Mechanism Design for Improved Resolution in Refreshable Tactile Graphics

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Abstract: ***Tactile perception is a medium that enables the blind to read text and diagrams. The available books are bulky and at times, expensive. Refreshable Braille Displays are commercially available devices that display one line at a time but a medium for reading diagrams remains absent from the market. Such a device would require thousands of independently actuated dots that need to be packed in a constrained area. Even if such scale is achieved, it comes with high costs and power consumption. Technologies have been developed that use small arrays of actuators but those are limited to reading braille text. The ability to identify and read diagrams remains essential for the blind to grasp knowledge and pursue their interests. A cost efficient and reliable device could empower the visually impaired and provide the advantages that auditory aids never could. This report discusses the choice and design of different actuators so as to develop graphics that offer a better resolution through a decrease in the dot to dot distance compared to existing devices, along with a cost-efficient mechanism. It finally discusses the design of a braille cell using a bimetallic actuator which offers improved resolution.***

Keywords: Braille, Tactile graphics, resolution, refresh rate

1. Introduction

Tactile perception is a medium that enables the blind to read text and diagrams. The available books are bulky and at times, expensive. Refreshable Braille Displays are commercially available devices that display one line at a time but a medium for reading diagrams remains absent from the market. Such a device would require thousands of independently actuated dots that need to be packed in a constrained area. Even if such scale is achieved, it comes with high costs and power consumption. Technologies have been developed that use small arrays of actuators but those are limited to reading braille text. The ability to identify and read diagrams remains essential for the blind to grasp knowledge and pursue their interests. A cost efficient and reliable device could empower the visually impaired and provide the advantages that auditory aids never could. This report discusses the choice and design of different actuators so as to develop graphics that offer a better resolution through a decrease in the dot to dot distance compared to existing devices, along with a cost-efficient mechanism.

2. Braille Devices

Digital devices such as auditory aids and text to speech synthesis have provided the blind an access to a lot of digital content but the need of braille literacy remains essential. Reading and writing play an important role while figures and diagrams are difficult to explain using oral means. Braille is not just limited to reading documents but is involved in every day to day activity of the blind where they would need labeling, be it identifying symbols or choosing items of daily use.

From infancy, sighted children are exposed to visuals everywhere, in books, on walls, on products, in textbooks while the blind kids grow up in the absence of all these visuals which hampers their learning and the choices they have. Tactile Graphics conveys to the blind, this information which is not found in text. This could be tactile representation of graphs, diagrams or any kind of image. These are raised lines that can be felt on touch and are used to obtain the same information that visuals could provide. Thermoforming is used to a great extent to create copies of such tactile diagrams where computer generated graphics are printed on a swell paper where risen lines are formed when the paper is sent through a special heating process. This remains a costly technique and the printed pages are very bulky to carry as well.

Multiple devices are commercially available that provide the function of reading braille text. These come in the form of keyboard like devices that offer a line at a time to read or mouse like devices that interpret word by word and convert it into braille. The feature to read graphics remains absent from these devices. American Printing House offers a device that allows graphics to be depicted by means of an array of variable – height pins. They use piezoelectric technology which is very costly. The resolution offered by the device also compromises on the quality of the graphics.

3. Challenge

The focus of the Refreshable Tactile Graphics (RTG) has now shifted towards offering a high resolution and low cost solution that could be brought into daily use. Thus, the challenge here is to create a mechanism to provide automated actuation of pins at a better resolution to cover for the non-affordability and poor resolution of existing solutions.

