Smart Material Actuators For Active Tactile Surfaces

A Thesis

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Abstract

The objective of this thesis is to identify actuation technologies for active tactile surfaces. Such surfaces are envisioned to change texture when given an electrical input. One way to change texture is to create button-like protrusions of different sizes. This technology is expected to combine the advantages of touchscreens and tactile buttons to create refreshable tactile surfaces. Suitable technologies that can be used to create protrusions are initially studied in a literature review. Based on the conclusion of comparative study in the literature survey, shape memory alloys are selected as the smart material and various actuators are built using SMA wires. Conical springs are used as SMA actuators and a $3 \times 3$ array is built. Modeling of the force versus deflection curve of helical and conical shape memory alloy springs is also presented.
Dedicated to my mentor and guide, Late Dr. S. R. Kajale and my mother, for her never-ending support and love.
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Chapter 1: INTRODUCTION AND COMPARATIVE STUDY OF SMART MATERIALS

1.1 Motivation

Many technologies have been developed for making man-machine interfaces more intuitive. Highly advanced haptic technologies such as touchscreens are found in commonplace electronic devices like mobile phones, ATMs and other such machines. Touchscreens provide faster and easier operation than traditional tactile buttons. They also save space and hardware by having the ability to refresh and produce a number of menus in the same limited amount of space, rather than using a separate assigned space for every button. Touchscreens are highly flexible while changing the layout, software and configuration of an interface.

Despite these advantages, touchscreens lack a major feature provided by physical buttons. Most touchscreens today provide a visual and auditory feedback, but low or no tactile feedback. Touchscreens require complete visual attention from the user and thus, are of no use to the visually impaired. Having touchscreens in devices like global positioning units, dashboards, etc. in a vehicle may distract the drivers from the road. Though certain touchscreens provide an auditory feedback, this feedback is not enough to guide the user without visual interaction.
Thus, there is a need of hybrid devices which can combine the advantages of touchscreens and physical buttons. Such hybrid devices will have a refreshable surface along with tactile and, if necessary, auditory feedback. The refreshable surface is envisioned to have buttons which traverse a linear path, having two distinct positions: raised and lowered. In the raised position, they will act like normal physical buttons and in the lowered position, they will be a part of the background surface of the interface. Such devices can be designed using passive actuators like hydraulics, pneumatics or active material actuators, like shape memory alloys, piezoelectrics, etc. which respond to electrical signals, to drive the buttons. A detailed literature review was done in order to determine which smart material technology, commercially available or published, can be used to develop such a device. In the next section, various smart material technologies and the current state of the art in this field are discussed.

1.2 Push button force-displacement requirements

The tactile feeling generated by the ‘click’ of a push button and its protrusion from the surrounding surface is what distinguishes push buttons from touchscreens. The force required to push a button is usually in the range of 1 N to 3 N depending on the type of button. Buttons like keyboard keys and those in cell phones are softer, i.e., require less force than bigger buttons such as those in a car or machine panel. The click feeling is produced by a sudden drop in the force after a continuous increase until it reaches a ‘switching point’. This force versus deflection response is produced by using tactile snap domes made of rubber or metal, as shown in Figure 1.1 [23]. The force versus deflection curve of a push button with adequate tactile feedback looks as shown in Figure 1.2 [23].
Figure 1.1: Tactile snap dome (diameter: 6 mm).

Figure 1.2: Force versus deflection curve for a push button.

Figure 1.3: Force versus deflection curve for a snap dome.
Figure 1.3 is the response of a typical metal snap dome used in a push button; F is the maximum actuation force, \( F_R \) is the return force and \( S_k \) is the maximum travel. Snap domes are used to provide tactile feedback and electrical contact in push button switches, keyboards, etc. Plastic or rubber domes can also be used instead, and they have a similar force versus deflection response. The term used to quantify the tactile characteristics is called ‘Click Ratio (\( C_R \))’ or snap percent. The target for \( C_R \) is between 30 and 50%. Click ratio is defined as:

\[
C_R = \frac{F - F_R}{F} \times 100.
\]  

(1.1)

According to Doerrer et al. [23], the force required for a comfortable click of a button is in the range 1.5 to 2.5 N. In the experiments conducted by Doerrer et al. [23], the participants were asked to imagine a button at a ticketing machine. The displacement was 5 mm and the force was varied from 0 to 5 N to find the optimum force range and characteristics for the most pleasant tactile feedback. The increase of force to the switching point was observed to be around 1 N, as well as the following decrease of force after the maximum force is reached. However, this increase and decrease of force may vary, as long as the maximum force lies in the given range.

1.3 Comparative study of smart materials for tactile surfaces

The objective of this study is to examine actuation technologies for active tactile surfaces. Such surfaces are envisioned to change texture when given an electrical input. One way to change texture is to create button-like protrusions of different sizes. Technologies that can be used to create protrusions are smart inchworm actuators, shape memory alloys utilizing creative displacement amplifying mechanisms, smart polymer based actuators, osmotic actuators used in microfluidics, electrostatic
actuators, surface acoustic waves and vibrations. The tactile surface device in consideration is expected to operate at low power ($\approx 12$ V, $4$ A), with sufficiently fast frequency response ($\approx 5$ to $10$ Hz) and small footprint ($8$ mm $\times$ $8$ mm). The target specifications for the tactile surface actuator investigated in this thesis are shown in Table 1.1. A review of millimeter and sub-millimeter level actuators is presented, in accordance to these parameters.

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
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<tr>
<td>Electrical</td>
<td>12 V, 4 A or less</td>
</tr>
<tr>
<td>Refresh rate</td>
<td>100 ms</td>
</tr>
<tr>
<td>Speed</td>
<td>30 mm/s</td>
</tr>
<tr>
<td>Wait time between refreshes</td>
<td>1000 ms</td>
</tr>
<tr>
<td>Footprint</td>
<td>$8$ mm $\times$ $8$ mm</td>
</tr>
<tr>
<td>Actuation deflection</td>
<td>$6$ mm</td>
</tr>
<tr>
<td>Vertical displacement</td>
<td>Discrete up or down states</td>
</tr>
<tr>
<td>Temperature range</td>
<td>$-40$°C to $+85$°C</td>
</tr>
<tr>
<td>Duty</td>
<td>$\approx 75000$ cycles</td>
</tr>
<tr>
<td>Self-sensing</td>
<td>Able to know when user is pushing/selecting surface.</td>
</tr>
<tr>
<td>Environmental</td>
<td>Device will be used by human hand (bare or gloved).</td>
</tr>
<tr>
<td></td>
<td>Potential exposure to liquids, direct UV exposure,</td>
</tr>
<tr>
<td></td>
<td>large temperature fluctuations, EM intrusion, etc.</td>
</tr>
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Table 1.1: Actuator performance targets.
Reviews on available technologies were conducted by Benali-Khoudja et al. [6] and Chouvardas et al. [17, 18]. These included piezoelectric, shape memory alloys, electrostatic, electroactive polymers, electro-rheological fluids, pneumatic and electrical (solenoids) actuation technologies. Most of the displays/surfaces have used pin arrays as taxels (tactile pixel elements). The next sections discuss the most promising technologies identified in this study.

1.3.1 Linear Piezoelectric Actuators

A number of different piezoelectric actuators have been investigated and commercialized. Uchino [80] and Watson et al. [86] have classified piezoelectric ultrasonic actuators into various types depending on their principle of operation. Linear piezoelectric actuators/motors are mainly discussed here because a linear motion is needed for discrete up and down movement of buttons for the tactile surface. Figure 1.4 shows the classification of linear piezoelectric actuators based on their principle of operation. Linear piezoelectric actuators have wide ranging applications in robotics,

![Figure 1.4: Types of linear piezoelectric actuators.](image-url)
micro-electro-mechanical systems used in biomedical applications, military, space, automobiles and even consumer products like cell phone cameras and watches. They are compact, simple in construction and precise. Design improvements over the years have also resulted in linear motors having large displacement, high force, faster response time, low voltage and very small size. Several types of actuation mechanisms can be used to produce the desired linear motion output. However, much of the relevant literature is focused on micron to sub-millimeter stroke actuators for refreshable Braille displays and similar applications.

**Inchworm actuators**

The principle of inchworm motors is that there is an intermittent contact of the stator and the rotor. Such motors are commercially available and are widely used in aerospace, biomedical and industrial applications. Most of these motors operate at ultrasonic frequencies. The basic working principle of inchworm motors is based on three smart actuators, two of which act as holding elements and one of them acts as a driving element. Linear motion is created by the sequential contraction and expansion of these three elements. These actuators have unlimited travel and can be reversed at any point of time by reversing the input signal. However, the maximum speed and step size that can be achieved is limited to the maximum strain of the drive element. Figure 1.5 shows the actuation principle of these actuators. Inchworm motors were first developed by Burleigh Instruments [1] in 1975. Since then, high resolution inchworm motors have been developed for various applications. Newton et al. [57] used piezoelectric stacks in the inchworm actuator and achieved speed up to 12 mm/s, with a frequency of 3.5 kHz, but employed very high voltages (up to 200 V). Konishi et al. [42] reported a high accuracy, high stroke inchworm motor having an
electrostatic clutch. They measured a velocity of 195 $\mu$m/s, with a voltage of 100 V. The largest incremental step was $\approx 0.41 \mu$m, but with a lower speed of 40 mm/s. Kim et al. [40] developed an inchworm motor with a stroke of 3 $\mu$m and a bidirectional step resolution of 10 nm. The inchworm actuator was optimized by Erismis et al. [25] by obtaining large stroke ranges and forces at lower operating voltages. They obtained $\pm 18 \mu$m with an operating voltage of 7 V and $\pm 24 \mu$m stroke with an operating voltage of 10 V. A large stroke, zero power latching piezoelectric inchworm motor was designed by Oh et al. in 2010 [58]. It has a very low volume (1 mm(w) $\times$ 3 mm(t) $\times$ 5 mm(l)), full stroke of 5 mm and a speed of 10 mm/s at a frequency of 50 kHz. The driving voltage is 80 V.

