Different Types of Control Systems for the Contraction Pneumatic Muscle Actuator

Heba Ali Mohsen, Alaa Al-Ibadi, *Member, IEEE* and Turki Y. Abdalla, *Member, IEEE*

***Abstract*— Controlling the pneumatic muscle actuator (PMA) represents a challenging problem in soft robotics research field, it is difficult for the soft robot to achieve a good control performance due to the nonlinear and the hysteresis performance of the PMA. In the following work, a contractor PMA of 30 cm nominal length have been constructed from soft materials, then several approaches of control schemes have been utilized to control the contraction length of the PMA. The controllers are simulated using MATLAB/SIMULINK package. The contribution of the paper is to carry out and compare Different control systems theoretically along with their performance analysis.**

Keywords: Pneumatic Muscle Actuator; Bang Bang; PID; Neural Network; Fuzzy

I. Introduction

Soft and flexible materials have been utilized in the construction of the soft robots that often were inspired from biological systems. By comparing between soft robots and rigid robots we found that soft robots have more advantages than the other type (conventional robots), a side from these advantages is the safe interaction between human and machine, exhibiting greater adaptability to wearable devices, the simplicity in the designed gripping system, high power to weight ratio for the actuator, in most cases a hundred newtons for several hundred grams. High stiffness materials were used in the construction of the conventional robots such as steel, titanium, aluminum, stainless steel, etc. On the other hand, soft robot forms are made from hyper elastic fabrics for the main body and running parts such as polymer, latex, silicone, or other soft materials. Mainly, these robot are constructed by utilizing a three dimensional (3D) printer, hand build, or 3D mold [1].

In the 1950s, Joseph L. McKibben developed the McKibben artificial muscle actuator which is one of the most effective and most widely used pneumatic artificial muscle, because of its simple design and construction. Its ability to combine ease of implementation and the simulating behavior for skeletal muscle [2].The muscle usually consists of an inner tube that made of an expandable elastic martial surrounded by a braided mesh, with dual solid caps which are firmly fixed by a strong glue or high tension cable ties. One of the caps has a narrow tunnel for input and output of actuated air. The artificial muscle normally operates with pressurized air and the system requires a compressor and an air storage container. The pressurized air is used to increase the volume of the inner tube and subsequently deform the braided mesh that make up the McKibben muscle. The working principle of PMA is that the braided sleeve transforms the increasing in the inner tube volume to a lengthwise contraction of the braid that is capable of generating contractile forces[3]. Such muscles were involved in a lot of industrial and medical applications worldwide, which led the researchers to pay a lot of attention to how construct these muscles and to control it. In view of this. The pneumatic artificial muscle control system performance has been improved in many researches that focuses on proposing different types of controllers and combining between them, also the using of artificial intelligence was involved in many of these studies.

PID controller was used by (Nandini Patra & Rohit Patil) [4], in which the fabrication process of peristaltic soft machine were done, also various form of PID control systems were developed to control the behaviour of the soft robot by applying Matlab Simulink. Each controller has its own advantages and implementations. The proportional controller (P) usually used to keep the system response stable as much as possible but at the same time it produces steady-state error (SSE). Then as a result the integral controller (I) required to reduce the SSE for the system response. Also the (PI) controller used to steady the gain of the system with reducing the steady-state error. Nevertheless, the system response becomes slow. In order to enhance the response for the controller, a derivative controller (D) is needed. As a result, we can utilize all of the benefits of the PID control system because each controller parameter is executed separately.

PID controller was used by Loai A.T. Al Abeach [5] to program a control system for adjusting the contractor muscles length that were used in the design of three-fingered dexterous gripper. Ameer Hamza Khan [6] also used the PID controller by presenting a comparison for the performance of different parameters of model-free PID-controllers, his results were done on a large set of experimental date. He also deduced that the manual tuning results in low accuracy comparing with the automatic tuning algorithm which give more accuracy.

