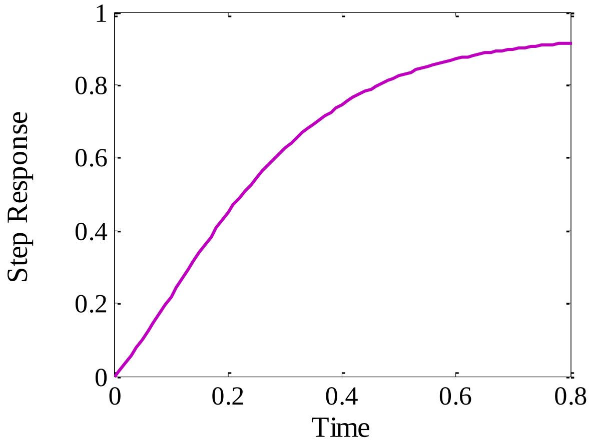


Figure 7. Transient response of the model

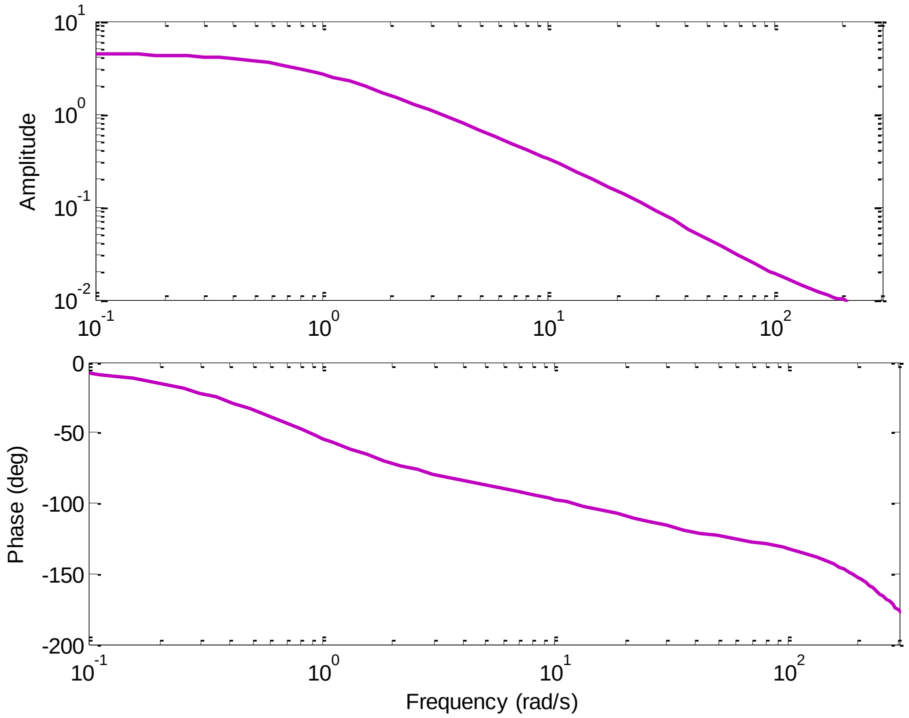


Figure 8. Frequency response of the model

V. CONTROLLER DESIGN AND VALIDATION

The self-tuning PID-type fuzzy controller is an auto adaptive controller that is designed by using an incremental fuzzy logic controller in place of the proportional term in the conventional PID controller to tune the parameters of PID controller on line by fuzzy control rules. The controller uses the error and the rate of change of error as its inputs and to meet the desired self-tuning parameters based on time-varying e and $\dot{e}$.

$$y(t) = Kp\, e(t) + Kd\frac{de(t)}{d(t)} + Ki\int_0^t e(t).d(t) \tag{9}$$

where $K_i = K_p/T_i$ and $K_d = K_pT_d, T_i$ 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 and derivation of error to PID parameters.