Physik Instrumente (PI) has developed PiezoWalk [36] non-resonant motors. These motors consist of a number of piezoelectric elements which are sequentially activated to expand and contract, resulting in clamp/unclamp cycles. At high frequency, this
produces a continuous linear motion of the rod being clamped. Figure 1.6 shows the actuation principle of this motor. The ‘NEXLINE’ motors of this type are used for high force and low speeds whereas ‘NEXACT’ motors have higher speeds (up to 10 mm/s), smaller dimensions and low forces. Both kinds of motors are non-magnetic and hence, do not create or get affected by magnetic fields. They provide much higher resolution than ultrasonic piezo-motors. However, both types of motors are bigger in size as compared to other commercial micro motors. MicroMo Electronics, Inc. [35] produces the ‘Piezo Legs’ motor which imitates the walking motion of an ant, based on a similar principle and is much smaller in dimensions.

**Ultrasonic motors**

These actuators use the resonant frequency of a piezoelectric element to create the desired linear output. An elliptical motion created at the stator tip is converted into linear motion by use of frictional force between the stator and rotor. Ultrasonic motors have very good scalability and can be easily miniaturized. Operating at resonant frequencies gives high speeds, but also reduces the life of the ceramic. Their
resolution is lower than inchworm motors and motion transfer through friction limits the repeatability of operation.

**Standing wave actuators**

Standing wave actuators use resonant vibration modes to create a planar two dimensional motion of the stator. The ‘Baltan’ actuator developed by Friend et al. [26] gave a sliding velocity of 100 mm/s and a peak velocity of 212 mm/s. Friend et al. [27] also developed a linear actuator fulfilling Feynman’s criteria of motor size less than 0.015625 inch on a side. It achieved speeds up to 40 mm/s and could generate forces up to 30 mN. PI [36] have a line of motors based in this principle. The smallest motor offered by PI is based on this principle. A piezoceramic plate is excited to produce high frequency oscillations to hundreds of kilohertz. A friction tip attached to the plate moves along an inclined linear path, and through its contact with the friction bar, it provides linear motion. Another example using this principle

![Figure 1.7: SQUIGGLE motor by New Scale Technologies.](image-url)

is the ‘SQUIGGLE’ motor marketed by New Scale Technologies [75]. This motor has four piezo elements attached to a threaded nut which mates with a small threaded screw. These elements vibrate in orthogonal bending modes, with a phase difference
and create a wobbling motion which results in linear motion of the screw. Several models have been developed, having different speeds and force ranges and are available commercially. The smallest motor needs only 2.3 V, has a travel range of 6 mm, typical speed of 10 mm/sec, resolution of 0.5 µm, operating frequency of ≈ 171 kHz and a wide operating temperature range. It is shown in Figure 1.7. It is 2.8 × 2.5 × 6 mm in dimensions. This motor is highly suitable for high density applications like tactile displays/surfaces, where a number of actuators may have to be accommodated in a small volume. MicroMo Electronics, Inc. [35] offers a ‘PiezoWave’ motor based on this principle. It is small in size and has speed up to 150 mm/s.

**Propagating / Traveling wave actuators**

The basic principle of operation is the same as standing wave actuators, however they differ in the elliptical motion, which is created not only at the tip of the stator but at every point on it. This is because a wave is generated by combining two standing waves [33, 86]. However these actuators are not as scalable as standing wave actuators and cannot be reduced in size very easily. As the scale reduces, the amplitude of the wave decreases and cannot be used as a driving force. Such type of actuators can be used for variable friction based tactile surfaces. Ultrasonic vibrations produce an air film effect which causes a reduction in the friction between the finger and the surface. Thus, by selectively actuating strips or parts of the piezo wafer or element, a difference in friction can be achieved between the actuated and the non-actuated parts.

Vanbelleghem et al. [81] used this principle to create a friction controlled tactile display. An ultrasonic actuator using this principle was developed by (Figure 1.8) by Bharadwaj S. [7]. The metal washer starts rotating when a voltage of 21.97 V
(frequency 16.5 Hz) is applied to the piezoelectric wafer. Since the surface of the ceramic is already quite smooth, no noticeable difference in the friction was observed on touching the wafer.

Figure 1.8: Ultrasonic motor [7].

Inertial / Stick-slip actuators

These are also called as (Smooth) Impact Drive Mechanisms (IDMs or SIDMs) [52]. They consist of an inertial weight attached to the stator tip. There are two modes, the ‘stick’ mode and the ‘slip’ mode in these actuators [47]. Input is given in such a way that the piezoelectric elements have a slow expansion and rapid contraction. Thus, due to inertial force, the mass remains at a constant velocity. Lee et al. [47] developed a 2 degree of freedom stick slip actuator that overcame the limitation of
backward motion of the slider. The size of this actuator was 70 mm × 70 mm × 50 mm.

These motors are commercially available and a few of the manufacturers are MechOnics [51] and Cedrat Group [29]. MechOnics builds miniature translational stages containing piezoelectric inertial motors, with travels from 2 mm to 30 mm. The smallest motor offered by Cedrat Group has a stroke more than 3 mm and speed greater than 50 mm/s. A comparative study of various tiny piezoelectric motors was performed by Belly et al. [5], which shows that the SPA30uXS motor made by Cedrat Group would suit the intended application.

Hybrid motors

Hybrid actuators incorporating more than one type of smart material have been considered. Kim et al. [39] developed a hybrid motor which used Terfenol-D as the push device and multi-stack piezoelectric elements as the clamping device. They achieved a maximum velocity of 0.925 mm/s, maximum displacement of 67 µm, with a voltage of 130 V. Due to the use of a magnetostrictive element, the size of the actuator increased and losses due to hysteresis were also observed.

Tactile displays or surfaces using piezoelectric actuators

Hayward and Hernandez [32] used lateral skin stretch stimulation to create a tactile sensation. Their device consists of a 112 contactor pin array actuated by 64 sandwiched (plate type) piezoelectric actuators. The actuators provided a displacement of ± 5 µm for an applied voltage of ± 200 V. Poupyrev et al. [64, 63] used the ‘TouchEngine Actuator’, as a sandwich of thin piezoceramic films and adhesive electrodes, made as a bending actuator/bimorph. One or two such layers require 80 V to
350 V voltage, however by sandwiching multiple piezoelectric layers, this voltage could be reduced to 8 V to 10 V. Frequencies up to 10 Hz could be produced, along with a very small displacement (about 0.05 mm). Takasaki and Nara explored traveling waves as actuation principle using piezoelectric actuators [71]. They used a surface acoustic wave (SAW) to reproduce the tactile sensation of roughness. Kyung et al. [44] designed a pin based tactile display using piezoelectric bimorph actuators. The vertical displacement of the pins was controlled between 0 mm and 0.7 mm. Biet et al. [8] used traveling Lamb wave (elastic acoustic waves which propagate through solid media) generated by using ‘Traveling Wave Ultrasonic Motor (TWUM)’, operating at a resonant frequency of 40 kHz to make variable roughness tactile display. Wiertlewski et al. [88] used the SQUIGGLE motor to create tactile stimulation of the fingertip by lateral traction. It is the same principle as used by Hayward and Hernandez [32], but using a commercial piezoelectric motor. Several researchers [65, 72, 73, 89] have used piezoelectric actuators in vibro-tactile devices.

Such vibro-tactile devices have now been commercialized by Senseg, headquartered in Helsinki [68]. This technology does not use any smart material; instead electric charges are used to create the tactile sensation.

Summary

Based on the literature review, the piezoelectric motors in Table 1.2 were shortlisted to be purchased. The M-661 motor was not purchased due to the high cost and Cedrat Group has delayed the launch of the demo kit for the SPA30uXS motor. A 3D model of a small mechanism was constructed showing the SQUIGGLE motor as an actuator to raise and lower a button resting on a spring.
Thus, piezoelectric actuators have the following advantages: good frequency response, compact structure, large operating temperature range, high speeds of operation, no thermal output, and commercial production by many companies. Limitations like high cost compared to other smart actuation technologies, generation of low forces, complex drive electronics required for operation and fragile material make piezoelectric actuators unsuitable for the intended application. A 5 × 5 array using piezoelectric motors would cost $12,000 at the current prices.

### 1.3.2 Shape Memory Alloy (SMA) actuators

Shape memory alloys (SMAs) have been traditionally considered as the most suitable technology for tactile surfaces due to their high force to volume and force to weight ratios. Shape memory alloys exhibit a temperature based phase change, low temperature (Martensite) phase and high temperature (Austenite) phase. A shape memory alloy in its low temperature phase, when plastically deformed with all the
external stresses removed, will regain its original (memorized shape) when it is heated above a certain temperature. Up to 8% of strain is recoverable in the high temperature superelastic phase. The stress-strain plot of SMAs (Figure 1.9) shows hysteresis and

![Figure 1.9: Shape memory alloy behavior [24].](image)

has four main transformation temperatures which govern the phase change: Martensite start \((M_s)\), Martensite finish \((M_f)\), Austenite start \((A_s)\) and Austenite finish \((A_f)\). In addition to the strain recovery, there is also a significant increase in the Young’s modulus when the material transforms from Martensite to Austenite.