4. Theory

Actuators working on different principles were analyzed and compared. The selection of the technology is based on the overlapping of characteristics of the actuator with the requirement of the task to be accomplished. These actuation technologies were plotted against each other and were rated based on the parameters-

The actuator principle (e.g. piezo ceramic stack actuator, solenoid actuator, hydraulic cylinder): [1]

- Set of non-geometrical design variables (e.g. the kind of active material used, the amount of pre-strain of a Shape-Memory wire)
- Set of geometrical variables
- The actuator input quantity
- The external load

Table 1: Comparative analysis of different Actuation technologies [2]

Actuator Type	Dimensional Feasibility	Actuator Power Density	Actuator Life and Reliability	Response Time	Cost and Affordability	Operational Energy Efficiency
Piezoelectric	↑	↓	↑	↑	↓	↑
SMA	↑	↑	→	→	↑	→
EAP	→	↓	unknown	↑	↓	→
Electromagnets	↓	→	↑	↑	→	↓
Hydraulics	↓	↑	↑	→	↓	→
Pneumatics	↓	↑	↑	→	↓	↓
Thermo-pneumatics	↑	→	↓	↓	↑	↓
ER/MR Fluids	↑	→	unknown	→	↓	unknown
MEMS	↑	→	unknown	→	↓	unknown

Key to Symbols: ↑ : Good →: Average ↓: Poor

Shape Memory Alloys- To understand the SMA the martensitic transformation that occurs in the shape memory alloys yields a thermos-elastic martensite and develops from a high-temperature austenite phase with long-range order []. The transformation, although a first-order phase change, does not occur at a single temperature but over a range of temperatures that varies with each alloy system. The alloy undergoes a martensitic transformation of a type that allows the alloy to be deformed by a twinning mechanism below the transformation temperature. The deformation is then reversed when the twinned structure reverts upon heating to the parent phase.

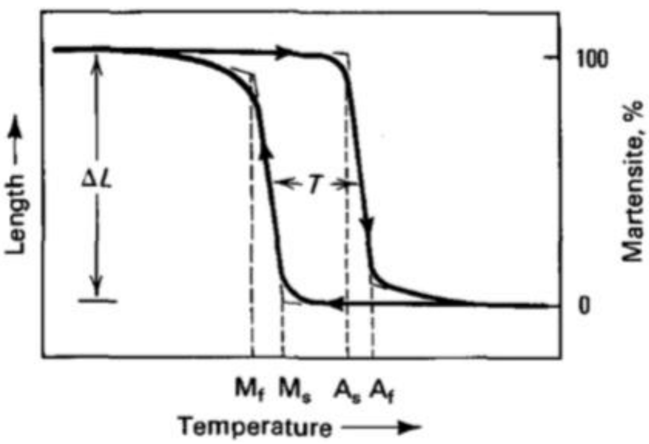

Figure 1: Typical transformation versus temperature curve a specimen under constant load (stress)

Microfluidic Device Design for Refreshable Braille and Tactile Graphics- The work suggests the application of microfluidic logic for controlling pneumatic actuators in a large-array tactile device []. Experimental devices were built in support of the modeling using microfluidic technology. A refreshable braille cell was constructed that relies on microfluidic logic to control eight actuators with only three electronic solenoid valves. While the device is larger than current commercial braille cells, it demonstrates the scalability of using microfluidic logic for a large-array of actuators suitable for refreshable braille.

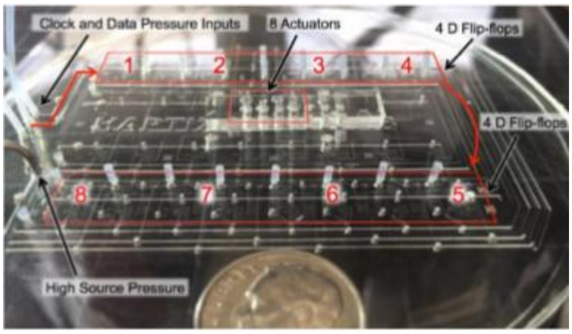

Figure 2: Pneumatic D latches are configured in series to create an 8-bit shift register [6]

Bi-material actuators are devices that utilize the motion created from the heating or cooling of a bi-material strip to translate into work. This work can be used, for example, to flip a switch in a thermostat. Bimaterial strips are comprised of two different materials (metals like copper and steel, or polymers like PE, PET, even wood) joined together along their surfaces. The materials are chosen have very different thermal expansion coefficients, such that one side of the strip will expand more when heated than the other. This causes the strip to bend when heated above its joining temperature.

