





















where  $K_i = K_p/T_i$  and  $K_d = K_p T_d/T_i$  is integral time parameter,  $T_d$  is derivative time parameter equation (9). Because the proposed fuzzy self-tuning PID controller aims to improve the control performance yielded by a PID controller, it keeps the simple structure of the PID controller and it is not necessary to modify any hardware parts of the original control system for implementation. Fuzzy self-tuning of PID parameters is finding out the fuzzy relation between the three PID parameters  $K_p$ ,  $K_i$  and  $K_d$ . It examines continuously  $e$  and  $\dot{e}$  then tunes the three parameters with fuzzy control rules online so that the controlled objects achieve better dynamic steady performance. The structure of the self-tuning fuzzy PID controller is shown in Figure 9 where  $e$  is the error between actual position and set point and the output,  $\dot{e}$  is the derivation of error. The PID parameters are tuned by using fuzzy inference, which provide a nonlinear mapping from the error(s) and derivation of error to PID parameters.

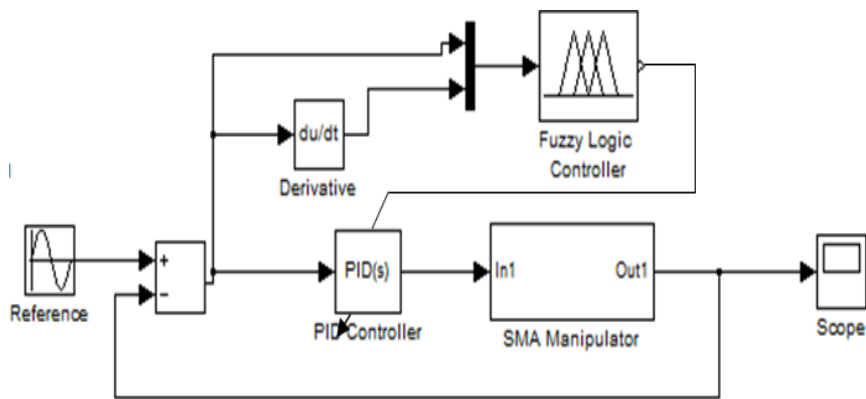


Figure 9. Controller structure

The fuzzy rules designed are based on the characteristic of the antagonistic shape memory alloy actuator and properties of the PID controller. Therefore, the fuzzy reasoning of fuzzy sets of outputs is gained by aggregation operation of fuzzy sets inputs and the designed fuzzy rules. The aggregation and defuzzification method used are respectively max-min and centroid method. Regarding the fuzzy structure, there are two inputs to fuzzy inference: error  $e(t)$  and derivative of error  $de(t)$ , and three outputs for each PID controller parameters respectively  $K'_p$ ,  $K'_i$  and  $K'_d$ . Mamdani model is applied as structure of fuzzy inference with some modification to obtain the best value for  $K_p$ ,  $K_i$  and  $K_d$ . Fuzzy inference block of the controller design is shown in Figure 10.

The variable ranges of the parameters  $K_p$ ,  $K_i$  and  $K_d$  of PID controller are respectively  $[K_{pmin}, K_{pmax}]$ ,  $[K_{imin}, K_{imax}]$  and  $[K_{dmin}, K_{dmax}]$ . The range of each parameter was determined based on the simulation on PID controller to obtain feasible rule bases with high inference efficiency. The range of each parameter are  $K_p = [1, 80]$ ,  $K_i = [0, 1]$  and  $K_d = [0, 0.1]$ . Therefore, they can be calibrated over the interval  $[0, 1]$  as follows:

$$K'_p = \frac{K_p - K_{pmin}}{K_{pmax} - K_{pmin}} = \frac{K_p - 1}{80 - 1} \tag{10(a)}$$

$$K'_i = \frac{K_i - K_{imin}}{K_{imax} - K_{imin}} = \frac{K_i - 0}{1 - 0} \tag{10(b)}$$

$$K'_d = \frac{K_d - K_{dmin}}{K_{dmax} - K_{dmin}} = \frac{K_d - 0}{0.01 - 0} \tag{10(c)}$$

