Challenges for practical applications of shape memory alloy actuators

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Abstract
Shape memory alloy (SMA) actuators present opportunities for the development of novel actuating systems. High force-to-weight ratio, silent operation, muscle-like motion, biocompatibility, and simple design possibilities have attracted researchers to SMA actuators. Many SMA actuated systems in engineering and medical domains have been reported in the literature. Recently, SMAs have also been used to develop soft robotic systems. However, low absolute force and high cycle time have limited the widespread use of these actuators. Moreover, non-linear and unpredictable behaviour caused by hysteresis results in difficulties to accurately control it. Some work detailing the strategies to overcome these shortcomings has been reported in the literature, this paper presents an articulated brief review of the techniques to overcome low force, long cycle time, and material non-linearity issues.

1. Introduction

Recent material and technological advancements have resulted in smart, adaptive, and intelligent robotic systems. Traditional systems use multiple actuators, sensors, and controllers resulting in voluminous and bulky systems. Conventional actuators such as DC (Direct Current), servo, and stepper motors are a major cause of the large volume and weight of these systems. Rapid developments in material science and engineering have resulted in the manufacture of smart actuators meeting the demands of modern robotic systems (Jani et al 2014, Mohd Jani et al 2017, Adarsh and Sampath 2019). Therefore, modern robotic systems are inclined to employ smart materials such as shape memory alloys (SMAs), piezoelectric ceramics and electroactive polymers to produce compact and light-weight systems. Among these materials, SMA has become a major point of interest due to its unique characteristics and potential for engineering applications. It has been used to develop novel systems for biomedical, automotive, aerospace, and robotic applications (Rao et al 2015, Saeedi et al 2019).

SMA is a distinctive memorizing material that remembers its parent form when exposed to heat. Although many materials possess shape memory properties, nickel-titanium (Ni-Ti) alloy has been widely used due to its low cost, biocompatibility, flexibility, excellent corrosion resistance, and ease of use. Commercially available Ni-Ti SMA actuators such as Flexinol (manufactured by Dynalloy Inc USA) and Biometal Fiber (manufactured by Toki Corp., Japan) have been widely used in robotic applications (Tadesse et al 2010). Ni-Ti SMA is available in various forms such as wire, spring, sheet, and tube so it could be easily integrated into different designs. A typical SMA wire actuator may undergo a 3%–5% contraction in length (Dynalloy Inc USA). SMA spring can undergo deformations of about 200% of its length. SMA torque tubes generate large forces in small volume (Wheeler et al 2016). In the beginning, SMA was used for static applications only. Later, it was employed in dynamic applications where it undergoes cyclic heating and cooling processes.

SMAs are a subclass of smart materials with a property known as shape memory effect (SME). SME refers to the recovery of predetermined shape on the application of the external thermo-mechanical stimuli. SME is a result of the presence of temperature and stress-dependent two different crystalline structures known as
austenite and martensite. Austenite (high-temperature phase) is harder than the martensite (low-temperature phase). When cooled, austenite microstructure transforms into twinned martensite. Stress is applied to remove twinning, resulting in a structure known as de-twinned martensite. When subsequently reheated above its phase transition temperature, the material will recover its original shape (Čorić and Franz 2009, Ayvali and Desai 2014, Suman et al 2015). This transformation is illustrated in figure 1.

SMAs are biocompatible, lightweight, and possess a high force-to-weight ratio. They result in noiseless operation and can absorb unexpected axial forces. High force-to-weight ratio and muscle-like actuation have made SMA actuators very suitable for soft robotic applications. However, they have small bandwidth and low operating frequencies mainly due to large cooling times (Ho and Desai 2009, Copaci et al 2017). Theoretically, their maximum energy efficiency lies within 10%–15% limiting the use of SMA as an actuator (Sohn et al 2018). However, challenges of low force output, long cycle time, and nonlinearity are being researched (Lange et al 2015, Boyraz et al 2018). Long cooling times make SMAs unsuitable for fast cyclic applications. For instance, a typical Ni-Ti alloy having a diameter of 0.25 mm takes about 5.4 s to cool off (Dynalloy). Adding one second for heating, the actuator will take about 6.4 s to complete one cycle of operation. This results in a very low cyclic frequency of approximately 0.056 Hz which may not be suitable for many of the applications (Coral Cuellar et al 2012). Moreover, nonlinear and hysteretic behavior of SMAs calls for special methods to control it (Cianchetti 2013, Huang et al 2019). In this paper, solutions reported in the literature for these core problems are reviewed.