Figure 3: Bending of bimetallic strip on change in temperature

The equation predicting the radius of curvature (RT) of a bimaterial strip (Timoshenko, 1953) is:

$$1/R_T\text{-}1/R_{T_o}\text{=}(6(\alpha_1-\alpha_2)(1+m)^2/3(1+m)^2 + (1+m.n)(m^2+1/m.n))T-T_o/s \quad (1)$$

where Rt is the radius of curvature at temperature T and Rto is the radius of curvature at some other temperature To. The thermal expansion coefficients of the materials are α, where material 1 has the lower thermal expansion coefficient (α1) and material 2 has the higher thermal expansion coefficient (α2). m and n in the equation are both ratios of values: m $=t1/t2$, the ratio of the thicknesses of the materials, and n = $E1/E2$, the ratio of the elastic moduli of the materials. Finally, s is the total thickness of the bimaterial strip (t1 + t2).

5. Mechanism Design process

Following methodology was adopted to come up with a desired mechanism-

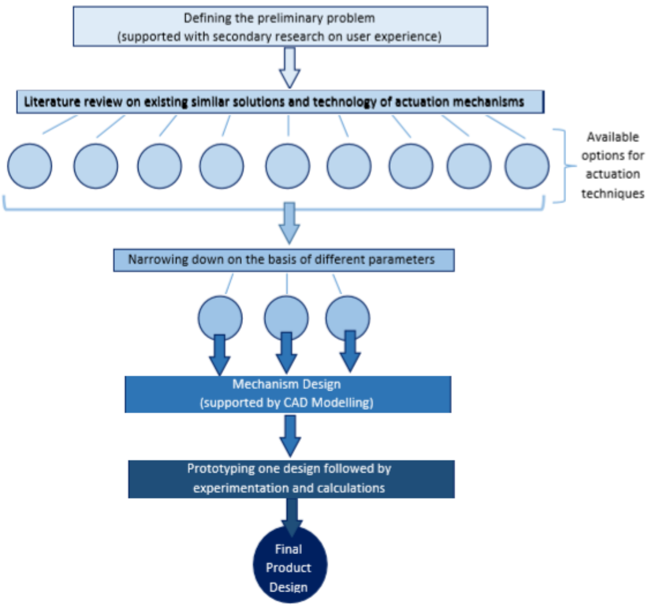

Figure 4: Design methodology

There have been recent developments in the domain of digital braille where resolution has been improved to the actual Braille framework but the same technology could not be used in graphics. The cell design does not allow the assembly of multiple braille cells adjacent to each other and is limited to a single line assembly. Limited options are available for graphics and that too either have a poor resolution or are just too heavy on the pocket. Hence, there is a need to develop a novel mechanism to raise and lower desired braille pins automatically that works with the given constraints. The dot to dot distance is desired to be kept under 3mm. The design of the single cell should be such that it can be assembled to create arrays of similar cells. Power consumption for the mechanism should be minimal so as to cover for the heating issues that could arise in the assembly.

Following these guidelines, these actuation technologies were considered that could suit our case-

Shape memory alloy based actuation:

The first version of **SMA mechanism** was based on simple lever system. SMA wire is known to contract on being heated (heat given through the current being passed through it), it pulls down the lever bar supported by a fulcrum which on the other end connected to the bottom of the braille dot pushes it upwards. The whole mechanism is meant to supported by the casing and an electronic panel at the bottom for current supply. Since dot-to-dot distance is 3mm as constrained above. The casing will have the square cross section of 3mm x 3mm.

