Ultra Low Cost, Low Power, High Speed Electronic Braille Device for Visually Impaired People

Md Zesun Ahmed Mia*
Department of Electrical Engineering
Pennsylvania State University
University Park, USA
zesun.ahmed@psu.edu

Kazi Toukir Ahmed*
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka, Bangladesh
toukirbueteee14@gmail.com

Abstract— **Highly advanced and sophisticated braille devices are always sought after, however, the expenses associated with them surpass the advantages for the majority of individuals with vision impairments. In this paper, we design an affordable, customized, and rechargeable braille pad utilizing solenoids that have the capability to read text quickly and with precise control. The device is constructed with great precision and compactness using 3D printing methodologies. A microcontroller is precisely installed within the gadget to control the entire process. The device can be easily handled in the palm of a hand and the sensitivity may be modified as well. In addition to its mobility, this device has a weight of only 338 grams and is capable of translating text into braille from both cellular devices and laptops. This specific structure serves as a prime example in reducing electricity usage and enhancing productivity.**

keywords— Braille, Tactile display, Cognitive, Piezo-electric, Pulse Width Modulation

I. Introduction

Sight and hearing are mainly involved in most communication techniques. But those without the gift of sight i.e. the visually impaired people, mainly rely on the other senses such as touch for communication. With the digitization of the world, technology for them is also entering a new era. Electronic formats of books and other contents are easily available today even to visually impaired people.

Many blind people use speech mode rather than the readable braille patterns as an electronic medium to surf the internet or access an e-reader. This is because speech mode is relatively more available and inexpensive. Varao Sousa *et. al.* have reported that between active mode (e.g. reading directly from braille) and passive mode (e.g. listening from another third party), the active mode is superior, especially when deep comprehension of the text is in question [1]. In other words, we can say readers can feel and understand the meaning of the content better if they use an active mode for reading. They can also set the pace of information flow and stimulate their imagination better when reading directly from the braille. Some contents are such that speech would fail to represent the whole picture and the complexity, like when reading a mathematical equation or musical notations or maps, one would need a direct mode of comprehension, not through a third-party translation [2].

Tactile technology uses touch-sensitive devices. This research focuses on visually impaired people and disabled tools. Braille displays mainly convert text to characters using touch. Braille displays have several cells with six or eight dots in two columns. To simulate the distortions caused by touching real objects, tactile displays send small-scale shape information to the fingertip. Removing spatially circulated contact forces to the fingertip impairs orientation detection, spatial acuity, pressure sensitivity, and roughness perception [3]. So, there is no universally acknowledged solution for a perfect tactile display. Also, Djkbvk et. al. have investigated several problems related to the mobility of visually impaired people and the design of assistive technology using tactile [4].

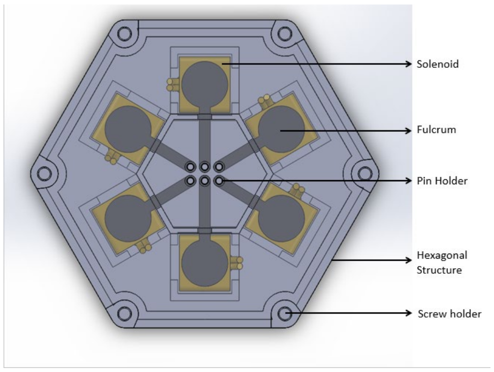
Braille displays are too expensive for the mass people. The cost for an 18-character refreshable braille display is about $2000 and astonishingly, a half-page refreshable braille display can even cost a staggering $10,000 [5]. Many commercial pin actuators are based on piezoelectric materials as they are free of the complexities associated with magnetic actuators but they are quite costly [6]. A normal piezoelectric Braille cell contains eight dots (pins) and eight piezo bimorph bars [7]. Due to their huge cost, other actuators have recently come to the center of attention using the movement of pins [8], electromagnetic, and pneumatic forces [9]. Recently, organic transistors have been used in developing large scale, flexible, and sheet type braille displays as portrayed by Yusaku Kato et. al. [10]. There has been attempts to integrate neuromorphic approaches leveraging bioplausibility [11] to braille pattern recognition [12].

