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Review:

Recent advances in nonlinear control technologies for shape memory alloy actuators

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Abstract: This paper reviews recent developments in nonlinear control technologies for shape memory alloy (SMA) actuators in robotics and their related applications. SMA possesses large hysteresis, low bandwidth, slow response, and non-linear behavior, which make them difficult to control. The fast response of the SMA actuator mostly depends upon, (1) type of controller, (2) rate of addition and removal of heat, and (3) shape or form of the actuator. Though linear controllers are more desirable than nonlinear ones, the review of literature shows that the results obtained using nonlinear controllers were far better than the former one. Therefore, more emphasis is made on the nonlinear control technologies taking into account the intelligent controllers. Various forms of SMA actuator along with different heating and cooling methods are presented in this review, followed by the nonlinear control methods and the control problems encountered by the researchers.

Key words: Shape memory alloy (SMA) actuators, Nonlinear control, Micro robots, Hysteresis, Position control, Robotic manipulators

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INTRODUCTION

Various types of smart materials and actuators, with different characteristic features and having shape memory alloy (SMA) as one of the functional intermetallics, have been developed by researchers especially in the last decade (Fletcher, 1996; Mavroidis *et al*., 2000). The major advantages of SMA actuators are their simultaneous sensing and actuation. They have the ability to return to some previously defined shape/size when subjected to appropriate thermal action, the phenomenon is known as shape memory effect (SME). Their distinguishing characteristics include SME, pseudo elasticity, large recoverable strains, high power density, high tensile strength, good damping properties, high thermal conductivity, and possession of two distinct phases with different resistivities. These properties make them appealing for both medical and non-medical application. On the other hand, properties like good kink resistance, steerability and torquability, less sensitivity to magnetic resonance (Morgan, 2004), crush recoverability, excellent pushability, Radiopacity, etc., make SMA a suitable candidate for medical applications. NiTi, also called Nitinol, is a typical SMA material, mostly employed in industrial applications. Another commonly used SMA material is NiTiCu, generally used in medical equipments.

The unique characteristics of SMA actuators such as one-way shape memory, two-way shape memory and pseudo elasticity make them suitable for specific applications. The response of SMA actuator depends upon (1) applied bias force, (2) type of sensor used for feedback, (3) way the heat is applied and removed, and (4) parameters used for obtaining the feedback, i.e. strain, resistance, temperature or the actuation force (van Humbeeck, 1999). The most essential part of any kind of nonlinear control method for SMA actuation is to add and remove heat from the actuator, which mostly depends upon (1) type of heating and cooling method, and (2) the form or shape of the SMA actuator. The former one is related to the mechanism of the heat removal and addition. The later one depends upon the exposed area of the actuator. Here we analyze the different forms of SMA actuators, their actuation and the type of control methodologies applied.

A great deal of literature dealing with design, modeling and applications of SMAs are already available for interested readers elsewhere (Ghomshei *et al.*, 2001a; 2001b; Dutta and Ghorbel, 2005). A number of recent review articles related to SMA are also available pertaining to their recent developments (Otsuka and Ren, 1999), medical applications (Duerig *et al.*, 1999; Hornblower, 2002; Mechado and Savi, 2003; Stevens and Buckner, 2005), non-medical applications (van Humbeeck, 1999), MEMS applications (Kahn *et al.*, 1998; Fu *et al.*, 2004), and smart structure applications (Seelecke and Muller, 2004). Recent metallurgical developments (Chen and Kubo, 1996; Otsuka and Ren, 1999) and an overview of the design aspects of SMA actuators (Reynaerts and Brussel, 1998) had already been reported and summarized. But, to the best of our knowledge, no review has been reported with focus on nonlinear control methods, and the heating and cooling problems for SMA actuators, which are associated with its time response. This manuscript is an attempt in this direction with particular concern to review the developments in nonlinear control technologies for SMA actuators during the last decade. Applications of different forms of SMA actuators i.e. single wire, spring, coil, ribbon, foil, strip and multiple wires are described. The heating and cooling methods to improve the time response, positioning accuracy, and frequency are also discussed. Thereafter, the control schemes applied for SMA actuators are described. Finally, the paper concludes with the directions for future research.

