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APPLICATION OF SHAPE MEMORY ALLOY (SMA) BASED ACTUATION FOR REFRESHABLE DISPLAY OF BRAILLE

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ABSTRACT

Persons with blindness access computers with the help of refreshable Braille displays and speech synthesis softwares. Braille has distinguished advantages over synthetic speech, especially because of its important role in uplifting education, employment and income. However, commercially available Braille displays are typically priced in the range of 2500-4000 USD (65-100 USD per Braille character) and are thus inaccessible to users in both developed and developing countries. Development of affordable Braille displays is thus a critical need.

Shape Memory Alloy (SMA) based actuation is a potential low-cost alternative to currently employed piezoelectric actuation, and is being used here to develop an affordable Braille display. This paper discusses key challenges identified in SMA based actuation and proposes methods to overcome the same. Prior attempts at developing tactile displays employing SMA based actuation are reviewed and important considerations for the present study are drawn. The configuration and the design of the actuator are thus arrived at. This paper further discusses the performance of fabricated prototypes and the feedback received from limited user trials. It concludes with a discussion on future scope of the work.

INTRODUCTION

Computers and other digital media have empowered persons with blindness by providing them access to vast banks of information through auditory and tactile outputs in place of visual output. Regular computers can be augmented with speech synthesis softwares for access through auditory output and with Braille display terminals for access through tactile output. The latter alternative, compared to the former, has penetrated far less among users, including both individuals and institutions, primarily due to its high cost [1]. Commercially available Braille displays currently cost to users in the range of 65-100 USD per Braille character and a typical device with 40 Braille characters is priced in the range of 2500–4000 USD. The price is prohibitive for most users in both developed and developing countries.

Use of Braille as a medium, compared to use of solely synthetic speech, has notable advantages. For instance, users of existing Braille displays find Braille output more convenient as it provides spatial aspects of the text and allows active reading. This helps users in retaining information better [2]. Moreover, for deaf-blind users, Braille output is the only available medium to access computers. With increasing dependence on synthetic speech, Braille literacy among persons with blindness is decreasing. Braille literacy plays a significant role in uplifting education, employment and income [3] and this trend is thus considered significantly damaging. An affordable Braille display, for wider access to computers via Braille output, is thus identified as a critical need by leaders in the field of assistive technologies for persons with blindness.

In a refreshable Braille display, heights of individual Braille dots are controlled electronically to selectively place them within or without tactile perception of the user. All Braille symbols can thus be displayed on individual Braille cells, each having six or eight independently controlled dots. Each dot requires a dedicated actuator, multiples of which need to be packed together to conform to standards of Braille size and spacing. Effectively, the challenge in devising a method for refreshable display of Braille is that of developing an electromechanical actuator suitable for the purpose and of packing multiples of these together according to display requirements.

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Commercially available Braille displays use bimorph piezoelectric bending actuators to control individual Braille dots [4, 5]. Attempts at reducing cost of these devices have brought it down to current levels that were mentioned earlier, which are yet significantly high [6]. Hence, recent attempts at developing affordable Braille displays have concentrated on developing new actuators, which are more cost-effective, as alternatives to piezoelectric actuators. A review of such attempts can be found in [7]. Notable actuation alternatives proposed and developed for this purpose historically include actuators based on electromagnetics, electrostatics, pneumatics, thermo-pneumatics and smart materials. Smart materials used for electromechanical actuation include Shape Memory Alloys (SMAs), electro-active polymers (EAPs), electro-rheological (ER) fluids and magneto-rheological (MR) fluids. Hitherto, no commercial Braille display has been reported which successfully exploits any of the above mentioned alternatives.

