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Design and Evaluation of Ni-Ti Alloy Actuator with Thermal Feedback for Tactile Presentations

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Abstract – Nickel-Titanium (Ni-Ti) alloy with their actuation and sensing abilities are proven to be the best alternatives in the design of micro tactile systems in Braille reading and writing. It is always needed to know what is being presented on display beforehand. Single-cell Braille systems are not adequate to make user unbiased discrimination of alphabets, numbers presented in different languages yielding less accuracy. Hence, this limits the user experience in identifying Braille characters. The biased conduction of the experiment may affect the overall identification accuracy. This paper proposes a novel technique to control actuation using thermal feedback evaluated using a 2-cell approach required for Braille reading. To achieve this, four types of Shape Memory Alloy (SMA) based actuators with wire and springs are designed and constructed for a two-cell Braille display. The implemented work allows the determination of the most effective actuation for the tactile pin in the Refreshable Braille Display (RBD. The obtained experimental result is found to be better in terms of time, displacement, and current required for actuation in comparison with the existing Braille display.

Index Terms **-** Tactile display, Shape Memory Alloy (SMA), Thermocouple, Nickel-Titanium alloy, Spring actuator, Refreshable Braille Display (RBD), SMA actuator

INTRODUCTION

In today's robotics and tactile modality applications, exceptional energy density and fatigue life have made them the best choices for SMA-based actuator systems however, a few are commercially available at a high cost. Inefficient thermal activation by the consumption of high energy added challenges to design and control of actuators. Innovative design and control approaches of SMA-based actuators can improve performance in a tactile system. Microactuators are essential parts of robotics and tactile modality. Thus, ensuring miniaturization with effect control is of paramount importance in design. The thermomechanical properties of wires degrade with a supply of over current. However, the force generated by the SMA wire enhances with an increase in the supply current. A low spring index SMA coils for morphing aerospace systems can produce significant linear forces and strain up their initial length [1]-[2].

The pseudoelastic behaviour of shape memory alloy (SMA) wires is investigated to understand loading rate dependency. The strain rate affects phase transformation stresses; an increase in temperature variation slightly increases strain rates [3]. Daudpoto, J. et al. reported a maximum strain of 3.25% and the higher stroke lengths require longer actuators, highlighting the limitations of a single strand of actuators. The long cycle time for the actuator is not suitable for fast applications. External cooling is necessary for some sources [4]. Jani J. M. et al. highlighted technical challenges to the SMA actuator with actuation duration. This numerical model is used for optimal performance and durability by considering the pre-stress and latent heat effects [5]. Lelieveld C. et al. performed mechanical characterization of a smart composite with SMA controlled by local thermal activation without supplying the continuous input. However, optimization in terms of fatigue and dimensions is needed [6]. A Doroudchi and M. R. Zakerzadeh developed a fast response SMA-actuated rotary actuator for controlled trajectory tracking purposes. However, sliding mode control using force feedback can further improve the performance in terms of speed by applying an input frequency of 1 Hz and an electric current of 1.5 A is achieved for 15 degrees of rotation angle [7].

A fine SMA wire with a diameter of 30 - 100 µm is used to develop a tactile display by H. Sawada. The tactile glove presents tactile sensations of a virtual object displayed in the head-mounted display (HMD). For presenting tactile sensations from a glove, nineteen SMA wires in total are stitched inside the glove, for displaying tactile sensation synchronizing with visual and auditory information are introduced [8]. The slope of the applied current passing through a sub-millimeter diameter SMA helical spring is seen to be directly proportional to its displacement. A method for sensorless displacement, heating control and the normalization of the data is to eliminate the ambient temperature dependence. An active model-based control scheme has reduced the absolute tracking error by more than 58% for three different frequency trajectories, and 89% for five other loads. It reduces the rise time from 6.1 s to 1.6 s and the settling time from 17.2 s to 7.5 s is proposed [9]-[11]. The target rotational angle of 30° is reached in about 7 s with a current of 500 mA. Heights up to 4.5 m and 3.6 m are achieved with and without gliding airfoil [12]-[13].