The remainder of the paper is organized as follows. Section 2 reviews solutions reported to overcome low output force, section 3 discusses strategies to solve the long cycle time problem, section 4 presents strategies to overcome difficulties in controlling SMA actuators, and section 5 summarizes this review.

2. Low force

Low force is one of the major challenges hindering the widespread use of SMA actuators. Typical forces generated by Ni-Ti SMA actuator marketed under the brand name of Flexinol are given in table 1. Thick wires may produce high forces at the expense of large cycle times making them unsuitable for most of the robotic applications. To increase output force without appreciably increasing cycle time, various methods such as bundling and elastic compensation have been reported in the literature (O’Toole and McGrath 2007, Mammano and Dragoni 2011). Two common bundling configurations, parallel and series, are shown in figure 2.

![Figure 1. SMA crystal structure during phase transformation.](image-url)
2.1. Parallel configuration
In this configuration, multiple SMA wires are arranged in parallel as shown in figure 2(a). Parallel SMA wires are attached to the brackets through crimps. One end of the SMA bundle is kept stationary and the other one is movable.

The output force increases proportionally to the number of wires. Figure 3 depicts changes in output force and inverse of cooling time for SMA actuator with change of its diameter. The strain produced will remain the same that would be produced by a single wire. Although this configuration results in a higher force, the small differences in lengths of SMA wire segments may result in an unequal contraction in different wires. This may result in uneven forces on the holder. Moreover, if the temperature gradients exist between the wires, they may undergo different contractions resulting again in uneven forces on the holder.

2.2. Series configuration
Here, a single wire is looped around low friction pulleys as shown in figure 2(b). This configuration results in greater stroke due to the long wire. However, due to friction between pulleys and wire, the generated force may be less than the force that would have been produced by a single actuator without pulleys. The Dynalloy datasheet suggests many possible configurations of SMA wire which will result in increased output force such as a structure given in figure 4. The structure is similar to a pair of scissors which in turn gives increased output force or stroke (Dynalloy Inc USA).

Table 1. Force produced by Flexinol wire actuators (Dynalloy Inc USA).

| Diameter (mm) | Pull force (gram) |
|--------------|------------------|
| 0.025        | 8.9              |
| 0.038        | 20               |
| 0.05         | 36               |
| 0.076        | 80               |
| 0.1          | 143              |
| 0.13         | 223              |
| 0.15         | 321              |
| 0.20         | 570              |
| 0.25         | 891              |
| 0.31         | 1280             |
| 0.38         | 2004             |
| 0.51         | 3560             |

Figure 2. (a) Parallel configuration of SMA bundle and (b) series configuration of SMA bundle.
Using parallel and serial configurations described above, various bundled actuators have been reported in the literature. For instance, (Mosley and Mavroidis 2001) have used the bundling technique to improve the lifting capabilities of SMA actuators for a robotic manipulator. They developed a powerful muscle using a bundle of 48 SMA wires to lift 45 kg load. (De Laurentis et al 2002) report optimized SMA bundled actuator to increase force without appreciably increasing cycle time. They report a bundled SMA muscle having different diameter SMA wires. They showed that a heterogeneous combination of 150 μm and 250 μm diameter wires gave greater force and efficiency. The authors in (O’toole and McGrath 2007) designed modular 12 degree-of-freedom (dof) prosthetic hand using a bundle of SMA actuators. Their modular design resulted in the easy replacement of actuator in case of failure. The fingertip force reported was 16.6 N which is approximately 30% of the average tip force of a human index finger. The analysis relating mechanics of finger moment revealed that this range of force may allow end-user to easily perform everyday tasks such as gripping a glass of water or picking a ball. In (Mammano and Dragoni 2011) elastic compensation embodying rocker-arm and double articulated quadrilateral mechanisms to increase stroke lengths are reported. It was shown to produce a twofold stroke than that for a single wire actuator. The cooling time, however, was increased due to the compensating mechanism. A cantilever bench bar type bending actuator with multiple Ti50Ni45Cu5 SMA wires reported by (Yao-Jen et al 2011) considerably increased bending force. The results confirmed that the force of the developed is directly proportional to the number of SMA wires. (Xiang et al 2018) report the development of soft artificial muscle using SMA-fishing-line and McKibben actuators. The reported actuator produced 3 N gripping force. It resulted in large contractions but with long cycle times. The force produced by the gripper was reported to be equal to 650 g. Table 2 lists some of the methods reported in the literature to improve force output.