Based on the presenting experimental results for soft robots, he found that the PID-controller particularly reductions to the PI control system. This performance has been detected in both manual and automatic modification experimentations. Other researches combine several control strategies to get a better system performance and more robustness for the proposed controller. Important work was done by Alaa Al-Ibadi [7] who presents combination of two types of control strategy, neural network control system and proportional controller in a parallel structure (PNNP) to control the single extensor PMA and single bending contraction artificial muscle actuator (SBCA) at different values for the attached load. A length formula has been proposing for a range of actuator lengths, from 15 cm to 40 cm [8]. A bidirectional continuum soft arm robot designed to make the interaction with the human more safely, the proposed control system gives a valuable following to the human hand movements.

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The results proved the effectiveness of applying the parallel combination of the control systems to minimize the tracking time and increase precision [7]. Ming-Kun Chang [9] created a novel technique to control the performance of the PMA. By suggesting an adaptive self-organizing fuzzy sliding mode controller (ASOFSMC) for 2-DOF rehabilitation robot system.by employing Lyapunov theory to prove the stability of the ASOFSMC. Excellent control performance was attained from this control strategy. A radial basis function neural network controller was used by Pang Wu [10] in which the ability of turning for the soft robot was train on three various surfaces. Also some coefficients were utilized to develop a mathematical model, these coefficients are time of inflation, friction, and angle of deflection.

The main contribution of this paper is to apply various control strategies on the mathematical model to find out which of these strategies is performed better than others, and comparing between the results in term of root mean square error and time domain characteristics.

II. CONTRACTION PMA

McKibben muscle is an artificial actuator which transforms the air pressure applied on the bladder inner surface into the shortening tension thus the mechanical energy has been generated from the pneumatic energy [11]. This actuator is usually made from a rubber cylinder surrounded by an expandable mesh, in order to describe the actuator operational basics, it can be said that the restricted pressure inside the rubber tube will generate a vertical tensile force.

Several pulling force values will be generated as a result to the different applied air pressure. As illustrated in Fig.1, the pneumatic artificial muscle actuator has the following features.

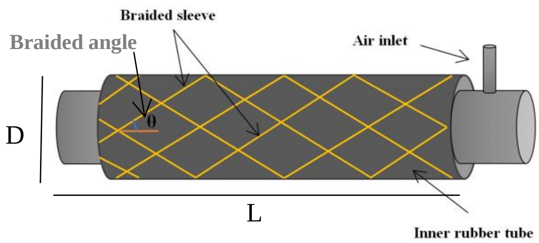

Figure 1. General construction of PMA

An actuator's length is L, its diameter is D, and θ refers to the braided angle, which it is measured in the middle of the perpendicular line and the braided sleeve thread (b). The angle value differs from 0◦ to 180◦ depending on the artificial muscle construction and it plays a vital role in the PMA's actions [8]. According to braided angle (θ)the PMA muscle will behave as a contractor or extensor muscle, when the pressurized air flows through the prosthetic muscle and cause it to contract or extend. As long as θ is smaller than 54.7, it is a contractor PMA, while if θ is greater than 54.7, it is an extensor PMA[12]. Fig. 2 shows the variation of the PMA length with different applied air pressure from (0-5 bar) for safety issues.

Recently, the mathematical modelling of contraction PMA was the main focus for a large amount of researches. This set of developing methodologies aims to establish a mathematical relationship between PMA length, air pressure inside the PMA rubber tube, and the generated force from PMA. Variable parameters will effect on these mathematical models such as the applied air pressure, tensile force, diameter and length of the PMA, as well as the properties of the used materials to build the muscle. The dynamic behavior of the soft actuators will be greatly affected by all of these factors [13].

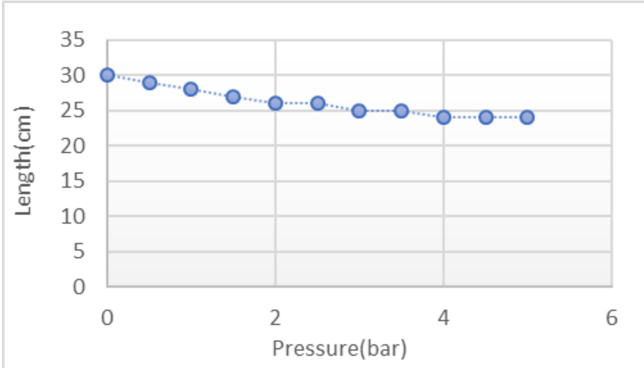

Figure 2. Variation of the contraction PMA length with different applied pressure

The muscle length is modeled as a function of the input air pressure, where several PMAs were used by Alaa Al-Ibadi [14] for different nominal lengths "L_0" .The behavior of the muscle length as it is given in Fig. 2 leads to model the length of PMA performing as a mathematical sigmoid type function.