Despite high cost being the main reason for the less use of electronic braille displays, there are also two more reasons. One is the decline in support for training blind children and newly blind adults in braille. This has caused a huge drop in levels of braille literacy in the community. And the other reason being

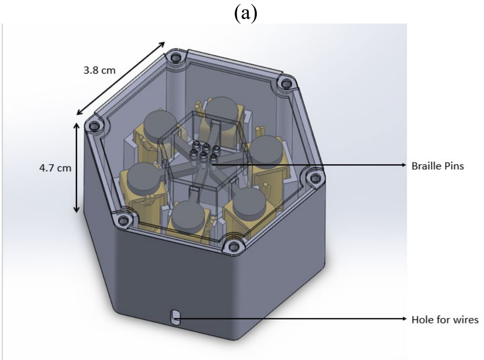
* The authors contributed equally to the work.

the continuous increase in the cost of producing hard copies of braille books which have reduced the amount and availability of recently published books in braille format and for this reason the interest in and practice of braille reading is declining particularly among the young readers. So, the need for a low-cost and easily available braille display has long since been upon us [13].

Worldwide, commercial piezoelectric materials are expensive and created utilizing sophisticated methods, making them a key bottleneck in the creation of a low-cost braille device. We develop a solenoids-based, ultra-low-cost (20 dollars), lightweight (338 g), portable, and low-power braille device. The device shows input text characters quickly. We use 3D-printed polymers to make this device. Low-cost, low-power braille devices could benefit science, education, and communication. This technology can inspire the future so visually challenged people can access the internet and perform what most of us do for cheap.



(a)



(b)

Fig. 1. (a) Top view and (b) 3-D view of the schematic design of the pocket braille gadget that has 6 solenoids going up and down following the received PWM signal of 50% duty cycle and reads out the braille symbols for the reader continuously.

II. Braille Display

A. Braille Reading Research

Braille is a means for visually impaired people to read what we read. It's relatable to the ability of an IDE reading a programming language. A blind person also has similar reading rules by which they can interpret the meaning. There has always been a constant push to make the braille system more modern and accessible. With that in mind, many have developed braille devices that use the sensation of touch. As the population of visually impaired people is growing, we strive to teach the young and newly blind people so that they become accustomed to using braille as a way of their life [13][14]. There are three primary reasons for studying braille as a reading medium, according to Foulke. The first purpose is to investigate the mechanisms that underpin braille perception and consciousness. The next purpose for this research is to establish the readability of the braille code, and the third reason is to investigate how reading performance changes when different types of displays and accessing mechanisms are employed. [14].

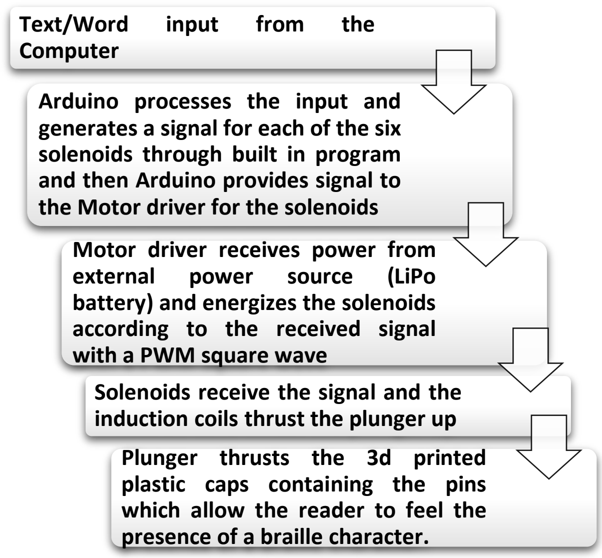
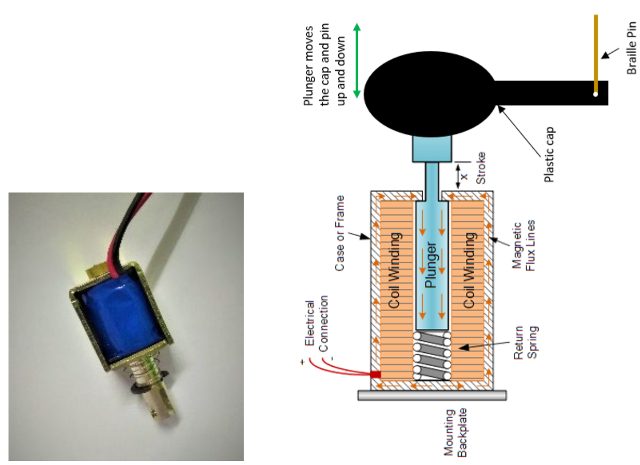


Fig. 2. The complete process flow showing how each component of the device performs its task enabling the user to experience the full extent of its ability.

