

Fuzzy PID Controller Design for Artificial Finger based SMA Actuators

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Abstract— Shape Memory Alloy (SMA) wires are currently employed in robotics, as well as prosthetic limbs and medical equipment. Due to advantages such as reducing the size in the application, high power-to-weight ratio, elimination of complex transmission systems and noiseless actuation, and human-machine interface, these materials are used as actuators in the prosthesis limb. Because of hysteresis property and nonlinear behavior of SMA, control of these actuators is very complicated. In this paper, the design of control algorithms has been discussed for SMA actuators in the artificial fingers with 3 DOF, which includes PID-fuzzy controller. Gains of controllers are set so that the current applied to SMA wires has minimum overshoot and output of system has minimal time to achieve stability. The simulation results compared with actual measured data show how well the controllers decrease the overshoot and time of stability of input signal to SMA wires.

Keywords- shape memory alloy; artificial hand; Fuzzy and Fuzzy-PID controller.

I. INTRODUCTION

Actuators are components of robot drive and caused the movement of them. Based of motion, actuators are divided in two types: linear and rotation, and based on performance they are divided in various types: electrical, hydraulic and pneumatic. Using actuators with physical characteristics of them such as weight and size has some limitation. So much activity on these systems has been carried out. In humanoid robots and artificial limbs, due to multiple active joints in limited space, need lightweight, small and powerful actuators for making large placement. SMA is used in robotics because of high ability such as reducing the size of robot and Compatibility with the human body. SMA constitutes a group of metallic materials with the ability of recovering a previous defined length or shape when stands under a thermodynamic process. The transition from one form of crystalline structure to another creates a mechanism by which the shape change occurs in SMAs. This change involves transition from a

monoclinic crystal form (martensite) to an ordered cubic crystal form (austenite). The austenite phase is stable at high temperature, and the martensite is stable at lower temperatures. So, the phase transformation between the two phases, martensite and austenite, is accompanied by variations in its resistivity [1]. The typical attribute of these materials is that their parameters can't be determined by simple interpolation of properties of alloys included in the compound. superplasticity, superelasticity, acid resistance and the shape memory effect (SME) make these compounds technically important. Due to advantages such as reducing the size in the application, high power-to-weight ratio, elimination of complex transmission systems and noiseless actuation, and human-machine interface, these materials are used as actuators in the prosthesis limb [2]. Disadvantages of these materials can be cited to hysteresis property. Despite these limitations, they are used in robotic hands and biomaterials.

In recent years, much researches aimed at controlling SMA actuators have been carried out in an artificial limb. Hull and et al. presented a PI controller for obtaining the desired position in SMA actuator [3]. Nguyen presented a new development of a SMA position control system by using a self-tuning fuzzy PID controller [4]. This control algorithm is used by tuning the parameters of the PID controller thereby integrating fuzzy inference and producing a fuzzy adaptive PID controller, which can then be used to improve the control performance of nonlinear systems. Bizdoaca presented a fuzzy logic controller for a SMA tentacle robotic structure [5]. Nicu-George was investigated PI, PD, PID and fuzzy logic controllers are connected to the single link SMA actuation [6]. Ahn used a PID controller for position control of SMA actuator that the parameters of this controller obtained by genetic algorithm [7]. J.Park presented combination of compliant tendon cables and one-way shape memory alloy (SMA) wires that form a set of agonist-antagonist artificial muscle pairs for the required flexion/extension or abduction/adduction of the finger joints [8]. The performance of the proposed actuation system is demonstrated using a 4

DOF artificial finger and for evaluation of finger's efficiency, he used PWM-PD controller.

In this paper, according to a dynamic model for an artificial finger with three degrees of freedom using the actuator of SMA [9], fuzzy-PID controller has been designed for position control of SMA actuators. Gains of controllers are carried out so that the current applied to SMA wires has minimum overshoot and output of system has minimal time to achieve stability.

