of dot ‘4’ in the first Braille character. As a whole, (s)he understands that the first Braille character contains dot ‘1’, ‘3’, ‘5’, and ‘6’, and thus, (s)he identifies the character as ‘Z’. Note that, for identifying the first Braille character through scanning all six relative positions, the points **a**, **b**, **c**, **d**, **e**, and **f** are followed in sequence using the pen. It is like a train of ‘U’ shaped path that defines movement of the pen. In a similar way, (s)he continues to read subsequent characters. To do so, the tip is glided towards right from point **f** to read out subsequent Braille characters on the first line. In order to read the next line, the tip has to be placed at the top notch of the next line, i.e., point **g**.

To this point, a question may strike the reader’s mind about how to hold the pen. Will slanting affect reading? The modified design of the tip and the trajectory guide board is designed in such a way that, there is only one definitive way of holding this pen; perpendicular to the surface of the board. It is not possible to fit the tip at a slanting position inside the trajectory guide board.

Chapter 6

User Evaluation

We conducted a second deployment after modifying the pen. Our main focus was to find out : (1) how quickly participants got used to *EyePen*, (2) the accuracy and time taken to recognize a set of dots, and (3) the accuracy and time taken to identify a set of Braille characters. In order to obtain a comprehensive result set from the experiment, we delved and contemplated at how the interaction with the system work - *EyePen* provides an audio beep feedback on every black dot and human acknowledges (recognizesing) that feedb. As a result, it was important for us to distinguish between a system generated error and human error. We therefore define them accordingly. **System error** is defined as the failure of the system when the system does any of the following : (1) outputs an audio beep while on a white dot (i.e., absence of dot), or (2) outputs no audible beep while on a black dot. **Human error** is defined as the apparent failure of the human participant in recognizing an audible beep and thereby acting upon it, or, mistakenly consider hearing an audible beep when the system produced no such audible beep, or, identify wrong character from the correctly recognized dot(s). Consequently, we undertook a simple validation and cross checking step while the participants were using *EyePen*. We therefore let the participants put one earphone into their best ear, and we used the other earphone for ourselves for real-time cross validation, as shown in Figure 6.1.

We organized our experimental study into one training session and five testing sessions. The testing sessions were mainly data collection intensive sessions, since we asked them to use *EyePen* and try reading the sample document. Each participant took part in all the sessions, averaging 30 minutes per session in 3 days time. The testing sessions consisted of a brief follow-up on *EyePen*, evaluation of dot recognition, and finally, character identification. In the rest of this chapter, we explain each step and outline results pertinent to that step.

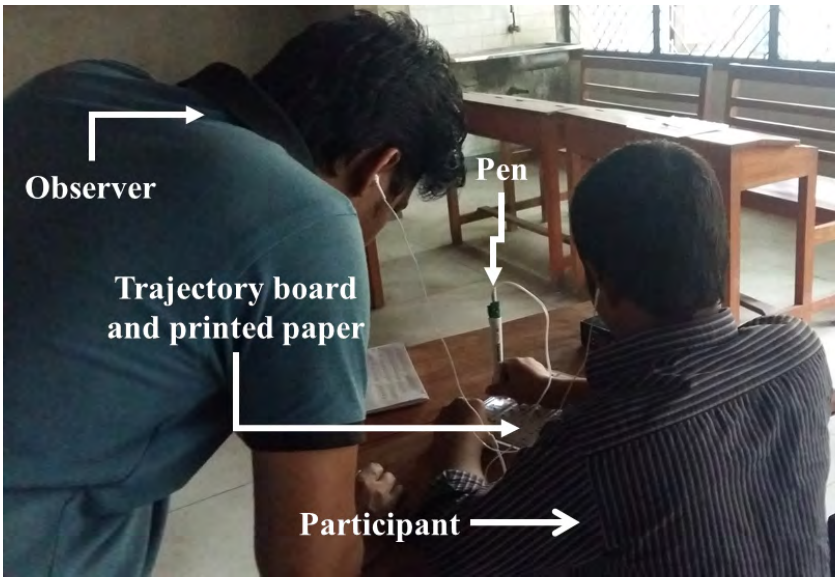


Figure 6.1: User evaluation setup

6.1 Training Session

The objective of this training session was to (1) familiarize participants with the concept of *EyePen* and its utilities, and (2) observe whether adoption of *EyePen* was easier and painless.

Our initial endeavor in the training session was to habituate and adapt the users with the system. We let the users intuitively feel the path defined by the trajectory board by touching it with fingers and move the pen through the path. We found the participants vibrant and excited after touching and feeling the trajectory board.