Authors of (Villoslada et al 2014) have presented a novel mechanical design of SMA actuator based on the Bowden cable transmission principle. The presented design is alternate to high-displacement SMA actuators.
made of long SMA wires and a large number of pulleys which in turn increases frictional losses, weight, and complexity. The design allows the SMA actuator to bend while preserving its capacity of transmitting motion and output force. The system incorporates a multilayer sheath having PTFE (Teflon) inner sheath which brings down the friction. It also uses stainless steel as an outer sheath which acts as a heat sink and reduces the cooling time of SMA actuator. The reduction in cooling time causes an increase in actuation frequency. Performance of the transmission system is greatly affected by inner and outer sheaths owing to their material properties. The design resulted in more flexible SMA actuators, silent operation, yielded greater output force, and linear-displacement. Authors suggest application of the design has great potential for humanoid robot owing to its advantages such as flexibility, silent operation, better actuation frequency and output force.

### 3. Long cycle time

The sum of time taken by SMA to heat and cool is known as cycle time. Heating time can be reduced by increasing the magnitude of stimuli. The cooling time is the time required to transfer the heat of SMA wire to its surroundings. Cooling time depends on the temperature, diameter of the SMA wire, thermal conductivity coefficient, and the ambient temperature (Nizamani et al 2017). Figure 3 depicts the cycle time of SMA actuator with respect to its diameter. The time required to cool Flexinol wire actuators is given in table 3.

SMA actuators have extensively been investigated for integration into robotic hands, arms, and manipulators. However, long cooling times restrict their use in robotic applications. Cycle time may be

### Table 2. Methods to increase generated force.

| References        | Structure                                                                 | Remarks                                                                 |
|-------------------|---------------------------------------------------------------------------|------------------------------------------------------------------------|
| Xiang et al 2018  | Soft artificial robotic muscle using SMA-fishing-line muscle and McKibben muscle | Hybrid muscle reduced non-linearity and was able to produce a force of 3 N but with a long cooling time. |
| Villoslada et al 2014 | Flexible SMA actuator based on Bowden cable transmission principle | The inner and outer sheaths over the long SMA wires caused an increase in bending, output frequency, and actuation frequency. It also caused a decrease in cooling time and friction. |
| Mammano and Dragoni 2011 | Elastic compensation (Rocker-Arm mechanism) | Technique generated 2.5 times force than traditional SMA actuator. Applicable to both wire and spring. |
| Yao-Jen et al 2011 | Cantilever type bending of Ti50Ni45Cu5 SMA actuator | The modular design resulted in the easier replacement of SMA wires. Bench-bar type actuator produced a bending moment of 0.096 Nm. It increased robot weight. |
| O’toole and McGrath 2007 | Bundled 12 DoF prosthetic hand | The design resulted in lower power input and better cycle time than wires of the same diameters. |
| De Laurentis et al 2002 | Bundle of different diameter SMA wires | Different diameter SMA wires increased output force with lower power input and better cycle time than wires of the same diameters. |
| Mosley and Mavroidis 2001 | SMA bundle of 48 wires | Increased output force but required more input power and resulted in longer cycle time than a single wire. |

### Table 3. The cooling time required by Flexinol wire actuators (Dynalloy Inc USA).

| Diameter (mm) | Cooling time (s) |
|---------------|------------------|
| 0.025         | 0.15             |
| 0.038         | 0.20             |
| 0.05          | 0.3              |
| 0.076         | 0.7              |
| 0.1           | 0.9              |
| 0.13          | 1.4              |
| 0.15          | 1.7              |
| 0.20          | 2.7              |
| 0.25          | 4.5              |
| 0.31          | 6.8              |
| 0.38          | 8.8              |
| 0.51          | 14.0             |
Table 4. Methods to improve cycle time.