VARIOUS FORMS OF SMA ACTUATORS

SMA actuators are present in various forms on the basis of their design and shape. For macro level applications, the actuator is mostly in the single/multiple wire form or in the coil form. But for micro robotic devices, the foil/diaphragm/strip form is more suitable. The selection of a particular form of SMA actuator for a specific task is based on strain, bias force, actuation force/torque, and frequency of operation. Thin film of Nitinol is another form of SMA actuator available mostly in 3D form in MEMS devices. This actuator has wide applications in medical field such as in thin film nitinol heart valve, thin film stent and diaphragm pump/valve. The diaphragm form had been described in detail by Fu *et al.*(2004). Various forms of SMA actuators for robotic applications, as illustrated in Fig.1, are described here.

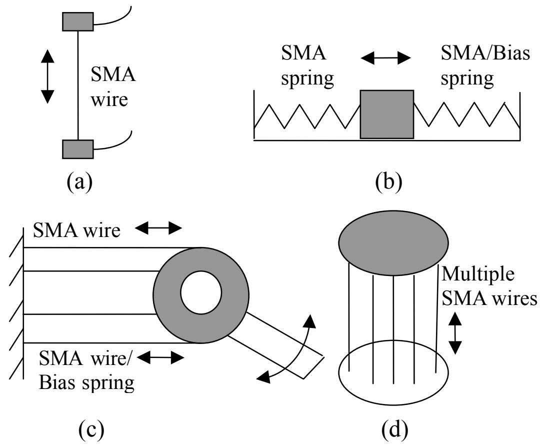

Fig.1 Different forms of SMA actuators
(a) Linear; (b) Spring; (c) Rotary; (d) Bundle actuator

Linear SMA actuators in wire form

These actuators are simpler and easy to integrate with robotic devices and structures. Mostly, the other forms of SMA actuators are also fabricated from wires. Its actuation is simpler and its response is faster compared to other forms, as discussed in the forthcoming sections. The time response of an actuator made up of NiTi wire of length 800 mm and 0.254 mm diameter was simulated with a numerical model based on the analysis of energy fluxes into and out of the actuator during phase transformation (Meier and Oelschlaeger, 2004). A computational study of the impact of variable material properties and environmental conditions on SMA wires, which undergo thermally induced transformation and stress-induced transformation, had been done by Sadek *et al.*(2003). An active 2D hydrofoil actuated by SMA wires of 0.38 mm and 0.686 mm diameters along with its finite element model was presented by Rediniotis *et* *al*.(1998), and Lagoudas *et al*.(1999). It was tested in still air, still water and moving water at different speeds. SMA wires were embedded with elastomers and other lightweight materials in structures like beams. These hybrid structures have wide ranging applications in robotics for manipulators and hydrofoils, which demand lightweight and more stiffness. Wire form had been used in the shape control of a flexible beam (Shu *et al.*, 1997), thermally driven bonded SMA-elastomer actuator (Gordaninejad and Wu, 2001), composite box beam consisting of SMA and elastomer layers (Ghomshei *et al*., 2001a; 2001b) and, SMA-glass-epoxy hybrid composite (Turner, 2001).

Spring SMA actuators

Lee and Lee (2000) tested the spring actuator for an active catheter fabricated by the heat treatment of wound SMA wire on a mandrel for four conditions i.e., isothermal loading and unloading, measurement of shape recovery force, temperature follow-up and, load follow-up. They proposed a combination of SMA modeling and neural network technology and later confirmed that the force feedback control was better than the temperature control. Spring actuator was characterized using a 1D phenomenological-polynomial-constitutive model based on the Devonshire theory by Duval *et al*.(2000). Simplified design and analysis of an SMA actuated compliant bistable mechanism was presented by Ishii and Ting (2004), in a way that the temperature dependent stress-strain relationship could be ignored. This literature combined with (Lee and Lee, 2004) would be very much useful for the design of SMA actuators in spring form.

Rotary SMA actuators

These are generally the combination of an SMA wire with a pulley system or an SMA strip in coil form, generally used to obtain rotary motion. They are made up of embedded SMAs and are the most suitable for meso or micro level robotic systems (Yesin, 2000). Micro fabrication of such actuators is normally done by Shape Deposition Manufacturing (SDM), and electroplating with polyurethane material is done afterwards to enhance the bending of SMA wire. This strategy could be applied for designing and fabricating bi-directional rotary joint actuators. It has been noted by researchers that the SMA rotary actuators based on the strain gradient are more tolerant to residual strains.

