Comparative testing of different mechanisms to identify cost-effective approaches for micro motion in braille-tab activation

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Abstract: This study addresses the challenge of text-to-Braille conversion for visually impaired individuals by evaluating various actuation mechanisms for cost-effective and efficient Braille display systems. Existing solutions are often limited by high costs, slow performance, and impractical designs for real-world applications. The research investigates four actuation methods: electromagnetic repulsion, thermal expansion, solenoid actuation, and vibration motors. Each mechanism was prototyped using 3D printing with PLA material and subjected to rigorous testing to evaluate performance metrics such as power consumption, response time, durability, and accuracy. The electromagnetic repulsion system demonstrated the highest accuracy and reliability but was bulky and expensive, with a relative cost index of 100. The solenoid system balanced cost and performance, proving to be a practical alternative with minor drawbacks such as heat buildup over time. The thermal expansion mechanism showed potential for long-term use but was hampered by slow response times and safety concerns. Finally, the vibration motor system was the most cost-efficient but lacked precision due to potential human error during interpretation. Through comparative analysis, the solenoid system was identified as the most cost-effective, while the electromagnetic repulsion system excelled in overall efficiency. The findings highlight the trade-offs between cost, speed, and accuracy across different mechanisms. This research provides a foundation for developing more accessible and scalable Braille conversion systems by optimising these mechanisms and integrating eco-friendly materials. Future work will focus on enhancing accuracy and reducing costs for widespread adoption.

Keywords: Text-to-Braille, actuation mechanisms, visually impaired, solenoid, electromagnetic repulsion, thermal expansion, vibration motors.

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1. INTRODUCTION

Visually Impaired individuals often face problems in reading text from physical books and pages. Over-reliance on braille textbooks leads to issues and may be expensive. Moreover, finding a braille version of all physical books is practically impossible to do. Therefore, there is a need for a device that can take any text from any textbook and output its braille version, allowing visually impaired individuals to freely understand any physical text they want to read.

A variety of approaches have been taken to address this issue leading to many existing methodologies. There have been devices that use thermal expansion of liquids to propel pins, electromagnets to repel magnetic pins [1], the implementation of the change of phase of wax to cause movement in the pins [2], and the use of solenoids to initiate the movement [3][4][5]. Moreover, some devices don't use pins and rather produce braille in the form of vibrations [6].

To develop a suitable text-to-braille conversion, this research presents the solution to take a look at the existing devices and to try and improve their functionality. Therefore, in this paper, several devices will be compared based on their accuracy, cost, power requirement, speed etc. This analysis will measure the devices and attempt to identify gaps in them along the lines of their real-world practicality. This may include their portability, feasibility for large scale implementation and how simple they are to use. Improvements will be suggested for improvements in fields such as the weight, accuracy etc. All the devices will be reviewed and attempted to be improved. After this theoretical analysis, the two best models will be re-created and tested to determine whether their practical implementation is suitable or not. These tests will measure the practicality of the models in the real world by testing them on odd/exceptional cases, judging their performance in non ideal conditions and for how long they will be able to work before showing error. This research will lead to discovering the ideal text to braille converter for the visually impaired.

To implement the final solutions, a range of tests must be performed beforehand. Thus tests will be conducted on the power consumption and time usage of the devices. This will measure the feasibility of utilising these devices on a daily basis. These tests may also present certain problems with the methodology that need to be addressed and fixed. After some final changes, one last comparison will be conducted among the devices and the most efficient and practical device will be concluded. This device will then be covered in more detail and its complete working will be unpacked, together with suggestions to further develop the model. A conclusion will be reached about the pros and cons of all the devices and methods to address the cons will be provided.

Motivation and Novelties

The primary motivation for this study arises from the challenges faced by visually impaired individuals in accessing written content. The reliance on Braille textbooks is limited by availability and cost, creating a pressing need for a device that can dynamically convert printed text into Braille. This research seeks to bridge this gap by exploring cost-effective, efficient, and scalable actuation mechanisms for micro-motion in Braille displays, thereby empowering the visually impaired with greater accessibility to textual information.

This study stands out due to its comparative evaluation of diverse actuation mechanisms electromagnetic repulsion, thermal expansion, solenoid actuation, and vibration motors—tailored for Braille tab activation. Unlike previous approaches, it combines theoretical modeling with practical prototyping using advanced 3D printing techniques. The emphasis on balancing cost, performance, and real-world applicability introduces a novel perspective to optimizing text-to-Braille conversion systems.