| References          | Cooling method                             | Remarks                                                                 |
|---------------------|--------------------------------------------|-------------------------------------------------------------------------|
| Cheng et al 2017    | Forced water and air cooling               | Forced water cooling halved the cooling time taken by forced air cooling. Water cooling increased the weight of the system. |
| Gurley et al 2017   | Bowlen Tube NiTi actuators with Linear parameter varying model | The cooling process of the Bowlen tube was much faster than a wire in the open air. However, the design caused increase in mass and power consumption. |
| Song et al 2016     | Thin SMA wires                             | Thin SMA wires embedded in soft structure resulted in 35 Hz cycle time. |
| Taylor and Au 2016  | Forced air cooling                         | Reduced cycle time from 9.5 s to 3.5 s for a prosthetic hand. |
| Schmidt et al 2015  | Elastocaloric training processes of NiTiCuV alloy | This method resulted in a smaller hysteresis. |
| Tadesse et al 2010  | Active Cooling methods                     | Fluid quenching reduced cooling time by 87%. |
| Zhang et al 2008    | Liquid jet heating and cooling             | The technique improved the heating and cooling times of SMA. |
| Russell and Gorbet 1995 | Mobile heat sink                          | Mobile heat sink improved bandwidth (cyclic frequency) to 0.8 Hz due to shorter cooling time. However, the system was bulky and unsuitable for short SMA wires. |

Improved by changing the geometry of actuator (Qiu et al 2000, Jani et al 2014), by applying large currents and by using coolants (Qiu et al 2001). The operating frequency of the SMA actuator may be described by equation (1) (Nizamani et al 2017).

\[
f_w = \frac{1}{t_h + t_c}
\]  

Where \( f_w \) is working frequency of SMA in Hz, \( t_h \) is heating time taken by SMA, and \( t_c \) is cooling time taken by SMAs in seconds.

Various methods to improve cycle time have been reported in the literature. In (Russell and Gorbet 1995) authors report a mobile heat sink resulting in a fast actuation frequency of 0.8 Hz. Mobile heat sink resulted in smaller cycle time and lesser power consumption compared to the static heat sink. The authors also reported a position control system with a temperature sensor to limit overheating. They demonstrated that in the absence of overheating, the actuator took lesser time to cool. However, this system was complex and bulky. (Zhang et al 2008) reported liquid jet heating and cooling of the moving mobile SMA actuator. In (Tadesse et al 2010) authors have investigated various active cooling methods such as heat sink, fluid sink, and air convection. They also studied the effect of pre-stress on the cooling time of commercially available Flexinol and Biometal actuators. They found that fluid flow and heat sink techniques resulted in decreasing cooling time from 1.6 s to 0.45 s. Forced air and fluid quenching methods resulted in 75% and 86% reduction in cooling time respectively. The results depicted a significant improvement in the actuation performance of Flexinol compared to Bimetal actuators. (Schmidt et al 2015) studied a possible relationship between SMA training process and cooling time. They report that a specific training process may positively impact hysteresis resulting in faster cooling. (Taylor and Au 2016) reported a prosthetic hand with a Proportional-Integral-Derivative (PID) controller for forced cooling of SMA actuator array. They report improvement of the cooling time from 8 s to 2 s.

Cheng et al 2017 reported water-cooled SMA springs to actuate minimally invasive neurosurgical intracranial robot. They found that forced water cooling resulted in a two-fold increase in speed translating into 1 mm s\(^{-1}\) speed for the neurosurgical robot. In (Song et al 2016) authors report smart-soft-composite actuator composed of multiple thin SMA wires to increase heat dissipation rate resulting in increased actuation frequency. Since time to cool is inversely and generated force is directly proportional to the cross-sectional area of the actuator, multiple small-diameter actuators resulted in shorter cooling time without affecting output force. They also showed that resonance could be used to achieve actuation frequencies up to 35 Hz. They proposed short actuators so that the natural frequency can be increased to match actuation frequency. The resulting soft actuator having 10–35 Hz frequency shows marked improvement over 0.3 Hz frequency reported in earlier research. Despite the drawback of relatively high power consumption, the reported layered reinforcement structure may result in fast robotic applications such as flying and swimming robots. Table 4 lists some of the methods reported in the literature to reduce cooling time.