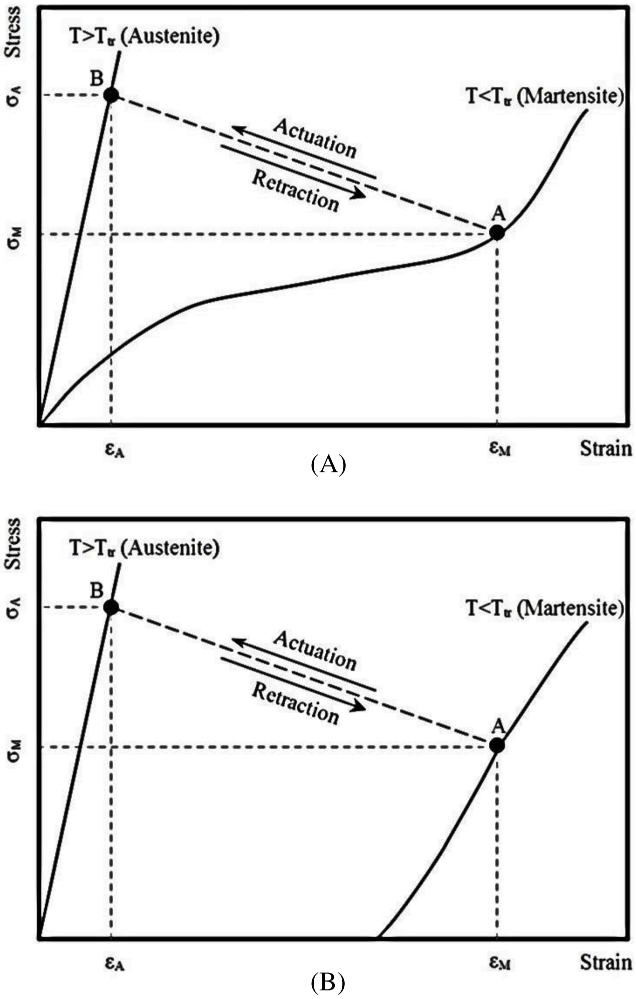
SMA based actuation, usually preferred for applications with significant size constraints and force requirements, offers a promising solution for affordable Braille displays. Although prior attempts at developing SMA based tactile displays (including both Braille and 2/2.5D graphic displays) have had limitations preventing translation into commercial products, they justified the applicability of SMA based actuation for refreshable display of Braille.

In the present paper, prior attempts at developing SMA based tactile displays have been reviewed. Existing limitations and key challenges in the application of SMA based actuation have been discussed and methods to overcome the same have been proposed. Configuration and design of an actuator suitable for the display of Braille have been presented. The paper further discusses the performance of fabricated prototypes and the feedback received from limited user trials. It concludes with a discussion on future scope of the work.

SMA BASED ACTUATION

SMAs, notably NiTi and derived ternary alloys, exhibit interesting thermo-mechanical properties due to their unique microstructural behavior. Martensite twinning/detwinning and martensitic phase transformations with changes in temperature and stress lead to characteristic temperature and history dependent stress–strain relations [8]. This property is usually exploited in the development of SMA based actuators, especially noted for commercial use in aerospace and automation applications.

Figure 1 illustrates the working principle behind SMA based actuation on typical stress–strain plots separately for unconditioned and conditioned SMAs. Points “A” and “B” represent the default and actuated states respectively of the SMA actuator element, and line “AB” represents the path followed by it between these states. The element in the default state, at a temperature lower than transformation temperature T$_{tr}$, is strained at ε_M due to an intentional bias force. The bias force is given by a bias-force component which is typically a dead weight, a regular spring or an antagonist SMA element. When heated to a temperature beyond T$_{tr}$, the strain decreases to ε_A. This change in strain of the SMA actuator element with change in temperature is exploited to generate mechanical work. Stresses σ_M and σ_A correspond to the default and actuated states respectively of the SMA actuator element. The slope of line “AB” is determined by the bias force component and is proportional to its stiffness for a regular spring or another SMA element, or zero for a dead weight.