RELATED WORK

An approach to design an SMA spring actuator to address total transformation strain may degrade the performance of an actuator. Hard stops can restrict transformation, while the partial transformation strain improves the ability of the SMA spring actuator. The needed wire diameter for the same actuation force is lower by compromising on more number of turns required for the same stroke. It is proved that the number of turns is directly proportional to deformation using a linear approach. A displacement of 10 mm is achieved during transformation temperature 90-100 °C. Characteristic analysis and testing of the SMA spring actuator, the output force, displacement of SMA spring for various temperature conditions are analyzed [14]-[15]. For a helical SMA actuator, the effects of design and operational parameters on thermal transients and stroke are experimentally validated. It is observed that the thermal cycling did affect the reaction times for 90 °C SMA springs. Each experiment is designed to be compared to a helical SMA actuator with a 0.25 mm wire diameter, a 3.175 mm spring diameter, 70 °C transition temperature, and 18 active spring turns bearing 30 g bias mass and actuated with a 0.55 A direct current [16].

The more extended actuation travel with SMA wire without compromising the increased dimension of the system is the real challenge. The force variation of 1.5-4.5 N during cooling and heating respectively with a maximum displacement of 140 mm is reported. Negator SMA springs have a unique property to provide very long strokes independent of output force which can lead to high-frequency actuation over helical spring [17]. D. Hwang and T. Higuchi realized an SMA rotary actuator using wobble motor, the experiment was conducted with 20-200 m length of wire, 15 mm diameter of bias spring with stiffness coefficient 0.15 N/mm on applied stress of 150 MPa. This is achieved by supplying a voltage of 1.5 V [18]. C. H. Park et al. have proposed a bundle of 12 g mass using 24 SMA springs. The actuating frequency of 1 Hz is applied for a mass of 10 kg. The bundle could generate a high 130 N of force based on the temperature change from 28 °C to 82 °C. The wire diameter used in the development set restrictions on heating and cooling cycles, water circulation system added limitations on ease [19]. Flexinol LT SMA wires with a diameter of 0.19 mm, lengths of 576 mm, and 600 mm are used in the experiment. It achieves the maximum of 4 % strain when the voltage applied is 12 V and a current of 1.5 A, it is observed that resistance variation is from 19.9 to 20.8 Ohms [20].

The above survey highlights that the tactile display is used in miniature size, low weight and low power for actuation in presenting patterns or Braille characters. The fabrication limitations are also big challenges in the miniaturization of the SMA tactile display. The actuators developed using SMA wire or bundle added long length and uneven displacement respectively. The wire-based actuators can be replaced by a spring-based actuator to reduce size and length. The miniaturization causes closeness of SMA springs, which affects the heating cycles of nearby pins directly. The temperature control ultimately controlling supplied current is of paramount importance in control system design for tactile displays. Improper actuation in terms of uneven displacement and low spring index increases power requirements and it restricts high tactile pin density which affects the thermal cycle again.

I. Major Contribution

This work proposes a design procedure to conceptualize the SMA actuator for the development of tactile display and is applied to a real prototype actuator. The size the actuator and optimal functionality is achieved by fixing constraints of the physical dimension's actuator frame. The actuation procedure is confirmed on a structure constructed using an SMA spring. The fabrication challenge is addressed by precise fabrication using a 3D printing technique. The major limitations in existing techniques for controlling and miniaturization are addressed by suitably selecting material properties, and control strategy through rigorous experimentation. A novel technique is used to control actuation through thermal feedback. The time and current required for the desired displacement in the proposed structure are also evaluated.

The remaining paper is organized as follows. Section 3 describes material choice, different types of actuators using SMA wire or springs, their limitations, and advantages. Further, step by step design calculation for each type, fabrication of 2-cell Braille display is discussed in detail. Control circuits and controlling techniques for an experiment are proposed. Section 4 highlights findings and presents a comparison with the existing literature to validate the choice of type of actuator and improved performance parameters.

PROPOSED TACTILE DISPLAY MATERIAL AND DESIGN METHOD

To design 2 Cell Braille display, the material, mechanical design, and fabrication are three major components. In the proposed actuator design, two springs are needed. A bias spring is of stainless-steel material, and the other is with an SMA material spring for actuation. A thin solid rod of a diameter of 1.7 mm and the length of 20 mm is used for all designs to achieve the desired displacement of 4 mm. It is used to actuate with the help of spring and wire. An actuator with one SMA element was considered during designing and testing. The actuation was tested with two different diameter springs of 0.2 mm and 0.25 mm respectively.