Authors of (Gurley et al 2017) have investigated the Bowden tube-based NiTi actuators using linear parameter varying model (LPV). Bowden tube is a method which transmits the antagonist force from one location to other through a flexible package. The force is transferred from one end to other end while pulling on the cable and pushing on the sheath, respectively. The Bowden tube is much flexible as it can be bent in any manner without affecting load transmission. It allows easy incorporation of a long SMA wire without parallel wire configuration and pulleys. It cools down much faster than a wire in the open air. LPV was employed to...
determine the inherent range of characteristics exhibited by the nonlinear SMA actuators and it is further used to design the controller. It was found that the Bowden tube causes an increase in the speed of response of SMA actuator but at the cost of increased power consumption and increased mass.

4. Difficult control

The SMA transformation is not instantaneous. Martensite-austenite phase transformation occurs over a range of temperatures. These ranges do not overlap in heating and cooling, resulting in transformation temperature hysteresis. The temperature hysteresis due to thermally irreversible phase transformation is a major challenge in SMA control (Pons 2005, Chen et al 2019). The temperature-phase and temperature-strain hystereses are shown in figure 5. In past, authors (Elahinia et al 2010) have reviewed literature related to various control problems for SMA in different applications. They have also reviewed different control designs developed at that time to rectify the control issues. Recently, many advance control designs have been developed which have been providing easy and accurate control of SMA actuator through addressing control problems.

Temperature-strain hysteresis results in complex mathematical modelling and control (Ru-bing and Xiao-xu 2010, Riad et al 2017). Various models and control techniques to overcome hysteresis have been reported in the literature. (Pons 2005) reported that pulse width modulation (PWM) improves the efficiency of SMA actuators. (Kuribayashi 1991) reported an efficient joint mechanism driven by a coil-shaped Ni-Ti actuator whose temperature was limited to avoid overheating. Silicon-controlled-rectifier (SCR) driver was used to power SMA after sensing temperature. The temperature sensing resulted in avoiding unnecessary actuator heating and cooling. The cycle time of 0.4 Hz was reported. (Mavroidis 2002) investigated the PID controlled SMA bundle actuator for disturbance rejection. Although the reported prototype showed a maximum steady-state error of 0.254% only, the controller took 2 s to correct disturbance, hence it was not found suitable for a disturbance filled environment where faster disturbance rejection is required. It was also reported that P, PI or PID controllers performed well only in the range where control gains were tuned.

(Teh and Featherstone 2008) report a system for accurate and fast force control of antagonistic SMA wires. PID based differential force controller with rapid-heat, anti-slack, and anti-overload mechanisms was used to control actuators in the presence of disturbances and large load inertias. With a reported error of 0.0001 N only, the rapid-heat and anti-overload mechanisms did not cause actuator overheating and overstressing. The reported system demonstrated fast tracking and external disturbance rejection. (Liu et al 2010) developed a self-sensing PWM powered model-based control incorporating hysteretic and thermodynamic effects. They used Duhem differential model given in equation (2) to model actuator hysteresis.

\[
\begin{align*}
\frac{dy(t)}{du(t)} &= g_+(u(t), y(t))(u(t)) - g_-(u(t), y(t))(u(t)), \\
y(0) &= y_0,
\end{align*}
\]

Where \(u(t), y(t), y_0 \) and \( g \) represent input, output, the initial value of output, and slope function, respectively. Subscripts ++ and -- denote increasing and decreasing slopes respectively. PID based Duhem hysteresis model produced a transient error of 0.1223 mm in tracking performance test. Experimental setup results depicted effective suppression of the chattering phenomenon and the achievement of smaller transient error. (Guo et al 2015) reported PI controlled compliant differential SMA actuator consisting of a torsional spring and two
antagonistic SMA wires. They used actuators of different diameters to evaluate this controller. It was reported that small diameter wires showed better tracking performance. Furthermore, control and regulation experimentation results showed that the compliant differential SMA actuator provides a larger output angle and higher response speed in comparison with the bias SMA actuator. In (Lange et al 2015) authors investigated adaptive PID and feed-forward controllers with an inverse hysteresis model to actuate SMA based robotic hand. They found that the adaptive PID controller removed overshoots resulting in good tracking control, though with some chattering problem. (Tai et al 2010) used a generalized predictive control (GPC) for non-linear behavior of SMA spring-based linear motion actuator. GPC is a model-based predictive control system that generates a sequence of control signals to tackle hysteresis with optimized control. It derived future output $y(t)$ close to the reference $r(t)$ using the cost function given in equation (3).