(A)

(B)

Figure 1. WORKING PRINCIPLE FOR (A) UNCONDITIONED SMA, AND (B) CONDITIONED SMA

Actuators in different applications may differ in terms of material and design of the actuator element, source of bias force, and design of the mechanism employed to utilize the change in strain. Actuator elements are typically thin SMA wires and coil springs. However, other forms, for instance beams and thin films, have also come into practice. The scope of this paper is limited to the use of SMA wires and springs as actuator elements. When actuated under stress, these elements change length that is used directly to perform linear mechanical work or indirectly, by manipulating using simple mechanisms, to magnify either force or displacement or, for instance, to convert linear motion to rotary motion.

Application in Braille Display

SMA based actuation, in general, offers certain distinct advantages compared to other actuation alternatives. Various such alternatives have been compared on critical decision parameters in [9]. When compared to other smart materials, SMAs offer higher actuation stress as well as strain, which is preferred for a Braille display due to definite requirements of stroke and resisting force. Compared to conventional actuation alternatives, SMAs offer a higher power density, allowing development of miniature actuators suited for the size and spacing requirements of Braille.

SMA based actuation, in like micro and miniature applications, offers other notable advantages, discussed in [10]. SMA actuators can be developed as simple mechanisms with a small number of moving parts, making them easy to assemble and more reliable. Unlike pneumatic actuators, they can be driven directly through electrical current and have noiseless operation, making them suitable for non-industrial applications. They can be driven with a driving voltage as low as 5V, whereas piezoelectric actuators used in Braille displays require a 200V driving voltage and electro-active polymer based actuators require kVs of driving voltage. Further, SMA is commercially available in various forms at a low cost, making it especially suited for an affordable Braille display.

SMA based actuation comes with certain disadvantages as well. Compared to other alternatives, it offers a lower actuation frequency [8]. The actuation frequency is limited by the rate of cooling of SMA actuator elements, even in case the retraction is forced by an antagonist actuator. A minimum actuation frequency of 5 Hz is desirable for refreshable Braille displays, which is possible with SMAs, but not without forced cooling. Another important concern is of failure due to SMA fatigue. An improper SMA choice and operation may lead to failure before a million actuation cycles. Yet another concern is of high current and power requirements. SMA based actuation has poor energy efficiency due to significantly high latent heats of the martensitic transformations and the associated hysteresis.

Prior Attempts

Multiple prior attempts [11–27] at developing refreshable tactile displays using SMA based actuators have been reported. Tactile displays include both Braille displays and 2/2.5D graphic displays. Displays proposed and prototyped in different attempts differ in terms of actuator configuration and design, actuator packing and display design. Many attempts have been for development of 2.5D tactile displays for virtual reality applications, and have thus focused on actuators with precise position control. Position control is not a necessity for Braille displays, and is hence not given importance in the present discussion.

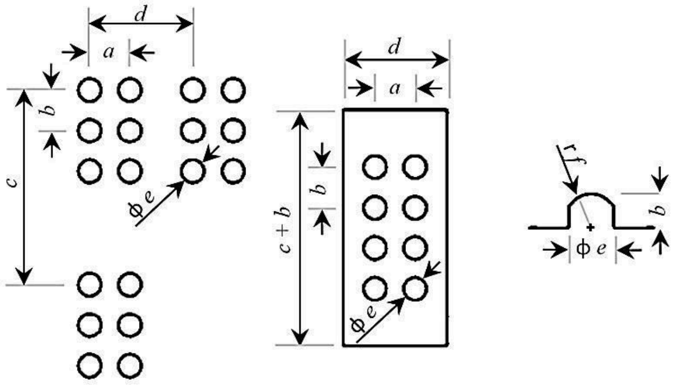
Considering actuator element, most prior attempts [11–21] have employed thin SMA wires, and a few, comparatively recent ones, [22–26] have employed helical springs (in either tension or compression) of thin SMA wires. An SMA bar has been employed in [27]. SMA wires may be preferred over springs due to multiple reasons. One reason is the requirement of an additional shape-setting process in the fabrication of SMA springs, which adds to their cost. Another reason is the slower cooling rate of springs in comparison to straight wires, especially if forced convective cooling is used for both. A benefit of using springs over wires is of compacter actuators and lower overall device height.