2. LITERATURE REVIEW

Sangmyungdae gil et al. [1] describes how text-to-voice conversion systems often lead to issues and inconveniences when over-relied on by visually impaired individuals and thus there is a need for a text-to-braille conversion device. The system makes use of a Raspberry Pi and Pi camera. OCR algorithm is used and the pins are pushed upwards using a magnet holder. A button is also used to view the next set of characters. A prototype is created which can display 20 characters at a time. However, Potential errors with the OCR algorithm such as bad lighting aren't addressed. Also, the scalability of the model is not mentioned. Klaus Schmidt-Rohr et al. [2] addressed the issue of the misapplication of formulas of thermodynamics regarding the expansion of a gas to push a piston. This research covers various calculations that may prove to be helpful when taking a thermodynamical approach to propel the pins in a braille conversion device. The paper goes through existing formulas and discovers errors in them. Using constant conditions, more information is gained and then various aspects such as expansion against friction are taken into account one by one. Using laws of thermodynamics, various formulas are developed. Through the research, the corrected formula to calculate the work done by expanding the gas to push the piston is obtained. Applications of the formulas on pushing pistons and bullets are also tested and results are given. However, the paper is quite theoretical and lacks sufficient tests of the formulas in real-world appliances. Daniele Leonardis et al. [3] took upon the challenge of creating a cost-effective and scalable text-to-braille converter via the use of pins that can be easily magnetised to initiate the up and down movement. The paper implements a single actuator slide to reset the pins. Moreover, this method is tested with experiments and FEM analysis, in which the research picks up components one by one and tests them under different conditions. The results of this methodology included the creation of a small-scale prototype that is efficient at tackling the problem. However, the research failed to acknowledge the magnetic effects of pins on each other. Also, potential problems associated with the downward movement of pins were not addressed. Sruthi Ramachandran et al. [4] take a look at the problems faced between visually impaired and deaf individuals in communication with each other. The research proposes the development of an app to enable communication that makes use of vibrators rather than pins to convert the text into braille. The respected vibrators vibrate to form a letter and a pause indicates the end of a letter. The software uses a microcontroller to conduct the vibrations. A prototype is developed, which allows users to send online messages to each other and receive them in the form of vibrations. This approach results in blind and deaf people being able to communicate with each other. Despite the uniqueness of the approach, the slow speed of the system and the potential human error in identifying the vibrations are challenges that still need to be addressed.

Sariat Sultana et al. [5] address the challenges faced by visually impaired individuals in reading text from physical books. The research proposes a system that allows for both English-to-braille and braille-to-English conversion. It makes use of solenoids to propel pins upwards and thus display English text as braille. Text can be typed in as braille as well which is displayed using an LCD screen. Through the research, a device that conducts this two-way conversion is developed which can handle a variety of input data, including punctuation. However, potential errors regarding the maintenance of the device are not addressed. Lohitha Lakshmi Guggilam et al. [6] worked towards making a device capable of converting any text to braille to solve the issue of visually impaired individuals needing special resources for reading any text in physical form. The research made use of Arduino to take text as input on an app and output the braille version of the same text on physical solenoids via the movement of pins. It first converts the text into a binary pattern to represent the braille then assigns those values to the solenoids to determine their position. Thus, the paper resulted in the creation of a device to simplify the text-to-braille conversion process by digitalizing the text. However, this approach has the problem of typing any text onto the app prior to conversion, which may be a tedious task. Alexandra-Maria Aluţei MEng et al. [7] delved into the problem of the lack of a braille-displaying device using thermal actuators to conduct a phase change of wax. To address this, their paper conducts tests with wax paraffin to identify important properties of the material regarding a phase change. It uncovers a lot of specifications with the design, including how much thermal energy would be emitted in the surroundings of the pin. The result is a prototype that is capable of displaying braille characters on a small scale. It heats the wax by supplying current to each pin individually. However, The mechanical aspects of the braille device aren't covered, and potential real-world problems such as durability aren't addressed.