$$J(u, t) = E \left\{ \sum_{j=-N_u}^{N_u} [y(t+j) - r(t+j)]^2 + \lambda \sum_{j=1}^{N_u} [\Delta u(t+j-1)]^2 \right\}$$

(3)

Where $y(t+j)$ represents a j-step prediction of system output depending on data up to time ‘t’, $r(t+j)$ denotes the future reference signal, $\lambda$ is the weight coefficient and E is expectation operator which indicates stochastic distribution model and computation of control values. $N_1, N_2$, and $N_u$ represent minimum prediction, maximum prediction and control horizons, respectively. The cost function provides error between output and reference to determine the control signal within a defined range. Authors showed that when compared to conventional controllers, the predictive control system achieved better actuator force and position control due to decreased error and chattering. (Alcaide et al 2017) designed fuzzy logic-based multiple-input and multiple-output (MIMO) controller for soft SMA actuator. Actuator comprised of SMA springs embedded in silicone rubber skin to produce passive recovery forces. They found that a linearized inverse kinematic model fuzzy logic-based MIMO controller removed steady-state errors, decreased overshoots, and provided a precise and fast response. The reported actuator bent between $+900$ and $-900$ with an average speed of 2 mm s$^{-1}$ and less than 2% overshoots.

(Song and Ma 2007) has designed and controlled a rotary servo through a SMA wire. The novel rotary actuator was developed using Nitinol wire wounded on the non-conductive rotor. To control the servo a sliding mode robust controller was employed which comprises of three parts: a standard proportional plus derivative (PD) term, feedforward term and a robust term. The feedforward term is utilized as a bias current, and the robust term is used to stabilize and increase the accuracy of the controller. It was confirmed that the controller can precisely control the position of the rotary servo. The rotary servo achieved a rotation of 100° with an error of 0.2°. Authors of (Song and Ma 2007) have designed and implemented a sliding mode controller to control the position of SMA actuated wing flap. The sliding mode controller is employed to deal with non-linear dynamics and uncertainties during the position control. The controller also increases positioning accuracy and stability. The testing results of the real-time control system demonstrated that the method has high control accuracy even with disturbances and uncertainties for both position control and trajectory tracking. Authors of (Grant and Hayward 1997) have employed a novel thin NiTi SMA wires of counter-rotating helical pattern woven on supporting disks with a variable structure controller. The structure allowed efficient transformation between displacement and force by overcoming the limited strain problem. The major advantage of the controller is that it requires knowledge of a few parameters of the plant. The disadvantage of the controller is its discontinuous nature which in turn causes an increase in power dissipation, ringing problem, and an increase in the excitation of undesired dynamics. The controller was applied on the pair of the antagonist SMA actuators. The feedback was obtained through displacement error between the actuators. The gross non-linearities were compensated through modulating the magnitude of the current. The experimental results demonstrated robust and smooth control with little complexity.

Authors of (El Dib et al 2011) have developed novel controllers for SMA using feedback resistance which can achieve consistent actuation within a range of ambient temperature. The design allowed to use more current than the prescribed by the manufacturers. The control approach had three parts: probing that was considered as online parameter identification process, priming controller brought SMA element close to the transformation temperature to prepare for actuation and actuation strategy which allowed to achieve consistent contraction of the SMA irrespective of ambient temperature. The controller was designed using a 9512 Freescale microcontroller. Among the investigated strategies Minus 4.5% strategy yielded most consistent actuation and it was substantial improvement compared to traditional control methods. Minus 4.5% demonstrated smallest time to cusp (TTC) for all temperature values except 40 °C where peak detector strategy had smallest TTC. Thus, the peak detector strategy was claimed as a second-best control strategy. (Wang et al 2012) have presented a self-sensing feedback-controlled actuator designed using antagonist pair of SMA wires. The stress between two SMA wires became constant under certain cycle time and pre-strain which in turn reduced the hysteresis gap between the heating and cooling curves of SMA. Then curves of the SMA wires were modelled such that is allowed to measure resistance directly which was employed to measure the testing values and the target strain. The strain to
duty cycle difference model was used as compensation. PID controller with the compensator used to achieve the target signal and control. PID controller was employed to yield the duty cycle for tracking the signal but it resulted in large tracking error owing to overheating. Thus, a duty cycle hysteresis compensator was employed to eliminate overheating. The experimental results showed that the root-mean-squared (RMS) error was less than 1.1%. However, overheating elimination process caused a decrease in the response speed. Authors of the paper proposed to employ a more robust controller for further improvement in the response.