On a normal page, the symbols are printed spatially and each of them comes following the same sequence as the other letters of different languages. Just as we, visual readers, become accustomed to seeing different words and be able to read much faster, it is debated whether or not braille readers can recognize the words the same way we do [15] [16]. The word superiority effect refers to how we distinguish words based on their overall form. The sequential processing theory suggests that tactile



(a) (b)

Fig. 3. (a) The solenoid used in the device (b) the mechanism of how the solenoid works showing induced magnetic field enabling the plunger and thus the pin to be thrust upwards provided a current signal flows through the solenoid coil.

reading is a productive process that follows Lederman and Klatzky's aspects of haptic form perception [17].

On the other hand, the global processing of word shapes can offer a better understanding. And like most of us, who can read by both tactile and global processing, experienced braille readers also employ these two approaches for better and faster reading. So, rather than reading letter by letter, the display of a whole word at once would provide better accuracy and speed. This process is analogous to learning to write with a keyboard. We cannot type without glancing at the keyboard at first, but as we become professionals, our typing speed increases, and we can type without looking. Touching does not reveal the letter's meaning; we only familiarize ourselves with its place. Even then, we often type wrong. Thus, tactile accuracy is much lower than ocular precision. [14]. In healthy individuals, the two-point discrimination threshold is 2-4 mm , which is in the same order as the dot spacing of the braille display[18]. When we touch a shape and when we see a shape, obviously we understand the visual shape better than the tactual shape. That's why braille symbols are not shaped with complexity like many of the alphabets of various languages. Roman letters are also one kind of symbol but the braille symbols are easily distinguished from roman letters [19]. Reading rate of braille characters is much slower (120 WPM (Words Per Minute)) than the visual reading rate(300 WPM) [20]. The main reason is that braille characters are read separately and sequentially rather than in small groups.

B. The miscellany of the visually impaired population

The amount of visually impaired people varies depending on the criteria and procedures [21]. According to the National Eye Institute, 4.2 million people under the age of 40 in the United States are vision impaired. This number increases with age. Of those, 1.3 million are blind. 2.9 million light-eyed people who do not meet the law's blindness criteria. There is no reliable information available for completely blind people, but they are 25% of the legal visually impaired people. There is a correlation between the incidence of gender and visual impairment. For example, while 66% of women are visually impaired, only 34% of the male population is there. This imbalance is related to the longevity of women in the long run. World Health Organization estimates that 285 million people with visual impairment worldwide, 39 million people blind and 240 million are low vision [22]. Many people in underdeveloped countries suffer from short-sightedness due to a lack of treatment. Young people with vision impairments are particularly benefited by hepatic technologies, especially in education and employment areas because they are adapting rapidly to modern technology. It is estimated that the number of blind people will increase over the next 15 years.

Some other diseases of the visually impaired also occur. For example, those who suffer from age-related Macular Degradation have high levels of depressive disorder [23] and cognitive deficits [24]. Blind people with diabetes often suffer from peripheral neuropathy, which reduces the tactile sensitivity of their fingers [25]. The use of refreshable textile displays is affected by age. Human tactile acuity continues to decline with age [26]–[28]. Individuals who have vision impairment later in life may have poorer tactile acuity than younger people. For those who are blind from the very beginning of life, reducing tactile acuity does not have much effect. Some studies of modern psychophysical have shown that spatial resolution is better in blind subjects than in age-matched sighted subjects [26]–[30].

There are variations in people with vision impairments. That is why technology needs to be varied to help them. Mainstream developers should try integrated and comprehensive technical designs. The purpose is to know that the machine can be used by a lot of people and functionally and commercially profitable.