Bundle SMA actuators

The salient features with the necessity for developing these actuators were presented by Mavroidis (2002). SMA bundle actuator design was based on four key parameters namely, wire diameter, number of wires, bundle length and number of parallel current paths. These parameters ultimately determined the load capabilities, displacement capabilities, and current/voltage requirements. Design and dynamics of a SMA bundle actuator made up of 48 wires, each of 150 μm diameter with the lifting capacity of 45.4 kg i.e. approximately 300 times its own weight, was presented by Mosley and Mavroidis (2001). For the same bundle actuator, an analytical dynamical model was developed and tested with different loads and inputs (step, ramp, sinusoidal, and half sinusoid) defined in the Visual C++ program. The authors observed unpredictable chaotic behavior of the actuator under certain low and moderate voltage inputs, which would affect the system design and cause control difficulties in high and fine accuracy tasks. Linear Quadratic Regulator (LQR), Kalman estimator method and H_2 Optimal Robust Control design methods were used by Lee and Mavroidis (2002) for the control of these actuators.

HEATING AND COOLING METHODOLOGIES

The response of the SMA actuators mainly depends upon the type of controllers incorporated and the way in which the heat is added and removed, which induce phase transformation. The generally applied heating methods, as described by Qiu *et al*.(2000) are conductive heat transfer, radiative heat transfer, inductive heat transfer through microwaves or infrared light and direct ohm or joule or I^2R heating. A number of techniques like water immersion, heat sinking, and forced liquid/air cooling are available to reduce the cooling time of SMA materials (Gorbet and Russell, 1995). But they suffer from adverse effects of increase in power consumption and heating time. ‘Cool chips’ is the most recent technology, which uses electrons to carry the heat from one side of a vacuum diode to the other side. It contains no moving parts or actuators and is more suitable for miniaturized applications like micro robots. The heating and cooling methods are summarized in Table 1.

Table 1 Heating and cooling techniques for SMA actuators

Heating techniques	Cooling techniques
Resistive (I^2R)	Still air
Capacitance assisted I^2R	Water immersion
Conductive	Heat sinking
Convective	Forced air/liquid
Radiative	Peltier effect
Laser	Cools chips technology

Wet actuators, also called fluidic actuators, were proposed by Asada and Mascaro (2002). These consisted of NiTi wire of 0.15 mm diameter and 400 mm length, threaded through flexible latex rubber tube of 3 mm diameter. Water was used as the cooling medium controlled by peristaltic pump and solenoid valve. The actuator was driven by a square wave pulse to allow cyclic heating and cooling of the wire. The authors also reported that the actuator achieved amplitudes of 10 mm with a bandwidth of 1.5 Hz. These types of actuators are suitable for on/off actuation with digital type of actuation being possible by connecting the actuators in series. A micro-actuated Ω-module controlled by Peltier effect was proposed by Abadie *et al*.(2002). It consisted of an SMA thin blade of 3 mm long, 0.8 mm wide and 0.2 mm thick connected with a thermoelectric bismuth telluride on both sides. The actuation frequency was reported to be 0.16 Hz. A laser displacement sensor was used to measure the deflection of Ω-module and a micro thermocouple of 25 μm diameter was used to measure the temperature.

A feasibility study of Fuel-powered and Thermoelectric SMA actuator was made by Rediniotis *et al*.(2002). It had separate heating and cooling circuits. The heating circuit consisted of a combustor and a pump whereas the cooling circuit was composed of a coolant and a pump. Thermoelectric SMA strip was employed as the actuator using two Peltier devices. Actuation frequency of 0.5 Hz was obtained under 150 MPa stress. The thermoelectric heat transfer problem present in the SMA actuators was analyzed for increasing the frequency of response by Bhattacharyya *et al*.(1995) and Ding and Lagoudas (1997) with particular emphasis on the 1D heat transfer. For this, a 1D model for a unit cell was considered and Peltier effect was used as heat sink/source. The experimental result showed the achievement of a frequency of 2 Hz on full phase transformation and 17 Hz on partial transformation of 25%.