As shown in figure 5 the bend angle in the version 1 mechanism can be effectively approximated to 00 (it has been pulleyed over cylindrical outer surface of lever) but according to the stress/strain theory for SMA wires, 1100 is the maximum recommended angle of bend to avoid fatigue and fracture.

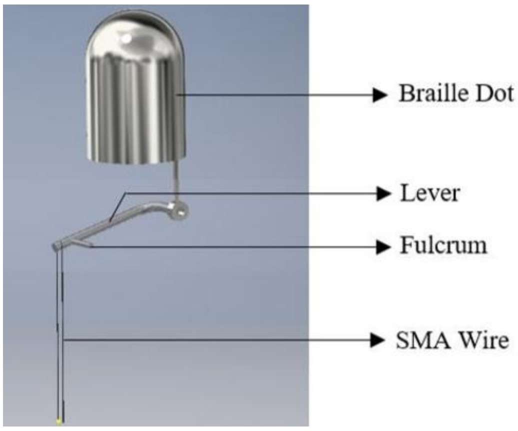

Figure 5: Simple lever based SMA mechanism

Another version includes the **SMA spring wire** which gives 35% compression rate on being heated as compared to just 3% in the previous case. Here, as shown in the figure the current supply is given from the green tape connecting wires (golden lines are representing wires), the black spring structure going through the middle of the hollow cylindrical casing of braille dot is SMA wire which is attached to the bottom of the casing. When the current is passed through the SMA wire it contracts and pulls the braille dot from the bottom considering the tape (1) to be stationary. The above compartment contains the mechanical spring to pull back the raised braille dot when current is drawn out and SMA wire relaxes to its initial length.

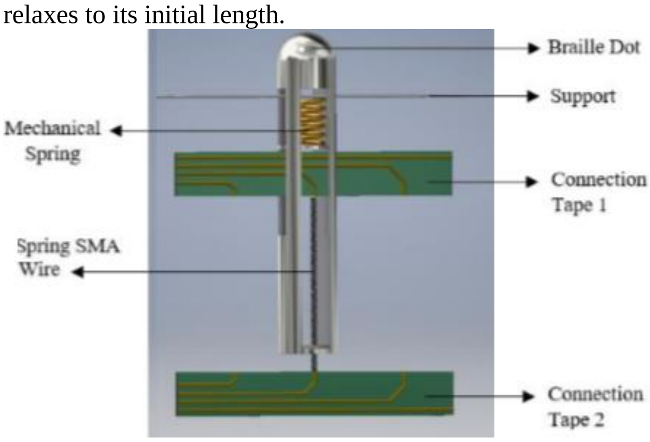

Figure 6: SMA spring based actuation mechanism

Problem occurs when one looks into the constraints of the size, when one talks about 3mm x 3mm cross-section, the feasibility of fabrication and availability of materials limits the pursuit of the idea further.

Electromagnetic actuation:

The proposed solenoid consists of a coil and a movable plunger as shown in Figure 7. The electromagnetically inductive coil is wound around the plunger. A permanent magnet is to be used as a plunger in order to generate a higher force. Hence, two kinds of force are now exerted in the solenoid, the electromagnetic force by the magnet field due to current and the other magnetic force from the permanent magnet.