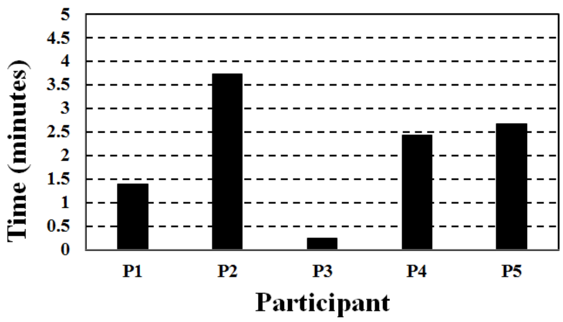


Figure 6.2: Trajectory board training time

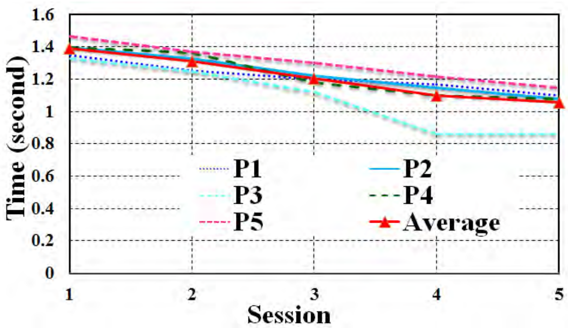


Figure 6.3: Dot recognition time for one dot

Figure 6.2 shows the time during which the participants were trained up with *EyePen* and were able to hold the pen and glide through the trajectory board successfully. Here, we observe that the least time period taken by a participant is only 15 seconds and the highest time period is 3 minutes 43 seconds, which is less than 4 minutes. Since the highest training period among sample participants is less than 4 minutes, we can infer that *EyePen* offers a flexible and easy-to-adopt mechanism of Braille reading system. In addition to that, we confirm an interesting relation here between visually-impaired people who are faster in grabbing tactile cues than others. Note that P1 and P3 demonstrated the least training time among all the participants.

6.2 Dot Recognition

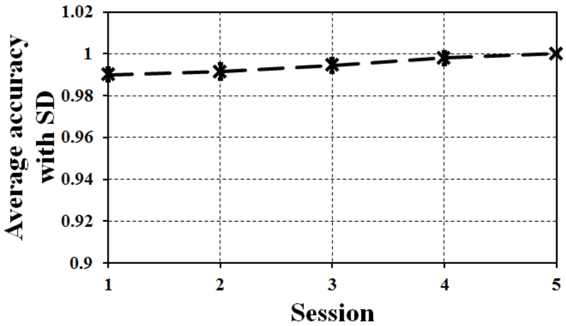
Dot recognition is important because this is a necessary step while identifying a character. Therefore, it is imperative that a reader is able to recognize a black dot as a black dot, and a white dot (i.e., white surface) as absence of dot. Here, we focus mainly on the accuracy of dot recognition and the time taken to recognize a set of dots. While the idea of plotting time may appear mundane at first, our observation is of the fact that, after each session, the required time and accuracy of recognizing the set of dots has improved over the previous session(s).

In this case, we asked the participants to recognize and enumerate the relative position of the dots as they read them. We conducted five sessions in total, with each session averaging five iterations. While performing this analysis, in each iteration, the provided sample document consisted of 60 dots in total (black and white dots inclusive). Note that, we provided a different set of dots in each iteration.

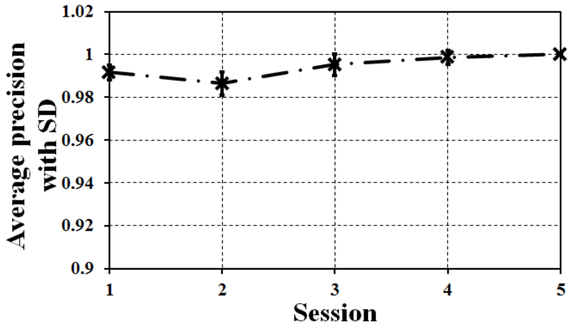
Figure 6.3 shows the per dot recognition time by each participant in different sessions. The general trend of this plot is gradual decrease in the time axis over subsequent sessions, which is confirmed by the trend of the average time for all participants. However, note that, the rate of this gradual decrease is different for individual participants.

While the dot recognizing time showed significant improvement over the time, it came at no loss of accuracy. Besides, the accuracy of using *EyePen* showed highly promising outcome. We asked the participants to demarcate the black dots from the white surface and enumerate the relative position of the black dots by using *EyePen*. In doing so, we made arrangements for real-time cross validation by using one of the earphones by ourselves. Consequently, we report the human error and system error in this case.