II. DYNAMIC MODEL OF ROBOT

A dynamic model for an artificial finger by using properties of the SMA actuator is designed and presented [9]. This robotic finger has been designed and modeled with 3 DOF, revolute joints, SMA wires as the tendon in order to adduct each phalange of finger and springs to restore each phalanges of finger to original position. In this model, the direct and inverse kinematics of robot and robot motion equations are presented. Mechanism schematic of robot with 3 DOF, parameters and coordinate system is shown in Fig. 1. As shown in this figure, the SMA wire as an actuator after passing the pulley is connected to links of robot. When electrical current is applied in these wires, the wires are hot and after the phase changing, their lengths become shorter so the link of robot starts to turn. After removal of current, the wires are cooled gradually and return to their initial length. Torsion springs in the joints will cause the links to go to the original position.

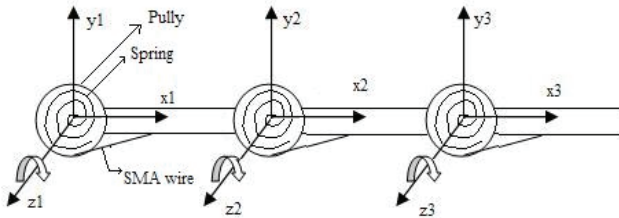


Figure 1. Mechanism schematic of robot with 3 DOF, parameters and coordinate

Kinetic of this robot with SMA actuators and thermodynamic properties of these actuators that include heat transfer, constitutive and phase transformation models are reviewed in reference [9]. Equation of motion of each robot's link by using Lagrange relations is expressed according to (1):

$$\tau_{ji} - \tau_{si} = \sum_{j=1}^n D_{ij}(q) \ddot{q}_i + \sum_{k=1}^n \sum_{j=1}^n c_{kj}^i(q) \dot{q}_k \dot{q}_j + h_i(q) + b_i(\dot{q}) \quad i=1,2,3 \quad (1)$$

For each link i , D_{ij} is mass matrix, c_{kj}^i is waste viscose term, h_i is terms related to the gravitational potential energy and b_i is frictional force. This model is ignored from friction of joints. Also τ_{si} the torque due to tensional spring and τ_{ji} the torque applied by the SMA actuator [9].

All elements expressed in equation (1), derived according equation and tables in [9].

Dynamic model of this artificial finger simulated in MATLAB/SIMULINK, as shown in Fig. 2. The entering input to and exiting output from this model are current and angles of joints respectively.

This simulation of dynamic model consists of SMA wire heat transfer model, SMA constitutive model and SMA phase transformation model.

The results of simulation model didn't have any offset and steady error; this means that after cutting off current, joints return to their initial position. Also joints reached the desired angle without fluctuation. In addition, after applying the current, joints begin to move immediately and it means that simulation didn't have delay and system motion is perfect (close to actual conditions).

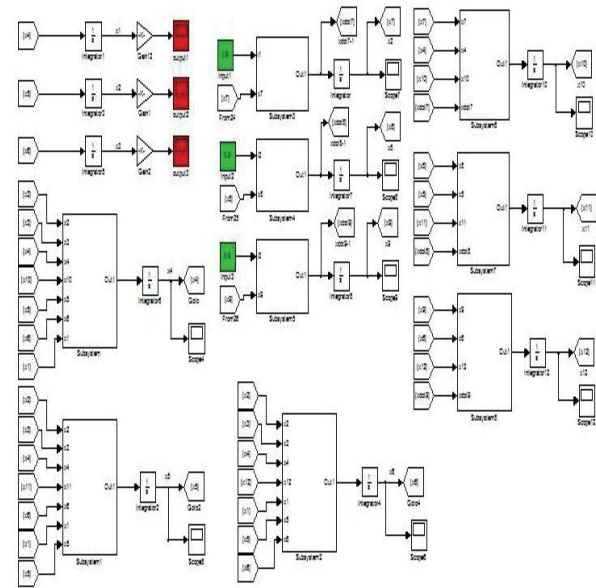


Figure 2. Simulation of dynamic model of artificial finger

III. DESIGN OF CONTROL SYSTEM

One of the most important parts of control system design is determining the appropriate controller parameters [10]. Planning system and achieving the best behavior is the definition that all the positive factors such as increased stability and reduced steady state error have been in the system.

In this paper a closed loop control method is expressed that is simulated in MATLAB /Simulation.