Mukherjee *et al*.(1996) presented an actuator matrix driver method for the actuation and control of multiple SMA elements in the form of 3×5 matrix, using minimum number of connecting wires. They also proposed that the concept could be extended for powering an array of actuators of any kind apart from SMAs and for the transmission of signals from an array of sensors. Most commonly SMA actuators made up of wires/springs (of up to 400 μm diameter) or of thin strips had been used. But as a special case as reported by Qiu *et al*.(2000) NiTi actuator in the form of rod of 5 mm diameter and 50 mm length was studied for the control of dynamic buckling of automobile frame during crash accident. The actuator possessed a very small resistance of 2.55 mΩ and the current requirement was larger than 3204 A for direct electric heating. For heating this thick wire, conventional electric heating was used together with three capacitors in parallel as shown in Fig.2 where one of these capacitors is illustrated. The response time was reported to be 4.6 ms and 6.5 ms for the unconstrained and constrained actuation respectively. This research could be of greater utility for heating SMA actuators of higher cross sections. But the adverse effects would be the requirement of more cooling time and hence, slow response for cyclic operations. Potapov and Da Silva (2000) confirmed with experiments that the SMA actuation frequency was mainly dependent upon the cooling time and could be improved by increasing the difference in temperature between martensite start temperature and ambient temperature.

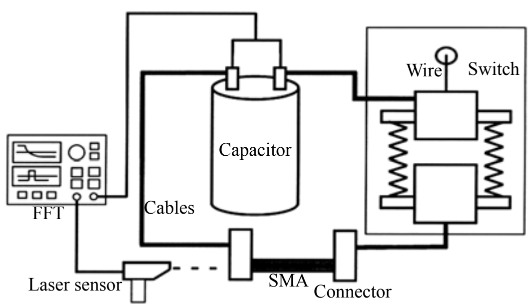

Fig.2 Electric heating using capacitor (Qiu *et al*., 2000)

CONTROL TECHNOLOGIES FOR SMA ACTUATORS

Control systems for SMA actuators are of many types ranging from simple proportional controllers to highly sophisticated nonlinear controllers like variable structure control and neuro-fuzzy control. The controlling strategies for SMA actuators could be generally divided into four categories as shown in Fig.3. Various models such as Preisach model, constitutive model, phenomenological model and heat transfer model had been integrated with conventional controllers for enhancing the SMA actuation.

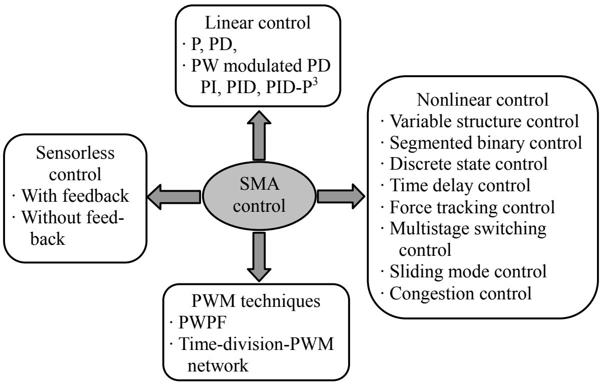

Fig.3 Control techniques for SMA actuation

Linear controllers and PWM schemes

Generally proportional controllers are not suitable for SMA actuators for critical applications due to the nonlinear behavior with hysteresis. Mostly, the modified forms of classical controllers like PI, PD and PID are used for SMA actuators. The nonlinear and hysteresis effects are tackled with the help of compensators and error governors by Tharayil and Alleyne (2004). A PI type controller for radiant energy powered SMA actuator developed by Hull *et al.*(2004) is shown in Fig.4. A 500 W halogen lamp was used to provide the radiant energy and the control was accomplished with LabVIEW6 software with SC-2070 data acquisition card. These kinds of actuators are more suitable for space applications as separate power source is not required. A modified PID controller called PID-P^3 was proposed by Shameli *et al.*(2005) for a typical SMA actuator, where a bending leaf spring (70 mm×2.5 mm×1 mm) was used to produce the bias force required for changing the SMA from twinned martensite to detwinned martensite. For larger values of error present in the position feedback, the cubic term of this controller produced great control effort that had considerable effects in reducing the settling time and overshoot of the system. For small error values, the cubic term vanishes and the controller works as a PID controller.