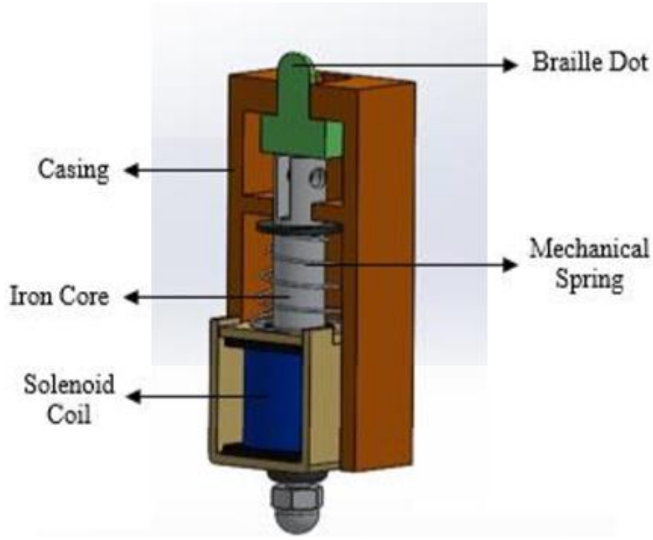

Figure 7: CAD model: Solenoid based actuator

The maximum resultant force by the solenoid depends on the length L, air-gap Z, number of coil turns N, applied current i, inner diameter d, outer diameter D and the type of permanent magnet. [3]

$$B_{sol,z} = \frac{\mu_0 N i}{2L(D - d)}(L + 2z_p)\, ln\left[\frac{D + \sqrt{D^2 + (L +}}{d + \sqrt{d^2 + (L +}}\right. + \frac{\mu_0 N i}{2L(D - d)}(L - 2z_p)\, ln\left[\frac{D + \sqrt{D^2 + (L - 2z_p)}}{d + \sqrt{d^2 + (L - 2z_p)}}\right. \quad (2)$$

The following relation is used to obtain the design parameters for a resultant force of .03N

$$\mathbf{F} = \frac{B_r B_{sol,z} A}{\mu_0}\hat{z} \quad (3)$$

Pnuematic actuation

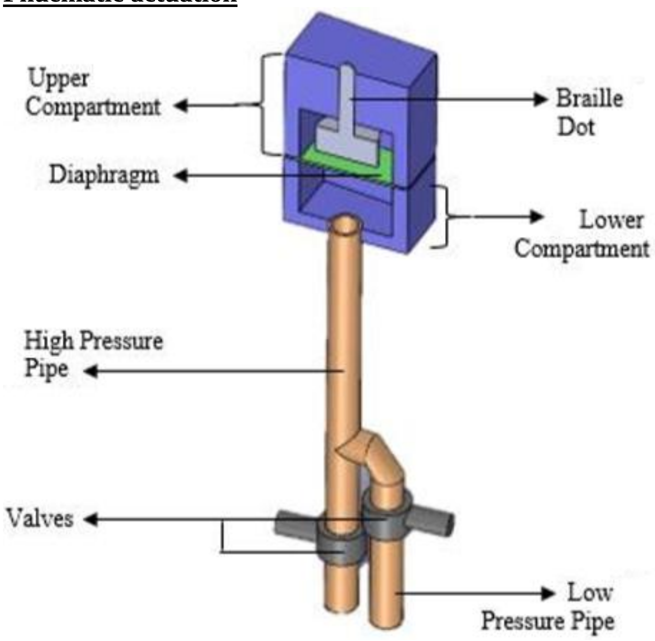

Figure 8: CAD model: Pneumatic actuator

As shown in the CAD model, this mechanism consists of one compartment and pipe assembly below it. The compartment is further divided into two parts via diaphragm (green) the upper part of the compartment contains the braille dot and the lower one contains the space for pressure variation. In the pipe assembly, the left pipe is for high pressure and the one towards right is a low pressure one. When the air is drawn into through the high pressure pipe towards the compartment by opening the black valve it pushes the diaphragm upwards and the braille dot is actuated and to bring it down back the air is drawn out from the side pipe which creates the vacuum and the braille dot comes to its resting position

Since this mechanism contains two components, the upper part when assembled will comprise the board and the lower part will constitute the actuation panel, which becomes bulky to handle due to involvement of large number of pipes and valves. The feasibility and usability parameter seems to get compromised in the given situation.

6. Final design

Failing to cater to one or the other objective in every scenario lead to rethinking on the basic problem statement and on further analyzing it, it was realized that since graphics do not require to be refreshed as often as text and the required refresh rate is not a constraint, one could simplify the mechanism and increase the area of possibilities.