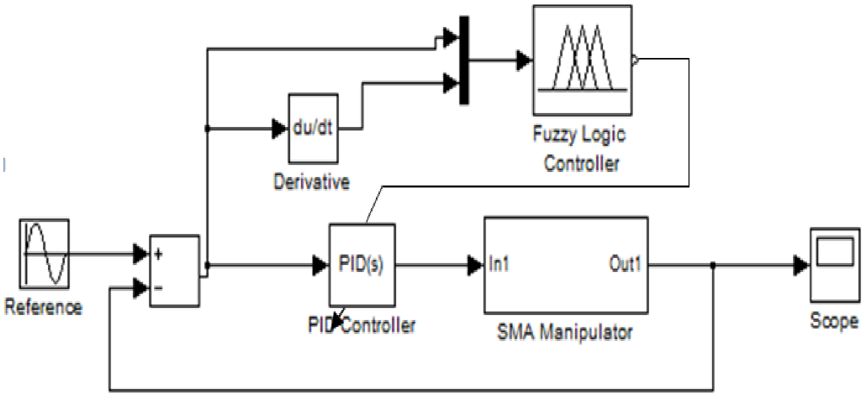


Figure 9. Controller structure

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:

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

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

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

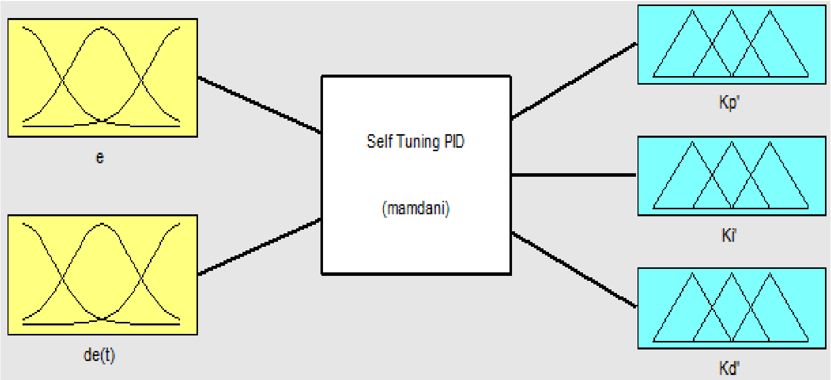


Figure 10. Fuzzy inference block

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.

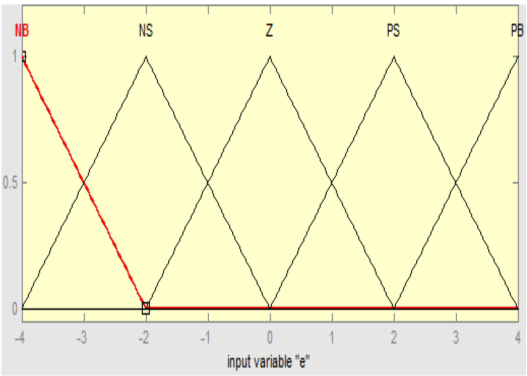


Figure 11. Membership function of $e(t)$

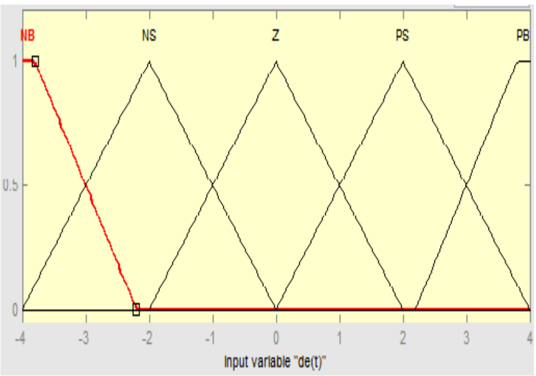


Figure 12. Membership function of $d\,e(t)$

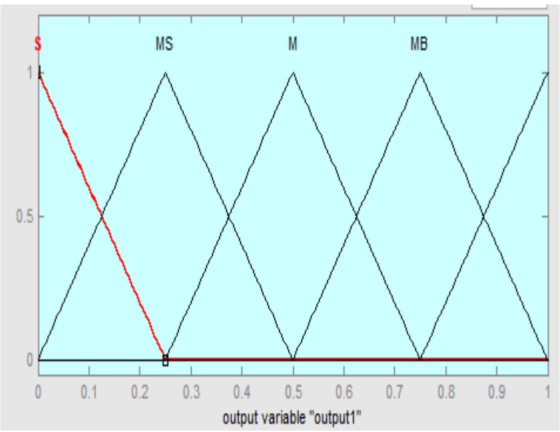


Figure 13. Membership functions of K_p', K_i' and K_d'