For each muscle, the variation of the muscle length with the applied pressure has been studied and recorded. He also shows that there is a significant matching between experimental and theoretical results. According to that a set of equations were defined by the author depending on the muscle nominal length (L_0) and the air pressure (p). The length mathematical model of the pneumatic muscle was described in (1) with both (p & L_0), the parameters values of (1) were evaluated in (2), depending on the nominal length of the PMA (L_0).

$$L = a + \frac{b}{[1+(\frac{p}{c})^{d}]^{e}} - 0.009 L_0 \sqrt{p} \quad (1)$$

$$\text{Where: } \begin{bmatrix} a \\ b \\ c \\ d \\ e \end{bmatrix} = \begin{bmatrix} 0.4351 & 0 & 0.0183 & -0.0003 \\ 0.5649 & 0 & -0.0183 & 0.0003 \\ -0.0141 & 0 & 0.0031 & -0.00006 \\ 0.5487 & 0 & -0.0136 & 0.00007 \\ 0 & 0.3694 & 0 & 0 \end{bmatrix} \begin{bmatrix} L_0 \\ L_0^{-0.248} \\ L_0^2 \\ L_0^3 \end{bmatrix} \quad (2)$$

A high accuracy was obtained from these equations by decreasing the error between the experimental data and the theoretical data for muscles with any nominal length L_0 ranging from 15 cm and 40 cm [14].

III. The PMA Control Systems

This section deals with different control strategies that were utilized to control the artificial pneumatic muscle from the simplest control systems the ON-OFF control system which also called bang-bang controllers, PID control system, to the soft computing techniques representing by the neural network controller, and the fuzzy logic controller. The results were obtained by the simulation process in MATLAB/SIMULINK.

A. Simulation-based Bang-Bang controller

Bang-Bang controller which is also called hysteresis controller or on-off controller is a type of discontinuous feedback controller that switches frequently between two states. This type of controller is often used to control a plant that receives a binary input, also it can be considered as the most common type of controller used in industrial field because discontinues actuators such as solenoid valves and relays are simpler and cheaper than the actuators used in the continues control systems [25]. As well it would be more suitable for problem that have a control action which is restricted between upper and lower bound, here, we used a rely to perform the control action on two different signals a step input signal and the sinusoidal wave signal, firstly the step input signal from 30 to 24 cm, as shown in Fig. 11 a very accurate response is occurred using this simple control strategy, with approximately zero steady state error.

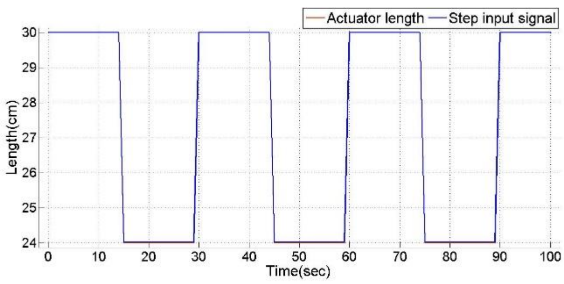

Figure 11. The Bang-Bang controller response for the step input signal

However, using the same controller for the second sinusoidal wave signal, led to an inaccurate tracking to the desired signal as shown in Fig. 12.

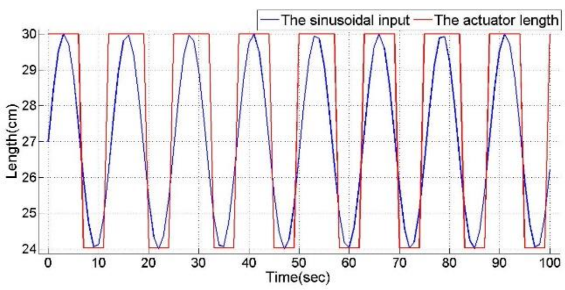

Figure 12. The Bang-Bang controller response for the sinusoidal wave signal

This type of controller would be optimal in some cases for its simplicity and convenience, e.g. in temperature and pressure control [25].