There are several alloys that exhibit this property: copper-zinc-aluminum-nickel and copper-aluminum-nickel, but the most common shape memory alloy is nickel-titanium or NiTi, also known as ‘Nitinol’. There are several compositions of this alloy. It is manufactured in various forms such as wires, sheets, ribbons by many
companies. Low temperature shape memory alloys (alloys with a low \( A_f \) temperature) are widely used in medical devices such as active catheters, stents, etc. The superelastic property of low temperature SMAs is used in applications like orthodontic braces, eyeglass frames, etc. The actuator applications of SMAs make use of the quasiplastic behavior, i.e., when the operating temperature is below \( M_f \). Generally, shape memory actuators are alloys with a high \( A_s \) temperature.

Wellman et al. [34, 87] used shape memory alloy wires to make a tactile display using an array of pins. The device has a stroke of 3 mm, force 1.5 N and a frequency response of 40 Hz. The SMA wires were arranged in a V shape and used water-based circulation system for cooling the SMA wires, thus improving the frequency response. Though adequate bandwidth and speed were achieved, use of water cooling increased the bulk of the display. An experiment was conducted to show that the temporal bandwidth of the tactile display should be a minimum of 30 Hz. Kohl et al. [41] designed an SMA micro-actuator of size \( 4 \times 4 \times 0.1 \) mm\(^3\), with a maximum stroke of 570 \( \mu \)m. Maximum actuation force achieved was 110 mN. Heating time was 300 ms and cooling time was recorded as 1.5 s. Brenner et al. [10] designed a pin based tactile display using SMA wire actuators. It included a clamping mechanism which can hold the actuator in position (either raised or lowered) until a change is needed. Thus, energy was consumed only when switching states. This display consisted of 16 taxels at a spacing of 2.54 mm, a maximum displacement of 0.8 mm, providing a force of 150 mN. However, it exhibited a slow time response. Actuating the SMA wires with a current of 90 mA took 0.5 s to 0.7 s. Nakatani et al. [54] used a coil-form SMA as a pin-rod actuator for a \( 4 \times 4 \) tactile shape display, mainly to re-create human faces in a ‘Face Phone’. Figure 1.10 shows the ‘Face Phone’ display. A maximum
range of 120 mm was achieved which is much greater than earlier work on tactile displays. This was achieved with a ‘Bio Metal Helix’ SMA actuator manufactured by Toki Corporation. It can extend to twice its length and be brought back to the original length by heating. Instead of using a different controller for each actuator, a matrix drive method was used to drive the actuators. The pin interval was 12 mm.

Velazquez et al. [82, 83] also developed an SMA based portable tactile display. It consists of an array of 8 × 8 upward/downward independent movable pins driven by miniature SMA actuators made of NiTi helical springs. The measured bandwidth is 1.5 Hz, with a total stroke of 3 mm, pull force of 320 mN and a size 45 mm × 45 mm × 45 mm, using a 6.8 W power signal as input. The complete system cost was $200. The actuators have discrete up and down states and a pin spacing of 2.6 mm with taxels measuring 1.5 mm in diameter. A regular computer mini-fan is used to provide forced air convection for cooling of the SMA actuators.

Vitushinsky et al. [84] used bi-stable thin film shape memory actuators for a tactile display (Figure 1.11). Ti-Ni-Cu and Ti-Ni-Hf were sputtered on a wavy structured
substrate on the top and bottom. The actuators were switched with voltage ranges from 0.2 V to 0.8 V and a displacement of 0.7 mm was achieved. Higher displacement (1.2 mm) was achieved by increasing the dimensions of the actuators and with higher voltages. Thus, these SMA actuators could provide a displacement suitable for Braille displays, which require much smaller displacement than haptic surfaces.

The prototype tactile display developed needed a power of 5 W for actuating all the actuators (64 × 64) and the heat produced was dissipated by natural convection. No other active method was used for cooling, since the actuation times would depend on the speed of reading, which is relatively low. Zhao et al. [91] used an array of SMA wires to create a vibration based Braille display. A high frequency pulse was used to actuate the SMA wire, whose small vibrations were amplified by the use of Braille pins. Nespoli et al. [56] reviewed miniature shape memory alloy actuators. They defined criteria for ‘ideal’ mini actuators, both linear and rotational. After reviewing a number of SMA actuators, they concluded that the spring shape provides the best mechanical output of the SMA element and the smallest geometrical dimensions.

Spinella and Dragoni [69] and Spinella et al. [70] designed and analyzed hollow SMA spring actuators. The advantages of hollow cross section SMA spring over solid
section are reduced mass, increased natural frequency, reduced cooling time due to higher surface area to mass ratio, and increased electrical resistance causing lower currents and higher voltages. The drawback is that due to the lower mass, the actuation time increases since there is less material undergoing phase change. Experimental results show that the cooling time decreases by 4 times, so it compensates for the increase in heating time, so that the overall cycle time is lower. Also, the mean coil diameter of the hollow spring is slightly higher than the coil diameter of the solid spring. The manufacturing of hollow springs of small size would be difficult since kinking of the hollow tubes must be avoided at all times during manufacturing or training of the SMA.

Thus, from the above applications it can be concluded that SMAs offer key advantages such as silent operation, low operating voltage, solid-state operation with no moving parts, large displacement and force, increase in stiffness upon actuation (the Austenitic phase of SMAs has 3 to 5 times higher Young’s modulus than the Martensitic phase), design flexibility and relatively low cost.

On the other hand, SMAs have a few disadvantages including slow response time (especially while cooling) and high thermal energy density. SMAs get heated up in milliseconds but cooling requires several seconds. Creative designs and cooling techniques can be incorporated in order to overcome this limitation. In cases when a dense matrix of actuators is required (about $320 \times 240$ taxels) [10] in a small area, the thermal energy density can be high. It can become difficult to thermally insulate the actuators from each other.
1.3.3 Electroactive Polymer (EAP) actuators

Electroactive polymers (EAP), also known as artificial muscles, respond to electrical stimulation [55] by a volume/shape change. These materials have been widely used as actuators for Braille displays where smaller displacements are required [4, 21, 22, 28]. Several researchers have successfully used electroactive polymers to make tactile interfaces having small displacements [9, 12, 13, 15, 50, 59, 77].

There are 2 main classes of electroactive polymers based on their activation mechanism: ionic and electronic. Within these categories, there are several materials: polymer gels, ionic polymer-metal composites (IPMCs), conductive polymers and carbon nano-tubes come under ionic EAPs and electrostrictive, piezoelectric, ferroelectric polymers and dielectric and liquid crystal elastomers (LCEs) come under electronic EAPs. Y. Bar-Cohen [3], Citerin et al. [19] and Carpi et al. [14] provide a detailed explanation of all these types of EAPs. The key material types are explained in the following sections.

Ionic EAPs

Ionic EAPs are polymers which are activated by electrically induced transfer of ions or solvent. These materials require a liquid electrolyte medium for operation and require high currents and much lower voltages (about 1 V to 10 V) than electronic EAPs. The wetness of ionic EAPs needs to be maintained at all times during operation.
Polymer gels

Polymer gels are activated by a chemical reaction stimulated by electricity, heat or light, resulting in the swelling or contracting of the gel. Since this process involves diffusion of the liquid medium in and out of the polymer, ionic polymer gels are slower than other ionic EAPs. Paschew et al. [61] used hydrogel (poly(N-isopropylacrylamide)) to create a high density tactile display. Photosensitive active polymers were used as actuators, controlled individually using a computer interface. These hydrogels not only change volume (causing a change in height from 250 µm to 500 µm) upon heating, but also change their transparency, color and softness. Since the change in height is very small, the actuators are covered with sheets having knobs, which enhances the tactile feedback. The temperature variation required for the activation of this hydrogel is very small (between 29° C to 35° C). These low temperatures pose the risk of undesired actuation. Mide Technology Inc. have developed commercial hydrogel-based bulkhead shaft seals [76].

Ionic Polymer-Metal Composites (IPMCs)

Ionic polymer-metal composites (IPMCs) are composed of ionic gel polymer plated with metal electrodes. They have a large bending response at low voltages (1 V to 3 V). Kato et al. [38] used IPMC actuators to make a soft sheet-type refreshable Braille display. However, encapsulation of the wet actuators was shown to be an issue. Konyo et al. [43] have developed a wearable tactile display which mounts on a fingertip and provides texture and pressure stimulation by controlling roughness, softness and friction using IPMC actuators. The driving voltage is less than 5 V and the displacement is less than 2 mm.
Conductive Polymers

Conductive (or inherently conjugated) polymers (CPs or ICPs) produce high strains (2% or greater) and low stresses compared to other polymer actuators. Reversible volume changes take place in ICPs due to the incorporation and expulsion of ions and solvent into and from the polymeric structure during their electrochemical oxidation or reduction at the electrodes (redox cycling) [3, 14]. When a CP is laminated on a flexible substrate, the volume change induces bending in the substrate and this mechanical action is used in actuation. If a free standing film or fibres of CP are formed such that the actuation occurs mainly in one direction, they can be used as linear actuators. However, they have a very low efficiency (less than 1%) and have stability problems when stressed and have slow response time (several seconds for complete actuation). The response time improves as the size is decreased, but this comes at the expense of a lower force output.