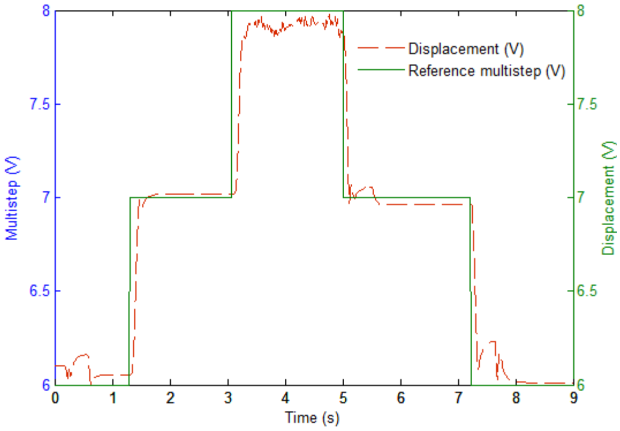


Figure 14. Multi step tracking

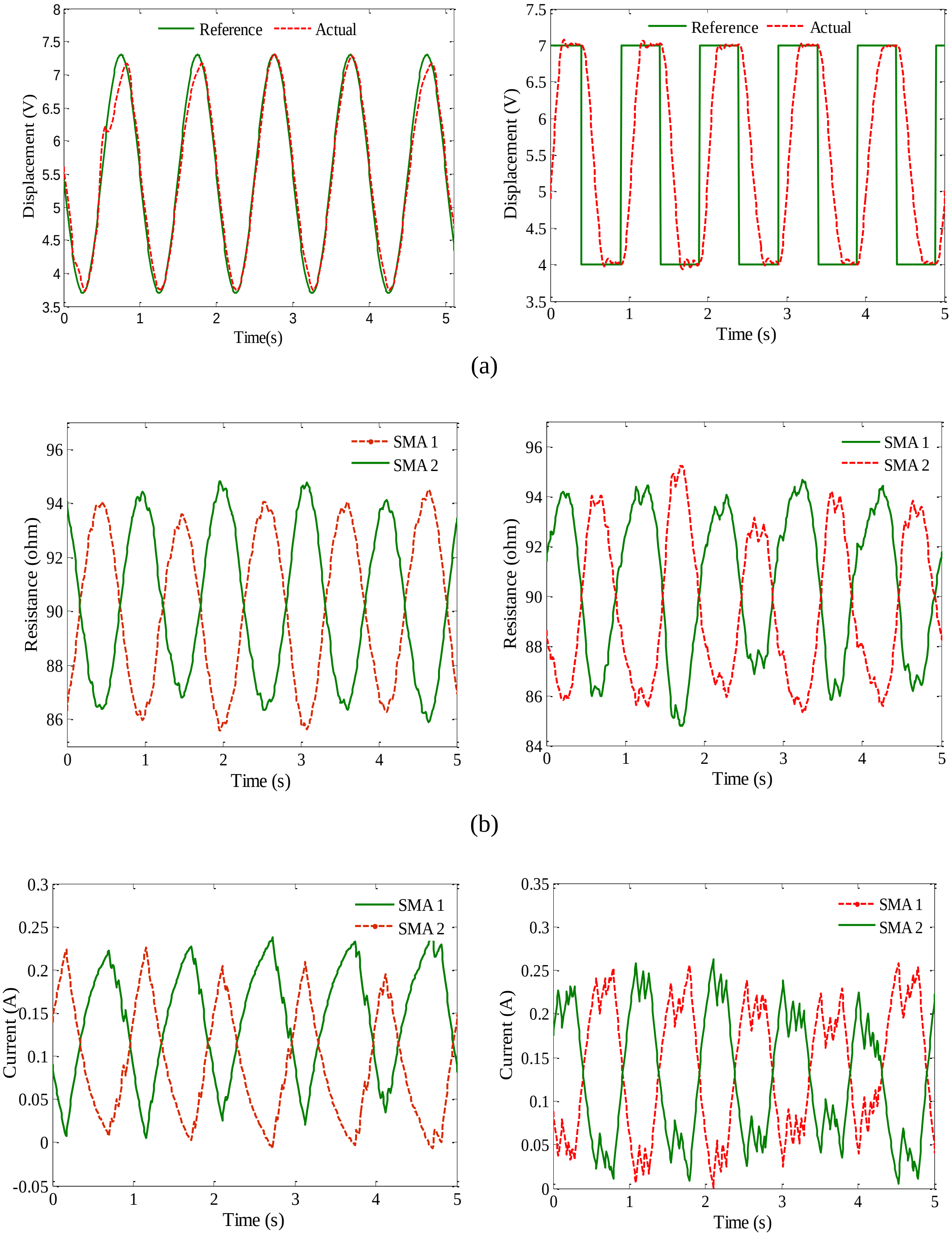
VI. EXPERIMENTAL AND SIMULATION RESULTS

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 Figure15 (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 Figure16.