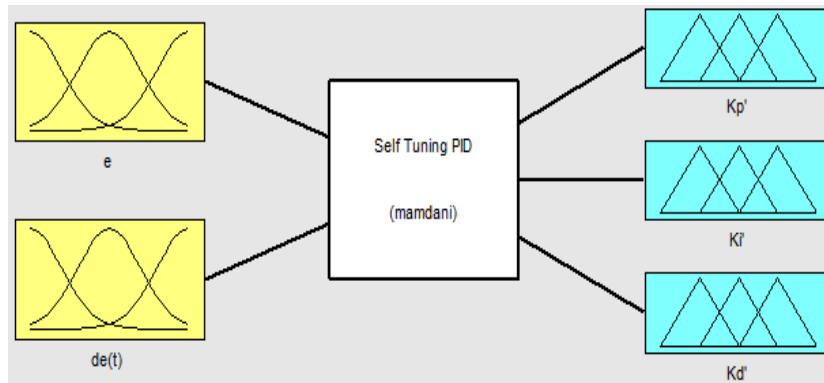


Figure 10. Fuzzy inference block

Hence the  $K'_p$ ,  $K'_i$  and  $K'_d$  values can be got from equation. (10). The membership functions of these inputs fuzzy sets are shown in Figure 11 and 12. The linguistic variable levels are assigned as NB: negative big; NS: negative small; ZE: zero; PS: positive small; PB: positive big. These levels are chosen from the characteristics and specification of the SMA actuator. The ranges of these inputs are from -0.1 to 0.1, which are obtained from the absolute value of the system error and its derivative through the gains, whereas the membership functions of outputs  $K'_p$ ,  $K'_i$  and  $K'_d$  are shown in Figure.13. The linguistic levels of these outputs are assigned as S: small; MS: medium small; M: medium; MB: medium big; B: big, where the range varies from 0 to 1.