C. Contact mechanics between a braille character and a fingertip

A lot of braille spots raised and lowered beneath a stationary finger deform the sensitive fingertip differently than several dabs that flow over the skin. Determining dynamic distortion designs in contact mechanics, which includes evaluating the sensitive fingertip touching the generally hard braille understanding surface, is difficult. This contact mechanics issue is being examined to compare the mechanical boosts delivered to mechanoreceptors by static and sliding spaces. Normally, as a braille character is read, the touch surface changes fast. The contact fix at each pin glides across the fingertip due to sliding space (customary perusing by scrutinizing). One such contact fix glides across, twisting the touch surface into a distinctive form for the braille character under examination. Another impression appears on the right when this one moves off the fingertip to one side. The skin might be considered to partially 'flow' across the state of a braille character since the finger mash is sensitive. Pulling forces acting on the skin are applied in a non-uniform manner throughout the contact surface. Even within a single contact repair, tractions do not have to be transmitted constantly. Pulling forces acting on the contact surface that are unrelated to the contact surface arise from rubbing impacts (staying or sliding), and pulling forces acting

Fig. 4. The 3D printed plastic caps that empower the solenoid plungers to control the fine metal pins' movement such that the user can feel the movements of the six braille pins on his fingertip.

on the contact surface that are specific to the contact surface arise from the skin's proclivity to reclaim its ostensible shape when pressed against the braille pins and substrate. Based on whether the finger slides horizontally relative to the braille pins (sliding) or does not move (not sliding), different pulling pressures apply on the skin (static). The parallel movement will supply more noteworthy Pulling forces digression to the understanding surface due to the goodness of rubbing powers developing with sliding contact. In static areas, on the other hand, pulling forces will be quite normal.

The fingerprint edges may play a significant role in determining the circulation and development of pulling forces at a finer level. The fingerprint edges, for example, are known to have a significant role in the initiation of a slide [27]. When the pins move all over beneath a finger that remains relatively static in contrast to the substrate, the fingertip is deformed from a relatively flat surface into a shape that is a signature for a certain braille character and back again. The contact surface between the fingertip and the substrate has relatively uniform borders. Due to a sliding gap, the distinctive surface shape slides across the skin into the contact surface from one side and out the other side.

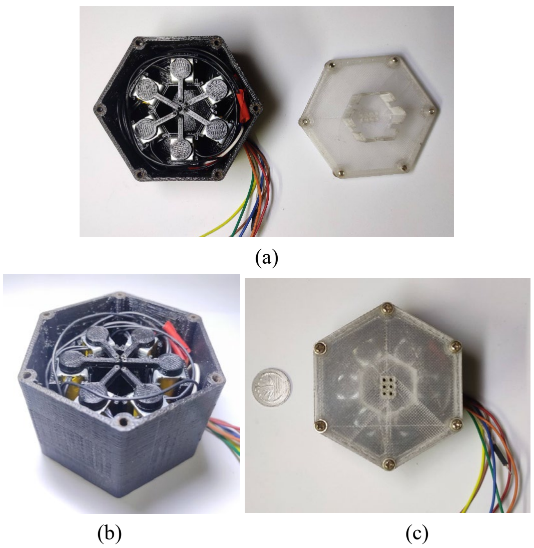


Fig. 5. (a) Top view of mechanical structure showing the lid having a special structure underneath to prevent the six caps from interfering with each other. (b) close view from an angle depicting the cap and wire placement inside the device. (c) Completed device with the input and neutral wires coming out from a miniature hole and also comparing its size with a standard 1 BDT coin.

III. Device Specification and Mechanism

The proposed tactile display is built around an electro-mechanical core structure, onto which are positioned six tiny holes on the upper surface, which serve as tactile pins. The necessary control electronics are positioned beneath this section. This configuration enables the device's overall size to be minimized. Fig. 1 displays schematic designs that are 3D printed. Electromechanical actuators are used to push pins up and down. Six push-pull solenoids are utilized for this purpose. Each solenoid is constructed of a large coil of copper wire with an armature in the center that looks like a slug of metal. When the coil is turned on, the slug is pushed into the coil's core. As a result, the solenoid can draw from one end while pushing from the other. The pins are mechanically attached to one side of the plastic caps, and the slugs at the push sides are mechanically attached to the other (Fig. 3(a)). Fig. 2 depicts the overall mechanism

The tactile pins and slugs are properly placed in the 3D printed plastic caps, as illustrated in Fig 4. Because the braille pattern is so tiny, creating a rectangle arrangement of actuators for each tactile pin is difficult. In such instance, the caps would be various sizes, and the pressures on the fingertips would be varied, resulting in distinct feelings of contact that may be irritating. As a result, they've been organized hexagonally. The caps are the same size in this example, and the distance and pressures at the fingertips are the same. The solenoids are arranged in a hexagonal pattern in a 3D printed hexagonal plastic box, allowing them to be readily changed if one becomes broken.