It was identified that if one uses actuation for one way and mechanical force to move the pin in the other direction, this could help simplify the mechanism and make it work in the constrained space at reduced costs. A little added effort is expected off the user in this case. A mechanical extension is used which swipes the screen on every refresh similar to the working of a slate. The pins are pressed down into the normal position and are ready to be actuated again.

Bi-metallic actuator:

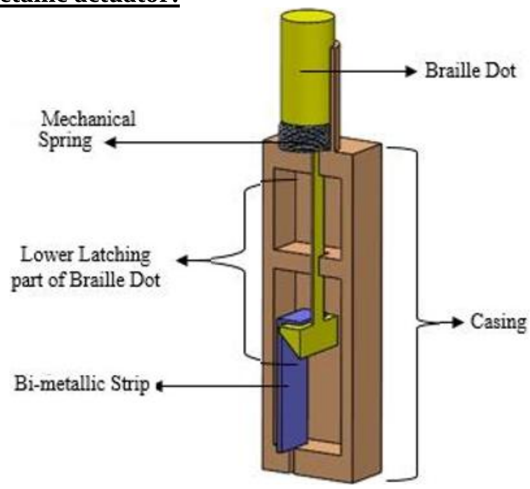

Figure 9: Single cell design

This mechanism comprises of 2 compartments, the lower compartment contains the hook part of the braille dot and the bimetallic strip inserted through the casing wall from the bottom. The strip is bent for 1mm at 900 to hold the hook when in relaxed position. The upper compartment contains the spring which is normally compressed and hold the potential energy to launch the braille dot after the latch is released when bi-metallic strip is heated. One part of the actuation is done. When the required braille dots are raised to make the tactile diagram, it is perceived by the visually impaired user meanwhile the bimetals are cooled and hot air is drawn out by the fans. When touch reading is done, braille dots are pushed back into the casing using the laptop-like rectangular pad, attached to the display as shown in figure 10.

Material selection

Depending upon the application, certain properties are more sought after than others. The primary bases of the choice of material of bimetallic for the mechanism is its Thermal Activity. It requires the highest activity at minimal temperature change so as to avoid power consumption and heating losses. A search through the catalogue of the manufacturer and through comparative analysis of different bimetallic grades on the bases of:

- Thermal Activity
- Electrical Resistivity
- Thermal Conductivity
- The Maximum Operating Temperature

The Temperature-range in which linearity of deflection is required. It was identified that type 721-112 has the highest activity. Type 721-112, because of its greatest deflection rate, is also the second most widely used type of bimetal with its properties as follow- [4]

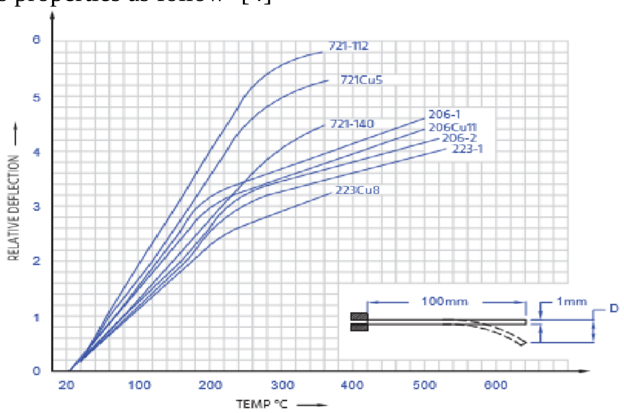

Figure 10: Deflection vs Temperature curve for different materials

Deflection calculations:

For the mechanism to work in the constrained space, the required deflection in the cantilever was kept to be 1 mm.