I. Different Configurations of Actuator

To achieve the desired displacement, type-1 SMA wire-based as shown in Figure 1 (a), type-2 single SMA spring-based is given in Figure.1. (b), type-3 SMA spring with bias spring is indicated in Figure.1. (c), and type-4 SMA spring and bias spring with a guide and temperature control as shown in Figure.1. (d) were designed. The four configurations are studied to fit the actuator requirements in the tactile display being developed.

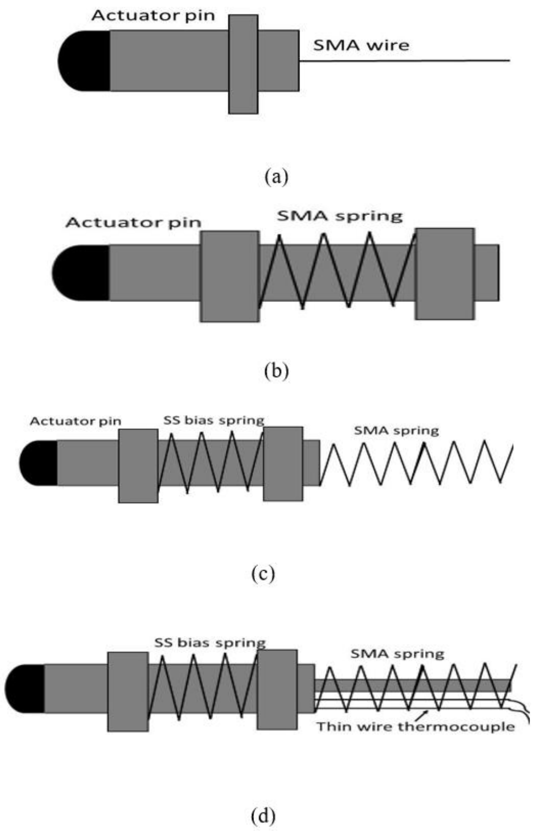

FIGURE. I

DIFFERENT ARRANGEMENT OF SMA IN THE ACTUATOR (A) SMA WIRE ACTUATOR (B) SMA SPRING ACTUATOR (C) SMA SPRING WITH BIAS SPRING ACTUATOR (D) SMA SPRING AND BIAS SPRING WITH TEMPERATURE CONTROL

Steps for the design of the wire-based actuator

The length of the required wire (L) for an actuator of type 1 is obtained as per (1) by considering 4% recoverable strain and a desired stroke of 3 mm.

$$L = \frac{stroke}{recoverable\ strain} \quad (1)$$

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The wire diameter (d) for actuator type 1 is obtained using (2) by considering force F up to 5 N. As per the data sheets, the maximum allowable stress ($\sigma_{max}\sigma_{max}$) for the material is 175 MPa.

$$A = \frac{F}{\sigma_{max}} \quad (2)$$

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SMA wire with a diameter of 0.190 mm and the length of 75 mm, is sufficient to achieve a displacement of 4 mm. Hence, a diameter of 0.2 mm, and an activation temperature of 90 °C supplied by Dynalloy Inc. are selected to fabricate an actuator of type 1. It restricts international standard dimensions needed for RBD because of the long length of wire, which causes uneven and limited displacement during excitation cycles.

Steps to design spring-based actuator

In this design of the actuator, an SMA spring and stainless-steel spring for bias are designed and rod dimensions are kept constant as per the wire-based actuator.

- Single SMA spring actuator

A rod through spring is arranged in such a way that it keeps the spring stretched and whenever joule heating is applied, it compresses the spring by generating the desired displacement. It causes uneven displacement during different cycles.

- SMA spring with bias spring and thermocouple

The actuation stroke is dependent on the wire length while cycling speed and pulling force are directly proportional to the wire diameter. In this type, bias spring helps to retain pin position during the unactuated stage. The bias spring and

SMA spring act in series to perform linear displacement. This arrangement overcomes the problem of uneven displacement but adds spring buckling and affects nearby pin operation due to closeness in RBD systems.

