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FUZZY-SLIDING MODE CONTROL OF A SMA MANIPULATOR

Kyoung Kwan Ahn, S M Mahfuzur Rahman and Nguyen Bao Kha

School of Mechanical and Automotive Engineering, University of Ulsan
San 29, Muger2dong, Nam-gu, Ulsan 680-749, Republic of Korea.
TEL: +82-52-222-1404; FAX: +82-52-259-1680.
Email: kkahn@ulsan.ac.kr, mahfuzme@gmail.com, nbkha@hcmut.edu.vn.

ABSTRACT
This work investigates an upstanding control algorithm for controlling a single-degree-of-freedom shape memory alloy (SMA) actuated manipulator. The SMA actuated manipulator has system nonlinearities, model and parametric uncertainties that make it difficult to control in application and some physical parameters of SMA are not available experimentally due to difficulties in measuring them. Thus, a sliding mode controller (SMC) would be the best choice to control this system in presence of system nonlinearities and parameter uncertainties. Sliding mode controller due to its nature is discontinuous and creates some problems in application, the most important one is chattering, which may excite high frequency dynamics neglected in the course of modeling. In order to eliminate or alleviate chattering phenomena, a heuristic based intelligent control approach like fuzzy logic theory is utilized to cope with the control problem. Thus, the resulting control algorithm would have a superior performance both in stabilization and tracking in the presence of modeling and parametric uncertainties of the SMA actuated manipulator system. Experimental results from real time control are presented to show the effectiveness of the controller. The results demonstrate that the controller designs are accurate in tracking both stationary and periodic variable input signals.

Keywords: Shape Memory Alloy, Sliding Mode Control, Fuzzy Logic, Manipulator.

1. INTRODUCTION

Shape Memory Alloy (SMA) composites are the smart materials that exhibit two very unique properties, pseudo-elasticity and shape memory effect those are made possible through a solid state phase change. The two phases, which occur in SMAs are Martensite and Austenite. Martensite is the relatively soft and easily deformed phase exists at lower temperatures and Austenite, the stronger phase of SMAs occurs at higher temperatures. SMAs have been used in a wide variety of actuation applications including space stations, automotive components, surgical devices, robotic arms and so on. There is also an increasing demand of SMAs for developing small size and lightweight devices that will be able to produce large forces, large displacements, high speeds, and will be highly energy efficient. The use of SMAs in applications necessitating actuation has several advantages such as excellent power to weight ratio, maintainability and reliability, large deformation, clean and silent actuations, smooth motion, etc. These advantages make SMAs ideal for use as a actuators in a variety of applications [4], [7], [10], [13].The disadvantages are low energy efficiency due to conversion of heat to mechanical work, slow response and difficulties in motion control due to following reasons [17]: a) SMA actuators presents complex thermal-electrical-mechanical dynamics that are difficult to model; b) due to their temperature dependency, SMA actuators are very sensitive in temperature changes; c) due to the flexible characteristics of SMA actuators, substantial vibrations can be exited when these are used to power the joints of robot system. Thus, controllers for SMA actuators need to be robust in system and environmental changes, and modeling errors. Several control methods of SMA actuators have been investigated; these can be categorized as linear control [15], nonlinear control [3],[6],[9], intelligent control [1], [8], [12], variable structure control [2], [14] and wide variations of Proportional Integral Derivative (PID) control [5].

In this work, we have developed a sliding mode controller that works in conjunction with intelligent fuzzy logic controller. Based on position error fuzzy logic calculates boundary layer thickness and sliding mode controller adjusts control input (volts) based on ratio of sliding surface to the boundary layer thickness. Joint angular positions are numerically calculated from a rotary encoder data.

2. SMA MANIPULATOR

There are two ways of providing the bias force and therefore two types of SMA actuators. The first one called bias type (or one-way actuator), is composed of a SMA element and a bias spring, and another called differential type (or two-way actuator), and is composed of two SMA elements. In one-way actuators, the resulting torque is the difference between the bias torque and SMA wire torque. Considering the hardware limitations, in our design the manipulator is actuated by a bias type SMA wire actuator without bias spring, where the bias force (torque) is provided by the weight of the moving arm and payload. A schematic of the manipulator system is shown in figure 1, and a photograph of the experimental setup is given in appendix (figure 10).