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

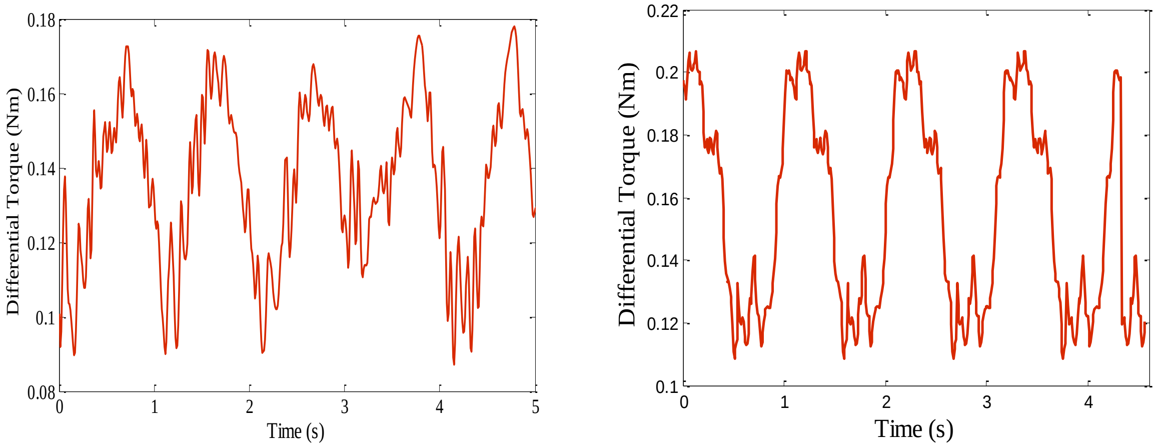
SMA actuator achieves more accurate and dynamic tracking performance compared to conventional controllers.



(a)

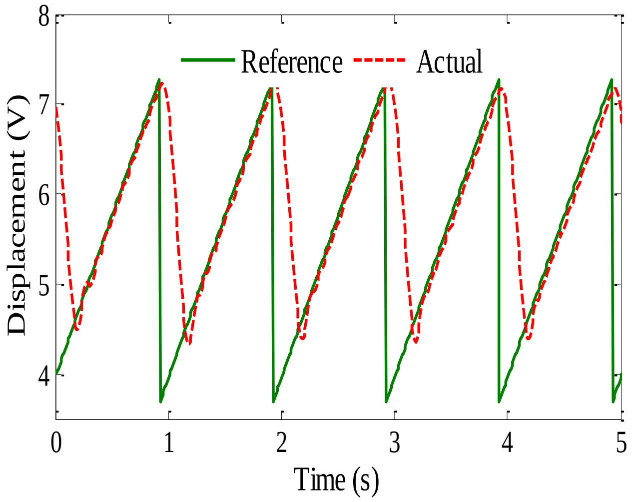
(b)

(c)