Considering bias force component, most prior attempts use passive components. A cantilever spring has been used in [11], regular helical springs have been used in [12–18, 22–24], elastic membranes have been used in [19, 27] and pneumatic force has been used in [20]. A few [21, 25, 26] use an active bias force component, which is an antagonist SMA element, similar to the primary actuator element in material and form. The benefit of using an antagonist SMA element is of faster retraction from the actuated position. However, it should be noted that the fast retraction is only to an intermediate actuator position, and both complete retraction and complete actuation require the other SMA element to be at a temperature below T_{tr}. Further, with an active element, the actuator commands heating in both actuation and retraction, increasing the overall power demand of the display.

Considering coupling mechanism between Braille dots and the actuator elements, most prior attempts [12–14, 20, 23–27] have Braille dots coupled directly and in-parallel with actuator elements thus having dot stroke equal to the change in wire/spring length. A few attempts [21, 22] have Braille dots coupled in-parallel with actuator element, but indirectly, through a latching mechanism. Latching mechanisms are used primarily to reduce power consumption. In [17] the in-parallel coupling is via a cam, to reverse the direction of actuation, and hence reverse the default state of Braille dots. Non-parallel couplings, used to magnify actuation displacement, have been employed in [11, 15, 16, 18, 19]. These are useful in reducing the size of actuator elements, thereby reducing power consumption. The disadvantages involved in incorporating features like latching mechanisms, cams and mechanisms for non-parallel coupling are the increase in number of moving parts, leading to a decrease in reliability, and the requirement of miniature parts with intricate features, leading to increase in manufacture complexity and cost.

Considering cooling methods employed, details of only a few attempts are available. Forced air cooling is suggested in [12, 15, 26], thermoelectric cooling is suggested in [22] and water bath and oil bath cooling are suggested in [19] and [24] respectively. Actuator packing approaches in [20, 23, 27] are such that SMA actuator elements are unable to interact with ambient air. This may decrease cooling rate, thereby increasing actuation cycle time considerably.

Considering packing and display design, each attempt differs significantly from the others. Some important observations are discussed here. A concern expressed by many is of electrical contacts and connections. Managing delicate crimped, soldered or welded joints is one challenge. The other challenge is of routing electrical connections, two for each actuator element within a compact setting. Another concern is



(A) (B) (C)

Figure 2. DIMENSIONS OF (A) 6-DOT PAPER BASED BRAILLE, (B) 8-DOT BRAILLE CELL, AND (C) BRAILLE DOT PROFILE

of challenges faced in fabrication and manufacture. The miniature size of actuators and mechanical components, and the need of fine dimensional and geometric tolerances make to-scale prototyping a challenge and increase manufacture cost. Yet another concern is of maintenance, repair and replacement of the actuators. These features are important and have not yet been addressed in packing and display design suitably.

DESIGN CONSTRAINTS

Primary constraints imposed on the design of a refreshable Braille display include the dimensional constraints of Braille dots and characters, and the operational constraints of a refreshable display. These constraints ensure convenience to users of both existing Braille displays and paper-based Braille and allow a new display to penetrate better among them. There are a few secondary constraints as well which are essential to overcome the challenges imposed by SMA based actuation.

Dimensional Constraints

Figure 2 illustrates the different dimensions for size and spacing of Braille on paper and on a Braille cell. Dimensional requirements of Braille dot and character are derived from various standards practiced internationally. Prescribed sizes and spacings according to different standards are given in [28]. It is however, impossible to conform to all standards, with a single choice for each dimension. Therefore, Braille readers have been consulted and acceptable ranges of each dimension have been determined. A single value for each dimension conforming to the acceptable range has been chosen such that each fulfills most international standards. Table 1 gives the acceptable ranges and chosen values for each dimension.

Profile of a Braille dot has been constructed with a dome shaped top for smooth tactile perception, as recommended in [29], and for its similarity to paper-based Braille.