Table 2: List of parameters used for calculating bi-metallic deflection

Parameter	Value
D	1 mm
a	$21.5 * 10^{-6}$ / °F
L	25 mm
t	0.17 mm
w	1 mm

The following equations relate the deflection required with the rise in temperature and the associated forces that could be generated. [5]

$$D = \frac{a\Delta T L^2}{t} \quad (4)$$

$$F_m = \frac{Ewt^3 D}{4L^3} \quad (5)$$

$$F_t = \frac{Eat^2 w\Delta T}{4L} \quad (6)$$

Table 3: List of variables used in the deflection equations

D	Deflection in mm
A	Angular deflection in degrees
ΔT	Temperature change in degree C
w	Width in mm
t	Thickness in mm
L	Active length in mm, i.e. the length free to deflect
a	Specific thermal deflection in per degree
E	Young's modulus in N/mm^2
F_m	Mechanical force in N, i.e. the force required to mechanically cause a deflection of D.
F_t	Thermal force in N, i.e. the force that would be developed if the bimetal is completely restrained.

On using the given parameters, the required change in temperature comes out to be approximately 12.6 °C. Mechanical force in N, i.e. the force required to mechanically cause a deflection of D is 0.011 N.

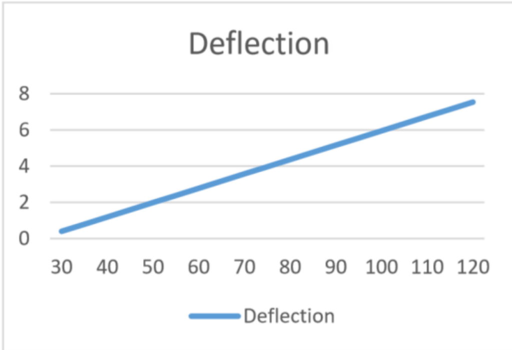

Figure 11: Temperature vs Deflection curve for the chosen bimetallic material

Spring of spring constant less than 73.33 N/m can be used for the mechanism. Thermal force in N, i.e. the force that would be developed if the bimetal is completely restrained is 0.01096 N. The chosen bimetallic material shows a linear behavior in deflection till a temperature around 200°C.

Power consumption:

Electric current is used to heat the bimetallic strip in order to cause the required bending of 1mm. To achieve this, the bimetallic has to be raised by a temperature of 12.6 °C. The following equations relate I, the current required to heat the bimetallic to the given temperature in a given time of 0.2 seconds, ρ, the resistivity, γ, the density, c, the specific heat capacity, w, width and t, thickness of the bimetallic material.

$$\Delta T = \frac{I^2 \rho \tau}{\gamma t^2 w^2 c} \quad (7)$$

Table 4: List of variables and their respective values used in power consumption formulae

Symbol	Parameter	Value
ρ	resistivity	1.122 Ω mm^2/m
γ	density	7800 kg/m^3
c	specific heat capacity	450 J/kg -°K
w	width	1mm
t	thickness	.17mm

The value of current required to cause the change in temperature is found to be 2.387 Amp. The corresponding value of resistance of the bimetallic material is .205 Ω. In an ideal scenario where the current supplied is used up in heating the bimetallic with zero loss of heat in the ambience, the required power consumption is found to be 5.865 Watt per cell.

Cooling rate:

The cooling rate of the bimetallic strip in the absence of any other cooling system is calculated. Assuming that the heat loss due to radiation is negligible, the following equation has been used to identify he cooling time.

$$T = T_e + (T_{initial} - T_e) * e^{-\lambda t} \quad (8)$$

Where, $\lambda = S * h/\rho VC$

$$h = Nu_L k/L \quad (9)$$

$$Ra_L = Gr_L \Pr = \frac{g\beta(T_s - T_\infty)L^3}{v\alpha} \quad (10)$$

$$\beta = \frac{2}{T_s + T_\infty} \quad (11)$$

$$Nu_L = [0.825 + \frac{0.387\, Ra_L{}^{1/6}}{[1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}]^{8/27}}]^2 \quad (12)$$

Table 5: List of variables and their respective values used in the calculation of cooling time