The whole device is powered by an external battery source and controlled by an Arduino and the process is depicted in

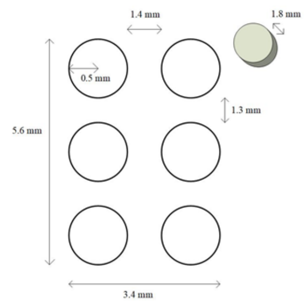


Fig. 6. Dimensions of tactile surface, pin holes and pin height showing how much the pins span over the length and width.

i2(a). Fig 3(b) shows how the solenoid uses the plunger to thrust up the pins connected by the plastic caps.

The top and side view of the mechanical structure is shown in Fig. 4. Pins are made of stainless-steel wire with a rounded ending. The diameter of each pin is 0.7 mm and the hole is 1 mm, the gap is 1.3 mm vertically and 1.4 mm horizontally. Fig. 5 shows the developed 3d printed device and the size is compared to a standard coin for clarity. The matrix size is 3×2 (Fig. 6).

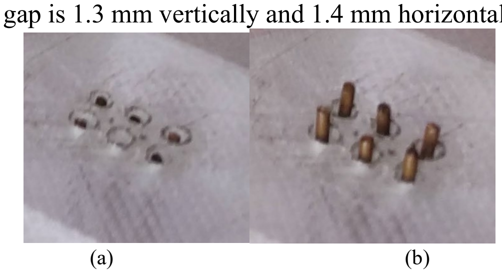


Fig. 7. Zoomed image of the pins (a) before energizing (b) after energizing the solenoids showing the pin height.

Each side is 3.8 cm wide with its height being 4.7 cm without considering the tips placed in the center at the top of the device. A positive voltage will raise the pins making them perceivable by the user. When raised, the resulting dot height is 1.8 mm above the surface to create a sensation on the finger (Fig. 7). Each of the tips is easily distinguishable by any of the fingers

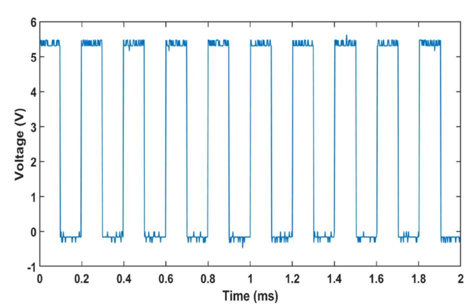


Fig. 8. Pulse width modulated (PWM) signal having a 50% duty cycle controls the energization of the solenoid according to the signal from the controller.

as it is placed on the center of the device. Six actuators are driven by two L293d motor drivers which are connected to Arduino and dc power supply. The actual high voltage applied to actuators can be digitally controlled through the Arduino. The actual driving voltage is 3.4 V, which creates enough torque to make effective sense at the tips of the fingers. A trial-and-error approach is used to fine-tune this arrangement. The Arduino implements the protocol for exchanging data with ICT systems, sends incoming data to the frame buffer, and regulates the DC supply using the inbuilt DAC. Currently, the system may be fitted with a USB port to link the device to a computer or with Bluetooth to connect it to any compatible device (e.g., mobiles, e-book readers). The present baud rate is 9600, which means that data may be transmitted in roughly 10ms, equivalent to a 100 frames/s refresh rate2, which is faster than similar interfaces [31].

In the current implementation, most power consumption is due to the high-voltage module. On top of this, dynamic variations are negligible, due to the fast transitions between the up and down pin positions. The above base power consumption can be lowered by PWM (Fig. 8). The supply signal consists of an impulse train of voltage pulses such that the width of individual pulses controls the effective voltage level to the load and produces enough torque to sense effectively the tips of the tactile display. Frequency of the PWM signal is 5 kHz. The duty cycle is 50% and enough torque is produced despite this duty cycle. The corresponding dc voltage is 3.4 volts, and the current is 0.4 A gleaned from the experimental result for each actuator. The maximum power is consumed when six actuators are energized simultaneously. However, there is no combination of dots for any symbol in symbols that have five dots. Most of the cases, one, two, and three or four dots have to be energized at a moment. Consequently, the maximum power consumed is 6.8 watt for which all six pins have to be raised. When only three pins bulge up, a power of 1.36 watt is consumed. Solenoid ratings are shown in Table 1.