This type of actuator offers fine movement. The addition of unsheathed wire thermocouples to measure temperature for each actuator pin. Thus, ensuring a small band of temperature change during the actuation and de-actuation cycle. The coil diameter D, the wire diameter d, and the number of active coils n are the parameters of the spring to decide spring dimensions, which are specific to the Nickel (Ni) and Titanium (Ti) proportion in the alloy. In this design, the proportion used is Ni (49%) and Ti (51%). Spring index (c), and spring constants (k) are obtained using (3) and (4) respectively where G shear modulus, and n number of active coils.

$$c = \frac{D}{d} \quad (3)$$

$c = \frac{D}{d}$ (3) $k = \frac{Gd^4}{8nD^3}$ (4)

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II. Proposed fabrication of an actuator

The 2-cell Braille display is fabricated using 12 actuator pins arranged in a 3 x 2 array to achieve the desired displacement showing the Braille letter. Figure. 2. (a) shows the left cell presenting a type of character being presented, and the right cell indicates the actual character being presented for identification, while Figure. 2. (b) shows three layers, where layer a, layer b of acrylic material and layer c are copper-clad for electric connection for spring and tactile pin. One end of the SMA spring is connected to the control unit at the printed circuit board placed at the c layer, other ends in the top are combined to supply the required power. Figure.2. (c) is a side view of a fabricated tactile display showing the closeness of pins. Figure.2. (d) provides a top view of 2 pin arrays of the fabricated unit. The tactile pin is 3D printed using Stereolithography (SLA) offering smoothness to travel through the acrylic guide.

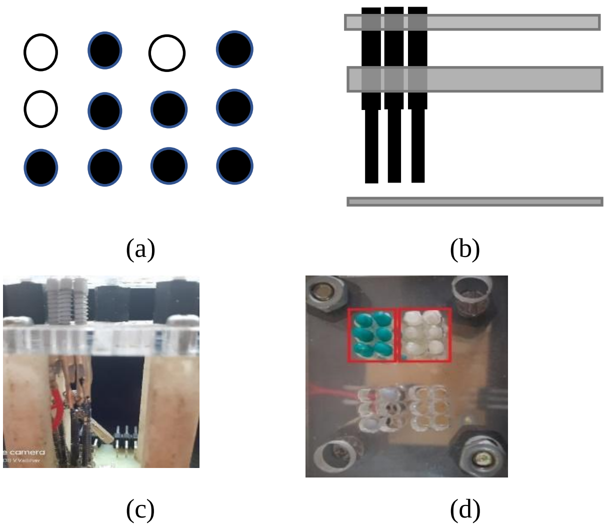


FIGURE.2

(A) LEFT CELL-1 INDICATES WHAT IS BEING PRESENTED IT IS NUMBER IN THE PICTURE, RIGHT CELL-2 SHOWS THE ACTUAL LETTER (NUMBER 1 IN THE PICTURE) PRESENTED FOR IDENTIFICATION, (B) 3-LAYER ARCHITECTURE, (C) SIDE VIEW OF THE FABRICATED UNIT, (D) SHOW TOP VIEW FABRICATED 2-CELL DISPLAY

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

I. System design

Arduino Mega 2560 controller is used for controlling the displacement of the desired pin. Integrated circuit (IC) ULN 2003A Darlington transistor array by Texas Instruments (TI) is used to drive each pin of the tactile display. Pulse Width Modulation (PWM) signals generated by the Arduino controller are supplied to the driver IC's input pins. Simultaneously temperature measurement using Omega COCO-005 thermocouple is carried out. The feedback of the thermocouple is used to keep the heating and cooling of the SMA spring in order.

II. Discussion of experimental results

Different actuator configurations are examined to select the best SMA actuator arrangement to use in applications such as tactile displays for Braille character presentation. To decide performance parameters of an actuator like current and time needed to achieve the desired displacement, an experiment is conducted. SMA wire actuator is excited by applying direct current. Each type of actuator is excited to note these parameters to find effectiveness in the tactile application. In a direct current method, current is slowly raised in steps from 0 to the maximum possible extent for the desired displacement.