Sangeeta Kumari et al. [8] address the problem of the lack of a portable and flexible method to translate physical text into braille. The paper proposes a method to first recognise the physical text, then map it to its respective grade 1 braille notation and finally output the braille version using solenoids. To recognise the text Optical Character Recognition (OCR) technology is used. The text is converted and outputted character by character by using a binary notation. The braille output is represented via the use of solenoids that initiate the up and down movement by the passage of electric current. The entire process is controlled by a raspberry pi. The research results in a prototype being developed that is capable of successfully displaying one character at a time. However, the concept of representing a large amount of text at once is ignored and the one-character-at-a-time method proves to be slow and inefficient. Sharavana K. et al .[9] addressed the challenges faced by visually impaired individuals in accessing information. The study suggests that existing methods of text to braille conversion have privacy issues. The research uses OCR to identify the text which is converted into both audio and braille formats. The audio conversion is done using a Text to Speech Synthesizer while the braille conversion is done via solenoids and a refreshable braille display. The chip used in the study is a Raspberry Pi 4b. The study proposes a system that can take digital text as input via photos and convert it into both audio and braille. Various formats, such as books and archives, are supported by the created device. However, the research is limited to converting only English in audio and braille which could create potential problems. Moreover, the use of a camera to take an image creates privacy issues. Khabibullo Nosirov et al. [10] tackled the problems faced by blind individuals in communication. The paper is a comparative study where it compares three innovations- smart glasses(explaining real-world activities to individuals through voice assistants), tactile(a real-time text-to-braille converter) and the Braille Device Sense U2(similar to tactile). The paper reviews each of the devices, covering both pros and cons. The paper concludes with a comprehensive tabular overview/comparison of all the devices. However, the innovations covered have not been improved in any way. No suggestion or additions to the innovations is provided, rather the pre-existing technology is just explained. Vrushabh S. Dharme et al. [11] address the problems that Visually impaired individuals face while communicating through electronic text. The paper covers various digital text-to-braille conversion systems, highlighting gaps in them. It proposes the use of Automated value Thresholding to convert the English text into braille. An embedded system is implemented in order to take the text from a phone as input and the output of braille is generated with the help of motors. A solution is proposed and explained in detail, which converts either text from an SMS message or a keyboard input into braille for the blind person to read and interpret. However, potential errors such as those of accuracy and speed are not addressed.

Aryan et al. [12] discuss the lack of an ideal braille conversion system and the problems in communication for visually impaired individuals throughout the paper. The paper proposes two solutions- a cam-actuated English to braille converter and an Android app aimed at making communication easier. The research introduces a mechanism that can raise and lower pins via cam activation. The Android application has features such as text to speech, braille conversion and gesture controls. However, The problem posed to underprivileged blind individuals isn't addressed, and any tests on the working of the mechanisms are absent. Sindhiya Sengole Raj [13] addresses the various problems visually impaired individuals face in accessing content due to the different text-to-braille converters proving to be inefficient and inaccessible. The paper makes use of Tesseract, a type of OCR algorithm to identify the English text from a scanned document. Various algorithms are implemented to convert text to braille, braille to text, handwritten text to braille and audio to braille. The result is a successful braille converter that makes use of deep learning to provide high accuracy as compared to the other alternatives. The conversion relies on scanned documents as input, which could pose problems. Moreover, issues related to the handwriting of an individual aren't addressed. Ahmed G. Mohammed [14] addresses the issue of problems faced by existing English to braille converters regarding the quality of the input data. If there is any noise, or inaccuracies in the input data, it could lead to problems in converting the text to braille and this makes it difficult for blind people to understand normal text. The paper makes use of an ANN to identify the characters from the text. A probability of the accuracy of the guess is calculated which helps in reducing errors due to noise. The characters are stored in a 2 by 6 matrix. A high-accuracy model to convert text, even in the presence of noise, to braille is developed. However, only grade 1 braille is covered and the actual display of the braille text is not addressed. Paul Blenkhorn et al. [15] puts forward the issue of formatting and layout errors during English to braille conversion, creating difficulties for visually impaired individuals. Thus there is a need for an effective and accurate English To braille converter. The research suggests a conversion process that makes use of a combination of state machine operations and context matching to be made more efficient. This system also allows for easy adaptation to other languages. A system using the above method to convert the text into braille is formed though it is not fully accurate. Specifically, there are syllabication issues with the conversion process. Furthermore, special cases lead to errors.

3. THE METHODOLOGY

Study of existing mechanisms

Multiple existing methods to study braille were studied and compared for their accuracy and actuation sensitivity, The best-performing small form factor methods were then selected for testing in order to gain knowledge about efficient methods for braille tab activation.

The types of braille actuators to be studied are mentioned herein forth:

Electromagnetic Repulsion Type System

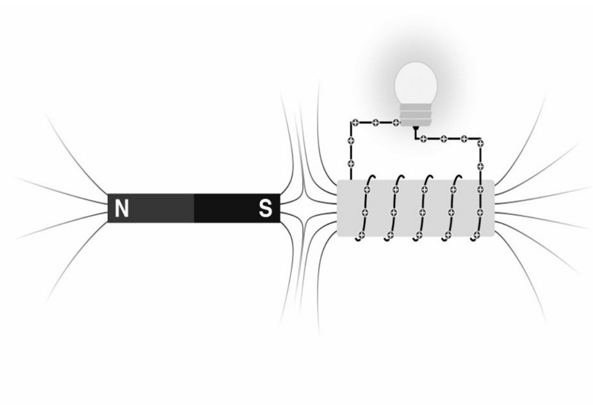

Fig. 1: Depiction of magnetic repulsion using an electromagnet [16]

The pins are made of magnetic materials and have another electromagnet beneath them. To push a pin-up, an electric current is passed through the electromagnet to repel the pin upwards. When the pin is supposed to come back down, the passage of the current is stopped.