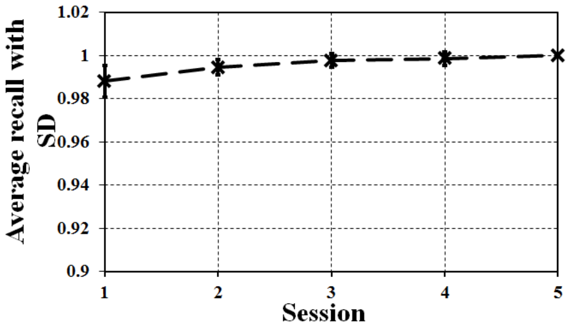
Here, accuracy refers to the percentage of correctly classified black and white dots over all the sampled dots. Figure 6.4a shows the average accuracy of dot recognition and dot enumeration for all sessions using *EyePen*. Note that, some participants were able to achieve maximum accuracy even from Session 3. We observed that all participants were able to achieve the maximum accuracy (average=1, SD=0) by Session 5. Figure 6.4b shows the average precision of all participants over all the sessions. Precision refers to the percentage of how often the classified black dots are actually black dots. Here, we discovered an interesting outcome. Whenever



(a) Average accuracy



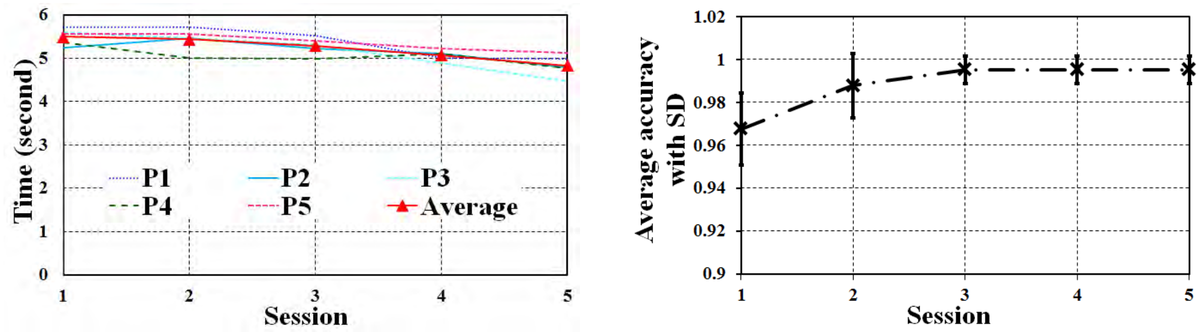
(b) Average precision



(c) Average recall

Figure 6.4: Average accuracy, precision, and recall of dot recognition by each participant in different sessions

the participants tried to glide the pen very quickly, their apparent perception was that, there were a stream of black dots. We found that the errors were mostly conceived during the following two patterns, (1) black dots were actually present at positions '1' and '3', however, the participant perceived to hear a dot at '2' as well on account of dragging the pen quickly, and (2) black dots were actually present at positions '4' and '6', however, the participant perceived to hear a dot at '5' as well on account of dragging the pen quickly while moving upward ('6', '5', and '4'). These two cases led the participants to consider a white dot as a black dot. Nevertheless, all the participants primed the highest precision as soon as they realized the reason of error (average=1, SD=0 at Session 5). Additionally, recall refers to the percentage of the recognized black dots by the participant over actual black dots. Figure 6.4c shows the average recall value over all the sessions. It shows that the participants were able to identify the presence of black dots in almost all the session, which explains the behavior of this graph as close to 1 in most cases. Our observation of the error conceived by other participants was that, they wrongly enumerated the relative position of the black dot with a white dot. Nonetheless, they showed improvements over the previous session(s) and all of them managed to achieve the maximum recall value by the end of all the sessions (average=1, SD=0).



(a) Identification time (b) Average accuracy

Figure 6.5: Per character identification time and accuracy of each participant in different sessions

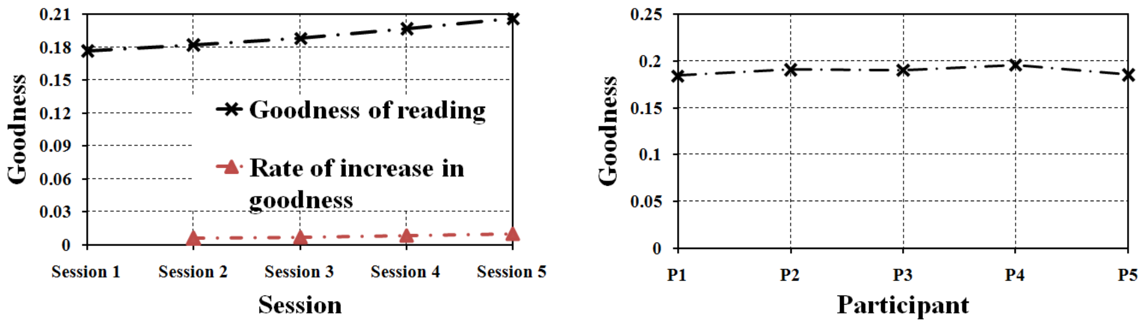
The system error in this case was 0%. We present the errors reported above as human errors, since participants were able to classify correctly whenever we asked them to repeat respective erroneous patterns. Moreover, our arrangement of real-time cross validation allowed us to closely observe the nature of the errors and the underlying reasons behind them.