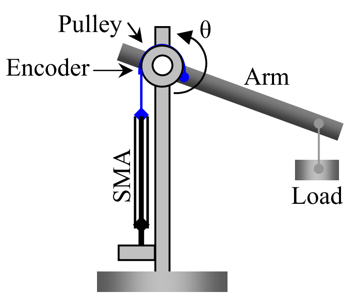


Fig 1: One-dof SMA Manipulator.

The SMA wire is heated with resistive electrical (Joule) heating by applying controlled input voltage, and beyond the activation temperature it contracts due to the phase transformation from Martensite to Austenite. Upon cooling, the wire's temperature falls and reverse phase transformation (from Austenite to Martensite) occurs, thus SMA wire is elongated under the action of bias force. The manipulator system is constructed such that the moving arm can rotate from 0^0 to 150^0 using a DM01 Linear Shape Memory Alloy Actuator, manufactured by MIGA^{TM} motor company, USA, and a rotary encoder is used to measure the joint angle of the moving arm.

3. CONTROL STRATEGY

A nonlinear sliding mode controller is used to calculate the adjustable applied input voltage to the SMA wire and an intelligent fuzzy logic controller is used to estimate the boundary layer thickness for the control input based on position error.

3.1 Sliding Mode Control

Sliding mode control, a particular kind of variable structure control, is a robust nonlinear control algorithm in which an *n*th order nonlinear and uncertain system is transformed to a 1st order system. Considering the *n*th order SISO dynamic system,

$$x^{(n)} = f(\mathrm{x}) + b(\mathrm{x})u \qquad (1)$$

Where scalar x is the output of interest, scalar u is control input and x is the state vector. $f(\mathrm{x})$ and $b(\mathrm{x})$ are the unknown nonlinear dynamic function and control gain respectively. The control objective is to follow a desired state vector x_d, such that $x_d(0) = x(0)$. A time-varying surface S(t) in state space R^n can be defined as,

$$s(\mathrm{x};t) = (\frac{d}{dt} + \lambda)^{n-1}\tilde{x} \qquad (2)$$

where $\tilde{x} = x - x_d$ is the tracking error and λ is a positive constant. It can be shown that, tracking the desired state vector is equivalent to that of remaining on the surface S(t) [14]. The sliding condition to track specific time-varying desired sate is,

$$\frac{1}{2}\frac{d}{dt}s^2 \le -\eta\,|\,s\,|, \qquad \eta \ge 0 \qquad (3)$$

Further detail on sliding mode control can be found in [14].

3.2 Fuzzy Logic Control

Sliding mode controller inherited chattering in applications. The constant width boundary layer design can reduce chattering of the control signals, but it decreases the control accuracy [16]. The compromise between smoothness of control signals and accuracy of control results is dictated by the proper adjustment of the boundary layer thickness. We thus choose a method of using fuzzy logic to control the width of boundary layer. Using error and rate of error as the control input, and the boundary layer width (φ) as the control output, the fuzzy control rules are set such that the system can get highest available input (voltage) initially to achieve the fastest possible response. The rule matrix of FLC is shown in table 1.

Table 1: FLC rule matrix for 5 membership functions
.

e / Δe	*NB*	*NM*	*ZERO*	*PM*	*PB*
NB	VL	L	M	S	VS
NM	L	M	L	M	S
ZERO	M	L	M	S	M
PM	L	M	L	M	S
PB	VL	L	M	S	VS

We chose five trapezoidal membership functions for each of control input and five Gaussian membership functions for control output with 'max-min' reasoning method, and center-of-gravity defuzzification method.