Electronic EAPs

This class of EAPs comprises polymers that exhibit electrostrictive and piezoelectric effects while performing electrical to mechanical energy conversion. Electronic EAPs operate in solid state, in air and are extremely fast compared to ionic EAPs.

Dielectric Elastomers

Dielectric elastomers (DEAPs) are attractive as both actuators and sensors. DEAPs exhibit higher strains than all other polymers [14]. DEAP actuators are based on the electromechanical response of an elastomeric dielectric film with compliant electrodes on each surface (Figure 1.12). The polymer film compresses in thickness and expands in area when high voltages are applied. When the film is constrained to
expand in a single direction, it can be made into a linear actuator. DEAPs can thus be made into various configurations like rolled actuators (Figure 1.13, [2]), diaphragms, bimorphs, etc.

Figure 1.12: Actuation principle of DEAPs.

Carpi et al. [13] have developed a tactile display using hydrostatically coupled dielectric elastomer (HCDE) actuators. A DE base active part is hydrostatically coupled, through an incompressible fluid, to a passive part which interfaces with the load. The Figure 1.14 shows the HCDE actuator. The actuator material is 66 µm
thick silicone elastomer manufactured by Danfoss PolyPower A/S [2]. Voltage up to 2.4 kV is used to actuate the DEAP film. The prototype bubbles have 3 mm base radius and 2.3 mm to 1.7 mm base to apex height. At no load, a relative displacement of 6% is achieved. Choi et al. [16] also developed a Braille display using DEAP actuators in a bubble shape. Though the device satisfies the criteria for Braille display, it has very high actuation voltages (in the order of kV) and a low bandwidth.

**Other EAPs**

Pei et al. [62, 90] have demonstrated a bistable electroactive polymer (BSEP) using poly(tert-butylacrylate) (PTBA), that can have a large strain deformation (up to 335% area deformation at 260 MV/m electric field, 70° C) when heated above the glass transition temperature and returns to the original shape when cooled. This polymer can withstand several thermal cycles unless there is failure due to mechanical fatigue [90]. At a temperature above the glass transition temperature, the strain is

![Diagram](image.png)
instantaneous upon application of electric field. This technology has the following drawbacks which makes it unfeasible for the intended application:

1. High actuation temperature: The BSEP needs to be heated above its glass transition temperature (Tg) for strain deformation. This temperature is at the higher end of the defined temperature range (70° C for PTBA). Using BSEPs for the intended application would require maintaining the high temperature at all times, which is not feasible.

2. High actuation voltage: At the temperature above Tg, very high electric fields need to be applied to the polymer for it to deform. PTBA requires actuation voltages of 1.8 kV for area deformation of 335%. The electric field for maximum possible deformation is 260 MV/m. These values are much higher than allowable in the intended application.

**Summary**

Electroactive polymers have very few commercial options for purchase. In most cases, EAPS are fabricated as per the application requirements in a laboratory environment. Danfoss PolyPower A/S [2] is one of the few companies that provides rolled dielectric EAP actuators, push-pull actuators and EAP films commercially.

From the above sections, it is noted that electroactive polymers have the following advantages: light weight, pliable, less fragile, and insensitive to magnetic fields. However, they have drawbacks which make them incompatible with the intended application. Ionic EAPs require a liquid solvent at all times to prevent drying out and do not work in air. They also have relatively slow response time. Electronic EAPs require very high actuation voltages (greater than 3 kV). EAPs have less strength,
force output, and are expensive compared to SMAs. EAPs have very few commercial options.

1.4 Concluding Remarks

A review of the literature on piezoelectric and shape memory actuators for tactile surfaces suggests that there are commercial piezoelectric motors, which can fulfill the requirements presented in Table 1.1. The main limitation of this technology has to do with cost, which on the retail market can reach up to $500 per device. The cost would go down dramatically in a mass production situation. Electroactive polymers are manufactured commercially by few companies (Dow, Danfoss PolyPower A/S). The EAP rolled actuators provided by Danfoss PolyPower A/S are large compared to the SMA and piezoelectric actuators and are hence not suitable for the intended application. Consistent with the lack of commercial vendors for this material, EAP actuators tend to be expensive (more than €300 for 1 EAP film kit). Building smaller EAP actuators is possible, but that has to be done in a laboratory environment. Table 1.3 gives the comparison of various smart material technologies for this application.

From Table 1.4, it is concluded that SMA actuators are the most promising and cost effective technology for active tactile surfaces. The compact operation, large displacement, and large force provided by these materials can overcome their current limitations. When carefully designed, for example via push-pull designs, SMA actuators can develop the necessary deflection with some compromise to the size and time respond demands. Further, these materials are structural in nature therefore
Table 1.3: Comparison of actuator technologies investigated in this literature survey. O - meets target; Δ - acceptable; X - does not meet target.

being compatible with the forces and fatigue cycles likely to be present in the display application.

1.5 Thesis Overview

The next chapters in this thesis are dedicated to designing millimeter level linear actuators using shape memory alloys. Various forms of shape memory alloys such as wire, thin sheets, different types of springs, etc. are designed to achieve the performance targets specified in Table 1.1. The most feasible form is then selected to make a $3 \times 3$ array. The last chapter presents concluding remarks and future work.
### Table 1.4: Summary of actuator technologies investigated in this literature survey.

<table>
<thead>
<tr>
<th>Actuation</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Overall judgement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric materials</td>
<td>Good frequency response, compact, large operating temperature range, no thermal output, very high speed of operation, different types of configurations easily available commercially, low operating voltages (e.g., SQUIGGLE motor)</td>
<td>High cost, low forces, complex drive electronics required for closed loop control, extremely fragile</td>
<td>X</td>
</tr>
<tr>
<td>Shape memory alloys</td>
<td>Silent operation, low operating voltage, simple mechanisms, clean operation, high force, increase in stiffness upon actuation, flexibility for innovative designs, lower cost compared to other smart materials</td>
<td>Slow response time (especially during cooling), somewhat high temperatures involved, special cooling mechanism may be required for faster operation</td>
<td>O</td>
</tr>
<tr>
<td>Electroactive polymers</td>
<td>Ionic EAPs (gels and IPMCs): Low operating voltages</td>
<td>Involve fluids, slow response, limited commercial options, difficult to control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DEAPs: Good frequency response, high speeds of operation, pliable and fracture-free</td>
<td>High voltage requirements, limited commercial options</td>
<td>△</td>
</tr>
<tr>
<td></td>
<td>BSEPs: No energy required to maintain actuated state</td>
<td>High temperature requirements</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.4: Summary of actuator technologies investigated in this literature survey. O-meets target; △ - acceptable; X - does not meet target.
Chapter 2: SMA CHARACTERISTICS AND ACTUATOR DESIGN

This chapter begins with a discussion of thermomechanical properties of shape memory alloys to understand their behavior. Then, various forms of SMAs, such as wire, helical spring, conical spring and thin sheet are each fabricated and studied to see if they meet the requirements for the intended actuator. Design of a latching mechanism is also discussed and implemented.

2.1 Overview of SMAs

There are various constitutive models to describe the thermomechanical behavior of shape memory alloy available in literature. As described in Chapter 1, Section 1.3.2, shape memory alloys exhibit two different microstructures, Martensitic and Austenitic. These existence of these microstructures is dependent on the temperature and stress state of the alloy. Austenitic microstructure is seen at high temperatures and has a cubic body centered structure. Martensitic microstructure is the low temperature state and has a monolithic lattice structure. Due to these microstructures, SMAs exhibit shape memory and superelastic behavior. The four main transformation temperatures of SMAs ($M_s$, $M_f$, $A_s$ and $A_f$, Section 1.3.2) determine the state of the alloy, whether it will have shape memory or superelastic properties at room
temperature. These transformation temperatures increase with the increase in the stress state of the alloy. Out of the various constitutive models available for modeling the response of SMAs, one dimensional constitutive model proposed by Brinson et al. [11] was used. In the next section, various physical forms of SMAs and their constitutive models are discussed.

2.2 SMA wires

The most commonly available form of shape memory alloys is the wire form. SMA wires are sold in varying lengths and diameters by several companies. SMA wire can be used against a bias force to induce stress and strain in the wire. This bias force can be applied using springs, levers, elastic material, etc. The wire can then be heated using electricity or other means to produce deformation, as the alloy tries to recover the strain introduced by the bias force. Considering the force versus displacement requirement for this application, a simple calculation as given below shows that a considerable length of wire is needed to produce the required deflection for the intended application. The cyclic memory strain in commercially available wires is 3 to 5% for over 100,000 cycles. Considering the actuation strain $\gamma$ to be an average, as 4%, total deflection to be 6 mm and the bias force to be 4 N, the diameter of wire to be used and its length can be found. The yield strength of the Flexinol wire by Dynalloy Inc. is 345 MPa. To have repeat cycling with Flexinol, it is recommended that no more than $2/3^{rd}$ of this value should be in use. For Flexinol, stresses below 103 MPa will keep the permanent strain below 0.5%, even after hundreds of cycles. At 138 MPa, up to 1% permanent strain can occur after 100,000 cycles. Considering that the cross sectional area of the wire as ‘A’, wire diameter as ‘d’, and the maximum
stress to be 138 MPa (20,000 psi), the required wire diameter obtained is 0.192 mm and length 150 mm, as seen in equations (2.1) to (2.4).

\[ \sigma = \frac{F}{A} \]  
\[ d = \sqrt{\frac{4F}{\pi \sigma}} = 0.192 \text{ mm} \]  
\[ \gamma = 0.04 = \frac{\Delta L}{L} = \frac{6}{L} \]  
\[ L = \frac{6}{0.04} = 150 \text{ mm} \]  

Thus, though the footprint of the wire is small, a very long wire is needed for actuation. Hence, other forms of the SMA wire need to be tested; such as, helical and conical shaped springs, in which the SMA can be packed into a small package. In the spring form, though the actuator footprint increases, a considerable amount of material gets packed into much smaller height, which results in higher deflections. The axial force produced in the helical coiled wire is lower than the wire, however it can be designed to meet the requirement.