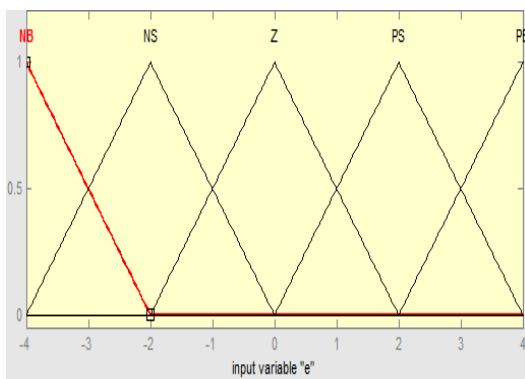


Figure 11. Membership function of  $e(t)$

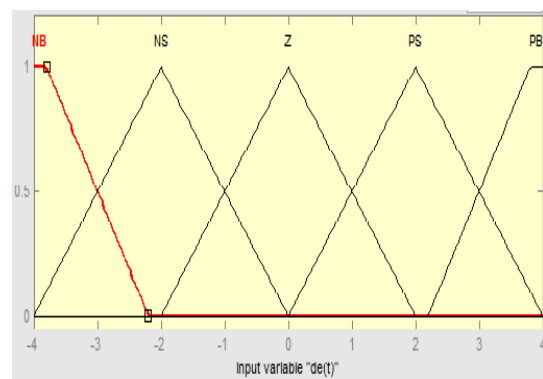


Figure 12. Membership function of  $d e(t)$

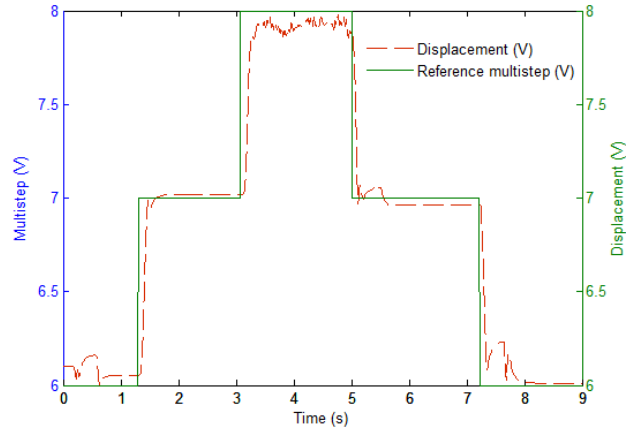
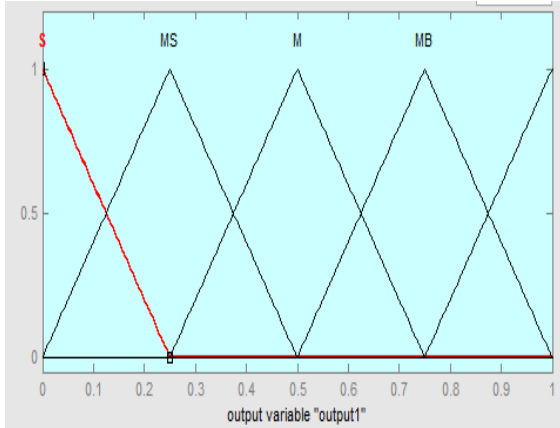


Figure 13. Membership functions of  $K_p'$ ,  $K_i'$  and  $K_d'$       Figure 14. Multi step tracking

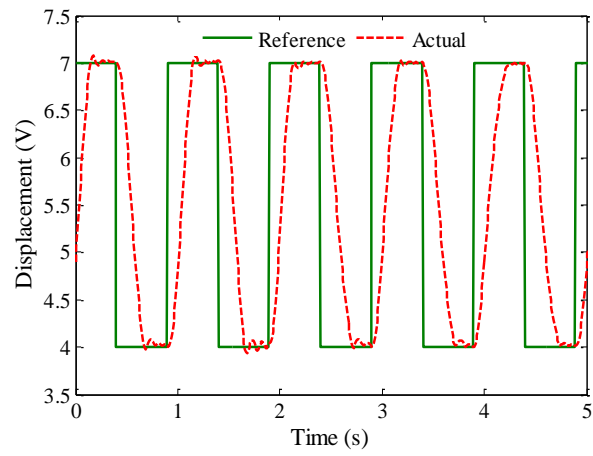
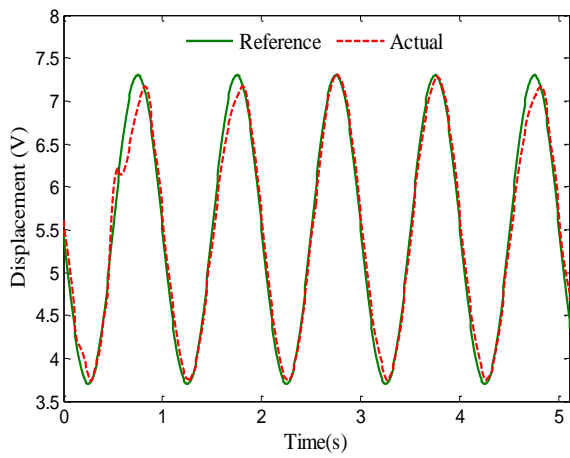
## VI. EXPERIMENTAL AND SIMULATION RESULTS

Experiments were performed to examine the angular trajectory tracking of the robotic arm using the PID control technique. To protect the SMA actuators from overheating, the applied current was limited to 210 mA. The repetitive step tracking of the arm is shown in Figure 14. The strain of the SMA actuator changes when it tracks the input reference signal. This motion of the arm is monitored by laser displacement sensor (Aquity AR200). Figure 15(a) represents the tracking of a sinusoidal and square reference trajectory by the SMA actuators in closed loop with a frequency of 1Hz. The electrical resistance change in the SMA actuators and the current signal driving the actuators are shown in Figure 15 (b) and 15(c) respectively. Figure 15(d) represents the differential torque acting on the manipulator. Subsequently the arm trajectory for a triangle wave with an input frequency of 1Hz is shown in Figure 16.