6.3 Alphanumeric Character Identification

The ultimate goal of *EyePen* is to enable reading alphanumeric characters. We analyze two sets of results in this experiment. First, we analyze the average per character identification time by all participants. Second, we analyze the accuracy of character identification by each participant. The time to identify a character and the accuracy at which this has been done is important to determine the effectiveness and usability of *EyePen* as an assistive device.

We conducted five sessions in total, each session consisting of five iterations. In each iteration, we asked the participants to read aloud the characters that they identify while reading the provided sample document. Each document had 80 alphanumeric characters. Note that, the provided documents had scrambled characters that did not represent any dictionary word. Moreover, each provided document represented a different set of characters.

Figure 6.5a shows the per character identification time by each participant in different sessions using *EyePen*. Here, the general trend for each participant over all the sessions was a downhill improvement in time. Figure 6.5b shows the average accuracy by all the participants in different sessions with standard deviation (SD). Note that, some participants were able to achieve the maximum accuracy even at Session 2. Moving towards the final session, we observed that 3 of them achieved the maximum accuracy and others were close to achieving maximum accuracy (average=0.9952, SD=0.006573).



(a) In different sessions

(b) For all the participants

Figure 6.6: Goodness of reading

6.4 Goodness of Reading

Since our objective is to maximize accuracy within the shortest possible reading time, we define goodness of reading as a measure of relative usefulness of *EyePen*. Here, goodness of reading is defined as the ratio of accuracy to the reading time for the same set of sample document. In Figure 6.6a, we observe that the trend of goodness of reading using *EyePen* is an uphill rise in every session. The rate of increase in goodness of reading is higher and better in each session. Moreover, the goodness of reading is uniform for all participants. Figure 6.6b shows that the goodness of reading through using *EyePen* is independent and unbiased of any participant.

Chapter 7

Usability Survey and Discussion

In addition to performing user evaluation, we also perform a usability survey over the participants to grasp an idea of the acceptability of *EyePen*. We discuss the lessons that we have learned during our study and participatory design phases, and hopefully, these lessons will help the other researchers in designing a solution focusing the similar context. Additionally, we discuss the cost-effectiveness and power consumption pertinent to our proposed system.

7.1 Adults' Perception of EyePen

We conducted both formal and informal discussions with two students aged between 19 and 21 pursuing their undergraduate degree at University of Dhaka. One of them was completely blind while the other was suffering from low vision. At the time of conducting our field level studies, we found both of them heavily dependent on audio based lectures. They did not own any smartphone or any gadgets that have OCR technology. Instead they had feature phones which could record voice and playback. They ask fellow sighted peers to record a lecture for them.

Although we received generous efforts and feedbacks from this focus group during design phase and goal settings, we found them less likely to embrace a new technology because of already being habituated with audio clips and lectures. This led us to concentrate more on designing for children and use them for evaluation. Nevertheless, the following are the findings here -

1. Visually-impaired students are not encouraged to study science in college and universities.

2. There is one Braille printer in the University of Dhaka, which is *out of service* for some years.

3. Braille is less appreciated beyond the scope of high schools in Bangladesh, because of cost involvements contrary to poor number of turnouts in higher education.

This statistics is important, particularly because similar condition is prevailing in other low-income countries.

7.2 Integrated Braille-based Solution

Diversified technical solutions for easing different parts of the primary education, e.g., reading, writing, arithmetic learning, etc., engender both adaptability and acceptability issues among the visually-impaired children. In addition, according to our participants, a solution exploiting their existing learning framework, which is Braille-based, is always accommodating. Here, Braille offers a common ground for designing an integrated solution. Besides, different studies reveal that Braille proficiency is always inevitably important for the visually-impaired people considering their employment, academic achievement, faster writing input, etc. [6, 35, 45]. Moreover, a recent study [7] also points that Braille exhibits utmost significance pertinent to mathematical education for the visually-impaired people.