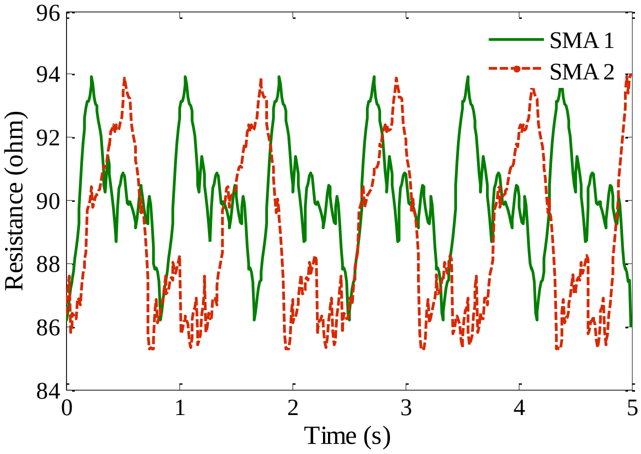


(d)

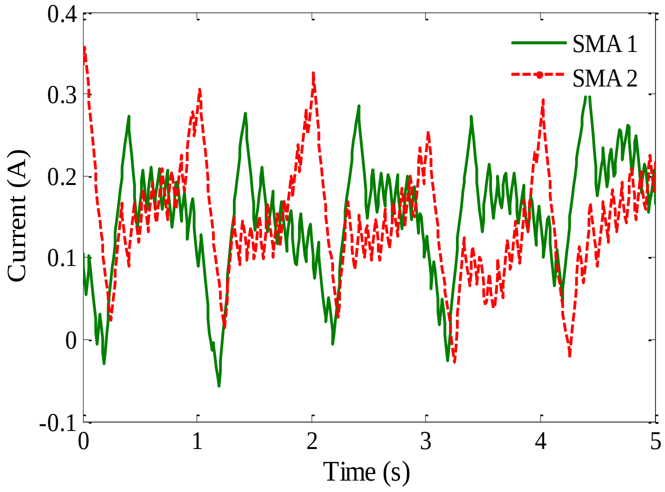
Figure 15. Experimental results for tracking a sinusoidal and square trajectory (a) desired and actual angular position (b) resistance change in SMA wire (c) current signal to the SMA wires (d) differential torque developed



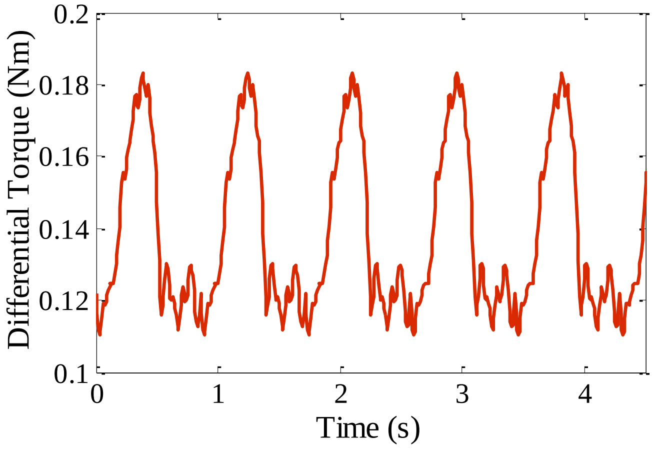
(a)



(b)



(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

REFERENCES

[1] K.F. Beyeler, A. Neild, S. Oberti, D. J. Bell, Y. Sun, J. Dual and B. J. Nelson, Monolithically Fabricated Microgripper with Integrated Force Sensor for Manipulating Microobjects and Biological Cells Aligned in an Ultrasonic Field, J. Microelectromech. Syst., Vol 16 No 1, pp. 7–15, 2007.

[2] T. C. Duc, G. K. Lau, J. F. Creemer and P. M. Sarro, ElectrothermalMicrogripper with Large Jaw Displacement and Integrated Force Sensors,J. Microelectromech. Syst., Vol 17 No6, pp. 1546–1555, 2008.

[3] S. Konishi, F. Kawai and P. Cusin, Thin Flexible End-effector using Pneumatic Balloon Actuator, Sens. Actuators A, 89, pp. 28-35, 2001.

[4] R. Lumia and M. Shahinpoor, IPMC Microgripper Research and Development, J. Phys.: Conf. Ser., 127, 012002, 2008.