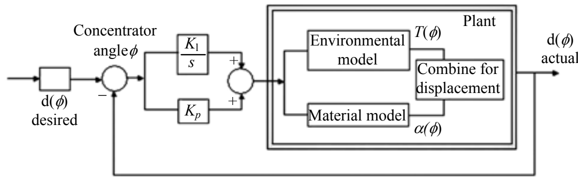

Fig.4 PI controller for SMA actuation (Hull *et al.*, 2004)

Design and experimental results of an SMA actuator control system using PWM to reduce the energy consumption by the actuator was presented by Ma and Song (2003). The control scheme was implemented using MATLAB/Simulink and dSPACE data acquisition system. It was shown that the actuator consumed 30% less energy than the continuous PD controllers while maintaining the same positioning accuracy. Song and Ma (2003) presented an improved PWM technique called Pulse-Width-Pulse-Frequency (PWPF) modulator that is comprised of a Schmidt Trigger, a Prefilter and a feedback loop. In this control scheme, PWPF modulated PD control was used to command the actuator to follow a square wave signal of 1/30 Hz, 40% duty cycle and −1 to −5 mm amplitude. The same controller was used without modulation also for the same task and it was found that the PD controller with PWPF modulation consumed 50% less energy than the other one without modulation.

A micro trolley actuated by SMA springs, suitable for inspection and maintenance of micro pipes and tubes, was designed by Yao *et al.*(2004) with a PIC control chip. The chip with PWM controlled the current to the spring actuator with the response obtained being less than 3 s. Asada *et al.*(2000-2002) developed a setup of a 4-dof marionette actuated by 8 SMA wires and controlled by a 3×3 matrix network as shown in Fig.5. The control system technique is called as Time-Division PWM Network Technique. They reported that the actuation period for each actuator was 80 ms, which was much smaller than the cooling time constant of 2 s to 10 s. In order to prevent too much current passing through the SMA wire,

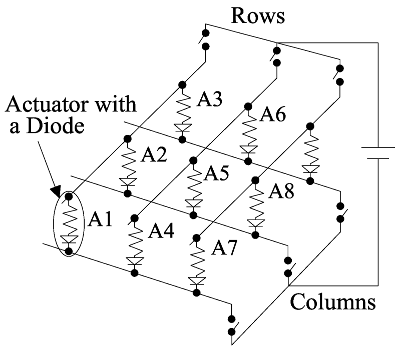

Fig.5 3×3 matrix network of SMA actuation (Asada *et al.*, 2000-2002)

the voltage drop across resistors was measured and used as a safety feedback signal. Li *et al.*(2005) designed a 2D alignment system that consisted of a microscope objective, a pinhole aperture (50 μm diameter and 15 μm depth) with four photodiodes, and four SMA actuators for positioning. Photodiode cells provided feedback (PI) control and the authors reported that they obtained a positioning accuracy of ±0.3 μm.

Nonlinear controllers

Song *et al.*(2000) made an active position control of an SMA actuated composite beam that was used for vibration reduction in rotorcraft blade. A robust compensator was employed to compensate for the nonlinearity and the hysteresis present in the SMA action. The problem of controlling the deflection of the tip of a curved elastomer beam embedded with a SMA wire was investigated by Icardi (2001) with the help of the 'theory of laminated beam'. A numerical procedure based on a constitutive equation was developed for solving the geometric non-linearity of the host structure and the hysteretic non-linearity of SMA wires.

A new approach called 'Segmented Discrete State control', using Peltier elements for cooling and heating SMA elements, was demonstrated by Mukherjee *et al.*(1996) and Selden *et al.*(2006). The controlling mechanism was based on the division of SMA wire into many segments and the control of their thermal states individually in a binary manner. Therefore, the total displacement was proportional to the number of segments in the heated state. The control scheme exploited the inherent hysteresis and nonlinearity and completely eliminated the latency-time of phase transition. The maximum frequencies obtained were 0.05 Hz and 0.1 Hz for one segment and for coordinated segment respectively. The major advantages of this control scheme over the control of entire wire were its robustness, suitability and faster response. A 'Time Delay Controller (TDC)' was implemented by Lee and Lee (2004) where the dynamics of the actuator was based on the Liang's model. Its structure and the control components are illustrated in Figs.6a and 6b respectively. Their results proved that the high gain tuned TDC was more robust than the low gain tuned PID control in terms of settling time, range of error and overshoot.