7.3 To What Extant Should Technology Aid?

At the first sight, we might think about availing top-notch features in a technology aiming at facilitating the Braille reading of visually-impaired children. However, during the sessions with the teachers and grown-ups, we found that, the privileges, offered by a technology, beyond a certain level can blunt the Braille proficiency and cognitive development of the children. Quoting a teacher, *"You can think about a solution like talking reader, but, for primary level learning, it'll reduce the visualization power of the students, increase the dependency on technology, and consequently, reduce the Braille proficiency."*

7.4 Cost-effectiveness

Our central motivation is to develop a low-cost device for low-resource constrained people. It is without doubt that *EyePen* presents a cost-effective ($<$ \$4) solution for reading Braille. The cost of our complete device is below \$4 including the retail price of LED, PT, microcontroller, PCB, trajectory board. etc. In commercial production, materials are purchased in bulk amount, which reduces the cost per item of materials by at least 2 to 3 times than the retail price [46]. A typical breakdown shows that the material cost is 72% of the total product cost, which considers labor cost within the rest 28% [47]. Hence, the product cost including all other costs will still be less than $4 in commercial production. We describe more about writing in Braille in Chapter 8. Note that the technologies used to build the pen are affordable and replaceable. The coin cell battery allows one to replenish the power supply. On the other hand, printing Braille characters using normal printers is advantageous in two folds - (1) organizations such as schools in low-income countries can now afford to print custom Braille texts using normal printers, which are cheap and available, (2) individual students can also afford printers on their own, or get printed from street stationaries, to access both academic and non-academic informations. It is not implied in literal sense that visually-impaired students will print on their own. We assume that parents, teachers, helpers, care-givers, or anyone will do the printing task for them. One of the teachers said, *"If we can print using normal printers, then its a life saver for us indeed. This is cheap, easy, and saves a lot of time. It brings us too much hassle to print questions from Braille printing press during examinations."*.

7.5 Ease of Use

Although the temporal disadvantages of *EyePen* was a concerning issue, focus groups were particularly happy about a potential writing aspect of *EyePen*. P3 opined that *EyePen* could be more useful during writing. He said, *"I cannot write more than 5 lines at a time in Braille currently. It hurts my palm and fingers"*. He still appreciated *EyePen* saying, *"... we generally do not read non-academic books, in fact, we cannot read them since they are not available in Braille. Your system may allow us to print page by page and read them"*.

On a similar note, the participants reported that the pen itself and trajectory board were intuitive and easy-to-use, however, participants had mixed feelings about the system. P5 said that the audio beep was *"irritating"* and less desirable.

7.6 Power Consumption

EyePen have three main power consuming components - LED, microcontroller, and earphone. Note that phototransistor [43] is an active component, and thus it does not consume any power from the battery. Since the opaque wall around the coupling unit surpasses the effect of ambient light, we incorporate a low power consuming LED which consumes ~ 2.3mW power. As we invoke a simplistic dot detection algorithm, we incorporate a lightweight microcontroller, ATtiny13A [48]. Our simplistic algorithm enables us to run the microcontroller in ultra low power consuming mode, and it consumes ~ 0.72mW in active mode. Next, the

Statement	**P1**	**P2**	**P3**	**P4**	**P5**
The overall experience was enjoyable	4	4	4	5	3
Learning *EyePen* was easy	5	5	5	5	5
Using the pen was easy	5	4	5	5	4
Using the trajectory board was easy	5	5	4	3	4
I will use *EyePen* in future	3	4	4	4	3

Table 7.1: Results from the questionnaire on 5-point Likert scale

power consumption of an earphone completely depends on its model. However, a viable earphone with a sensitivity of 105dB SPL/mW consumes $\sim$ 0.1mW power. Now, *EyePen* has two operation modes - audio generating mode and silent mode. In audio generating mode, the overall power consumption is $\sim$ 3.12mW, and in silent mode, it is $\sim$ 3.02mW. From the aforementioned power profiling, we can extrapolate that, with a viable coincell battery [49], *EyePen* can run for more that $\sim$ 210hours.

7.7 Usability

A primary concern in this case is the usability of the system. Using *EyePen*, one can read as much as 12 characters per minute based on the current prototype. Although this statistic appears to be a disadvantage, we argue about the relative advantages over other factors, such as cost saving, ease-of-use, availability, etc. When we asked the students to comment about *EyePen*, P2 and P5 said that *EyePen* lacked the speed that they enjoyed with palpable Braille reading system. Instead, they used their imagination and said that, *"It would have been better if this pen could tell me the character, or at least enumerate the dot positions"*. However, they were also quick to point out by themselves that *EyePen* was offering them a solution that could let them use conventional ink-jet printers and read Braille from a printed paper.