This system primarily required an electromagnet, magnetic pins, and an actuator for the electromagnet. The concept of electromagnetic repulsion is shown in Fig. 1. In theory, magnetic repulsion to propel pins is reliable, accurate, and power efficient. Moreover, in this system the pins are independent and their behavior does not affect surrounding components. However, this model may prove to be expensive, and finding an equilibrium between height gained by repulsion and resistance to force created upon touch may be difficult.

To calculate the magnetic force required to propel the pin, we can use the formula [17]

$$Fg = Fm \quad (1)$$

Where Fg is the weight of the pin = m * g, M is the mass of the pin, g is the acceleration due to gravity, Fm is the magnetic repulsion force required to lift this pin up.

Therefore we get the formula

$$Fm = m * g \quad (2)$$

Where m = 0.02 kg and g = 9.8 m/s which gives a value of Fm of 0.196 N.

This force can be manipulated by altering the voltage supplied to get a lower power consumption which will increase the efficiency of the system.

Heat Expansion Type System

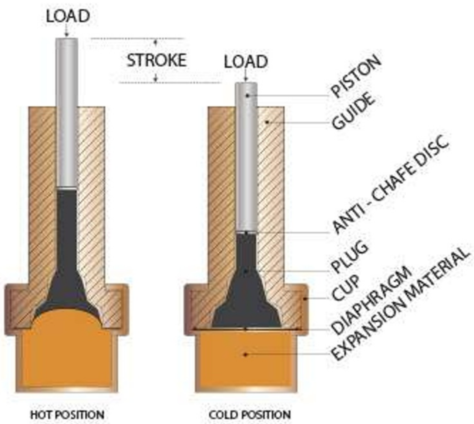

Fig. 2: Depiction of the working of heat expansion type system [18]

As shown above, in Fig. 2, liquids with high coefficients of thermal expansion are used to push pins upwards. This is done by heating the liquid which causes a plug to move vertically upwards, pushing the pin in the process. The pin can be brought down by turning off the heat supply.

This system will require a number of components, including a PTC thermoelectric heater, a liquid with a high rate of thermal expansion(silicon oil is a viable option), insulating material, a plug, and heat-resistant pins. Furthermore, sufficient resistive force will be created to avoid the pin being pushed down when being read. There are a variety of liquids that can be experimented with and given a high enough coefficient of thermal expansion, power consumption may be low. However, this system is highly dependent on the initial temperature of the pin which may lead to inaccuracies. Overheating and spreading of thermal energy are among other potential issues.

The force generated by the thermal expansion of liquids is affected by several factors but primarily relies on the increase in the volume of the liquid. This can be calculated using the formula[19]

$$dV = V_0 \beta (t_1 - t_0) \quad (3)$$

where, $dV = V_1 - V_0$ = change in volume (m^3, ft^3), β = volumetric temperature expansion coefficient (m^3 /$m^{3\,o}$C, ft^3 /$ft^{3\,o}$F), t_1 = final temperature (^{o}C), t_0 = initial temperature (^{o}C).

With an initial volume of 20ml, a temperature difference of 100 ^{o}C, and the use of silicon oil(with a volumetric temperature expansion coefficient of 0.001), a change in volume of 2 ml should be obtained in theory which would displace the diaphragm to obtain a visible difference in height of the pin.

Solenoid Type System

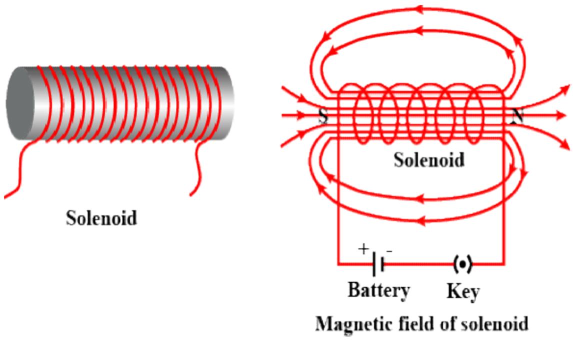

Fig. 3: Depiction of solenoids [20]

Solenoids as with the mechanism shown in Fig. 3, are also used instead of the pins to represent braille. After the conversion of the text to braille, either a Raspberry Pi or an Arduino can be used to control the solenoid and initiate movement using a relay.