3.3 Controller Design

Since only joint angle θ is measured using a rotary encoder, we can define a proper sliding surface as a function of position error and velocity error as,

$$s = \lambda_P \tilde{\theta} + \lambda_V \dot{\tilde{\theta}} + \lambda_I \int_0^t \tilde{\theta} dt \qquad (4)$$

where, $\tilde{\theta} = \theta_d - \theta$ *and* $\dot{\tilde{\theta}} = \dot{\theta}_d - \dot{\theta}$, subscript d stands for desired values, and an integral term in the sliding surface is added to reduce the steady-state errors. Adjusting the boundary layer thickness properly using FLC, the decision rule or switching function can be defined as,

$$u = \begin{cases} V_h & if \ \frac{s}{\varphi} > 1 \\ s & if \ |\frac{s}{\varphi}| \leq 1 \\ V_l & if \ \frac{s}{\varphi} < -1 \end{cases} \qquad (5)$$

As we are using a bias type (one-way) actuator, the application of possible high voltage, V_h to the SMA actuator will force the trajectory to reach sliding surface expressed in equation (4). Once the sliding surface is reached, sliding mode controller keeps the states on the close neighborhood of the sliding surface (zero tracking error). This surface is asymptotically stable and the stability of the control system can be verified through sliding mode control theory [14]. The block diagram of the controller is shown in figure 2.

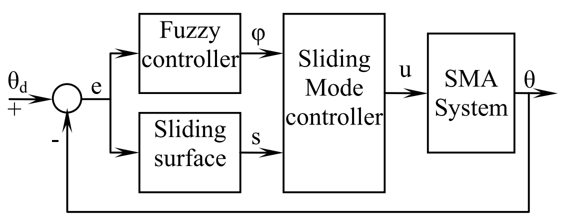


Fig 2: Block diagram of the controller.

4. RESULTS

A small-scale one-dof SMA manipulator has been constructed for experiment, shown in figure 1, 10, and all experiments have been done through real time control in MATLAB/Simulink environment. This section shows the experimental results. A PID controller, based on position error, is also used for comparison with the performance of fuzzy-SMC controller. It can be noted that at local minima, the desired trajectories require a rate of cooling that is higher than that of natural convection [9]. Hence, the actual trajectories differ a bit from the desired trajectories. Figure 3, 4 and 5 show that the controller works well in tracking desired steps. The others commanded trajectories are associated with frequencies; figure 7 (for a time period of 20 sec) shows a comparatively good performance of the controller than figures 6, 8 and 9. It can be explained that the SMA possesses a physical limitation of slow response and thus its performance decreased with increasing frequencies, as shown in figures 6, 7, 8, 9. Hence, we can say that, the small discrepancies between the desired and actual trajectories are due to the inherent physical limitations of the SMA actuator itself, and are not indicative of any drawback for the controller [9]. Furthermore, since, weight of the arm and payload produced bias torque, and there is no bias spring, some overshoots are found in the following figures, these overshoots also insist on the requirement of faster cooling [6].

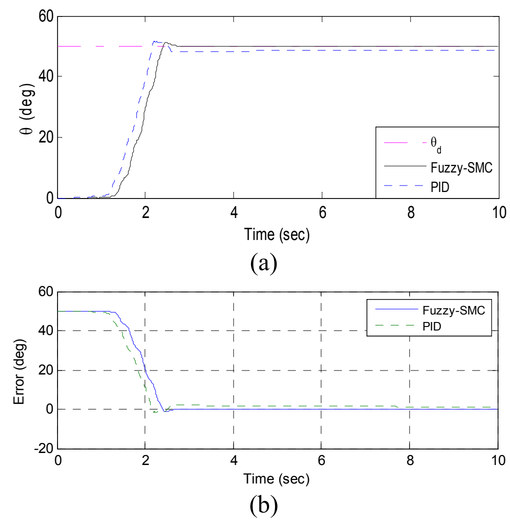


Fig 3: (a) Controller performance in tracking a desired step ($\theta_d = 50^0$) and (b) comparable tracking errors.