One of the teachers said, *"Its not of any particular importance to me how fast EyePen can do now. To me, its more about knowing that there is something which is cheap and affordable and which can be improved over the time."*. It is important to note that, acceptance of any new technology is not always easy, even so when it comes to people with disabilities. The acceptance of Braille itself was controversial. The Institute for Innovative Blind Navigation discussed humorously that Braille would have been turned down if he had proposed Braille today [50].

7.8 Summary

To evaluate the usability of the system, we exploit classical System Usability Scale (SUS) and Single Ease Question (SEQ) scale. After our tuition session, we gathered individual feedback from all participants according to these scales. The average SUS score calculated for all participants is 83. In the SEQ scale of 7-point rating ('1' referred to 'very difficult' and '7' referred to 'very easy'), the average score is 5.2. Further, we summarize the system-specific user feedback here. Table 7.1 shows the outline and the corresponding results of the questionnaire. We let the participants answer or express their opinion based on the 5-point Likert scale. Here, '1' referred to 'strongly disagree', '2' referred to 'disagree', '3' referred to 'undecided', '4' referred to 'agree', and '5' referred to 'strongly agree'.

Chapter 8

Future Work

We summarize here the potential future work in this chapter.

8.1 Potential for Aiding in Writing

In addition to facilitating reading by visually-impaired people, our system possesses a good potential for aiding in writing by visually-impaired people. It is worth reminding that existing embossed Braille character writing technique is cumbersome. Our proposed *EyePen* incorporates a design that can allow visually-impaired person write seamlessly using the same set of devices following the usual direction. Here, the modified system with trajectory guide board can work coherently with the writing system. The main challenge in establishing coherence is to fuse reading and writing tools together in the same body. Such a design and development is underway in our laboratory. Our preliminary experiment with the writing tool comprised of making dots over a paper through the trajectory guide board using a separate marker pen. We read back the same with *EyePen*. In each of the cases, we blind-folded ourselves in the laboratory environment and tested the procedure. The preliminary results suggest that the writing tool and the procedure can facilitate visually-impaired people in writing.

8.2 Escalating Reading Process

The current implementation of *EyePen* presented in this paper follows a sequential dot recognition process rather than simultaneous recognition. The sequential dot recognition process is slow and prone to human error. Instead, a modified Coupling unit can be designed that can read all six dots simultaneously. Moreover, the system can produce a speech-based output that can sequentially enumerate the available black dot positions to the user. Alternatively, the speech-based output can directly process the character. Nevertheless, both ways will increase the reading efficiency and will reduce human errors over the time.

8.3 Encourage Science Through EyePen

The state-of-the-art Braille reading and writing processes are cumbersome for practicing mathematics and geometry. *EyePen*, along with the trajectory guide board, can significantly improve the experience in practicing mathematics for visually-impaired people. It is also possible to identify basic geometric shapes such as triangle, rectangle, circle, etc., by following locus of their shapes using the tip of *EyePen*. However, a thorough user evaluation is needed for augmenting mathematical learning experiences in the same framework having regular text based learning.

Chapter 9

Conclusion

Visually-impaired people are minority group of people whose number is increasing and projected to double within the next decade. It is imperative that a simplified and unified reading and writing system is designed for ease of access to information for them. Moreover, state-of-the-art assistive technologies are yet to reap any benefits for low-resource constrained people. To address these issues, in this paper, we propose a low-cost system (named as *EyePen*) for reading printed Braille characters. Here, instead of depending on costly Braille embossers, *EyePen* offers an easy-to-afford solution that uses conventional ink-jet or laser printers available in our homes, offices, street stationaries, etc., for printing Braille characters.

We conducted user evaluation showing effectiveness of *EyePen*. We evaluated the performance of *EyePen* from both system and human perspectives. Evaluation results confirm that *EyePen* achieve 0% system error during dot recognition of printed Braille characters. Besides, human error rate also converges to 0% during both dot recognition and character identification. Additionally, *EyePen* demands a very small amount of time for learning. Besides, the reading time decreases with added experiences, which we confirm through user testing and analysis. With no major setup and external computing devices needed, *EyePen* is indeed a cost-effective system for reading, having the potential of offering easy writing experience for the less-privileged community abiding in low-income and low-resource settings.

Bibliography

[1] M. Center, “Visual impairment and blindness,” August 2014. Retrieved February 15, 2016 from http://goo.gl/BG8XTG.

[2] V. Lévesque, “Blindness, technology and haptics,” *Center for Intelligent Machines*, pp. 19–21, 2005.

[3] R. M. Leonard, *Statistics on vision impairment: A resource manual*. Lighthouse International, 5th ed., 2001.