Table 1. RANGE AND VALUE OF VARIOUS DIMENSIONS

Dimension	Acceptable Range (mm)	Chosen Value (mm)
a	2.3 – 2.6	2.5
b	2.3 – 2.6	2.5
c	10 – 13	12
d	6.0 – 7.0	6.4
ϕ e	1.3 – 1.6	1.4
r f	0.7 – 0.8	0.75

Table 2. OPERATIONAL CONSTRAINTS

Parameter	Value
Resisting force	min. 20gf per Braille pin, preferably 30 gf
Refresh frequency	min. 5 Hz
Minimum actuator life	min. 10^6 cycles
Operating temperature	0 – 40°C

Operational Constraints

Operational constraints define the minimum desired performance of a Braille display and are derived primarily through user interaction. Table 2 enlists critical operational parameters.

Resisting force is defined as the resistance offered by each perceivable Braille dot to pressure exerted by a reader’s finger. It is quantified as the amount of force needed to push a Braille dot to a position just above the display surface. Resisting force in commercial Braille displays is approximately 12gf [30], which is lower than the preferred value observed.

Refresh frequency is defined as the number of actuation cycles that can be completed by a Braille dot in one second. It is an important parameter for user convenience as it directly affects reading speed. A lower limit on refresh frequency has been determined by observing users. A 40-character display is expected to refresh within a maximum of one second, while individual cells even earlier.

Minimum actuator life is defined as the number of cycles each actuator must perform without failure. A minimum life of 10^6 cycles comes out as equivalent to two to three years of undisturbed above average use.

Secondary Constraints

A controlled cooling system is imperative to satisfy the operational constraint of actuation frequency. However, all cooling systems increase the net electrical power consumed by the display as well as increase the overall device cost. It should be noted that actuator packing and display design form an essential part of the cooling system.

SMA actuator elements are usually heated at actuation to beyond 50°C to as high as 90°C, depending on the alloy chosen. The display needs to be such that it prevents accidental user contact with actuator elements. Further, excess heat needs to be expelled immediately and its accumulation, especially near display surface and Braille dots, needs to be prevented.

SMA elements are usually available at low-cost. They are thus only a fraction of the net Bill-of-Material cost. Hence, failure of SMA elements due to fatigue or shock need not lead to the discard of a whole Braille display. A modular design of the display with individually replaceable cells is necessary. Further, Braille cells need to be designed such that individual actuator elements are repairable and replaceable.

The use of touch to read Braille leads to continuous damage of Braille dots and the display surface because of wear. Maintenance, repair and replacement of these components should be facilitated. Further, to prevent premature failures and reduce manufacture cost, moving parts should be kept at a minimum.

SYSTEM DESIGN

This section presents the detailed system design of a refreshable Braille display using SMA based actuation. Key challenges in SMA based actuation have been targeted with methods discussed above.

Actuator Configuration

A precursor to actuator design is the selection and testing of a suitable shape memory alloy. A variety of SMAs are available, varying in alloy composition, heat treatment and conditioning processes employed. Binary and ternary alloys of NiTi are usually preferred for thermo-mechanical actuation applications over other SMAs [31]. Other popular SMAs are CuZn alloys and CuAl alloys. Specifically, NiTiCu, a ternary alloy with 5–10 at% Cu, is suitable for actuation applications due to smaller hysteresis in thermo-mechanical cycling [8] and higher fatigue stability [32].

Flexinol® NiTi alloy procured from Dynalloy Inc. has been used for the purpose of developing prototypes due to its ready availability. The characteristic stress – strain relation of Flexinol® HT wires was obtained experimentally using isothermal tensile tests performed on Instron® MicroTester. Flexinol® HT wires were found to be highly-conditioned to exhibit two way shape memory effect. The obtained relation was verified with experimental isotherms given in [33].