B. Simulation-Based PID Controller

The most common form of feedback type conventional controller is the PID controller. When process control emerged in the 1940s; PID control system became the standard tool in many applications. In process control today 95% of the control loops and more are of PID type, actually most loops are PI control [15]. In industrial and control systems applications the PID controllers usually used control loop feedback to do the control action. The error value is first computed by the controller as the difference between a measured process variable and the desired set point. The controller then tries to minimize the error by decreasing or increasing the inputs or outputs of the controller in the process so that the process variable converges towards the set point. When the process mathematical model or control is unknown for the system or too complicated, this method is most useful. In order to get the desired controller response, the PID parameters must be adjusted according to the specific application, the tuning process typically done to increase the whole system performance [16]. The proportional (P) term, the integral (I) term, and the derivative (D) term make up the PID controller. Fig. 3 shows the PID controller structure.

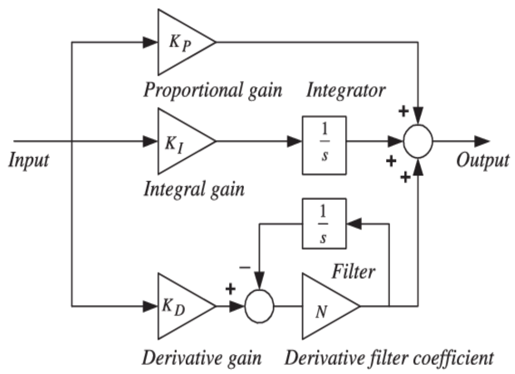

Figure 3. PID control system structure

In its ideal form, a PID controller output u(t) is the sum of the three terms as shown in (3): -

$$u = k_1 e(t) + k_i \int e(t)dt + k_p \frac{d}{dt}(e) \tag{3}$$

In this section a PI controller was designed in Matlab Simulink to control the contraction length of the contraction pneumatic muscle actuator, there is an obvious reason to not add the derivative (D) term to the PID and reduces it to PI controller, because we found after adding the D term the controller's response will oscillate to a very high values and an undesired response will Acquired. A step input signal of 30 sec periods and 50 pulse width was used. Using the trial-and-error method for tuning the controller parameters, the results in Fig. 4 were obtained.

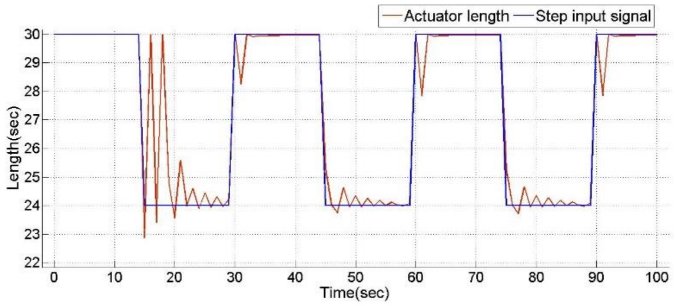

Figure 4. The PID controller response for the step input signal

Another input signal was applied to the PI control system which is a sinusoidal wave signal, Fig. 5 shows the controller response to the applied signal.