The design of a fuzzy-PID controller can be achieved in different ways. One way is to build a fuzzy controller with three inputs: the error (proportional action-GE), the delta error (derivative action-GCE) and the sum of the error (integral action-GIE) (see Fig. 3). The inconvenience for such a controller is that the number of rules will grow and instead of 25 rules (for system with 5 membership functions on each input), this controller will have 125 rules, making the tuning task very difficult. The solution is to divide the controller in two controllers, one that is the PD equivalent and another one

that provides the integral action. It will reduce the number of rules to 30 (see Fig. 4).

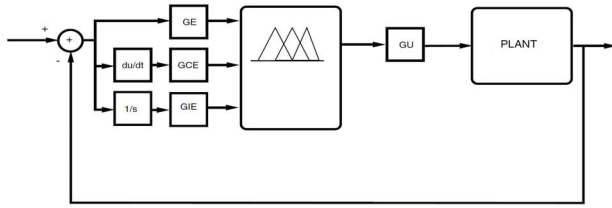


Figure 3. Fuzzy PID controller [10]

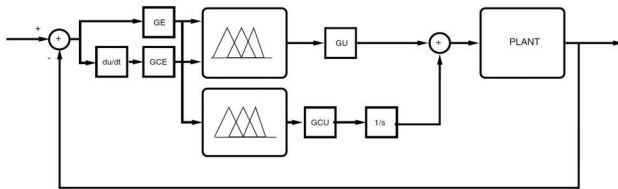


Figure 4. Fuzzy PD+I controller [10]

The use of the “gain constants” can be avoided using a more complex initialization on the fuzzy system where the inputs are not scaled and the singletons of the output are calculated using its direct relation with model values of the membership function in the antecedents, in the similar way as the rules are initialized in the training algorithm.

Further improvement will be done by trial and error, if there is no model of the plant, or via optimization, if a model is available. Using this initialization, the controller will guarantee a performance at least as good as the one provided by the linear PID controller.

Some of the typical actions in the trial-and-error procedure are to increase the impact of the proportional action when the error is very large and slightly reduces the integral action. These two actions tend to reduce the settling time and the overshoot.

In PID-fuzzy, value of desired angle is compared with the amount of feedback. Difference between these two signals is called the position error that it is input of fuzzy controller. The inputs of first fuzzy controller in each link are error (proportional action) and the delta error (derivative action) and because of fuzzy controller introduction in normal form, output is multiplied in a gain. The input of second fuzzy controller in each link is error (proportional action) and output of this controller is multiplied in a gain firstly then enters into the integral. Finally, the total outputs of both controllers are added together, current rate of SMA wire for achieving the desired angle is obtained.

In this section the structure of the fuzzy controller designed for artificial fingers, is investigated. Assuming five membership functions as Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB) on each input of the fuzzy controller and seven membership functions as Very Low (VL), Low (L), Middle Low (ML),

Middle (M), Middle High (MH), High (H) and Very High (VH) in the output of the fuzzy controller. The membership functions of inputs and output, which are defined normally, are shown in Fig. 5 and Fig. 6 respectively.

To express the rules, we need to note, the negative error means that the value of position is upper than desired position and applied current must be reduced for reducing the temperature of the wire and the positive error means that the value of position is lower than desired position, so the applied current should be increased for increasing the temperature of wire. With this definition, rules of first and second fuzzy controller are shown in Table 1 and Table 2 respectively.