The required footprint of the actuator is 2 mm × 2 mm. The minimum force variation that human fingers can sense is 0.5 N [74] and the minimum pressure is 0.002 N/mm² [30]. For the range of force 1.5 N to 2.5 N, the pressure will lie in the range 0.375 N/mm² to 0.625 N/mm². This pressure is considerably higher (about 188 to 315 times) than the minimum pressure, though there is no prescribed upper limit to the pressure on a button. Thus, there is a scope of increasing the footprint of the actuator while designing. This gives more freedom while designing the actuator using shape memory alloys, as various configuration of SMAs can be considered.
2.2.1 Embedded SMA wires

If a circular ring made of shape memory alloy wire is embedded in a polymer/elastomer sheet, when the area of the ring decreases, the elastomer could be raised as a part of a spherical cap/dome. Considering the cap height to be 5 mm, the footprint of such kind of actuator is calculated.

![Figure 2.1: Spherical cap.](image)

As shown in Figure 2.1, \( r \) (mm) is the radius of the SMA ring before actuation.

\( a \): Radius of the ring after actuation (mm).

\( R \): Radius of the sphere (mm).

\( h \): Height of the cap. Let \( h=5 \) mm.

Considering that the strain in the SMA wire is 5\%, radius of the ring after actuation is given by equation (2.5).

\[
a = 0.95r
\]  

(2.5)
Surface area of the elastomer before the wire is actuated is taken as same as the area of the ring (equation (2.6)).

\[ S_{\text{ring}} = \pi r^2 \] (2.6)

Assuming that the elastomer does not stretch and the surface area remains the same, surface area of the spherical cap is calculated using equations (2.7) to (2.9).

\[ S_{\text{cap}} = \pi (a^2 + h^2) = \pi [(0.95r)^2 + h^2] \] (2.7)

\[ S_{\text{cap}} = S_{\text{ring}} = \pi r^2 \] (2.8)

\[ S_{\text{cap}} = \pi r^2 = \pi [(0.95r)^2 + h^2] \] (2.9)

Substituting the value of \( h \) as 5 mm results in \( r = 16.01 \) mm and \( a = 15.21 \) mm. The footprint of this type of actuator is \( \pi \times 16.01^2 \) = 805.25 mm\(^2\). Thus, to gain a height of 5 mm, the initial SMA ring diameter must be 32.02 mm. This is assuming that the elastomer does not offer any resistance to the strain in the wire, which will not be the actual case. The stiffness of the elastomer will cause an increase in the required diameter of the SMA ring. This makes the footprint too large. Hence, this option is ruled out for linear actuation.

### 2.3 Helical SMA springs

Several researchers have done the thermomechanical modeling and experimental validation of helical SMA springs. A few of them are reviewed below.

H. Tobushi and K. Tanaka [78] proposed an elastoplastic constitutive relation to predict its SMA force versus deflection behavior. This theory has been used by Velazquez et al. [83] for validation through experiments. Liang and Rogers [48] also proposed a one dimensional model for SMA springs using the SMA theory published
by them, combining it with spring theory. This model was used by Hyo Jik Lee et al. [46], however the experimental results did not match very well with the simulations. Majima et al. [49], Jairakrean et al. [37] and Toi et al. [79] have used the one dimensional Brinson model [11] to develop thermomechanical equations for the behavior of SMA springs. Ryu et al. [67] had used a modified Brinson model to predict the pseudoelastic behavior of SMA springs. They defined and ‘effective’ Young’s modulus of the SMA and derived the equations with conventional strain energy analysis. Several other researchers as Lagoudas et al. [45] have used other SMA constitutive models to describe SMA spring behavior.

Based on its simplicity and accuracy, the Brinson model was chosen to be used for developing the thermomechanical constitutive models for SMA actuators. In the next section, the Brinson model combined with the spring design equations is used to describe the thermomechanical behavior of SMA springs.

2.3.1 Modeling of helical SMA springs using Brinson model

The behavior of shape memory alloy springs can be described by combining the constitutive model for shape memory alloys with the normal helical spring theory.

Shape memory alloy model

The modified constitutive model for shape memory alloys given by Brinson [11] is given by equation (2.10).

\[ \sigma - \sigma_0 = E(\xi)\varepsilon - E(\xi_0)\varepsilon_0 + \Omega(\xi)\xi_S - \Omega(\xi_0)\xi_S_0 + \Theta(T - T_0) \]  

(2.10)

The subscript 0 denotes initial conditions. The Martensite volume fraction \( \xi \) is given by equation (2.11).

\[ \xi = \xi_S + \xi_T \]  

(2.11)
where

\( \sigma \): Stress

\( \epsilon \): Strain

\( E(\xi) \): Martensite dependent Young’s modulus

\( \Theta \): Stress/temperature coefficient

\( \Omega \): Phase transformation coefficient

\( \xi_T \): Martensite volume fraction due to temperature

\( \xi_S \): Martensite volume fraction due to applied stress.

The Martensite dependent Young’s modulus \( E(\xi) \) and the phase transformation coefficient \( \Omega \) are functions of the volume fraction, given by equations (2.12) and (2.13).

\[
E(\xi) = E = E_A + \xi(E_M - E_A) \quad (2.12)
\]

\[
\Omega(\xi) = \Omega = -\epsilon_L E(\xi) \quad (2.13)
\]

where \( \epsilon_L \) is the maximum recovery strain and is experimentally determined.

Several researchers [20, 31, 78, 83] have used the above equation for modeling SMA springs. The modeling done here is based on similar procedure used by Aguiar et al. [20], but uses as slightly different approach. Pure shear stress equation for SMAs is obtained by replacing \( E \) (Young’s modulus), \( \sigma \) (stress) and \( \epsilon \) (strain) by \( G \) (shear modulus), \( \tau \) (shear stress) and \( \gamma \) (shear strain) respectively in equation 2.10, giving the constitutive relation given by equation 2.14.

\[
\tau - \tau_0 = G(\xi)\gamma - G(\xi_0)\gamma_0 + \Omega(\xi)\xi_S - \Omega(\xi_0)\xi_{S0} + \Theta(T - T_0) \quad (2.14)
\]

Shear stress \( \tau \) can be written as

\[
\tau = \tau_0 + G(\xi)\gamma - G(\xi_0)\gamma_0 + \Omega(\xi)\xi_S - \Omega(\xi_0)\xi_{S0} + \Theta(T - T_0). \quad (2.15)
\]
The equations (2.12) and (2.13) can also be similarly modified as below.

\[ G(\xi) = G = G_A + \xi(G_M - G_A) \tag{2.16} \]
\[ \Omega(\xi) = \Omega = -\tau_L G(\xi) \tag{2.17} \]

Using Figure 2.2, the equations giving the stress and temperature induced martensite volume fraction are defined by the Brinson model as given in equations (2.18) to (2.24).

Conversion to detwinned Martensite: For \( T > M_s \) and \( \sigma_s^{cr} + C_M(T - M_s) < \sigma < \sigma_f^{cr} + C_M(T - M_s) \):

\[ \xi_S = \frac{1 - \xi_{S0}}{2} \cos \left\{ \frac{\pi}{\sigma_s^{cr} - \sigma_f^{cr}} \times [\sigma - \sigma_f^{cr} - C_M(T - M_s)] \right\} + \frac{1 + \xi_{S0}}{2} \tag{2.18} \]
\[ \xi_T = \xi_{T0} - \frac{\xi_{T0}}{1 - \xi_{S0}}(\xi_S - \xi_{S0}) \tag{2.19} \]
For $T < M_s$ and $\sigma_s^{cr} < \sigma < \sigma_f^{cr}$:

$$\xi_S = \frac{1 - \xi_{S0}}{2} \cos \left[ \frac{\pi}{\sigma_s^{cr} - \sigma_f^{cr}} \times (\sigma - \sigma_f^{cr}) \right] + \frac{1 + \xi_{S0}}{2} \quad (2.20)$$

$$\xi_T = \xi_{T0} - \frac{\xi_{T0}}{1 - \xi_{S0}} (\xi_S - \xi_{S0}) + \Delta T \xi \quad (2.21)$$

Where, if $M_f < T < M_s$ and $T < T_0$:

$$\Delta T \xi = \frac{1 - \xi_{T0}}{2} \{ \cos \{ a_M (T - M_f) \} + 1 \} \quad (2.22)$$

else $\Delta T \xi = 0$

Conversion to Austenite:

For $T > A_s$ and $C_A (T - A_f) < \sigma < C_A (T - A_s)$:

$$\xi = \frac{\xi_{A0}}{2} \left\{ \cos \left[ a_A \left( T - A_s - \frac{\sigma}{C_A} \right) \right] + 1 \right\} \quad (2.23)$$

$$\xi_S = \xi_{S0} - \frac{\xi_{S0}}{\xi_{A0}} (\xi_0 - \xi) \quad (2.24)$$

where

$$a_M = \frac{\pi}{M_s - M_f}, \quad a_A = \frac{\pi}{A_f - A_s}. \quad (2.25)$$

Combining spring theory with SMA model

For a helical spring of mean diameter $D$ and wire diameter $d$ the axial load is given by Wahl [85] as shown in equation (2.26).

$$F = \frac{2}{D} \int_0^{d/2} dM = \frac{2}{D} \int_0^{d/2} \frac{4\pi \tau a^3}{d} da \quad (2.26)$$

$a$ is the radial coordinate along the wire cross section. This is based on the assumption that an element of an axially loaded spring behaves like a straight bar in pure torsion. Solving for $\tau$, equation (2.27) is obtained.

$$\tau = \frac{8FD}{\pi d^3} \quad (2.27)$$
This is the uncorrected shear stress, neglecting effects due to bar curvature and direct shear. Equating shear stress from equations (2.15) and (2.27) results in equation (2.28).

\[
\tau = \tau_0 + G\gamma - G\gamma_0 + \Omega\xi_S - \Omega\xi_{S0} + \Theta(T - T_0) = \frac{8FD}{\pi d^3} \tag{2.28}
\]

Thus, the shear strain is given by equation (2.29).

\[
\gamma = \frac{8FD}{G\pi d^3} - \frac{1}{G}[\tau_0 - G\gamma_0 + \Omega\xi_S - \Omega\xi_{S0} + \Theta(T - T_0)] \tag{2.29}
\]

Consider an element ‘ab’ on the surface of the bar, parallel to the axis. After deformation, this element will rotate by an angle \(\gamma\) to the position ‘ac’, as shown in Figure 2.3. From elastic theory, this angle is equal to the shear strain [85].

![Cross sectional element of spring under torsion (elemental theory)](image)

Figure 2.3: Cross sectional element of spring under torsion (elemental theory) [85].

Assuming that the spring may be considered as a straight bar of length \(L = \pi n_a D\), the total angle \(\beta\) by which one end of the spring rotates with respect to the other is given by

\[
\beta = \int_0^{\pi n_a D} \frac{2\gamma}{d} \, dx. \tag{2.30}
\]
\( n_a \) is the number of active coils.

Using equation (2.29) in equation (2.30), equation (2.31) is obtained.

\[
\beta = \frac{16FD^2n_a}{Gd^4} - \left\{ \frac{2\pi n_a D}{Gd} \left[ \tau_0 - G\gamma_0 + \Omega \xi_S - \Omega \xi_{S0} + \Theta(T - T_0) \right] \right\} \tag{2.31}
\]

The effective moment arm of the load \( F \) is equal to \( \frac{D}{2} \), the deflection at load is given by equation (2.33).

\[
x_t = \frac{\beta D}{2} \tag{2.32}
\]

\[
x_t = \frac{8F n_a D^3}{Gd^4} - \left\{ \frac{\pi n_a D^2}{Gd} \left[ \tau_0 - G\gamma_0 + \Omega \xi_S - \Omega \xi_{S0} + \Theta(T - T_0) \right] \right\} \tag{2.33}
\]

### 2.3.2 Plots

Using this theory, taking force as a function of stress, strain and temperature, the stress versus strain and force versus deflection plots were generated in Matlab. A nitinol compression spring of the dimensions in Table 2.1 was purchased from Jameco Electronics Ltd. It has an \( A_f \) temperature between 55° to 65°C. The properties for SMA were taken from the paper by Brinson [11], as given in Table 2.2.

### Table 2.1: Helical spring dimensions.

| \( D \) | mean diameter | 7.0358 mm |
| \( d \) | wire diameter | 0.5 mm |
| \( n_a \) | number of active coils | 17 |
| \( n_i \) | number of inactive coils | 0 |
| O.D. | outer diameter of the spring | 8.0518 mm |

Using
<table>
<thead>
<tr>
<th>Transformation temperatures</th>
<th>Transformation constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s = 9^\circ C$</td>
<td>$C_M = 8 \text{ MPa/}^\circ C$</td>
</tr>
<tr>
<td>$M_f = 18.4^\circ C$</td>
<td>$C_A = 13.8 \text{ MPa/}^\circ C$</td>
</tr>
<tr>
<td>$A_s = 34.5^\circ C$</td>
<td>$\sigma_s^{cr} = 100 \text{ MPa}$</td>
</tr>
<tr>
<td>$A_f = 49^\circ C$</td>
<td>$\sigma_f^{cr} = 170 \text{ MPa}$</td>
</tr>
<tr>
<td></td>
<td>$\epsilon_L = 0.067$</td>
</tr>
</tbody>
</table>

Table 2.2: SMA properties.

the above SMA properties and spring dimensions (Table 2.1), plots were generated in Matlab. Figure 2.4 shows the force versus deflection characteristics of a shape memory alloy helical spring of the given dimensions. The compression spring of dimensions

![Figure 2.4: Force versus deflection for a helical SMA spring: Matlab result.](image-url)
mentioned in Table 2.1 was tested at different temperatures under a 50 lb load cell on a small load frame with an environmental test chamber. It should be noted that though the spring tested is a nitinol spring, the exact transformation temperatures and other constants for that material are not known. Therefore, the Matlab plots cannot be directly compared to the actual experimental result. Also, since the sample tested was a compression spring, the deflection could not go beyond a certain value (i.e., free length - solid length of the spring). Due to this, at high temperature, not enough stress was generated to cause stress induced Martensite formation. Therefore, a hysteresis loop is not seen in the Austenitic phase of the SMA. The experimental force versus deflection plot at 2 different temperatures is given in Figure 2.5.

![SMA helical compression spring](image)

**Figure 2.5**: Force versus deflection for a helical SMA spring: experimental result.
Figure 2.6: Force versus deflection for a helical SMA spring at 34°C: experimental result.

It is seen that the spring is much stiffer at temperatures greater than $A_f$, i.e., at 89.44°C than at 34°C. It is also observed that at lower temperature (Figure 2.6), the spring has an initial constant stiffness, followed by a plateau and then rise in stiffness again, similar to that seen in the Matlab plots (Figure 2.4). There is no hysteresis observed at 90°C. The spring that was tested had open ends, due to which it buckled when the force increased. Hence, as the turns of the springs start closing onto one another, they slip under high pressure due to imbalance and the spring suddenly buckles. The sudden dip in the force at the end of the curve seen in Figure 2.5 is caused due to this buckling. The picture in Figure 2.7 shows the spring buckling under pressure.
2.3.3 Push-pull and latching mechanism

Helical SMA springs were also fabricated in the lab by wrapping an SMA wire around a steel rod and subjecting the rod to shape memory training. The rod with the SMA wire wrapped on it is heated in a furnace at a temperature if 500°C for about 15 minutes. Then it is quenched in cold water and the SMA spring is set. A push-pull mechanism is built using two SMA helical extension springs acting opposite each other, as shown in Figure 2.8. A small metal snap dome can be added in series with these springs to provide the click feeling or to complete a circuit when the user presses the button.

A latching mechanism can be used with a push-pull mechanism, such that the SMA spring needs to be actuated only to reach the up/down position and gets mechanically
latched in that position. This saves energy as the spring needs to be actuated only to reach the required position and not to hold that position.

The latching mechanism shown in Figure 2.9 is the similar to that of a retractable pen, with an SMA compression spring providing the clicking force instead of the user. There a few design differences but the basic function of locking is the same. The cam rotates and latches in two positions: up and down, on being pushed down by the push-rod (Figure 2.10). The restoring force opposing the SMA spring is provided by a steel/music wire spring. Initially, the SMA spring is in cold state and gets compressed to its solid length due to the restoring spring and the restoring spring is partially compressed. When the SMA is heated by passing electric current, the SMA spring extends and gains its memorized state. Thus it provides linear motion and force to compress the restoring spring, pushing the push-rod down to rotate the cam. The SMA spring pushes the push rod, which in turn pushes the wedged rod. The angular surfaces make the wedged part to rotate and the steel spring then pushes it all the way up. To bring the actuator up, the SMA spring has to be actuated for a very short duration, just enough to cover the rotation of the wedged part. To
reach the down position, the SMA spring has to be actuated to cover the entire stroke distance. Thus, since the actuation time is reduced in one half of the cycle, the overall actuation time is less than a normal SMA push-pull actuator. As soon as the cam is latched, the current can be stopped. The button will remain in this position until the SMA spring is again actuated to rotate the cam again. The basic mechanism is two helical compression springs in series.

Figure 2.9: Retractable latching mechanism.
The restoring spring is a music wire spring of the following properties:
Outer diameter O.D.: 4.318 mm (0.170 inch), wire diameter d: 0.3556 mm (0.014 inch), length L: 23.495 mm (0.925 inch), number of active turns: 11, spring rate k: 0.2146 N/mm (1.2257 lbs/in).