The solenoid has a soft iron core housed inside a wound coil and when charge is passed through the winding it pulls the iron core through and it gets actuated.The magnetic field strength is calculated using [21]

$$B = \mu N I / L \quad (4)$$

Here, B is magnetic field strength (Tesla or weber/m2), N is the number of coils, μ is the permeability of free space = $4\pi \times 10$ T·m/A, L is the length of the solenoid in metres

This model needs comparatively fewer components, as only a solenoid along with a relay is required. In theory, this system should provide sufficient resistance to the force created upon the reading of the braille and should prove to be accurate. However, magnetic fields of the solenoids may interact while the formation of eddy currents may make it power inefficient. A large number of solenoids will also be required, making this system relatively more expensive.

Vibration Motor Type System

Fig. 4: Depiction of vibration motor [22]

Vibrations are another viable option to represent braille. The several dots are each represented by a vibration of the device, and the absence of a dot is represented by a long pause in the vibration. One character is represented at a time via this method.

This system only required a vibration motor and a controller. The simple nature of this system as depicted in Fig. 4 shows a motor with an offset weight to create vibrations makes it both cheap and power efficient though the process may be slow as only one pin can be read at a time. Potential human errors while reading are another drawback.

A Comparison Between the Mechanisms

The paper will be in the form of a comparative study where different existing braille displays will be compared based on their accuracy, speed, and cost. This study will conclude the best type of mechanism and focus on improving its functionality.

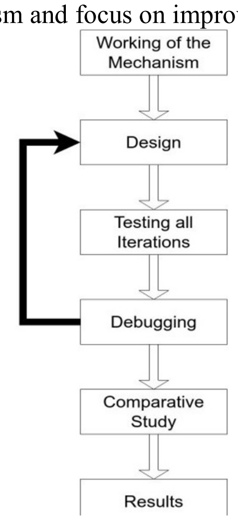

Fig. 5: Flowchart of methodology

The flowchart in Fig. 5 represents the methodology used during execution. Mechanisms and their working are explored and evaluated

3D Modelling of the Systems

Electromagnetic Repulsion Type System

This system works based on the repulsion of a magnetic pin made from an electromagnet upon supplying voltage. The pin rests upon a rectangular container containing neodymium magnets which experience this repulsive force. The outer casing is made using Fusion deposition modelling 3d printing using Poly Lactic Acid (PLA) material. This system weighed 250 grams and was bulkier than the other systems with an outer diameter of 56mm and height of 65 mm. The 3D printed model of this type along with its design is shown in Fig. 6.

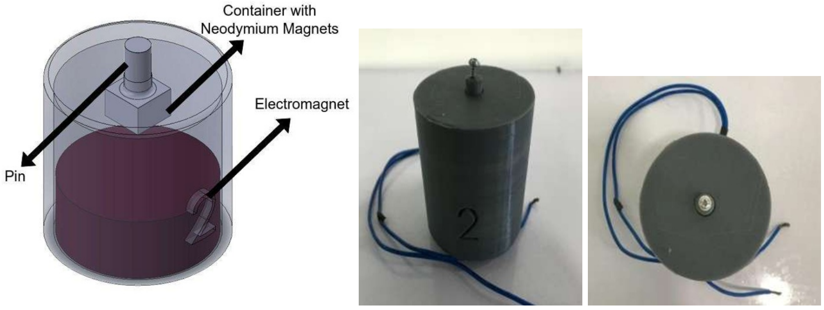

Fig. 6: (a) CAD Model of Electromagnetic Repulsion Type System, (b) 3D Printed Electromagnetic Repulsion Type System (side view) & (c) 3D Printed Electromagnetic Repulsion Type System (top view)

Heat Expansion Type System

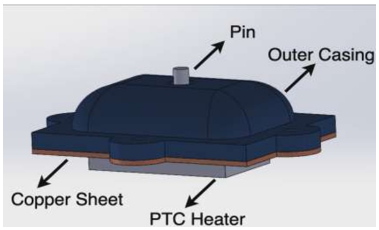

Fig. 7: Parametric CAD Model of Heat Expansion Type System

Fig. 7 shows the heat expansion type system that weighed 51g and was manufactured using Fusion deposition modelling (FDM) 3d printing with Polylactic acid (PLA) material and a sheet of copper to conduct the heat, and dimensions 55mm x 40mm x 25mm.