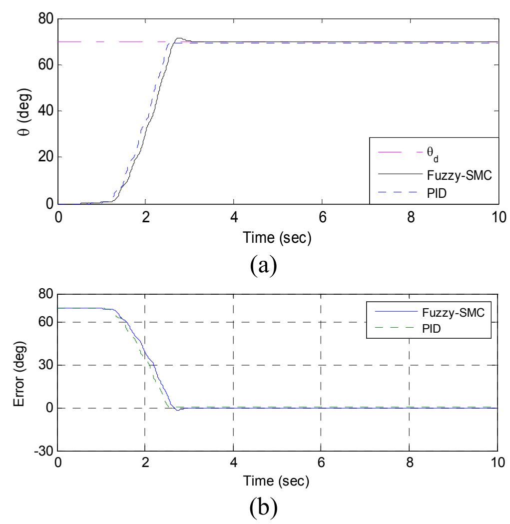
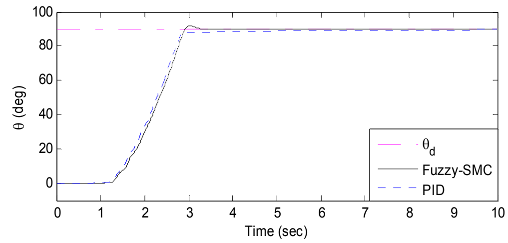
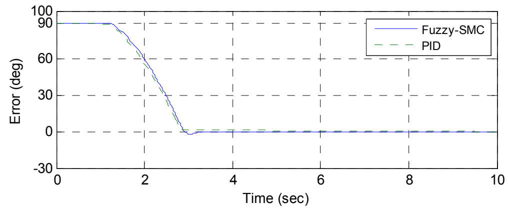


Fig 4: (a) Controller performance in tracking a desired step ($\theta_d = 70^0$) and (b) comparable tracking errors.

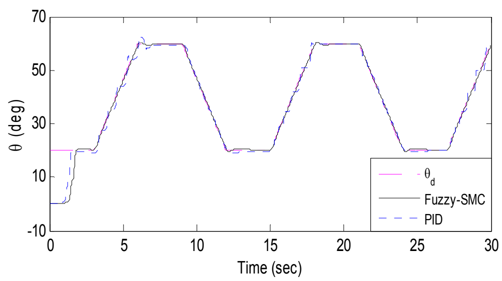


(a)



(b)

Fig 5: (a) Controller performance in tracking a desired step ($\theta_d = 90^0$) and (b) comparable tracking errors.



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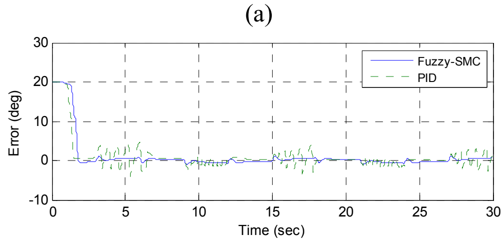
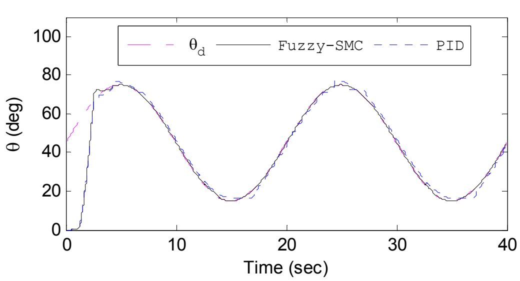
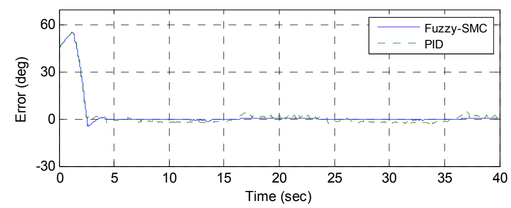


(b)

Fig 6: (a) Controller performance in tracking a desired repeating step varies between 20^0 to 60^0 and (b) comparable tracking errors.

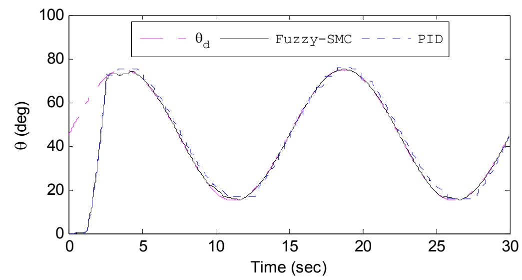


(a)



(b)

Fig 7: (a) Controller performance in tracking a desired sinusoidal of time period 20 sec and (b) comparable tracking errors.