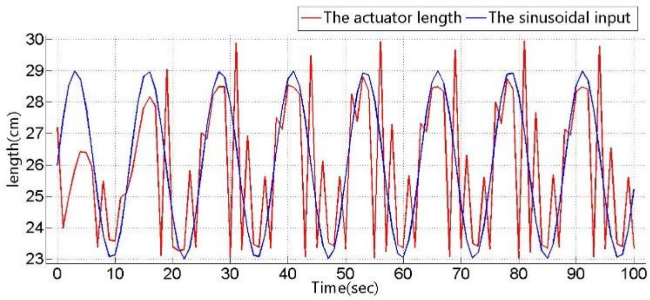

Figure 5. The PID controller response for the sinusoidal wave signal

C. Simulation-based Artificial Neural-Network (ANN) Controller

An artificial neural network (ANN) basically trying to mimic the way that the human brain operates and finding the relationship between the sets of data, several different types of ANNs have been used in many applications [17], and it represent a very good solution for problems which have a complex and noisy sensor data. The original form of a neural network has three layers input layer, hidden layer, and the output layer, the numbers of the NN layers will increased with the increasing complexity of the model. The input signals transfer from the input layer to the next layer, hidden layer , and finally to the output layer which produces the final prediction, different training algorithms were used to train the neural networks as well like machine learning algorithms [18]. ANNs are formed by neurons or nodes which are highly interconnected units of calculation, also several parameters (biases and weights) have to be tuned to perform the control action, by changing the parameters values a large number of different outputs can be achieved. Also, by changing the number of layers and the number of neurons for each layer, solving an infinite number of tasks with high level of complexity can be done by the ANN [19]. The one used here in our case those called Nonlinear Autoregressive Moving Average (NARMA-L2) model, which is a popular NN architecture used for prediction and controlling, several process control systems utilize this simulation approach, such in cancer chemotherapy to regimens the drug dosage and in magnetic levitation process. Also from its advantages is reducing the computation time and the amount of memory, and due to its mapping capability an accurate and faster output planning is expected [20].

The ANN controller architecture used in this section is termed to by two different terminologies: NARMAL2 control and feedback linearization control. When the model has a particular shape, it is called feedback linearization (companion form). NARMA-L2 controllers, on the other hand, are used when the plant model can be approximated by the same form [21]. It is a representation for the discrete-time nonlinear dynamical system that's close to equilibrium state. By canceling the nonlinearities, the nonlinear system dynamics will transform to linear dynamics which is the central idea of this type of controller. The controller is trained offline and it is simply a rearrangement for the plant model of the neural network [22].

The NARMA-L2 NN controller output u can be defined as:

$$\boldsymbol{u}(\boldsymbol{k}) = \frac{\boldsymbol{y_r(k+1) - f[y_n(k), u_m(k-1)]}}{\boldsymbol{g[y_n(k), u_m(k-1)]}} \tag{4}$$

Where $\boldsymbol{f}(\ )$ and $\boldsymbol{g}(\ )$ are approximated using neural networks. And:

$$\boldsymbol{y_n(k) = [y(k), \ldots, y(k-n+1)]^T} \tag{5}$$

$$\boldsymbol{u_m(k-1) = [u(k-1), u(k-2), \ldots, u(k-m)]^T} \tag{6}$$

Matlab Simulink have been utilized to design the NARMA-L2 NN-controller, single hidden layer has been chosen of 5-neurons, 2-delayed plant input signals, and 1- delayed plant output signal. The training process for the NN has been done for 100 Epochs by 'trainlm'. The controller output signal used to adjust the amount of the pressurized air flowing inside the PMA tube for both the filling and the venting processes to achieve the desired length (here between (29-24cm)) for the contraction pneumatic artificial muscle. A sinusoidal signal is applied to the controller system at 0.5 Hz,

The block diagram of the proposed NN control system is shown in "Fig. 6".

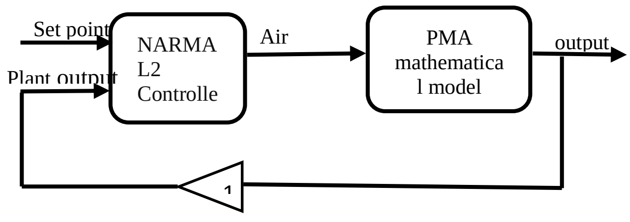

Figure 6. The schematic diagram of the NN control system

and "Fig. 7" illustrated the controller response which shows more accurate tracking and less signal oscillation than the PID controller for the same input signal.

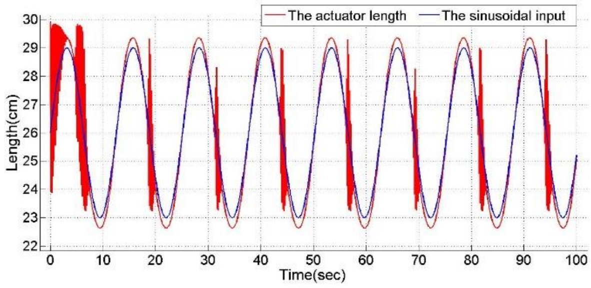

Figure 7. The NARMA-L2 NN-controller response for the sinusoidal wave signal

In Fig. 8, another input signal is used to test the controller performance which is the step input signal for 0.5 Hz. Noticing that less tracking errors have been resulted from the desired signal.