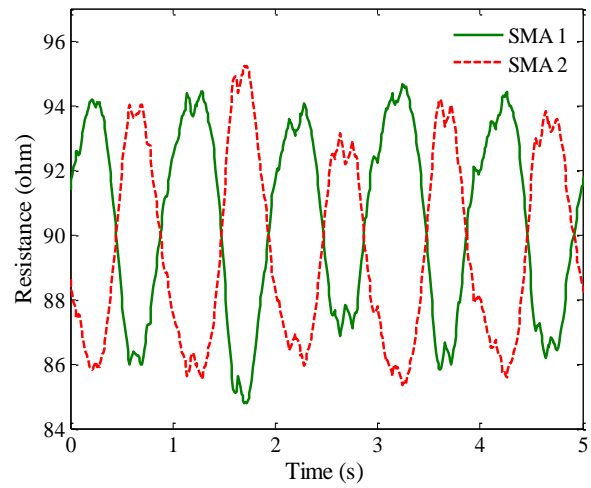
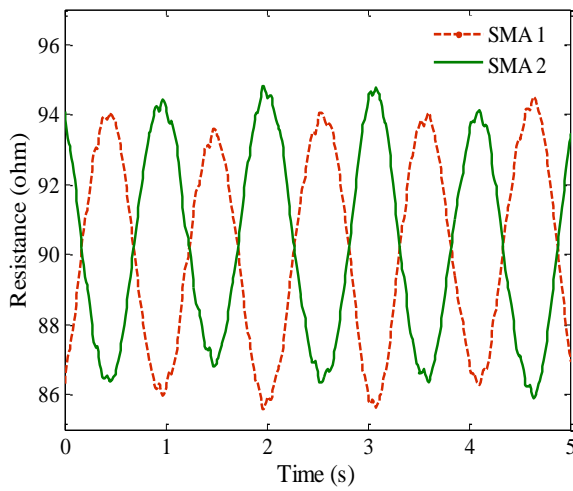
## VII. CONCLUSION

The paper presents the design, model and control of an antagonistically connected SMA wire actuator suitable for any robotic application. System identification technique is employed to obtain a state space model of the system. The self-tuning fuzzy PID controller employed here uses strain as a feedback signal and drives the actuators. The experimental results indicate that the controller can perform well in regulating the one joint arm manipulator to closely track the desired reference signal with a frequency of 1Hz, achieved smaller transient error and the appropriate selection of the pulley radius made the controller to track effectively and also retain stable behavior. The control scheme applied to the one joint arm driven by antagonistic