As a result of implementing PWM, a slight noisy sound is created, and a little heat is generated inside the solenoids due to

TABLE I: SOLENOID DATA OBTAINED FROM THE EXPERIMENT

Parameter	Values
DC Voltage	3.4 volt
Current	0.4 A
Power	1.36 watt

mechanical vibration. Nevertheless, as solenoids are energized only for a moment, the generated heat should be negligible to the reader. Also, tactile pins having no direct metallic connection to the solenoids remain insulated from any kind of heat or electrical transmission.

The device is portable thanks to two-cell Li-ion batteries. It's light at 338 grams. Its 35.57 cm^2 size makes it easy to place over the palm and use whether standing or walking. Six non-sharp edges make the surface and sides smooth. This whole exoskeleton is 3D printed and the solenoids, wires, and tips are mechanically inserted and snugly bonded for accurate, user-friendly, handy, and lightweight results. A small hole on the side connects electrical wires to the control circuit. Since tips and solenoids are replaceable, the gadget can be repaired. It is affordable and provides a flexible maintenance schedule compared to other braille devices.

TABLE II: PWM SQUARE PULSE SPECIFICATIONS

Parameter	Values
Frequency	5 kHz
Period	0.2 ms
Duty cycle	50 %
Amplitude	5 volts
DC average value	3.4 volts

IV. COST ANALYSIS

The device is completed using good quality materials and parts but at the lowest price. The device structure is 3D printed using plastic material for experimentation and costs $5 including the outer layer and inner mechanisms, i.e. the fulcrums and solenoid holders. For industry production, the cost would be lower. Six screws are used to attach the cover and seven wires come out of the device connecting the solenoids and the microprocessor. The microprocessor together with other wires and battery cost about $5 and each of the solenoids cost $1. The pins used for tactile display which are responsible for touching the finger skin cost 10 cents each. We also use a Bluetooth module costing $2. Thus, putting the whole device together cost us $18.6. So, we can say, even after including miscellaneous costs, the individual manufacturing cost of the device would be only $20.

If we consider industrial production of the device, the production cost might be reduced to 50% the cost of this prototype. Industrially, the structure can be built in bulk which should cost only $1 each. Even each of the solenoids would cost no more than 50 cents. Moreover, the direct import of the microprocessor and Bluetooth module integrated into a printed circuit board would reduce the cost to $3. The wires, pins, screws, batteries bought in bulk, would cost no more than 60 cents for a single device. All these values are estimated after discussing with the importers and industry management for such devices. So, we can accurately estimate the cost of the device to be $8.6 if produced in bulk industrially. After considering the machinery and labor cost, marketizing the device for $10 might not be just a dream.

V. FUTURE PROSPECT

The proposed technology could revolutionize visually impaired people's lives. In beta, it can adjust display speed and import textual material from the computer. We want to integrate this module with an Android or iOS mobile app with more capabilities and an audio-enabled interface to connect with blind people. Additionally, visually handicapped folks can use the gadget like an e-book reader. We can reduce its size to make it easier to carry. After shrinking, it can be worn as a bracelet. We can add features that make the device easier to operate and encourage daily use. There are also rechargeable batteries that last 12 hours per charge. Works using developing technologies like TFET, GAAFET, etc. may design more compact devices. [32]. Additionally, energy-efficient machine learning algorithms are being developed to enable edge devices like smart braille with in-memory computing [33-35].

VI. CONCLUSION

This study evaluates an assisted reading device for visually impaired people, considering its possible expansions and benefits. Our goal was to construct a low-cost mobile device with flawless operation using solenoids and a hexagonal design. Cost-effective components and Pulse Width Modulation (PWM) to reduce power consumption and maintain speed achieve the low-cost goal. Its hexagonal shape was designed to be lightweight, portable, attractive, and easy to carry. We 3D printed the structure and used plastic to insulate the electronics and wiring for long-term use. We expect this technology to create a market for visually impaired people to use at low cost. This device will be efficient and satisfy customers, with room for improvement.

REFERENCES

[1] T. L. Varao Sousa, J. S. A. Carriere, and D. Smilek, "The way we encounter reading material influences how frequently we mind wander," *Front. Psychol.*, vol. 4, 2013, doi: 10.3389/fpsyg.2013.00892.

[2] M. A. Heller, "Tactile picture perception in sighted and blind people," *Behav. Brain Res.*, vol. 135, no. 1–2, pp. 65–68, Sep. 2002, doi: 10.1016/S0166-4328(02)00156-0.