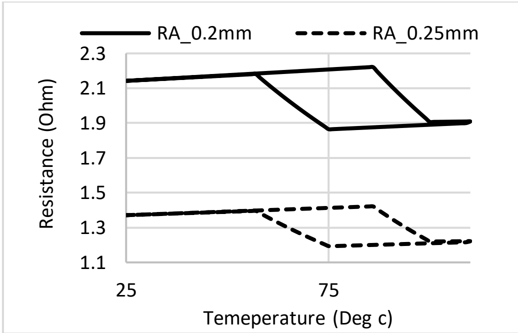
The experimental results for SMA spring and SS spring with various parameters and symbols obtained are listed in Table 1. The diameter of wire for SMA and SS spring are selected closer to fit into standard Braille cell dimensions. This arrangement can maintain closeness further avoided interference of nearby pins during actuation.

TABLE 1. OBTAINED PARAMETERS FOR SMA AND SS SPRING

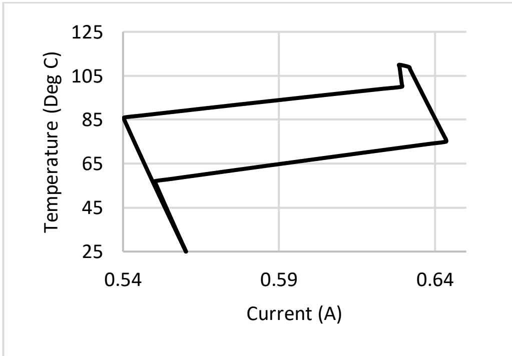
Parameter, symbols	**SMA wire spring values**	**Stainless steel wire spring values**	**Unit**
Diameter of wire (d)	0.2	0.25	mm
Outer diameter of a coil (D)	1.37	2.1	mm
Free length (Lo)	15	10	mm
Number of active winding/coils (a)	18	8	--
Shear modulus $(\tau_s)\tau_c$	28.195	29.64	GPa
Modulus of elasticity (E)	75	30	GPa
Material Density	6540	8000	Kg/m^3
Spring constant (k)	0.0826	9.12	N/mm
Spring index (c)	5.86	7.4	N/mm
Deformation force (F_d)	0.0009	0.07	N/mm
Material composition	Ni (49%)-Ti (51%)	SS Music Wire	--

The wire owns the property of change in length due to a temperature change. Applied current results in an increase in temperatures. Further, the resistance of a wire is temperature-dependent is of paramount importance to decide a control strategy. The experiment is conducted to find a change in resistance over a temperatures profile and the current required to raise the temperature for successful phase transformation. In the experiment, two wires of diameters 0.2 mm and 0.25 mm are used to decide the above-mentioned parameters. The obtained results for change in resistance due to temperature change are shown in Figure.3. (a). As RA_diameter of wire and temperature variation due to change in applied current is given in Figure.3. (b) for 0.2 mm and Figure.3. (c) for 0.25 mm diameter of a wire. It shows that a wire with a diameter of 0.25 mm offers low values for resistance hence current is needed to increase the temperature from room temperature phase transformation temperature varied from 0.8-1 A and with a wire diameter of 0.2 mm needs 0.5-0.65 A.

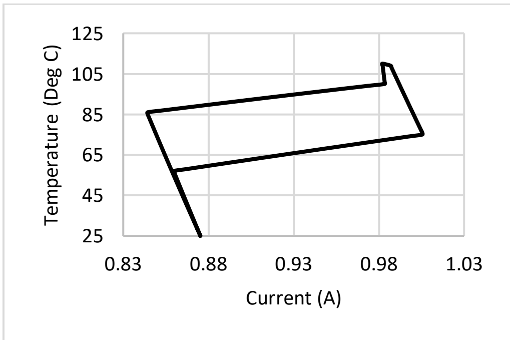
It is observed that phase transformation occurs between small temperature changes of 85-100 °C during heating and 75 to 57 °C during cooling. This is achieved with a wire diameter of 0.2 mm effectively with low power consumption. Hence this wire is selected for spring design and further, all the experiments are conducted with the same wire.



(a)



(b)



(c)

FIGURE.3

(A) WIRE RESISTANCE VARIATION OVER TEMPERATURE (B) CURRENT NEEDED FOR 0.2 MM (C) CURRENT REQUIRED 0.25 MM

In this novel approach, experimental results with excitation techniques and feedback are verified with major improvement in parameters. It is understood that cooling time is troublesome in such applications. Hence, for natural convection, actuator assembly is kept open from all sides to have proper air circulation. The excitation current is removed during the cooling phase to follow natural convection instead of reducing the current in steps. The performance of each type of actuator is listed in Table 2. In table column D indicates displacement and column I indicate the current supplied for respective displacement. It is seen that a maximum of 5 s is taken by the wire actuator to achieve 4 mm displacement, an actuator of type-3, type- 4 with thermal feedback taking 3 s for the same. The current required for actuation during heating is 0.1 A type-4 with feedback and 0.3 A for a type-1 actuator. This ensures less power consumption during actuation.