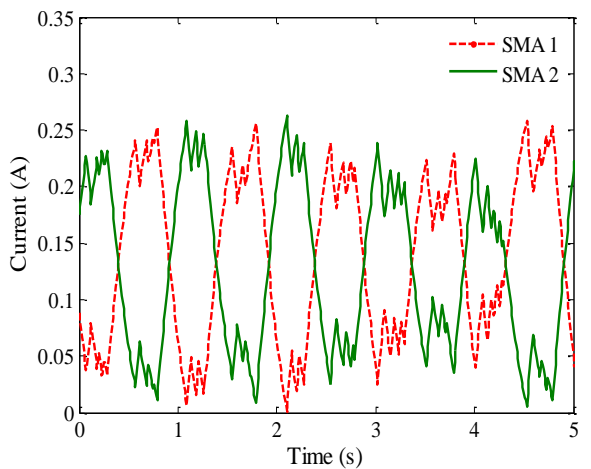
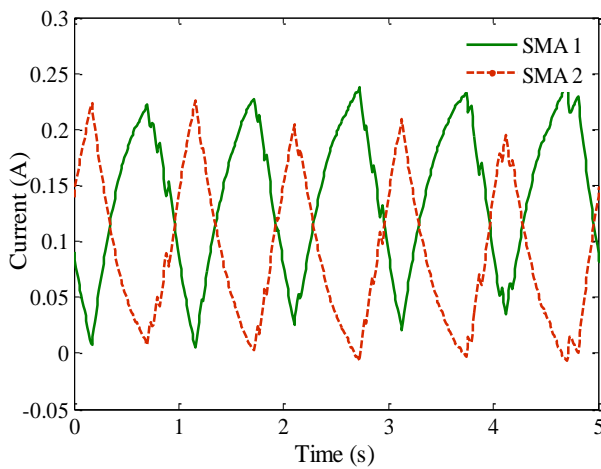
SMA actuator achieves more accurate and dynamic tracking performance compared to conventional controllers.



(a)



(b)



(c)