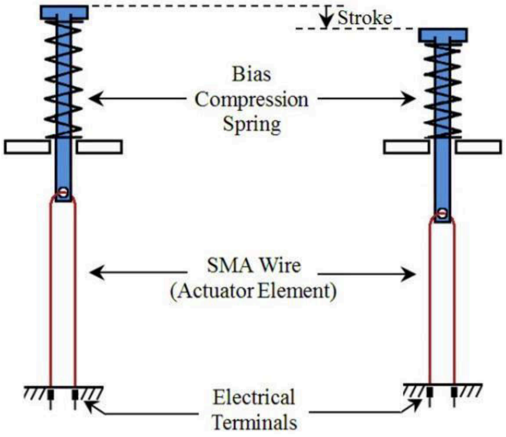


Figure 3. ACTUATOR CONFIGURATION

SMA wire is chosen as the actuator element, for its advantages discussed earlier. Figure 3 gives a schematic of the actuator configuration. Different from a regular spring-biased SMA wire actuator, the proposed actuator uses the SMA wire element in an inverse-U configuration. With such a configuration, all the terminals are placed on a single plane, simplifying electrical connections. Further, it allows the wire to have removable connections to the structure, allowing easy assembly and disassembly.

First order calculations were performed to determine the natural length L_n of the SMA wire, stiffness K_s of the bias compression spring and the stress σ_A and strain ε_A in the actuated SMA wire. Following design equations were used:

$$K_S x = 2A_w\sigma_M \tag{1}$$

$$K_S(x+\Delta x) = 2A_w\sigma_A \tag{2}$$

$$L_n(\varepsilon_M - \varepsilon_A) = \Delta x \tag{3}$$

$$K_s(x+\Delta x) \geq F_R \tag{4}$$

Here, σ_M and ε_M are the stress and strain, respectively, in unactuated SMA wire, A_w is the cross-section area of the SMA wire, Δx is the Braille dot stroke, x is the compression of the spring in the default state and F_R is the minimum desired resisting force. ε_M has been purposefully kept below 2.5%, as recommended in [34, 35] for an average actuator life greater than 10^6. Δx has been chosen as 0.7 mm for a stroke of 0.6 mm, to compensate effects of functional fatigue instability. Further, K_s has been constrained by practical considerations of spring material, size and manufacture limitations.

Actuator Packing

Actuator packing and cell design is such that it suitably meets both primary and secondary design constraints discussed in previous section. Figure 4 is an exploded view of a Braille cell, illustrating the assembly of the parts and subassemblies.

The packing provides for forced convective cooling of SMA actuator elements, as illustrated in Figure 5. A right cylindrical channel formed by Braille cells assembled together encloses all the actuator wires. Continuous or intermittent air draughts in the channel prevent heated air from enveloping the actuators. This providing for faster convective cooling and prevents undesirable heat accumulation. Enclosure of SMA wires within the channel also protects the user from any accidental contact with them.

Individual actuator wires are readily replaceable from the housing incorporated into the cell structure. This facilitates assembly and disassembly as well as repair and replacement of individual actuator elements.

The attachment between a Braille dot and the wire is such that it restricts heat transfer to the display surface and the Braille dots. Further, the attachment is non-permanent, thus allowing disassembly of actuator wires and Braille dots for purpose of repair.

RESULTS

To-scale functional prototypes of the Braille display were fabricated and their performance was evaluated. Prototypes were demonstrated to limited users for feedback.

Prototypes

Figure 6 (A) is a photograph of one functional Braille cell. Eight Braille cells form a Braille display module which is self-sufficient in terms of electrical control and operation. Figure 6 (B) is a photograph of one such Braille module. Multiple modules can be placed together to form displays with larger number of characters. Typical Braille display terminals with 30 – 40 Braille characters can contain 4-5 such Braille modules.

Developed prototypes have been laboratory tested on parameters defining functionality. The results prove that the designed actuator and packing help meet the desired level of functionality. Device specifications, as observed, have been tabulated in Tab. 3.

User Feedback

The design, development and prototyping processes have been interwoven with interactions with current users of refreshable Braille displays, users of paper based Braille, and students learning Braille. Interaction has also been with special educators and other individuals working in the domain of blindness. Figure 7 is a photograph of a pupil with blindness observing a prototype.