[3] S. J. Lederman and R. L. Klatzky, "Sensing and Displaying Spatially Distributed Fingertip Forces in Haptic Interfaces for Teleoperator and Virtual Environment Systems," *Presence Teleoperators Virtual Environ.*, vol. 8, no. 1, pp. 86–103, Feb. 1999, doi: 10.1162/105474699566062.

[4] E. E. Pissaloux, R. Velazquez, and F. Maingreaud, "A New Framework for Cognitive Mobility of Visually Impaired Users in Using Tactile Device," *IEEE Trans. Hum.-Mach. Syst.*, vol. 47, no. 6, pp. 1040–1051, Dec. 2017, doi: 10.1109/THMS.2017.2736888.

[5] "Braille displays are pretty common, but awfully expensive. If your side project ... | Hacker News," news.ycombinator.com. https://news.ycombinator.com/item?id=37074356 (accessed Feb. 22, 2024).

[6] Sekhar, B. C., Dhanalakshmi, B., Rao, B. S., Ramesh, S., Prasad, K. V., Rao, P. S., & Rao, B. P. (2021). Piezoelectricity and its applications. Multifunct. Ferroelectr. Mater, 71.

[7] Lee, J. S., & Lucyszyn, S. (2005). A micromachined refreshable Braille cell. Journal of Microelectromechanical Systems, 14(4), 673-682.

[8] J. M. Lee, C. R. Wagner, S. J. Lederman, and R. D. Howe, "Spatial low pass filters for pin actuated tactile displays," in *11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings.*, Los Angeles, CA, USA, 2003, pp. 57–62. doi: 10.1109/HAPTIC.2003.1191230.

[9] G. Moy, C. Wagner, and R. S. Fearing, "A Compliant Tactile Dis for Teletaction," p. 7.

[10] Y. Kato *et al.*, "Sheet-Type Braille Displays by Integrating Organic Field-Effect Transistors and Polymeric Actuators," *IEEE Trans Electron Devices*, vol. 54, no. 2, pp. 202–209, Feb. 2007, doi: 10.1109/TED.2006.888678..

[11] Mia, M. Z. A., Bal, M., & Sengupta, A. (2023). Delving Deeper Into Astromorphic Transformers. arXiv preprint arXiv:2312.10925.

[12] Müller-Cleve, S. F., Fra, V., Khacef, L., Pequeño-Zurro, A., Klepatsch, D., Forno, E., ... & Bartolozzi, C. (2022). Braille letter reading: A benchmark for spatio-temporal pattern recognition on neuromorphic hardware. Frontiers in Neuroscience, 16, 951164.

[13] N. H. Runyan and D. B. Blazie, "The continuing quest for the 'Holy Braille' of tactile displays," in *Nano-Opto-Mechanical Systems (NOMS)*, Aug. 2011, vol. 8107, p. 81070G. doi: 10.1117/12.897382.

[14] W. Schiff and E. Foulke, "Tactual perception : a sourcebook." Cambridge University Press, Cambridge [Cambridgeshire] ; New York, 1982. Accessed: Jun. 19, 2021. [Online]. Available: http://www.gbv.de/dms/bowker/toc/9780521240956.pdf

[15] L. E. Krueger, "A word-superiority effect with print and braille characters," *Percept. Psychophys.*, vol. 31, no. 4, pp. 345–352, Jul. 1982, doi: 10.3758/BF03202658.

[16] S. Millar, *Reading by Touch*. London: Routledge, 1997. doi: 10.4324/9780203359440.

[17] S. J. Lederman and R. L. Klatzky, "Hand movements: A window into haptic object recognition," *Cognit. Psychol.*, vol. 19, no. 3, pp. 342–368, Jul. 1987, doi: 10.1016/0010-0285(87)90008-9.

[18] J. Tong, O. Mao, and D. Goldreich, "Two-Point Orientation Discrimination Versus the Traditional Two-Point Test for Tactile Spatial Acuity Assessment," *Front. Hum. Neurosci.*, vol. 7, 2013, doi: 10.3389/fnhum.2013.00579.

[19] J. M. Loomis, "On the tangibility of letters and braille," *Percept. Psychophys.*, vol. 29, no. 1, pp. 37–46, Jan. 1981, doi: 10.3758/bf03198838.

[20] G. E. Legge, C. M. Madison, and J. S. Mansfield, "Measuring Braille reading speed with the MNREAD test," *Vis. Impair. Res.*, vol. 1, no. 3, pp. 131–145, Jan. 1999, doi: 10.1076/vimr.1.3.131.4438.