[5] R. Pérez, J. Agnus, C. Clévy, A. Hubert, and N. Chaillet, Modeling, Fabrication, and Validation of a High-Performance 2-DoF Piezoactuator for Micromanipulation, IEEE/ASME Trans. Mechatron., 10(2), pp. 161-171, 2005.

[6] D.H. Kim, B. Kimand H. Kang, Development of a Piezoelectric Polymer-based Sensorized Microgripper for Microassembly and Micromanipulation, Microsystem Technologies, 10, pp. 275–280, 2004.

[7] Z. W. Zhong and C. K. Yeong, Development of a Gripper Using SMA Wire, Sens. Actuators A, 126(2), pp. 375–381, 2006.

[8] J. H. Kyung, B. G. Ko, Y. H. Ha, and G. J. Chung, Design of a Microgripper for Micromanipulation of Microcomponents Using SMA Wires and Flexible Hinges, Sens. Actuators A, 141, pp. 144–150, 2008 .

[9] J. M. Stevens and G. D. Buckner, Actuation and control strategies for miniature robotic surgical systems, ASME J. Dyn. Syst., Meas. Control, Vol. 127, pp. 537–549. 2010.

[10] F. Morra, R. Molfino and F. Cepolina, Miniature gripping device, Proc. Int. Conf. Intell. Manipulation Grasping, pp. 363–368. 2004.

[11] H. Fischer, B. Vogel and A.Welle, Application of shape memory alloy in medical instruments, Minimally Invasive Therapy Allied Technol., Vol. 13, No. 4, pp. 248–253, 2004.

[12] M. Hashimoto, M. Takeda, H. Sagawa, I. Chiba and K. Sat, Shape memory alloy and robotic actuators, J. Robot. Syst., Vol. 2, pp. 325, 1985.

[13] K. Dhanalakshmi, Aditya Avinash, M. Umapathy, M. Marimuthu, Experimental study on vibration control of shape memory alloy actuated flexible beam, International Journal on Smart Sensing and Intelligent Systems, Vol 3,No 2, pp. 156-175, 2010.

[14] Nakshatharan S, Ruth D J S, Dhanalakshmi K, Design based active vibration control of a flexible structure using shape memory alloy wire actuators, IEEE International Conference on Sensing Technology, pp. 476-480, Dec 2012.

[15] Ruth D J S, Nakshatharan S, Dhanalakshmi K, Angular trajectory tracking using antagonistic shape memory alloy actuators, IEEE International Conference on Sensing Technology, pp.748-753, Dec 2012.

[16] M. Moallem and J. Lu, Application of shape memory alloy actuator for flexure control: Theory and experiments, IEEE Trans. Mechatronics, 2005, Vol. 10, No. 5, pp. 495–501.

[17] N.Ma and G Song, Control of shape memory alloy actuator using pulse width modulation, Smart Mater. Struct., Vol.12, pp. 712–719. 2003.

[18] Kevin M. Lynch, Matthew T. Mason, Dynamic manipulation with a one joint robot, IEEE International Conference on Robotics and Automation, Vol 1,pp 359-366,1997.

[19] S. Majima, K. Kodamaand T. Hasegawa, Modelling of shape memory alloy actuator and tracking control system with the model, IEEE Transactions on Control System Technology, Vol 9, pp.54, 2001.

[20] K. Kwan Ahn and B. Kha Nguyen, Position Control of Shape Memory Alloy Actuators using Self-Tuning Fuzzy PID Controller, J. Control Automation, Vol. 4, pp. 756-762, 2006.

[21] V. A. Tabsizi and M. Moallem, Nonlinear Position Control of Antagonistic Shape Memory Alloy Actuators, Proceedings of American Control Conference, pp 88-93, 2007.

[22] H. Li, C. Mao and J. Ou, Strain self-sensing property and strain rate dependent constitutive model of austenitic shape memory alloy: Experiment and Theory, Journal of Materials in Civil Engineering,Vol.17, No 6,pp 676-685,2005.

[23] Zulfatman and M. F. Rahmat, Application of self-tuning Fuzzy PID Controller on Industrial Hydraulic Actuator using System Identification Approach, International Journal on Smart Sensing and Intelligent Systems, Vol. 2, No. 2,pp 246-261,June 2009.