The SMA spring is made of 0.5 mm diameter Flexinol wire, with a pitch of 0.8 mm and a mean diameter of 3.57 mm. The number of active turns is 29. The displacement obtained is about 6.5 mm. The resultant displacement obtained is 4.5 mm. The heating up of the SMA spring occurs very fast, but cooling needs more than 30 seconds in still air. All parts were initially made using 3D printing. Figure 2.10 shows the parts which were printed. However, since the resolution of the printer was not high enough, a normal retractable pen was cut and installed in the setup. This increased the overall size of the setup. Supporting structure was designed and 3D printed. Figure 2.11 shows the design and Figure 2.12 shows the prototype.
Figure 2.11: Helical SMA spring with music wire spring; exploded view of parts.

Figure 2.12: Prototype: button lowered (left), button raised (right).
2.4 Conical SMA springs

Conical SMA springs have an advantage over normal helical springs because they can provide the same stroke, but their overall height can be much less than helical springs. Conical springs can be made to be telescoping or non-telescoping. Telescoping conical springs can be pressed down to the diameter of a single wire. As mentioned in Section 2.2, since there is a scope to increase the footprint of the actuator, conical SMA springs are a good option to reduce the height of the actuator, while keeping the stroke/deflection the same.

2.4.1 Modeling of conical SMA springs

The model for SMA helical spring presented in Section 2.3 is extended to describe the thermomechanical behavior of conical SMA springs. The analysis of conical springs has been done by very few researchers. The static model for conical compression springs proposed by Rodriguez et al. [66] and the one dimensional constitutive model for shape memory alloys by Brinson [11] has been used in this analysis. For a conical spring, the variable spring diameter is a function of the coil number \(n_D\) \((n_D\) being the continuous variable, running from 0 to \(n\)), given by equation (2.34).

\[
D(n_D) = D_1 + \frac{(D_2 - D_1)n_D}{n_a}
\]  
(2.34)

\[
n_a D = \int_0^{n_a} D_1 + \frac{(D_2 - D_1)n_D}{n_a} \, dn_D
\]  
(2.35)

For \(n_a\) active coils and \(n_i\) inactive (end) coils, the free length of the active coils \(L_a\) and solid length of the spring \(L_c\) are given by equations (2.36) and (2.37).

\[
L_a = L_0 - n_i d
\]  
(2.36)
Figure 2.13: Design parameters of a conical spring [66, 60].

\[ L_c = L_s + n_d d \]  \hspace{1cm} (2.37)

\( L_s \) is the solid length of the active coils. From Section 2.3, axial deflection of helical SMA spring is given by equation (2.33) as:

\[ x_t = \frac{8F_n a D^3}{Gd^4} - \left\{ \frac{\pi n_a D^2}{Gd} [\tau_0 - G\gamma_0 + \Omega \xi_S - \Omega \xi_{S0} + \Theta (T - T_0)] \right\}. \]  \hspace{1cm} (2.38)

Substituting equation (2.35) in equation (2.38) gives equation (2.39) for the axial deflection of a conical spring at a given load.

\[ x_t(F, T, \xi_S) = \left\{ \frac{2F n_a (D_1 + D_2)(D_1^2 + D_2^2)}{Gd^4} \right\} \]  \hspace{1cm} (2.39)

\[ - \left\{ \frac{\pi n_a (D_1^2 + D_1 D_2 + D_2^2)}{3Gd} [\tau_0 - G\gamma_0 + \Omega \xi_S - \Omega \xi_{S0} + \Theta (T - T_0)] \right\} \]

Equation (2.39) gives the thermomechanical behavior of linear (non-telescoping) conical SMA helical springs, together with equations (2.16) and (2.17).
For a telescoping spring (one in which the coils telescope) with constant pitch, the force displacement curve has two regimes. The linear regime, described by equation (2.39), is until the first active coil touches the ground. After that the response becomes non-linear due to subsequent coils touching the ground, thus increasing the stiffness. As the active coils are gradually compressed to ground, \( n_f \) is the number of free coils (those which have not been compressed to ground). Thus, \( n_a - n_f \) is the number coils compressed to ground. The transition point from the linear to nonlinear regime occurs when the first active coil touches the ground and is no longer able to deflect, thus becoming inactive (i.e., solid). After this, \( n_f \) continuously decreases from \( n_a \) to 0.

For such type of spring, the total deflection is the sum of the total axial deflection of free coils and the total axial deflection of the solid coils. This can be approximated by addition of the elementary deflections of the free coils and solid coils, given by equation (2.40).

\[
x_t = x_f + x_s = \int_0^{n_f} \delta_f(n_D) + \int_{n_f}^{n} \delta_s \tag{2.40}
\]

Using equation (2.39), the elementary deflection can be written as

\[
\delta_f(n_D) = \left[ \frac{8F[D(n_D)]^3}{Gd^4} \right] \, dn_D - \left[ \frac{\pi[D(n_D)]^2}{Gd} \left[ \tau_0 - G\gamma_0 + \Omega \xi_S - \Omega \xi_{S0} + \Theta(T - T_0) \right] \right] \, dn_D.
\]

51
For a constant pitch spring, the axial distance between consecutive coils is constant. Therefore, the elementary deflection of the solid coil is equal to the maximum geometrical elementary deflection.

$$\delta_s = \frac{L_a - L_s}{n_a} \quad \text{dn}_D \quad (2.42)$$

The transition load, $F_T$, is the load at which the first active coil (with diameter $D_2$) reaches its maximum deflection $\delta_s$ and becomes solid. So, for this point T, equating the maximum deflection and elementary deflection gives equation (2.44).

$$x_f(n_a) = \delta_s \quad (2.43)$$

$$\left\{ \frac{8F_T D_2^3}{Gd^3} - \frac{\pi D_2^2}{Gd} [\tau_0 - G\gamma_0 + \Omega \xi_s - \Omega \xi_{s0} + \Theta(T - T_0)] \right\} = \frac{L_a - L_s}{n_a} \quad (2.44)$$

Thus,

$$F_T = \frac{Gd^4(L_a - L_s)}{8n_a D_2^3} + \frac{\pi d^3}{8D_2} [\tau_0 - G\gamma_0 + \Omega \xi_s - \Omega \xi_{s0} + \Theta(T - T_0)]. \quad (2.45)$$

At the ultimate compression state of the spring, $F_C$ represents the force required to compress the smallest active coil to ground. This happens when the spring reaches its maximum deflection $L_0$. So this point can be described similar to the transition point and the force at coil close is given by equation (2.46).

$$F_C = \frac{Gd^4(L_a - L_s)}{8n_a D_1^3} + \frac{\pi d^3}{8D_1} [\tau_0 - G\gamma_0 + \Omega \xi_s - \Omega \xi_{s0} + \Theta(T - T_0)] \quad (2.46)$$

For any load between $F_T$ and $F_C$, the number of free coils $n_f$ can be calculated as the value $n$ for which the elementary deflections of the free coils reaches the elementary deflection at solid/ground, i.e., $n_D = n_F$. Thus, for $F \in [F_T, F_C],

$$\delta_f(n_f) = \delta_s. \quad (2.47)$$
From equation (2.41), equation (2.48) is obtained.

\[
\left\{ \left[ \frac{8F[D(n_f)]^2}{Gd^4} \right] - \left[ \frac{\pi[D(n_f)]^2}{Gd}[\tau_0 - G\gamma_0 + \Omega\xi_S - \Omega\xi_{S0} + \Theta(T - T_0)] \right] \right\} = \frac{L_a - L_s}{n_a}
\]

(2.48)

This cubic equation in \(D(n_f)\) has to be solved to obtain the value of \(D(n_f)\) and thereby the value of \(n_f\) using \(n_D = n_f\) in equation (2.35). Since the coefficients of \(D(n_f)\) are real, the nature of the roots of equation (2.48) can be determined. As a consequence of the intermediate value theorem, every cubic equation with real coefficients has at least one real root. The nature of the roots can be determined by considering the value of a discriminant. For a cubic equation of the form

\[
a x^3 + b x^2 + c x + d = 0,
\]

(2.49)

the discriminant is given by

\[
\Delta = 18abcd - 4b^3d + b^2c^2 - 4ac^3 - 27a^2d^2.
\]

(2.50)

For equation (2.48), \(c = 0\), \(b < 0\), \(d < 0\). This gives

\[
\Delta = -4b^3d - 27a^2d^2.
\]

(2.51)

Thus, \(\Delta < 0\). This means that the equation (2.48) has one real root and two complex roots. Since complex roots are not valid in this case, only one real value for \(D(n_f)\) is obtained. This can then be substituted in equation (2.52) to get \(n_f\).

\[
D(n_f) = D_1 + \frac{(D_2 - D_1)n_f}{n_a}
\]

(2.52)

\(n_f\) is then substituted in equation (2.40) to get the total axial deflection of a conical SMA spring for a given force.
2.4.2 Plots and mechanism

Using this theory, taking force as a function of stress, strain and temperature, force versus deflection and stress versus strain plots were generated using Matlab for a spring of dimensions given in Table 2.3 and using the SMA properties listed in Table 2.2. Figure 2.14 shows the shear stress versus shear strain plots for the spring.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>D₁</td>
<td>small mean diameter</td>
<td>2.794 mm</td>
</tr>
<tr>
<td>D₂</td>
<td>large mean diameter</td>
<td>8.382 mm</td>
</tr>
<tr>
<td>d</td>
<td>wire diameter</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>L₀</td>
<td>free length</td>
<td>15.24 mm</td>
</tr>
<tr>
<td>nₐ</td>
<td>number of active coils</td>
<td>6</td>
</tr>
<tr>
<td>nᵢ</td>
<td>number of inactive coils</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.3: Conical spring dimensions.