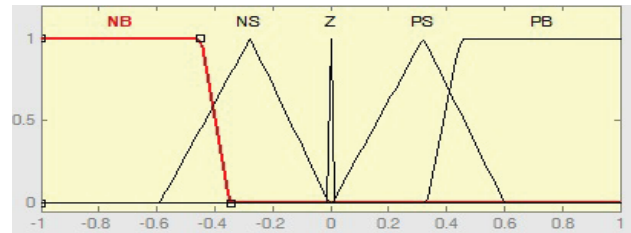


Figure 5. Membership functions for the input variables

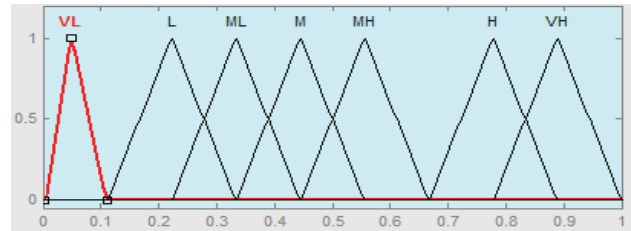


Figure 6. Membership functions for the output variable

TABLE I. RULES BASE FOR FIRST FUZZY CONTROLLER

e $de(t)$	NB	NS	Z	PS	PB
NB	VL	ML	M	H	VH
NS	L	M	VL	H	VH
Z	L	M	VL	H	VH
PS	L	M	VL	H	VH
PB	L	MH	VL	L	H

TABLE II. RULES BASE FOR SECOND FUZZY CONTROLLER

e	i
NB	VL
NS	L
Z	MH
PS	H
PB	VH

Gain scheduling has been used extensively on industrial applications. The advantage of this technique is the use of liner techniques to design controllers for nonlinear systems by applying linearization around the different operating points. In this way several linear controllers are designed and “connected” to the plant according to the current operating point. Fuzzy systems offer to these techniques the advantage of integrating in one mechanism the detection of the operating point and the interpolation among the different operating points, providing a smooth nonlinear control law. It has been proved that the fuzzy controllers can be seen as smooth gain scheduling controllers [10].

We used an approach intelligent to determine gain, so that for optimization of fuzzy controller, the code is written for checking the behavior of the system to different inputs and obtaining optimal output (angle of link) in the system. Then this code has been approximated as a linear relationship for each link and is used for obtaining value of error’s gain and delta error’s gain.

Before entering error to fuzzy controller at the first link, a gain $GE_1(t)$ is used which is obtained by (2):

$$GE_1(t) = 1/(\text{Setpoint1} - 3) \quad (2)$$

And before entering delta error to fuzzy controller at the first link, a gain $GCE_1(t)$ is used which is obtained by (3):

$$GCE_1(t) = 1/(GE_1(t) * 10) \quad (3)$$

Before entering error to fuzzy controller at the second link, a gain $GE_2(t)$ is obtained by (4):

$$GE_2(t) = 1/(\text{Setpoint2} - 2) \quad (4)$$

And before entering delta error to fuzzy controller at the second link, a gain $GCE_2(t)$ is used which is obtained by (5):

$$GCE_2(t) = 1/(GE_2(t) * 10) \quad (5)$$

Before entering error to fuzzy controller at the third link, a gain $GE_3(t)$ is obtained by (6):

$$GE_3(t) = 1/(\text{Setpoint3} - 3) \quad (6)$$

And before entering delta error to fuzzy controller at the third link, a gain $GCE_3(t)$ is used which is obtained by (7):

$$GCE_3(t) = 1/(GE_3(t) * 10) \quad (7)$$

The output gain of the first controller is chosen to be constant at 0.9 (GU). Maximum rate of reducing temperature in the wire is achieved with minimum current and maximum

rate of increasing temperature in the wire is achieved with maximum current. Due to the overheating phenomenon in the wire, maximum applied current is 0.9A.

Also is used a gain in constant 0.001 (GCU), after exiting of output from the second fuzzy controller which decreases fluctuations in the output of system.

IV. DISCUSSION

In this section, results have been investigated by using membership functions in first and second fuzzy controller and system simulation in MATLAB.

A. Performance of PID-Fuzzy controller in position control on the first link of artificial finger

Fig. 7 shows control signal is generated by the PID-Fuzzy controller with the setpoint 12 (degrees) at the first link. Output of system to this setpoint is shown in Fig. 8.

As shown in Fig. 7 and Fig. 8, Less time to reach the desired angle and uniformity of control signal show successful performance of controller at the first link of artificial finger. Also system is not disturbed and fluctuated and its steady state error is low.