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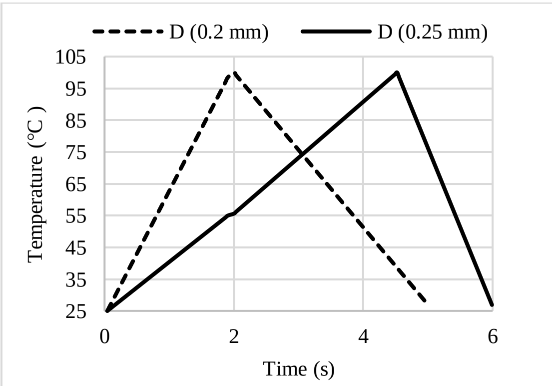
TABLE 2. PERFORMANCE OF EACH TYPE OF ACTUATOR

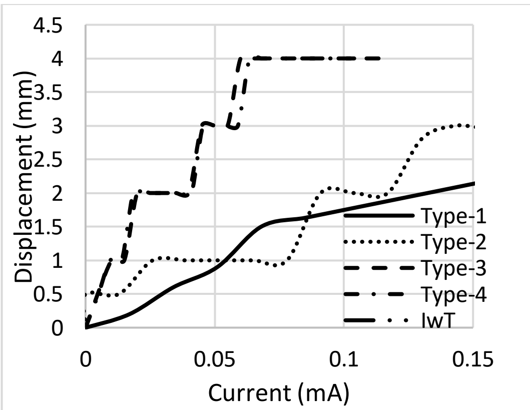
Performance Parameter	**Wire actuator (type-1)**		**Spring actuator (type-2)**		**SMA with Bias spring actuator (type-3)**		**Spring with a guide and thermal feedback (type-4)**	
Time (s)	D	I	D	I	D	I	D	I
0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.9	0.1	1.0	0.0	2.0	0.0	2.0	0.0
2	2.0	0.1	2.0	0.1	3.0	0.0	2.0	0.0
3	2.7	0.2	3.4	0.2	4.0	0.1	4.0	0.1
4	3.3	0.3	4.0	0.2	4.0	0.1	4.0	0.1
5	4.0	0.4	4.0	0.3	4.0	0.1	4.0	0.1

The position of the tip of each pin is kept at 1 mm height from the surface showing raised condition. Figure.4 (a) indicates the time required to raise the temperature to change phase for two different diameters of wire. It also shows that a lower diameter approximately requires 2 s for heating and 3 s for cooling, thus a 0.2 Hz operating frequency. For higher diameters heating time also increases.

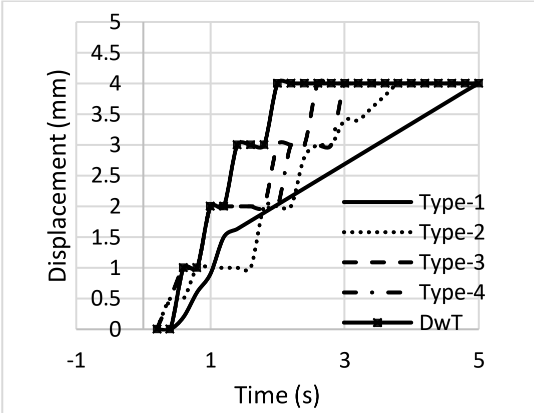
In Figure.4 (b) the current needed to achieve 4 mm of displacement for each type and type-4 with thermal feedback as DwT and without feedback as type-4 are shown. It is seen that DwT needs 70~80 mA, while types -1, 2, and 3 require more than 150 mA of current to have 4 mm displacement. Figure.4 (c) shows displacement with time for each actuator configuration. The actuator DwT has achieved 4 mm displacement in 2 s, shown by a thick black line with a square marker on it. Type-1, 2, 3, take 3~4 s for the same displacement. In Figure.4 (d) power needed for the desired displacement concerning time for all configurations are plotted, and the actuator with thermocouple has shown 0.2 W for 2 s power consumption. A wire-based actuator requires power up to 2 W for the desired displacement. In this figure type-4 with thermal feedback is highlighted as power consumption which in both the cases are fairly similar.