1. PTC Heater- This study used a 12V PTC Heater which took approximately 28.3 seconds to propel the pin from room temperature to ~95 °C with a power consumption of ~11.58W. These tests were then repeated 9 times at a higher initial temperature while keeping the final temperature constant. The initial temperature was higher in every test due to the after-effects of the previous experiment, which led to an increase in efficiency on every use(less wattage consumed).
2. Silicon Oil- It was used as the expansionary fluid and was filled in via a syringe. 22-23 ml was used with an expansion rate of ~10% per 100 degree Celsius rise in temperature. Upon applying excessive force, the propelled pin could be pushed into the liquid but it quickly recovered its upright position.
3. Diaphragm- This was used to not let the silicon oil seep out and so that any expansion of the oil could directly be related to the movement of the pin. It was made out of thermoplastic polyurethane with a shore hardness of 60. The 3D model of this system is shown in Fig. 8 (a).
4. O'Ring Seat- It is used to not allow any oil to seep out as shown in Fig. 8 (b).

Fig. 8: (a) Diaphragm to allow for movement and (b) O'ring Seat

The braille can be actuated to a height of 6 mm from the unraised to the raised position, making the depiction easily identifiable, by simply applying a voltage to the heater module. Fig. 9 (a) shows the Heat Expansion Type System running at an insufficient voltage while Fig. 9 (b) shows the same at sufficient voltage.

Fig. 9: (a) Pin fell down due to cold expansion media and (b) Pin upright due to sufficient voltage to PTC heater expanding the silicone oil media.

Solenoid Type System

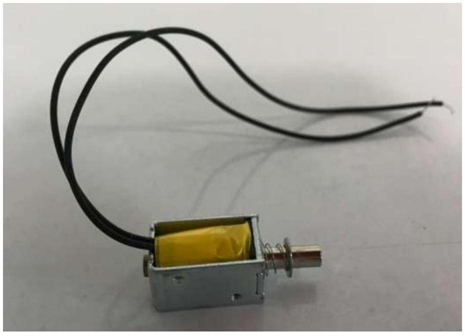

Fig. 10: Solenoid used in the Solenoid Type System

The system uses a micro solenoid to actuate a pin to represent the braille, The pin can be moved from the actuated to unactuated condition by the application of a voltage across the terminals. This system is the lightest of all at 13 grams and runs at a voltage of 12V DC. The design of the system is shown in Fig. 10.

Vibration Motor Type System

This system makes use of a vibration motor along with a 3d printed pin casing made by Fusion Deposition Modelling using polylactic acid, the pin can be turned on using a simple circuit commencing the vibration by simply applying power to it(6-12 volts DC). The pin weighed 14 grams and was very compact. The system and its CAD model are shown in Fig. 11 (a) and (b).

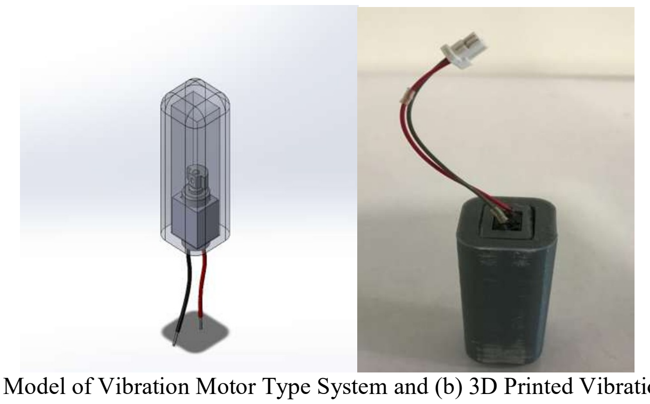

Fig. 11: (a) CAD Model of Vibration Motor Type System and (b) 3D Printed Vibration Motor Type System

https://doi.org/10.1051/matecconf/202641901017

5. RESULTS

Magnetic repulsion type

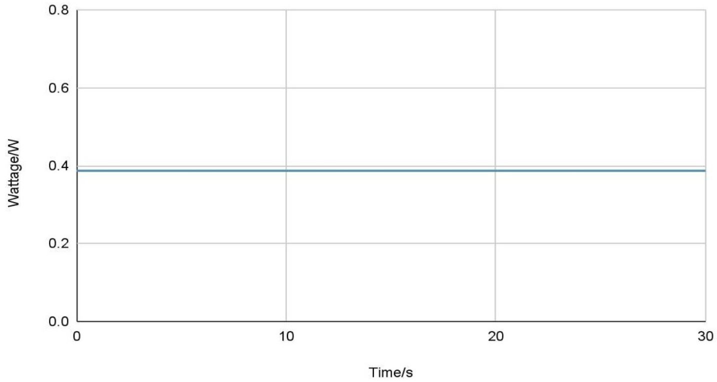

Fig. 12: Constant Wattage consumption with time to keep the pin raised.