From Figure 2.15, it is clearly seen that the stiffness of the spring increasing as the temperature increases. It is also observed that the initially the spring behaves like a normal conical spring but as the stress goes beyond the \( F_t \) value, the shape memory effect comes into the picture. For a solid coil (non-telescoping) spring, curves shown in Figure 2.16 are obtained. Conical springs were made in the lab by wrapping Flexinol wire on a mold with a helical path engraved on it, and heating it in a furnace at 500°C for 15 minutes. Figure 2.17 shows the molds used to make the springs. These springs were then tested at various temperatures under a 50 lb load cell to obtain their force versus deflection characteristics. Figure 2.18 shows the response of a conical spring.
of dimensions given in Table 2.3 made using high temperature \((A_f > 90^\circ C)\) Flexinol wire.

From the Figure 2.18, it is seen that the springs get stiffer as the temperature rises. The notches in the curves are due to slipping of the turns as they ground on each other first and then slip to touch the ground. At room temperature, it is observed that there is some residual deflection in the spring, whereas at higher temperatures, the spring completely recovers its length. At room temperature, a slight decrease in slope is observed which is similar to that seen in the Matlab simulations.

These experimental results could not be directly compared to the Matlab simulations because the transformation temperatures and other material constants of the
Figure 2.15: Force versus deflection for telescoping conical SMA spring at various temperatures.

0.5 mm diameter HT Flexinol wire (purchased from Dynalloy Inc.) are not known. A push-pull mechanism consisting of two opposing conical SMA springs alternately actuated is shown in Figure 2.19.
Figure 2.16: Force versus deflection for solid coil conical SMA spring.

Figure 2.17: Molds used to make conical SMA springs.
2.5 SMA sheet

Thin SMA sheets or strips can be used to provide linear motion as shown in Figure 2.20. The opposite strips have similar memorized shape. Two of the strips are
memorized to be straight and two of them are trained to be curved. Actuating these strips alternately will provide a linear motion in the vertical direction. An SMA sheet of 0.05 mm thickness was bought from Memry in order to build this prototype. The sheet was flat annealed. Two strips of the sheet were trained in a curved shape using the mold shown in Figure 2.21.

Figure 2.20: Concept of SMA sheets producing linear motion.

Figure 2.21: Mold for training SMA sheets into a curved shape.
Curved SMA sheets electrically insulated and bonded in opposite configuration can also be alternately actuated to achieve linear motion.

![Diagram of curved SMA sheets bonded in opposing configuration: no actuation (left); sheet 1 actuated (upper, right); sheet 2 actuated (lower, right).](image)

Figure 2.22: Curved SMA sheets bonded in opposing configuration: no actuation (left); sheet 1 actuated (upper, right); sheet 2 actuated (lower, right).

In order to provide an elastic support, bonding a rubber sheet sandwiched between two nitinol sheet was tried using epoxy as the bonding agent. This would provide a bi-directional motion as explained in Figure 2.22. However, the epoxy could not bond the rubber and nitinol very well and the bond became undone upon the first actuation. Kaptan tape was then used as an insulating material between the two sheets to achieve this motion. Figure 2.23 shows the trained SMA sheet. The thin sheet shown in Figure 2.23 is made of 0.05 mm thick Nitinol sheet, 10 mm × 4 mm, with a maximum deflection (without bias) ≈ 6 mm. Though the sheet cools much faster than the SMA wire (in < 8 s) and requires less power (< 2 W) to produce the required deflection, it produces very little force (< 1 N). Hence, it cannot be used against a substantial bias force. As mentioned in Section 1.2, the force of a push button should be in the range of 1 N to 3 N. Using a thicker sheet would produce more force, but would also take more time and power to actuate.
2.6 Concluding Remarks

In order to compare the various designs, a spider chart was made for visual comparison. Figure 2.24 shows the spider chart. The plot has a common origin (i.e., 0). Some values such as power have been plotted as a reciprocal because a smaller quantity in these cases is a positive for the actuator. Maximum area occupied on the chart indicates that the design is more suited to the required application. Comparing the three types, the conical springs use less material (hence, speed can be increased), produce enough force and displacement and have a lower total volume. Though the sheet actuator fulfills the size and material volume criteria, it does not produce enough force required for tactile feedback. Hence conical springs were chosen to make a $3 \times 3$ array. The next section gives details of the $3 \times 3$ array.
Figure 2.24: Spider chart comparing various actuator designs.
Chapter 3: ACTUATOR ARRAY

Based on the conclusion from Chapter 2, a 3 x 3 array of conical springs was built. The conical springs are telescoping springs made of 0.5 mm diameter Flexinol wire, small diameter 3.048 mm, large diameter 8.128 mm and 15.24 mm free length. Two such springs in a push-pull configuration provide a deflection of up to 5 mm in both directions (i.e., up and down). The main challenge in working with nitinol is that it is very difficult to join nitinol with other materials. It cannot be soldered and has to be mechanically fastened by methods like crimping, etc. In order to avoid wires interfering with the motion of the SMA springs, a PCB was designed to mount the springs. Single wire poke-in connectors were used to position the springs on the PCB. The Figure 3.1 shows the PCB. The conical springs were made in the lab using Tyco micro poke-in connectors (part number 2134611-1) and AVX discrete wire to board poke home connectors (part number 009276001021106) were considered. Tyco connectors were selected due to their smaller size. 10 pin right angle Molex connectors were used to connect the springs via the board to power supply. All components were selected based on their current carrying capacity and temperature range since this is a high current, high temperature applications.

Figure 3.2 shows a 3D rendering of the array. All the components used had to have a current capacity up to 3 A as that would be the maximum current required
to activate one SMA spring at a time. For activating multiple springs at a time, the current capacity of all the components would have to be much higher. This would increase the size of the electrical components. If conical springs made of thinner wire diameter are used, the current capacity can be reduced, but this would also reduce the force generated. Also, currently there are no single wire to board connectors available for wire diameters less than 0.405 mm (i.e., 26 AWG). Thus, the SMA wire diameter selected must be such that there must be an optimization of force, current capacity and availability of electrical components and SMA wire sizes.

Figure 3.1: PCB with springs and connectors mounted.

The overall dimensions of the array box are 63 mm length, 59 mm width and 39 mm depth. These dimensions include the 10 pin board to wire connectors to connect the SMA springs to power supply. The size of the array was optimized by placing the single wire connectors diagonally as shown in Figure 3.1. Figure 3.3 shows the actual array box. The top of the SMA springs (i.e., the small diameter) has to be connected to ground. Since this is a moving part, it is essential that the ground wires do not interfere with the surrounding springs. Therefore a hollow aluminum rod was used to act as a guide and as a taxel (tactile pixel or pin). The upper and lower
springs are separated by a plastic standoff to prevent thermal conduction through the rod, since only one of the two springs must actuated at a time. The tactile rods are thus two separate parts connected by the plastic standoff. Ground wire is passed through the hollow rod though the bottom and is connected to the bottom PCB. Figures 3.3 and 3.4 show the actual array.
Figure 3.3: 3 x 3 array of conical SMA springs.

Figure 3.4: 3 × 3 array of conical SMA springs with individual switch for each spring.
Chapter 4: SUMMARY AND FUTURE WORK

4.1 Summary

In this project various smart materials like piezoelectrics, electroactive polymers and shape memory alloys, that can be used to make actuators for active tactile surfaces were explored. Piezoelectrics and electroactive polymers have long been used for making Braille displays, where the strain required in the material is very small, resulting in a very small overall displacement. Different types of commercially available piezoelectric motors were reviewed and a few were studied. However, due to high cost and low strain rates, piezoelectrics and electroactive polymers were ruled out as an option to be used as actuator for active tactile surfaces. Shape memory alloys, with their high strain and stiffness change properties and low cost were concluded to be the most suitable candidate for this application. Though SMAs are slower than the other two materials, the speed can be controlled by introducing forced cooling. Prototypes of various configurations of shape memory alloys, such as SMA wires, helical springs, conical springs and thin sheet, were made to see which configuration can provide an optimization of actuator volume, material volume, force and deflection. Theoretical modeling of shape memory alloy springs was done by combining the one dimensional Brinson model with spring theory. Conical and helical SMA springs were
tested in the lab at different temperatures to obtain force versus deflection curves. A 3 × 3 array was made using conical SMA springs as a prototype of the active tactile surface.

### 4.2 Future work

This section deals with the work that can be done by building upon this thesis.

- The current array box design does not containing a latching mechanism, however the ratchet mechanism discussed in Section 2.3.3 can be used by replacing the helical springs with conical SMA springs.

- In order to achieve a smooth surface when the taxels are lowered, a rubber sheet can be attached on top of the PCB, so that the taxels push against the rubber sheet to create protrusions on the rubber sheet. In such a design, the rubber sheet will add to the force that the actuator, conical SMA springs here, will have to overcome in order to reach the required position. This increase in force will have to be accommodated by increasing the material volume of the SMA actuator, by increasing the footprint, wire diameter or height of the springs.

- The modeling done in Section 2.4.1 should be extended further by using advanced constitutive models of SMAs, as the Brinson model does not differentiate between tensile and compressive detwinned Martensite. Brinson model also does not account for various minor loops and hysteritic behaviors. A better understanding of the behavior of conical SMA springs will help to better design the springs to interface with the rest of the system.
• Since the array is a close placement of SMA springs, heat interaction between the SMA springs should be studied to optimize the response time of the array and better control of the SMA actuators.
Bibliography