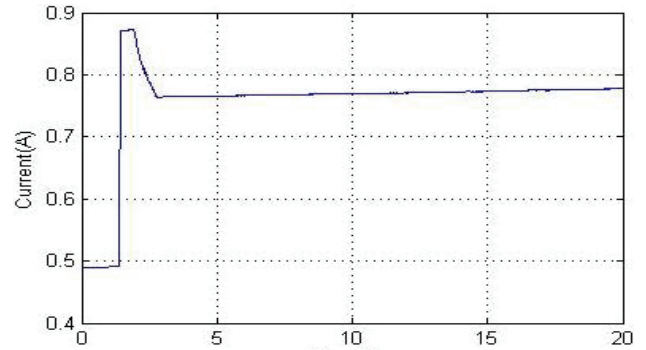


Figure 7. Output of PID-fuzzy (current) in the first link

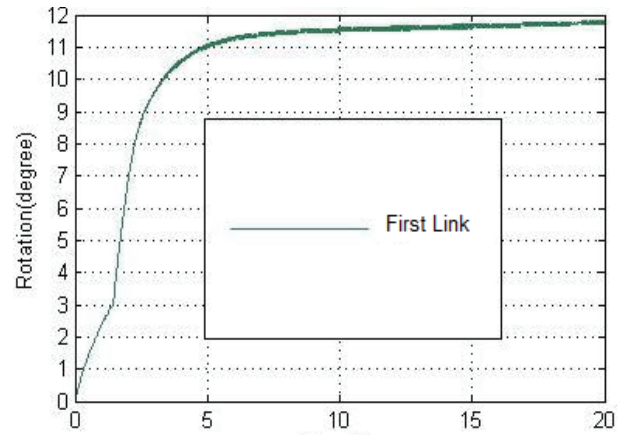


Figure 8. Output of system (rotation of link) in the first link

B. Performance of PID-Fuzzy controller in position control on the second link of artificial finger

Fig. 9 shows control signal is generated by the PID-Fuzzy controller with the setpoint 10 (degrees) at the second link. Output of system to this setpoint is shown in Fig. 10.

As shown in fig. 9 and Fig. 10, time to reach stability is acceptable and appropriate. Less time to reach the desired angle and uniformity of control signal shows successful performance of controller at the first link of artificial finger. Also system is not disturbed and fluctuated and its steady state error is low.

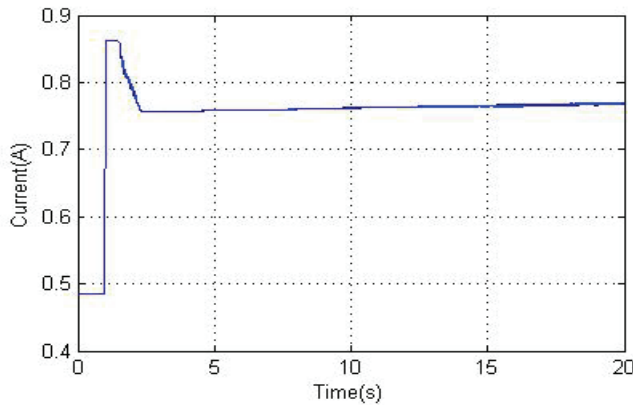


Figure 9. Output of PID-fuzzy (current) in the second link

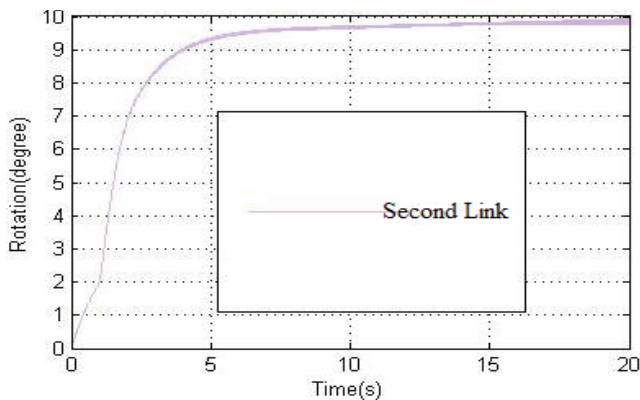


Figure 10. Output of system (rotation of link) in the second link

C. Performance of PID-Fuzzy controller in position control on the third link of artificial finger

Fig. 11 shows control signal is generated by the PID-Fuzzy controller with the setpoint 8 (degrees) at the third link. Output of system to this setpoint is shown in Fig. 12.