A self-sensing approach was employed (Ruth et al 2015) for SMA through direct differential resistance feedback. The approach is applied to the one link SMA actuated manipulator with discrete-time sliding mode controller (DSMC). The method allowed to measure angular position directly in terms of resistance. The experimental results confirmed the effectiveness of the approach in servo control and thermal disturbances rejection. It was observed that compared to PID controller the DSMC has a faster rise time and settling time, lesser steady-state error, and does not exhibit overshoot. It took 0.15 s to reject disturbances and track the signal while PID took 0.35 s. The controlled bandwidth was DSMC was 2 Hz while PID had 0.9 Hz. The DSMC demonstrated better tracking by reducing hysteresis. Authors of (Gurley et al 2016) have presented robust self-sensing in SMA actuator based on dual measurement technique. The authors measured voltage across the entire SMA wire and voltage of its fixed-length segment. Both the measurement allowed direct computation of the length of the actuator without using any model. After performing 30 tests, the measurement was obtained with an error of 0.5 mm compared to true length. The experimental results showed a RMS error below 0.033 mm and a standard deviation of 0.154 mm. The measurements are affected by the noise therefore, the author suggests future work related to noise filtration. The developed technique has the potential to make SMA applications more cost-effective through eliminating the need for position sensors in designing of a feedback controller. Moreover, they have recommended designing a feedback controller using the dual self-sensing measurement which can effectively control SMA response in unknown loading and ambient conditions.

(Ayvali and Desai 2014) have presented a PWM based non-linear PID controller using temperature feedback for desired temperature tracking and control strain of an SMA wire. Authors have used temperature feedback as an effective method when direct measurement of strain is not possible. A model was developed to find the relationship between heating time and temperature which reduced steady-state error at high temperatures and acted as a feedforward term to reduce heat loss. Thus, along with the compensator it allowed to control the temperature of SMA. Subsequently, the constitutive model of SMA with temperature feedback allowed to control the strain. The experimental results confirmed the effectiveness of the controller in tracking complex discrete and continuous trajectories. Since this controller can only be used during the heating phase of SMA. Therefore, it is not suitable for application requiring fast switching owing to delay in the cooling phase. The authors suggest future work for modelling of heat transfer under different ambient conditions. A model with two control schemes was developed by (Jayender et al 2008) to control the strain of SMA actuators. The model consisted of three equations: joule heat, convection which described temperature dynamics, a two-state system which described mole fraction distribution with temperature, and a constitutive equation which described the relation of change in temperature and mole fraction to the strain and stress produced in SMA. Two controllers used included; gain-scheduled PI controller and H_∞ loop-shaping controller. The gains of the PI controller were obtained through linear quadratic regulator (LQR) optimization. The H_∞ loop-shaping controller improved stability through minimizing impact unmodeled dynamics at high frequencies. The simulation and experimental results of both controllers confirmed effectiveness in rejecting uncertainties. However, in the presence of perturbations H_∞ loop-shaping controller yielded better results compared to the LQR controller. Authors endorsed applicability of controller in critical applications which require safe use of SMA. Table 5 gives various methods to effectively control SMA.

5. Summary

Despite the challenges posed by SMA actuators, they are being investigated for various robotic applications. Although, some reviews on SMA actuators have appeared in literature; key challenges and possible solutions need to be presented in a concise form for the prospective researchers in this area. This paper provided a state-of-the-art review of these challenges. Solutions to low force, long cooling time, and difficult control were reviewed in this paper.