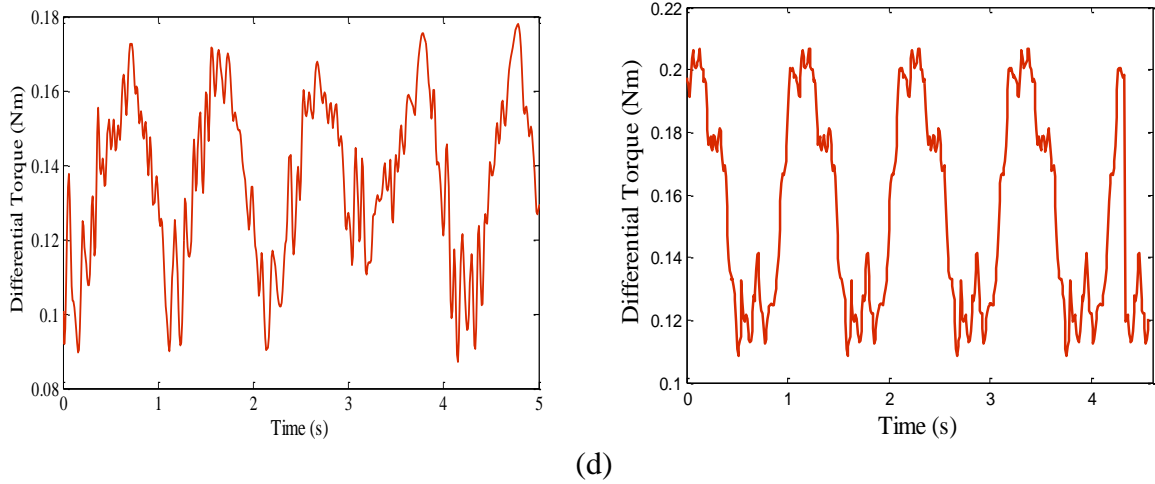
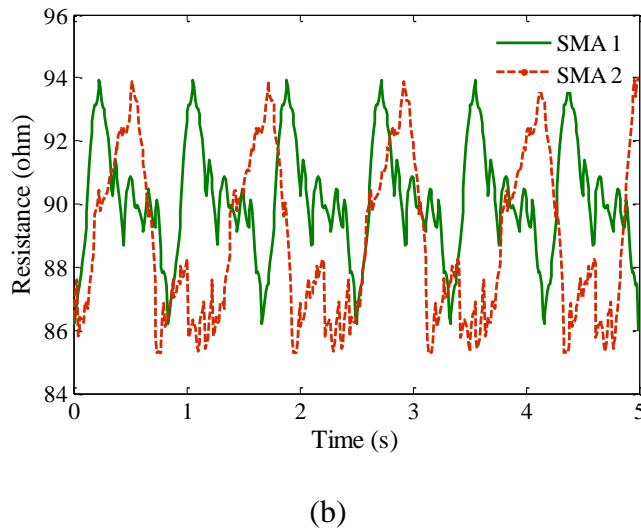
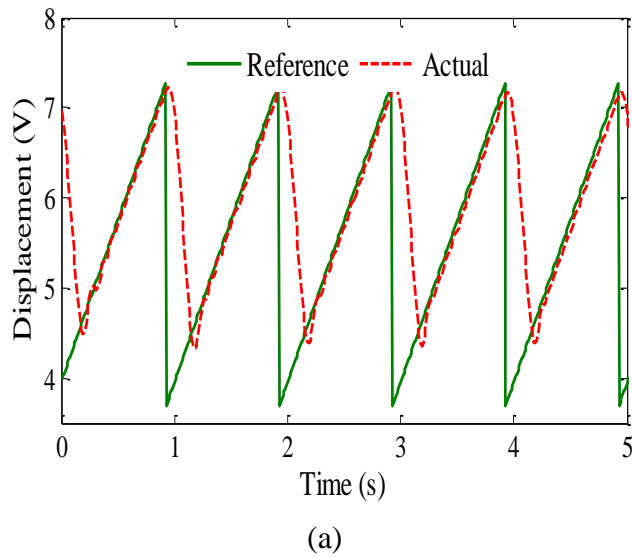
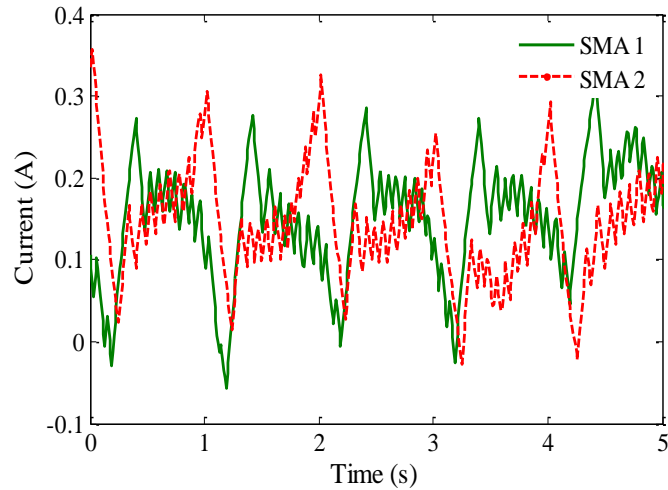
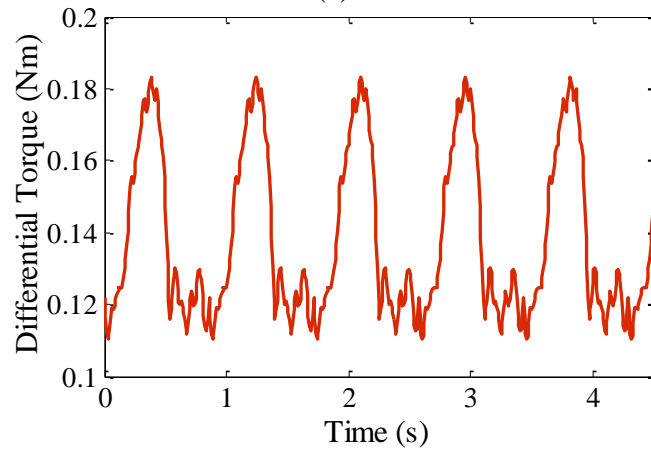


Figure 15. Experimental results for tracking a sinusoidal and square trajectory  
(a) desired and actual angular position  
(b) resistance change in SMA wire  
(c) current signal to the SMA wires  
(d) differential torque developed





(c)



(d)

Figure 16. Experimental results for tracking a sinusoidal trajectory  
 (a) Desired and actual angular position (b) Resistance change in SMA wire  
 (c) Current signal to the SMA wires (d) Differential torque developed

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