As shown in Fig. 11 and Fig. 12 Less time to reach the desired angle and uniformity of control signal show successful performance of controller at the first link of artificial finger. Also system is not disturbed and fluctuated and its steady state error is low.

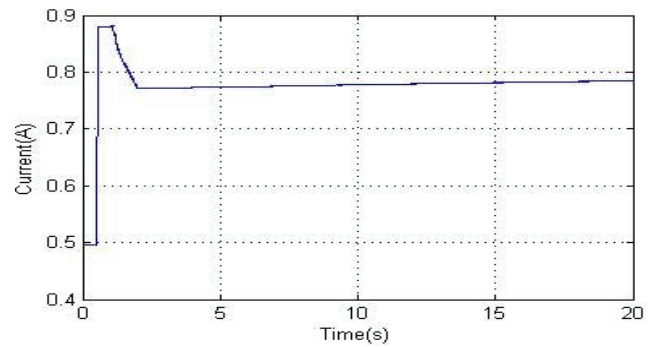


Figure 11. Output of PID-fuzzy (current) in the third link

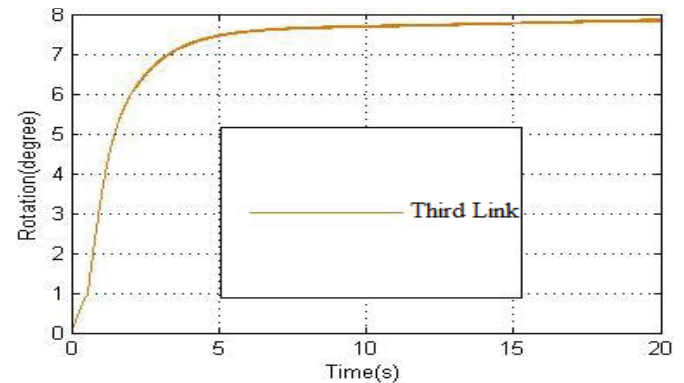


Figure 12. Output of system (rotation of link) in the third link

Results of control system which is designed to bind the model to this controller has been compared with the results of PWM-PD control system which were provided by Bundhoo [11]. Bundhoo designed a PD controller, which is designed to control the current applied to SMA actuator for arriving links of artificial fingers to desired position. Figure 13 shows output of PD controller provided by Bundhoo (apply current to the actuator in the first link).

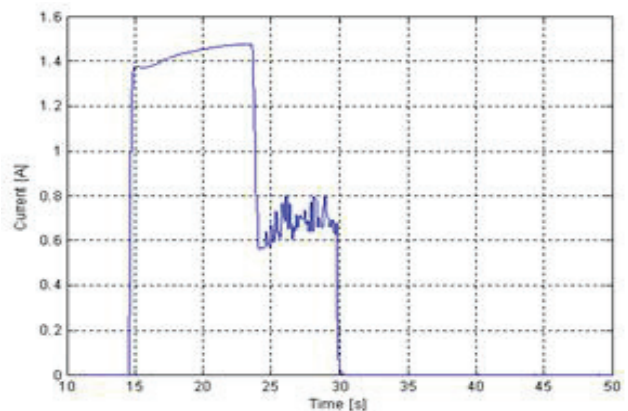


Figure 13. The current profile of the corresponding SMA actuator [11]

The obtained results in this paper with PID-fuzzy controller (first link Fig. 7) is better than Bundhoo's controller because

the overshoot and time stability of output signal in PID-fuzzy controller are smaller and less than Bundhoo's controller.

V. CONCLUSIONS

In this paper, algorithm and performance results of PID-fuzzy controller for the artificial finger with three degrees of freedom are presented. Gains of controllers are carried out so that the current applied to SMA wires has minimum overshoot and output of system has minimal time to achieve stability. Results obtained from simulation and comparison with experimental results show that the PID-fuzzy controllers have good performance in reducing the maximum overshoot and stability of time in input signal to the SMA actuators. Also this controller was able to produce reliable outputs with relatively small errors.

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