The review reveals that low force may be improved by using bundles of actuators. Although bundling increases generated force, it also results in uneven actuation and loss of force in friction. However, a well-ventilated bundle may not significantly increase the cooling time. The heterogeneous bundling technique may produce non-uniform force at the bundle holders and hence it may not be a choice for the increasing force generated by the actuator. In the light of reviewed literature, for higher force, a thin-wire bundled actuator is better than a single thick-wire actuator. The SMA systems based on Bowden cable transmission principle can yield more output force, faster actuation, silent operation, and larger bending. The long cycle time may be
overcome by using coolants. Air and liquid cooling greatly decrease cycle time but results in a complex and heavier system. SMA actuators inside coolant filled soft tubes may result in fast cooling but at the cost of higher power input as heat will be dissipated to coolant during heating also. Although Bowden tube-based systems can cool faster than a bare SMA wire, however, it causes an increase in power consumption and increases the mass of

Table 5. Methods to effectively control SMA.

| References       | Control technique                                      | Remarks                                                                                      |
|------------------|--------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Alcaide et al 2017 | Fuzzy logic based Multiple Input and Multiple Output controller | It reduced steady-state error with less than 2% overshoots.                                      |
| Gurley et al 2016  | Robust self-sensing and dual measurement technique for controller design | Experimental results confirmed the effectiveness of the dual measurement technique which can directly measure the length of SMA actuator in the absence of any model with an error of 5 mm. It eliminated the need for position sensors in the designing process of a feedback controller. |
| Guo et al 2015     | Saturated PI controller                                | A compliant differential actuator with a saturated PI controller reduced the error and improved tracking frequency. The tracking error ranged from $-1^\circ$ to $1^\circ$. Hysteresis was not fully dealt with. |
| Lange et al 2015   | Adaptive PID controller                                | The results confirmed the effectiveness of the approach and the controller. The DSMC was able to effectively reject disturbances and tracking with wider bandwidth compared to the PID controller. DMSC rejected disturbances within 0.15 s while PID took 0.35 s. |
| Ayvali and Desai 2014 | PWM based non-linear PID controller                    | The approach can only be applied for the heating phase of SMA. It is not suitable for applications which require fast switching because SMA will take much time to cool down to the martensitic state. |
| Wang et al 2012    | Self-sensing feedback-controlled actuator with PID controller and hysteresis compensator. | It was observed that approach effectively controlled the response and tracked the signal with RMS error of less than 1.1%. However, response speed declined owing to the compensation process of overheating. |
| El Dib et al 2011  | 9S12 microcontroller based controller using resistance feedback | Among different strategies Mine 4.5% strategy yielded consistent actuation of SMA with smallest TTC expect at 40 °C, where peak detector strategy demonstrated minimum TTC. |
| Liu et al 2010     | Model-based PID control with self-sensing               | The Duhem model-based control system rejected the hysteresis. The techniques reduced error to 0.1223 mm only. |
| Teh and Featherstone 2008 | Generalized Predictive Control                        | It reduced hysteresis, chattering, and tracking control errors which are major problems when PID is employed for SMA actuators. |
| Jayender et al 2008 | $H_\infty$ loop-shaping controller and LQR controller | The position control did not reject disturbances. Results demonstrated that in the presence of perturbations the $H_\infty$ loop-shaping controller yielded better performance compared to the LQR controller. |
| Song and Structures 2007 | Sliding mode controller for SMA actuated rotary servo | The controller was able to control the position of SMA actuated rotary servo precisely with a steady-state error of $0.2^\circ$. |
| Song and Ma 2007    | Sliding mode controller for SMA actuated wing flap      | The testing results demonstrated the effectiveness of the controller in dealing with disturbances and uncertainties which in turn enhanced position control accuracy and tracking. |
| Mavroidis 2002      | PID controller                                         | PID controlled bundle actuator took 2 s to overcome disturbance hence not suitable in disturbance filled environment where fast disturbance rejection is required. |
| Grant and Hayward 1997 | Variable structure controller                         | The results showed the effectiveness of the controller in dealing with nonlinearities. However, the discontinuous operation caused an increase in power dissipation, excitation of undesired dynamics, and ringing problem. |
| Kuribayashi 1991    | Temperature control                                    | Temperature control method decreases the cycle time. |

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the system. The authors suggest that a design in which coolant comes into contact with the actuator only during the cooling period will result in a more energy-efficient system. PID, feed-forward, fuzzy logic based MIMO, and inverse-hysteresis based PID controllers have been tried to control SMA actuators. These controllers were not able to fully address actuator nonlinearity. Although they reduced overshoots, the chattering was still present. Moreover, GPC resulted in reduced chattering. After reviewing various control strategies, the authors are of the view GPC with fuzzy logic and/or neural network-based approaches may deal with the transformation hysteresis more accurately. Compared to PID and other traditional controllers, the sliding-mode controller was able to provide easy and robust control of SMA in different applications.

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