Symbol	Parameter	Value
T_∞	Ambient Temperature	298 K
ρ	Density of Bimetallic	7800 kg/m^3
V	Volume of strip	4.25 $*10^{-9}m^3$
C	Heat Capacity	450 J/kg -°K
T_s	Temperature of bimetallic	311 K
h	Convective heat transfer coefficient	13.464
S	Surface area	.000025 m^2
β	Volumetric thermal expansion of air	3.2 $*10^{-3}K$
Pr	Prandtl Number	0.7
Ra	Rayleigh Number	2.24 $* 10^5$
Gr	Grashof Number	
ν	Kinematic viscosity of air	20.92 $* 10^{-6}m^2$/s
α	Thermal diffusivity of air	29.9 $* 10^{-6}m^2$/s
k	Thermal conductivity of air	30 $*10^{-3}\, W/_{m-K^{-1}}$
L	Length of strip	.025 m

In the following calculations, these assumptions were made The value of h has been taken constant with temperature being 298K for the sake of simplicity. Temperature change of 15°C has been taken as a standard for the required deflection. Cooling time measured theoretically at different temperatures has been recorded in the following table. Natural convection has been taken as the only medium of heat loss.

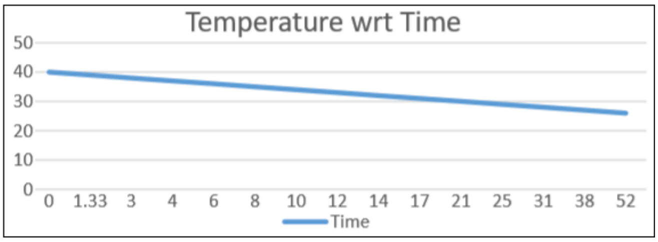

Figure 12: Cooling of bimetallic wrt time

Thus, it takes 52.2185 seconds for the bimetallic strip to revert back into its normal position.

Final assembly:

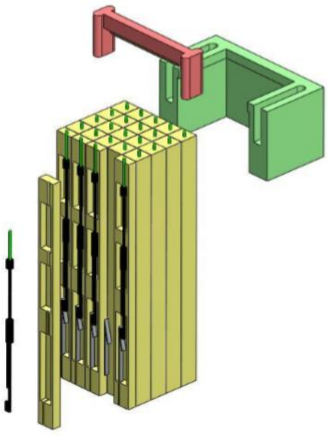

Figure 13: Exploded view of assembly of stacked bimetallic braille cells

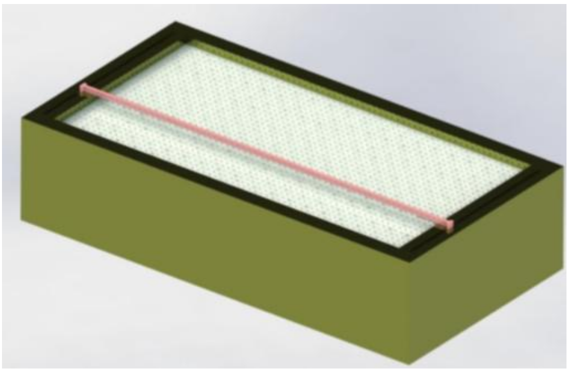

Figure 14: Final view of the Refeshable Braille Tactile product

7. Conclusions

This project proposes a bimetallic actuator based one-way actuated Braille dot cell which has a better resolution as compared to existing refreshable graphics. The specifications of the design have been mentioned.

Table 6: List of parameters used in final design in bimetallic actuation

Parameter	Value
D	1 mm
a	21.5 $* 10^{-6}$ / °F
L	25 mm
t	0.17 mm
w	1 mm

Table 7: List of resulting physical parameters for actuation cycle

Parameter	Value
Required change in temperature	12.6 K
Cooling time	52.2185 second
Current Required	2.387 Amp
Power Consumption	5.865 W
Force when restrained	0.0109 N

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