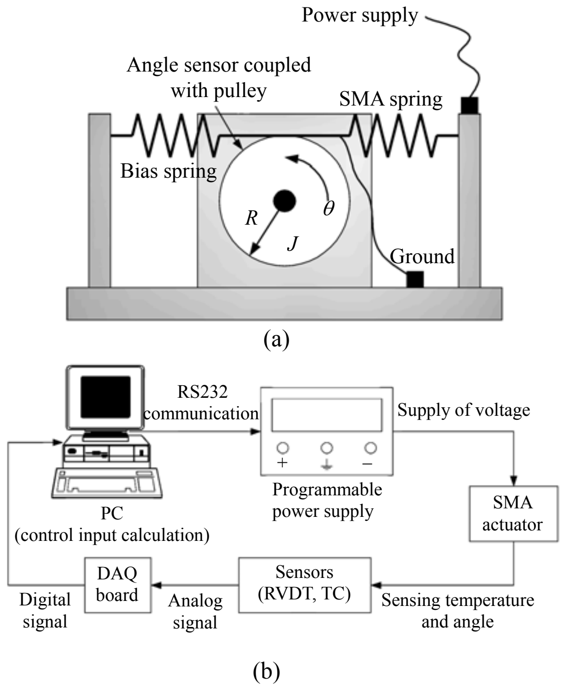

Fig.6 SMA spring actuator and its control scheme (Lee and Lee, 2004). (a) Actuator construction; (b) Control scheme

A 'Sliding Mode Controller (SMC)' was designed by Elahinia *et al.*(2004a; 2004b) to calculate the desired stress of the NiTi SMA wire of 150 μm diameter. It was based on the desired angular position of a single degree of freedom (dof) rotary manipulator. A feed forward and feedback controller with the extended Kalman filter was used for the stress based sliding mode control, as shown in Fig.7. Its performance was also compared with that of the PID controller. SMCs are most suitable for vibration control and to deal with uncertainties and noises. A robust SMC was designed by Lim *et al.*(2001) for controlling the motion of a hard-disc-drive (HDD) suspension using SMA actuators. The controller was formulated with uncertainties in natural frequency and time constant. The limitation of the application was the unwanted actuation of the SMA from the heat generated by the HDD. A composite controller was implemented by Etxebarria *et al.*(2005) with sliding mode and LQR optimal design considering the dynamics of a flexible link robotic manipulator. Their research showed that the controller with composite structure endowed the manipulator with superior tracking properties and adoption capabilities.

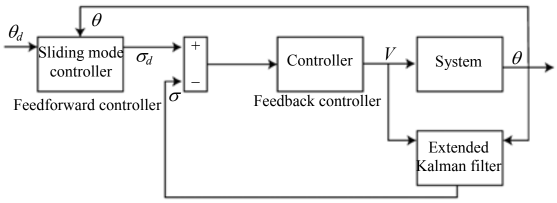

Fig.7 Feed forward-feed back controller with extended Kalman Filter (Elahinia *et al.*, 2004a)

In robotic applications, the tracking control of SMA actuators is very much essential for obtaining a desired trajectory. Choi (2006) described a two dof single link mechanism with spherical workspace that was actuated by SMA springs. An SMC actuator was designed for this mechanism by considering the variations in time constant and spring constant. The performance of the controller for various end trajectories was also analyzed. It was found that the tracking accuracy was favorably good but the response time still required improvement. Choi *et al*.(2001) reported a 'robust force tracking control' method for a flexible gripper. The governing equation for the gripper in the partial differential form was derived by employing Hamilton's principle. The experimental setup employed is shown in Fig.8. Generally, a position feedback system was supposed to be required for accurate position control of SMA actuated systems. But Moallem (2003) and Moallem and Jun (2005) experimentally proved that force feedback alone was sufficient for position control of a flexible beam driven by two SMA actuators of differential type. The control scheme was based on partial feedback linearization and Lyapunov stability analysis. Ma *et al*.(2004) developed an electrical resistance feedback control system that eliminated the need for a separate position sensor.

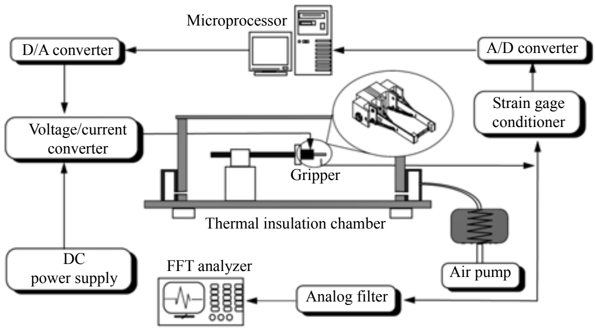

Fig.8 Force tracking controller for flexible gripper (Choi *et al*., 2001)