[21] J. E. Crews *et al.*, "The Variability of Vision Loss Assessment in Federally Sponsored Surveys: Seeking Conceptual Clarity and Comparability," *Am. J. Ophthalmol.*, vol. 154, no. 6, pp. S31-S44.e1, Dec. 2012, doi: 10.1016/j.ajo.2011.10.029.

[22] "Vision impairment and blindness." https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment (accessed Jun. 19, 2021).

[23] B. L. Brody *et al.*, "Depression, visual acuity, comorbidity, and disability associated with age-related macular degeneration," *Ophthalmology*, vol. 108, no. 10, pp. 1893–1900, Oct. 2001, doi: 10.1016/S0161-6420(01)00754-0.

[24] H. E. Whitson *et al.*, "Comorbid cognitive impairment and functional trajectories in low vision rehabilitation for macular disease," *Aging Clin. Exp. Res.*, vol. 23, no. 5–6, pp. 343–350, Oct. 2011, doi: 10.1007/BF03325233.

[25] J. C. Stevens, E. Foulke, and M. Q. Patterson, "Tactile acuity, aging, and braille reading in long-term blindness," *J. Exp. Psychol. Appl.*, vol. 2, no. 2, pp. 91–106, 1996, doi: 10.1037/1076-898X.2.2.91.

[26] D. Goldreich and I. M. Kanics, "Tactile Acuity is Enhanced in Blindness," *J. Neurosci.*, vol. 23, no. 8, pp. 3439–3445, Apr. 2003, doi: 10.1523/JNEUROSCI.23-08-03439.2003.

[27] D. Goldreich and I. M. Kanics, "Performance of blind and sighted humans on a tactile grating detection task," *Percept. Psychophys.*, vol. 68, no. 8, pp. 1363–1371, Nov. 2006, doi: 10.3758/BF03193735.

[28] G. E. Legge, C. Madison, B. N. Vaughn, A. M. Y. Cheong, and J. C. Miller, "Retention of high tactile acuity throughout the life span in blindness," *Percept. Psychophys.*, vol. 70, no. 8, pp. 1471–1488, Nov. 2008, doi: 10.3758/PP.70.8.1471.

[29] R. W. V. Boven, R. H. Hamilton, T. Kauffman, J. P. Keenan, and A. Pascual, "Tactile spatial resolution in blind Braille readers," p. 8.

[30] R. S. Johansson and G. Westling, "Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects," *Exp. Brain Res.*, vol. 56, no. 3, Oct. 1984, doi: 10.1007/BF00237997.

[31] Vidal-Verdú, F., & Hafez, M. (2007). Graphical tactile displays for visually-impaired people. IEEE Transactions on neural systems and rehabilitation engineering, 15(1), 119-130.

[32] Fahim, K. A. H., Khalid, M. J. H., Mia, M. Z. A., & Rasheduzzaman, M. (2022, July). Study of 3-nm Cylindrical GAAFETs with Variations in High-k Dielectric Gate-oxide Materials. In 2022 IEEE Symposium on Industrial Electronics & Applications (ISIEA) (pp. 1-5). IEEE.

[33] G. Latif, G. B. Brahim, S. E. Abdelhamid, R. Alghazo, G. Alhabib, and K. Alnujaidi, "Learning at Your Fingertips: An Innovative IoT-Based AI-Powered Braille Learning System," Applied System Innovation, vol. 6, no. 5, p. 91, Oct. 2023, doi: https://doi.org/10.3390/asi6050091.

[34] Mia, M. Z. A., Islam, M. M., Haque, M., Islam, S., & Rahman, S. M. (2021, December). IRFD: A Feature Engineering based Ensemble Classification for Detecting Electricity Fraud in Traditional Meters. In 2021 24th International Conference on Computer and Information Technology (ICCIT) (pp. 1-6). IEEE.

[35] Islam, M.M., Haque, M., Islam, S., Mia, M.Z.A., Rahman, S.M.A.M. (2022). DCNN-LSTM Based Audio Classification Combining Multiple Feature Engineering and Data Augmentation Techniques. In: Vasant, P., Zelinka, I., Weber, GW. (eds) Intelligent Computing & Optimization. ICO 2021. Lecture Notes in Networks and Systems, vol 371. Springer, Cham. https://doi.org/10.1007/978-3-030-93247-3_23