Critical feedback specific to the display was obtained from limited users exposed to early prototypes. It helped in

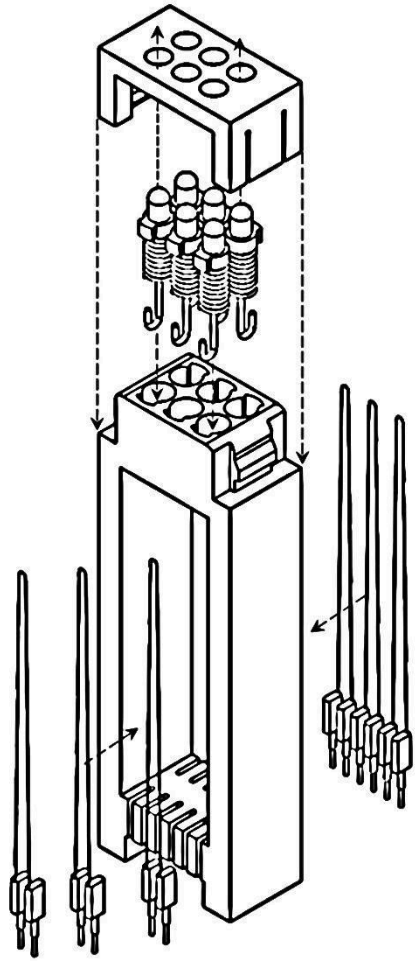


Figure 4. EXPLODED VIEW – BRAILLE CELL

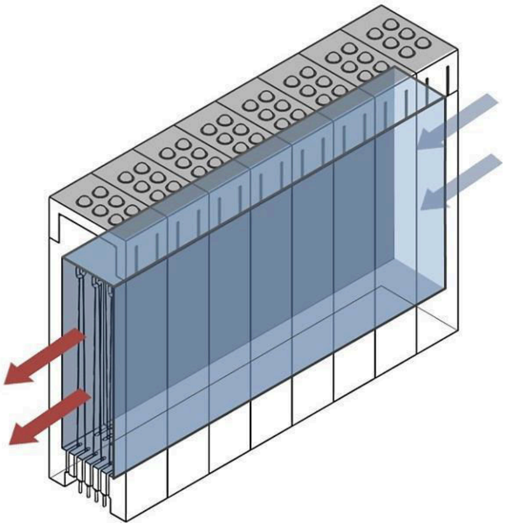


Figure 5. CHANNEL FOR CONVECTIVE COOLING

Table 3. PERFORMANCE AND SPECIFICATIONS

Parameter	Performance
Braille Dot Stroke	0.7mm
Inter-Dot Spacing	2.5mm
Inter-Character Spacing	6.4mm
Dot Base Diameter	1.4mm
Dot Profile	Dome (Radius 0.75mm)
Refresh Frequency	5 – 6Hz
Resisting Force	50gf
Operating Temperature Range	0 – 40°C
Max. Power Requirement (per cell)	1W (5V, 200mA)
Character Configuration	6-dot and 8-dot
6-dot Cell Dimensions	$6.5\times12\times45\text{mm}^3$
8-dot Cell Dimensions	$6.5\times14.5\times45\text{mm}^3$