A nonlinear robust control algorithm based on 'variable structure control' was successfully developed and implemented by Grant and Hayward (1997) for an actuator made of multiple SMA fibers with one-way SME. Elahinia and Ashrafiuon (2002) also applied similar control scheme for a single dof manipulator, with the algorithm based on manipulator dynamics, a constitutive model, phase transformation model and a heat convection model. The authors claimed that the control algorithm was fast and efficient since it avoided actuator overshoot and chattering. A closed loop control approach by Dickinson and Wen (1998) was based on the strain feedback of a flexible beam for compensating the hysteresis with a simple lumped temperature and SMA force/displacement model. The researchers showed that the system developed steady state error that was subsequently removed by an adaptation scheme and thereafter, the system was found globally asymptotically stable. Similar control system was proposed by Majima *et al*.(2001) by modifying the classical Preisach hysteresis model for compensating the hysteresis. It consisted of PID feed forward and feed back loop. This control system was based on a static model of SMA actuator and was more suitable for reducing the limit cycle oscillations. However minor hysteresis effects were ignored while designing the controller. But for position control, minor hysteresis is also one of the factors to be considered. A feedback control system was designed by Madill and Wang (1998) and Gorbet and Wang (1998) to model the minor hysteresis loops. The authors proved the L_2 stability of a position control system. The energy properties of the Preisach hysteresis model were considered by Gorbet *et al*.(2001) to design passivity-based rate controller for a differential SMA actuator.

Adaptive/intelligent controllers

Generally, adaptive controllers are considered as one form of intelligent controllers of nonlinear type that are designed with some kind of adaptive or training mechanisms to deal with the nonlinear and hysteresis effect of SMA actuation. These adaptive mechanisms can be designed to work online and off-line. Accurate control is possible if the mechanism works online, provided the dynamics of the actuators are taken care off. An adaptive tuned model for off-line identification and closed loop compensation for hysteresis was shown by Webb *et al*.(1998). However, the online identification was not explored and thus, left for future research. When the measurement of strain in SMA actuators is not feasible or expensive and cumbersome, intelligent control schemes can be adopted by inverting the relationship between strain and stress and/or temperature as showed by Briggs and Ostrowski (2002). Tan and Baras (2005) developed an adaptive inverse control scheme, based on Preisach operator for a magnetostrictive actuator that is also a smart material like SMA, possessing hysteresis.

Kumagai *et al.*(2006) developed a motion controller for SMA actuators that consisted of feed forward and feed back parts. The feed forward part was used to calculate the open-loop input voltage that was based on the dynamic model and fed to the amplifier. This control scheme was developed using ANFIS, an adaptive neuro-fuzzy inference system in MATLAB environment. The feedback part used an ordinary PD controller to compensate for the error present in the open loop. The experimental results proved that the controller is more suitable for motion control and tracking trajectory. However, the authors did not mention the construction detail of the actuator and strategies for increasing the actuator's response. Similarly, a composite controller consisting of feedback and open loop was designed and experimentally tested by Wijst *et al*.(1997) for a system with one dof. It was found that the tracking error obtained was smaller than the one with feedback control alone. A new approach for controlling SMA actuators with hysteresis compensation by using a 'neural network feed forward controller' and a 'sliding-mode based robust feedback controller' was presented by Song *et al*.(2003). The former one was used to reduce the hysteresis effect and the later one was employed to compensate for uncertainties such as the error in hysteresis cancellation and to ensure the systems stability. The network controller was designed using neural network toolbox in MATLAB and, a low-pass filter with cut-off frequency of 10 Hz to filter out the high frequency noise present in the LVDT output signal.

Rustighi *et al*.(2005a) exploited change in Young's modulus of the SMA, while designing an adaptive tuned vibration absorber. However, they observed that the actual increase in Young's modulus was only 47.5% compared to the expected increase of about 150% due to the fact that the dynamic properties of the SMA were different from the static ones. The major drawback of the system was the slow response time. Rustighi *et al*.(2005b) designed and tested a PD and fuzzy controller for the same vibration absorber. It was concluded that the fuzzy controller was superior to the PD controller due to its improved tracking and smaller steady state error. As the modeling of both fuzzy controller and SMA actuation was non-linear, the former one was used to control the later. This was a model-based system combined with a fuzzy controller whose inputs were force and stiffness as shown in Fig.9. A 'neural network based control system' with resistance feedback was proposed by Lee *et al*.(2001) for the bending angle control of SMA actuated catheter and its performance was compared with the PID controller. Song (2003) designed a neural network feed forward controller for open loop tracking control of an SMA wire actuator without a position sensor. The experimental results confirmed that the control design could track a sinusoidal reference command with reasonable degree of accuracy.