[4] A. F. f. t. Blind, “School experience for children and youth with vision loss,” January 2015. Retrieved February 21, 2016 from http://goo.gl/1Np4m2.

[5] R. Ryles, “The impact of braille reading skills on employment, income, education, and reading habits,” *Journal of Visual Impairment and Blindness*, vol. 90, pp. 219–226, 1996.

[6] R. Ryles, “New research study: Early braille education vital in establishing lifelong literacy,” *Future Reflections*, vol. 18, no. 2, 1999.

[7] A. Brawand and N. Johnson, “Effective methods for delivering mathematics instruction to students with visual impairments.,” *Journal of Blindness Innovation & Research*, vol. 6, no. 1, 2016.

[8] L. Newman, M. Wagner, R. Cameto, A. Knokey, J. A. Buckley, and D. Malouf, “The post-high school outcomes of youth with disabilities up to 4 years after high school,” 2009. Retrieved September 18, 2016 from https://goo.gl/eLOaxg.

[9] B. M. Eyes, “Be my eyes | lend your eyes to the blind,” 2016. Retrieved September 15, 2016 from http://goo.gl/wiBP0B.

[10] OrCam, “Orcam - see for yourself,” 2016. Retrieved February 20, 2016 from www.orcam.com.

[11] R. Shilkrot, J. Huber, W. Meng Ee, P. Maes, and S. Nanayakkara, "Fingerreader: A wearable device to explore printed text on the go," in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pp. 2363–2372, ACM, 2015.

[12] A. F. f. t. Blind, "Refreshable braille displays." Retrieved June 20, 2016 from `https://goo.gl/x71RY3`.

[13] I. Medhi, M. Jain, A. Tewari, M. Bhavsar, M. Matheke-Fischer, and E. Cutrell, "Combating rural child malnutrition through inexpensive mobile phones," in *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design*, pp. 635–644, ACM, 2012.

[14] B. Plimmer, A. Crossan, S. A. Brewster, and R. Blagojevic, "Multimodal collaborative handwriting training for visually-impaired people," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 393–402, ACM, 2008.

[15] H. Shen and J. M. Coughlan, "Towards a real-time system for finding and reading signs for visually impaired users," in *ICCHP (2)*, vol. 7383, pp. 41–47, Springer, 2012.

[16] A. Squared, "Zoomtext," 2016. Retrieved on March 22, 2016 from `http://goo.gl/LFLQSj`.

[17] DocScanner, "Saytext," June 2010. Retrieved March 23, 2016 from `http://goo.gl/aLvPBS`.

[18] Blindsight, "Text detective," 2014. Retrieved March 23, 2016 from `http://goo.gl/uJao4O`.

[19] K. R. LLC, "Introducing the knfb reader," 2016. Retrieved February 20, 2016 from `http://www.knfbreader.com/`.

[20] C. Jayant, C. Acuario, W. Johnson, J. Hollier, and R. Ladner, "V-braille: Haptic braille perception using a touch-screen and vibration on mobile phones," in *Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility*, pp. 295–296, ACM, 2010.

[21] C. Fernandez, "The 'life-changing' glasses helping blind people to 'see': Orcam headset recognises faces, objects and reads words aloud," 2016. Retrieved September 17, 2016 from The Daily Mail `https://goo.gl/ZDZW7e`.

[22] L. Stearns, R. Du, U. Oh, C. Jou, L. Findlater, D. A. Ross, and J. E. Froehlich, "Evaluating haptic and auditory directional guidance to assist blind people in reading printed text using finger-mounted cameras," 2016.

[23] U. Minoni and M. Bianchi, "Aiding device for reading a printed text," September 2013. Retrieved March 22, 2016 from US Patent 8,538,087.

[24] M. A. Mattar, A. R. Hanson, and E. G. Learned-Miller, "Sign classification using local and meta-features," in *Computer Vision and Pattern Recognition-Workshops, 2005. CVPR Workshops. IEEE Computer Society Conference on*, pp. 26–26, IEEE, 2005.

[25] C. Yi and Y. Tian, "Assistive text reading from complex background for blind persons," in *Camera-based Document Analysis and Recognition*, pp. 15–28, Springer, 2011.

[26] L. Stearns, R. Du, U. Oh, Y. Wang, L. Findlater, R. Chellappa, and J. E. Froehlich, "The design and preliminary evaluation of a finger-mounted camera and feedback system to enable reading of printed text for the blind," in *Computer Vision-ECCV 2014 Workshops*, pp. 615–631, Springer, 2014.