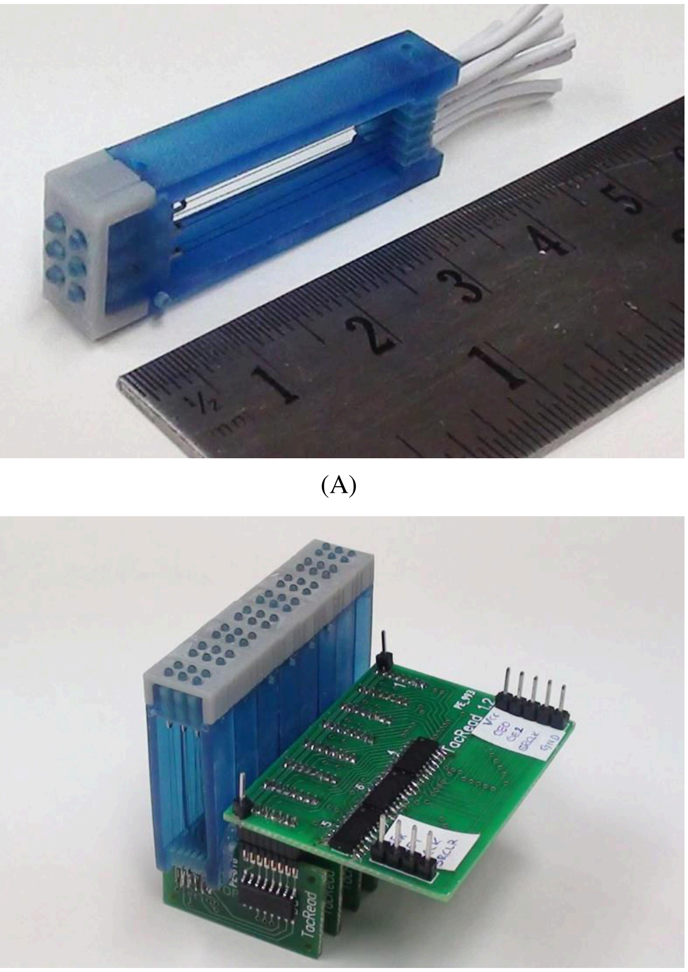
identification of critical performance parameters including consistency in Braille dot height, importance of Braille dot profile, actuator refresh frequency and importance of display life and repair. Feedback obtained with later prototypes has helped in realization of secondary features including device weight, display surface texture, display ergonomics and connectivity to a computer and other electronic devices.

Overall response to the display, its prototypes and developments, has been overwhelmingly positive, especially from students and special educators. Multiple possible applications of the display have been suggested, one being as a teaching aid in classrooms. Such applications have yet been impractical due to high cost of commercial Braille displays.

FUTURE SCOPE

The performance of the developed SMA-based refreshable Braille display, both in the lab and in the field, has been highly motivating. With presented developments the feasibility of taking the technology ahead has been proven. It is expected that the display would cost to users less than one-tenth of what existing displays cost.

In future, developments in SMA based actuation, for example, improvements in materials and processes and evolution of joining and attachment methods may help in further reduction of display cost and improvements in performance.



(A)

(B)

Figure 6. PROTOTYPES

Figure 7. USER DEMONSTRATION

SUMMARY AND CONCLUSION

In the challenge of developing affordable refreshable Braille displays, developing a suitable low-cost alternative to piezoelectric bending actuators is the key. Although prior efforts have identified multiple such alternatives, none has translated into successful products.

SMA based actuation, usually used in micro and miniature actuation applications, is among the proposed alternatives. It carries certain advantages making it suitable for Braille displays. However, certain challenges in actuator design and packing, actuation frequency, power requirement etc. have limited prior attempts. Prior attempts were thus reviewed and classified according to actuator parameters. Important experiences were selectively noted from different attempts to help in the design and development process.

Design constraints include dimensional, operational and secondary constraints. Dimensional constraints were drawn from standard practices and user interactions, and operational constraints, including refresh frequency, actuator life and resisting force, were drawn from literature and user interactions. These and secondary constraints specific to SMA-based Braille displays were discussed in detail.

Detailed system design of a refreshable Braille display using SMA based actuation was presented. In actuator design, the choice of shape memory alloy was justified and experiments were performed on Flexinol® HT wires. Results of the same were used to perform first-order design computations. The actuator was developed with an SMA wire in an inverse-U configuration. Actuator packing was discussed and provisions for cooling were explained. Further, provisions for maintenance, repair and replacement of individual components were discussed.

Results of performance evaluation of developed prototypes were presented. Multiple Braille cells were fabricated and assembled to form eight-character Braille modules. These modules were tested on parameters defining functionality and found to be satisfactory. Feedback received from limited user trials was also presented. Overall feedback received from users has been overwhelming.

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