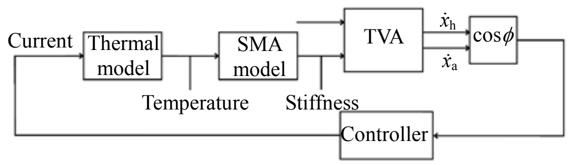

Fig.9 Model based control system for SMA actuator (Rustighi *et al.*, 2005b)

A 'trained fuzzy logic controller' was designed by Sreekumar *et al*.(2006) for the control of SMA actuators. It reduced the number of fuzzy rules using table-lookup scheme based on heat transfer dynamics. The MISO (Multiple Inputs and Single Input) Mamdani type fuzzy controller with table-lookup scheme as its training algorithm was employed for the control of SMA actuators. Fuzzy controllers are most effective for mapping the nonlinearity present in any nonlinear control problems as justified by the 'universal approximation theorem'. The inputs and outputs for the controllers were obtained from the heat transfer model and were arranged in a table. The results obtained by simulation with the help of MATLAB were presented. Various software and hardware methods are available for the implementation of fuzzy controllers. Hull *et al.*(2004) stated that by using Motorola HC12 microcontroller a 'fuzzy-logic control' scheme would be naturally and efficiently implemented.

Sensorless control system

Sensory feedback is usually required for the control of any system employing SMA actuators. The type of sensors could be for the measurement of force, temperature, strain or displacement. But if the actuator is used merely for on-off applications, then a sensor is not required. In other applications also, where the actuator is divided into segments and controlled independently, as in segmented binary control shown by Mukherjee *et al.*(1996) and Selden *et al.*(2006), a sensor is not needed. A sensorless control system for multiple SMA actuators was designed and demonstrated experimentally by Sujan and Dubowsky (2004), for a parallel compliant mechanism called Binary Robotic Articulated Intelligent Device (BRAID). A decoder chip was fixed with each actuator that was triggered to actuate the selected SMA actuator into a binary state as shown schematically in Fig.10.

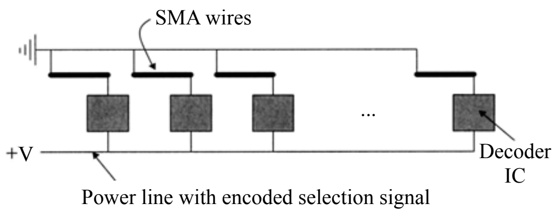

Fig.10 Control system with decoder for multiple SMA actuators (Sujan and Dubowsky, 2004)

CONCLUSION

Recent developments for the efficient control of SMA actuators, with emphasis on nonlinear control technologies, and their heating and cooling methods, had been discussed and described in detail. Various types of nonlinear control schemes employed by researchers exploited the SMA's nonlinear hysteresis and change in Young's modulus/resistance/strain for obtaining optimal performance. Selection of appropriate heating/cooling techniques, control strategies and position feedback methods for controlling SMA actuators in robotics had also been described. The resistive heating method was most commonly employed for heating wires up to 400 μm diameter and indirect techniques like conductive, convective, or radiative methods were used for heating wires beyond 400 μm.

Based on the review of literature, the resistance feedback control of SMA elements is ideal for micro robots as it eliminates the need for additional sensors. Control through resistance feedback is a good method for applications with limited space but precise control is very difficult, especially for position control. Instead of resistance feedback, force feedback can also be used. Control system with dual feedback could satisfy the criteria wherever precise tracking or position control is needed. SMA actuators can be controlled without feedback sensors also. But in that case, the actuation becomes a binary one and has limited applications with less complication due to the hysteresis effect. For multiple position control, the nonlinear hysteresis curve can be linearized by dividing the same into segments with different slopes. A fuzzy controller or neuro-fuzzy controller with suitable training scheme or an optimization algorithm could achieve accurate position control by controlling the input current/voltage/both depending on the slope of the linearized segments. This is one of the most potential areas for future research, and would have diverse applications in the field of advanced robotics.

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