(a)



(b)



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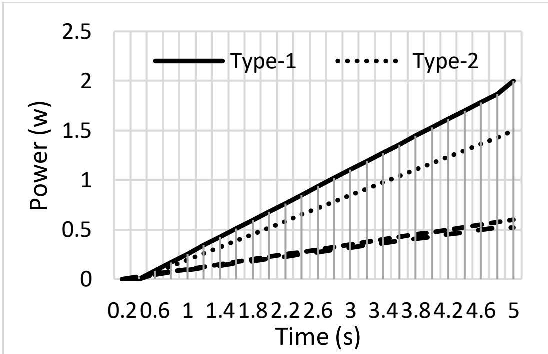

(d)

FIGURE.4

(A) TIME AND TEMPERATURE RESPONSE OF SMA SPRINGS (B) CURRENT REQUIRED TO ACHIEVE THE DESIRED DISPLACEMENT (C) TIME REQUIRED TO ACHIEVE THE DESIRED DISPLACEMENT (D) POWER REQUIRED FOR ACTUATION

III. Comparison of existing approaches

The implemented approach compared with existing SMA actuator techniques in the tactile display. A single wire Ni-Ti actuator to demonstrate actuation function utilizing 0.3 mm diameter and 1200 mm length wire with supplying a current of 0.5-1.5 A variation displacement of 5 mm was achieved. These actuators have limited applications because of their size and force generated. The implemented approach achieved a displacement of 3mm with a current required of 0.1-0.42 A which is quite lesser than in [21].

Aniello Riccio et al. [22], Dorin Copaci et al. [23], Cheol H. Park et al. [24], Janeth A Guadalupe et al. [25] have proposed different spring-based actuators to overcome the high force needed in actuators. Multiple wires or spring actuators can improve the position response of the actuator, but the electrical efficiency is very less. Heating and cooling time is more. Resistance variations are not used in the design. This added limitation in miniaturization for tactile displays. In the implemented approach, tactile display pins generate a maximum of 5 N force during contraction which is more than enough to have a displacement of 4 mm which is found to be better as compared to all the existing SMA actuators as reported in Table 3. The small heating time of 2 s and cooling time of 2~3 s is achieved in the work by following international standards in the development of the Braille display.

TABLE 3. COMPARISON OF ACTUATOR PERFORMANCE PARAMETERS WITH AN EXISTING SYSTEM.

Parameter	Ersin [21] 2020	Aniello [22], 2021	Dorin [23], 2019	Cheol [24], 2019	Janeth [25], 2021	Proposed
Actuator type and material	Single wire, Ni-Ti	Spring, Ni-Ti	Spring	Spring Bundle, Ni-Ti	Spring, Ni-Ti	Spring, Ni-Ti
Wire/ spring diameter (mm), Length (mm)	0.3, 1200	2.5, 106	0.51, 0.2	2.5, --	0.51, 1000	0.2 -0.25, 10
Displacement (mm)	5	42	--	69.9	32	4

Current required (A)	0.5-1.5	--	--	--	--	0.1-0.42
Heating and cooling time (s)	--	200, 300	--	0.5, --	420	2, 3
Resistance (Ohm)	5.9-6.7	--	--	--	--	7-11

CONCLUSION

The work carried out intends to decide the best possible and effective actuator configuration to integrate into a tactile display. It is found that the wired actuator generates less force with long lengths, hence setting restrictions on the actuator size. The SMA spring actuators are best over wires but require the support of a bias spring. The SMA spring is normally in the expanded form due to heat it pulls the tactile rod down, during heating buckling may occur, and it touches a nearby pin. This is overcome by a guide through SMA spring. The thermocouple set for thermal feedback showed improved performance over other configurations and reduced current by 30 % of that without guide and feedback, and power requirements by improving electrical efficiency. The total displacement work in the proposed tactile display is seen to be improved with a refresh rate of 4 Hz. Furthermore, this work can be extended to develop display and validate the representation of alphanumeric characters for improving the perception of Blind subjects.

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