Inferences drawn;

The representation of the braille by this mechanism is very easily identifiable and instantaneous, however, the braille can be actuated to a height of 5 mm from unraised to the raised position, making the depiction easily identifiable, the pin is held with the power applied to it, making the magnetic repulsion hold it in place, hence it cannot very easily be unactuated making the representation unmistakable, however, this does end up consuming power continuously.

The mechanism is slightly bulky as the electromagnet has to be powerful enough to cause a rise in the pin purely through repulsion.

Table 2 . PTC heater type

Test number	Initial Temp/*C	Pin Rise Time	Wattage Consumed(W)
1	28.0	26.3	11.580
2	61.5	8.2	7.346
3	62.1	8.1	7.345
4	62.2	8.1	7.345
5	62.2	8.1	7.345
6	62.4	8.0	7.233
7	62.1	8.2	7.345
8	62.3	8.1	7.345
9	62.2	8.1	7.345
10	62.5	8	7.233

The table above represents the number of tests carried out to raise the pin for this mechanism, the initial temps of the working media is noted, the pin is heated till the pin is raised, the time of pin erection is noted and the amount of power consumed is calculated.

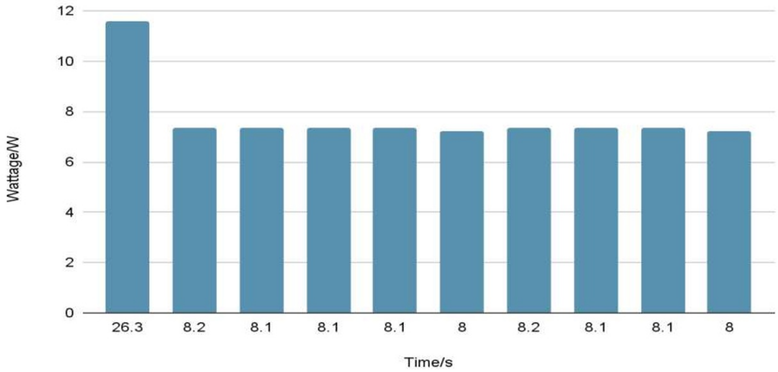

Fig. 13: Wattage vs time consumed to raise the pin. This Fig. represents the above table where the wattage consumed decreases with each subsequent pin rise.

The wattage consumed vs time are subsequently represented in the graph in Fig. 13.

Inferences drawn:

The representation of the braille by this mechanism, albeit accurate is not instantaneous, for both the actuated and un-actuated phase, making this actuation mechanism response time slow, however, each consecutive actuation also takes up lesser power than the first as the expansion fluid, in this case Silicone oil is preheated to and does not need to be heated up from ambient temperatures.

However, the system does not possess any strength to lock the pin in place and may be easily pushed down.

This system consumed ~15.82W of power at 12V with a negligible initiating period. However, there was a formation of eddy currents in the soft iron core which led to the heating of the pin to very high temperatures upon excessive use. The pin proved resistive to any downward force. The power consumption stayed constant in every use. However, the wattage varied with time as given in the table below.

Table 3 . Solenoid type

Time(s)	Wattage(W)	Voltage(V)
0	15.28	12
60	15.55	12
120	15.61	12
180	15.80	12
240	15.91	12
300	16.40	12
360	16.60	12

Therefore, with time the power consumption of the solenoid increases, reducing the efficiency of the system as also shown in Fig. 14.

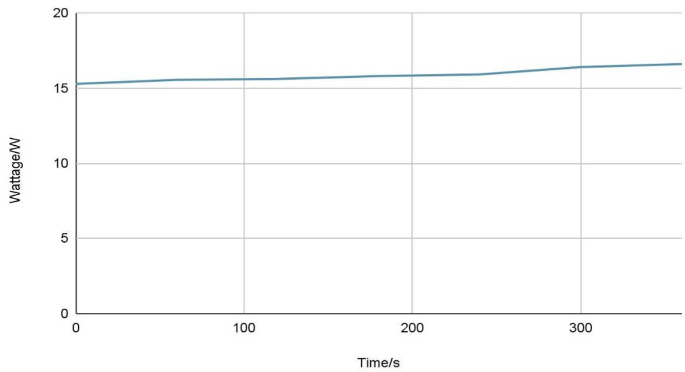

Fig. 14: Wattage consumption increases as time progresses, lowering the efficiency.