[27] T. Fukuda, H. Morita, F. Arai, H. Ishihara, and H. Matsuura, "Micro resonator using electromagnetic actuator for tactile display," in *Micromechatronics and Human Science, 1997. Proceedings of the 1997 International Symposium on*, pp. 143–148, IEEE, 1997.

[28] Y. Kato, T. Sekitani, M. Takamiya, K. Asaka, T. Sakurai, T. Someya, *et al.*, "Sheet-type braille displays by integrating organic field-effect transistors and polymeric actuators," *IEEE Transactions on Electron Devices*, vol. 54, no. 2, pp. 202–209, 2007.

[29] L. Yobas, D. M. Durand, G. G. Skebe, F. J. Lisy, and M. A. Huff, "A novel integrable microvalve for refreshable braille display system," *Journal of Microelectromechanical Systems*, vol. 12, no. 3, pp. 252–263, 2003.

[30] C. A. Peterson, "Light-activated assistive reading device for visually impaired individuals," March 2012. Retrieved March 22, 2016 from US Patent 8132733.

[31] H. Nicolau, J. Guerreiro, T. Guerreiro, and L. Carriço, "Ubibraille: Designing and evaluating a vibrotactile braille-reading device," in *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, p. 23, ACM, 2013.

[32] M. N. Bonner, J. T. Brudvik, G. D. Abowd, and W. K. Edwards, "No-look notes: Accessible eyes-free multi-touch text entry," in *International Conference on Pervasive Computing*, pp. 409–426, Springer, 2010.

[33] M. C. Buzzi, M. Buzzi, B. Leporini, and A. Trujillo, "Designing a text entry multimodal keypad for blind users of touchscreen mobile phones," in *Proceedings of the 16th international ACM SIGACCESS Conference on Computers & Accessibility*, pp. 131–136, ACM, 2014.

[34] S. K. Kane, M. R. Morris, and J. O. Wobbrock, "Touchplates: Low-cost tactile overlays for visually impaired touch screen users," in *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, p. 22, ACM, 2013.

[35] B. Frey, C. Southern, and M. Romero, "Brailletouch: Mobile texting for the visually impaired," in *International Conference on Universal Access in Human-Computer Interaction*, pp. 19–25, Springer, 2011.

[36] S. Mascetti, C. Bernareggi, and M. Belotti, "Typeinbraille: Quick eyes-free typing on smartphones," in *International Conference on Computers for Handicapped Persons*, pp. 615–622, Springer, 2012.

[37] S. Azenkot, J. O. Wobbrock, S. Prasain, and R. E. Ladner, "Input finger detection for nonvisual touch screen text entry in perkinput," in *Proceedings of Graphics Interface 2012*, pp. 121–129, Canadian Information Processing Society, 2012.

[38] S. Azenkot and N. B. Lee, "Exploring the use of speech input by blind people on mobile devices," in *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, p. 11, ACM, 2013.

[39] W. Bank, "Country and lending groups," 2016. Retrieved June 20, 2016 from `http://goo.gl/bDO9Gw`.

[40] A. F. for the Blind, "Braille printers," 2016. Retrieved September 18, 2016 from `https://goo.gl/C14WYk`.

[41] M. Hussain, "Delayed supply of books for visually-impaired," 2012. Retrieved September 15, 2016 from `https://goo.gl/4xzrnP`.

[42] I. M. Thies, "User interface design for low-literate and novice users: past, present and future," *Foundations and Trends in Human-Computer Interaction*, vol. 8, no. 1, pp. 1–72, 2015.

[43] K. K. Corporation, "St1cl3h," 2006. Retrieved February 15, 2016 from `goo.gl/kgkJ1a`.

[44] Arduino, "Arduino uno," 2016. Retrieved March 15, 2016 from `https://www.arduino.cc/en/Main/ArduinoBoardUno`.

[45] N. B. Press, "The need for braille?," 2015. Retrieved on August 17, 2017 from https://goo.gl/dq1xDE.

[46] T. design trust, "Cost price, trade price, wholesale price?." http://goo.gl/XmdeX8, 2014. Accessed: Feb. 12, 2017.

[47] N. Dewhurst and D. Meeker, "The true cost of oversea manufacturing." http://goo.gl/nKNbuL, 2004. Accessed: Feb. 12, 2017.

[48] A. Corporation, "Attiny 13," August 2010. Retrieved March 15, 2016 from http://goo.gl/0g0Kvq.

[49] S. Electronics, "Coin cell battery - 20mm (cr2032)," 2016. Retrieved March 20, 2016 from https://www.sparkfun.com/products/338.

[50] D. Baldwin, "Inventing the future of wayfinding technology." Retrieved June 20, 2016 from http://goo.gl/vYZJjo.