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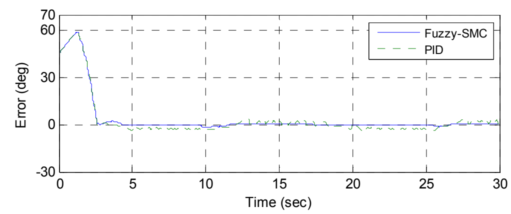
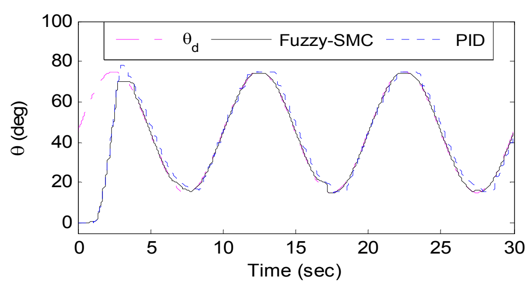
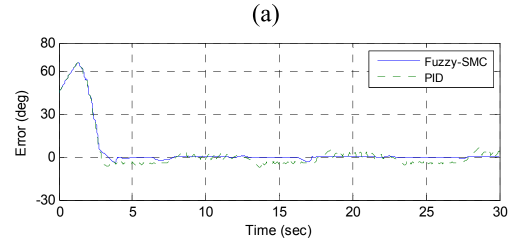


(b)

Fig 8: (a) Controller performance in tracking a desired sinusoidal of time period 15 sec and (b) comparable tracking errors.



(a)



(b)

Fig 9: (a) Controller performance in tracking a desired sinusoidal of time period 10 sec and (b) comparable tracking errors.

5. CONCLUSIONS

A sliding mode controller is designed that works in conjunction with a fuzzy logic controller. The fuzzy algorithm is defined for two significant reasons. One for reducing (eliminating) undesirable chattering and second one for making the system modeling very simple, because fuzzy logic works on a linguistic control approach that makes it insensitive to the unmodeled parameters and parameter uncertainties. The angular position of the manipulator is measured by a rotary encoder that is feedback to the controller. A sliding surface is designed based on the position and velocity errors, the sliding mode controller computes ratio of sliding surface to the boundary layer thickness as control index for applying control input (voltage) to the SMA actuator. In real time control, steps, repeating step and sinusoidal references are used, and the results show effectuality of the controller except very small discrepancies between commanded and actual trajectories due to the physical limitations of the SMA. The first step of the control algorithm (SMC) ensures robustness against parametric uncertainty [14], simultaneously the second step (FLC) ensures robustness against high frequency un-modeled dynamics. It is therefore possible to realize smooth and robust control avoiding the system's complexity in real time controls. This control algorithm can be applied extensively in the field involving the actuation of SMA and piezoelectric actuators.

6. REFERENCES

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7. NOMENCLATURES

Table 2. Meaning of symbols

Symbols	Meaning (value)	Unit
V_h	Highest voltage (6)	Volts
V_l	Lowest voltage (0)	Volts
φ	Boundary layer thickness	--
θ	Joint angle	deg
θ_d	Desired input	deg
u	Control input	Volts
e	Error	deg
λ	Gain	--

8. ACKNOWLEDGEMENT

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9. APPENDIX

Table 3. Joint and arm parameters.

Parameters	Value	Unit
Pulley diameter	4.8	mm
Arm length	115	mm
Mass (with payload)	76	Gm
Inertia	2.023e-4	Kg-m^2
Joint range	0 – 150	Deg

Table 4. List of hardware used in the experiment.

Name	Model	Manufacturer
SMA	DM01	MIGA mortor
Rotary encoder	S30-4-1024ZO	Metronix
D/A board	PCI 1711S	Advantech
Wiring Terminal	PCLD-8710	Advantech
A/D board	PCI QUAD04	Computing Measurement

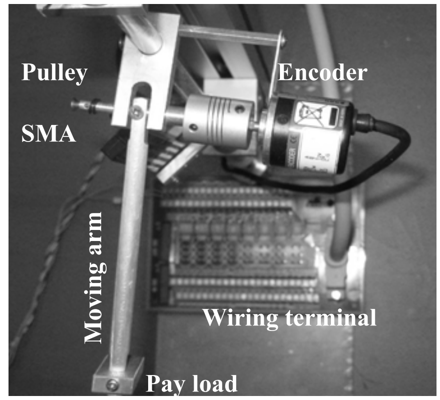

Fig 10: Photograph from experimental setup of one-dof SMA manipulator.