Inferences drawn:

The representation of the braille by this mechanism, is accurate and instantaneous, making this actuator the best for this use case, however, each consecutive actuation also takes up slightly more power as compared to the previous as the eddy currents developed within the solenoid heat the core up and consume more power to raise the pin to the desired height, The braille can be actuated to a height of 5 mm from unraised to the raised position, making the depiction easily identifiable, the pin is held with the power applied to it hence it cannot very easily be forcefully un-actuated making the representation unmistakable, however, this does end up heating the solenoid itself.

Vibration motor type:

The Vibration Motor Type System consumed ~3.43W at 12V and was instantaneous with a negligible initiative period. Applying force had minimal effect on the vibration of the pin. The power consumption remained constant in every use. This wattage consumption is constant with time, as shown in Fig. 15.

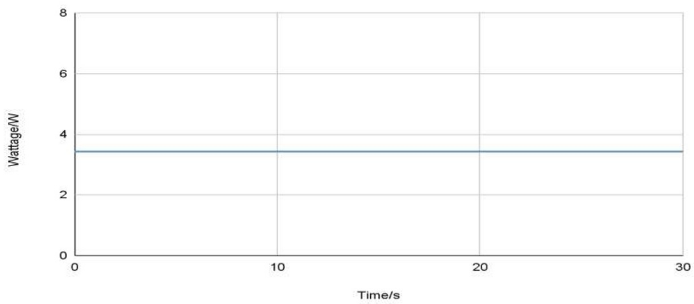

Fig. 15: Constant Wattage consumption with time.

Inferences drawn :

The representation of the braille by this mechanism is harder to recognize, and with multiple pins in its vicinity, the neighbouring pins may also feel as if they are vibrating, lowering the accuracy. It will require some training to accurately identify each vibrating pin.

The pin goes from actuated to un-actuated instantaneously, as the vibration is controlled by the means of an electronic circuit.

Relative Cost

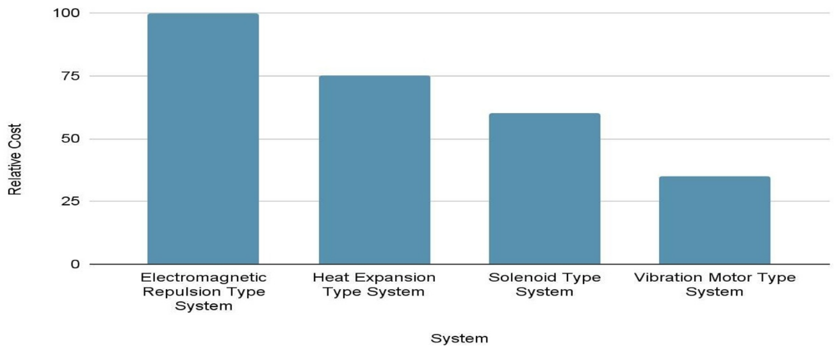

Fig. 16: Relative cost of all the systems

Fig. 16 correlates the costs of all the systems. More accurate models, such as the Electromagnetic Repulsion Type System are problematic in terms of price, while a less feasible system such as the Vibration Motor Type is very cost-effective.

6. CONCLUSION

This study compares multiple mechanisms for micro-motion in Braille actuation, evaluating their cost-effectiveness, accuracy, speed, and power efficiency. All systems had their pros and cons which can be summarised as follows-

- The solenoid-type system proved to be a cost-effective method to reliably execute consistent actuation under load. This type had a relative cost of 60(on a scale of 0-100) but problems such as heat buildup and formation of eddy currents hinder the efficiency of the system.
- The vibration motor type system proved to be the least costly at a relative cost of 35 but was less reliable than the other types due to the likely probability of human error.
- The PTC heater type proved to be accurate and efficient for long-term use but had a high relative cost of 75. The model proved to be efficient though the involvement of thermal expansion leads to slow responses and also dangers the structural integrity.
- The electromagnetic repulsion type system proved to be the most efficient in terms of accuracy and results with minimal issues. However, the system was bulky and expensive at a relative cost of 100.
- This comparative analysis revealed the trade-offs between cost, power efficiency, and real-world applicability of each method. The electromagnetic repulsion type system proved to be the most efficient but when looking at cost-effective approaches then the solenoid type system was of the most practical. In the future, the accuracy of these systems can be improved and they can also become more eco-friendly. This can be done by optimization of design and use of renewable materials.
- The outcomes of this research have significant societal implications, offering visually impaired individuals affordable and efficient access to printed materials. By enabling real-time conversion of text into Braille, the proposed mechanisms can revolutionize educational and professional opportunities, fostering inclusivity and reducing barriers to information for this underserved community.

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