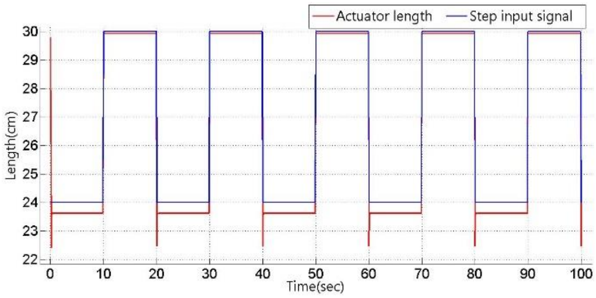

Figure 8. The NARMA-L2 NN-controller response for the step input signal

C. Simulation-Based Fuzzy Inference Control System

Lotfi Zadeh invented fuzzy logic in 1965 as an extension of boolean logic based on the fuzzy sets mathematical theory, which is a general form of the classical set theory. Which is mean that the classical set theory is a subset of the fuzzy sets theory. The notion of degree has been introduced in the verification of the conditions, which enable them to be in a state other than true or false. Also the fuzzy logic control system introduced a very valuable flexibility in solving inaccuracies and uncertainties exist in several complex problems [23].

Fuzzy inference system (FIS) is an approach to mimic the human reasoning, it's also a representation for the human operator knowledge and experience. The linguistic fuzzy rules usually depending on the decisions and procedures performed by human to solve a particular problem. The fuzzy logic controller (FLC) has an adaptive and nonlinear behaviors in nature that gave it a robustness even with the parameter variations. It can also track desired control actions for complicated, unpredictable, and nonlinear systems without the need for mathematical models or parameter estimation[24].

FLC based through three consecutive steps: fuzzification, fuzzy inference and defuzzification. In the first step the fuzzification process is applied to convert the crisp variable (input and output) from the classical variables to fuzzy variables by defining the membership function for both input and output variables and transform them to linguistic variables. Here, in our case the membership function was derived for both the set point (actual length for the muscle) and the error value as inputs to the FLC, and the air pressure value as output from the FLC. In the next step the fuzzy variables will be processed by the fuzzy inference to obtain the desired output, nine fuzzy rules will be defined here. These rules represent the expert knowledge in any related field of application. Fig. 9 illustrates the representation of the FIS decisions, the fuzzy outputs must be turned back to crisp variables by the defuzzification procedure in order to achieve the required control objectives [23].

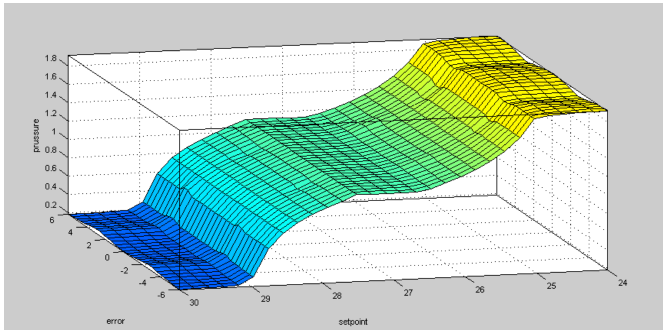

Figure 9. The fuzzy rules of the proposed FLC

After the simulation process have been done for the fuzzy control system, the results in Fig. 10 and Fig. 11 were obtained for the step input signal and the sinusoidal signal respectively, by comparing with the PID control performance we found that the FLC is more adaptive and have a better response than the other one with less oscillation and steady state error in the output signal.

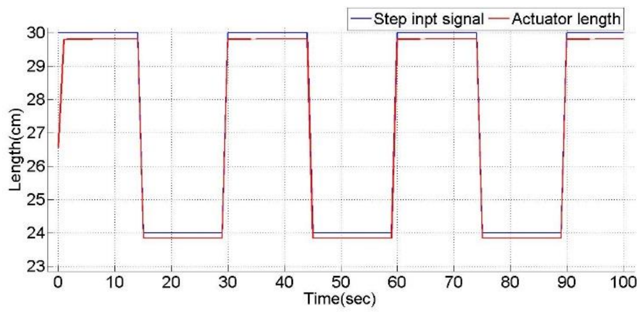

Figure 10. The fuzzy controller response for the step input signal

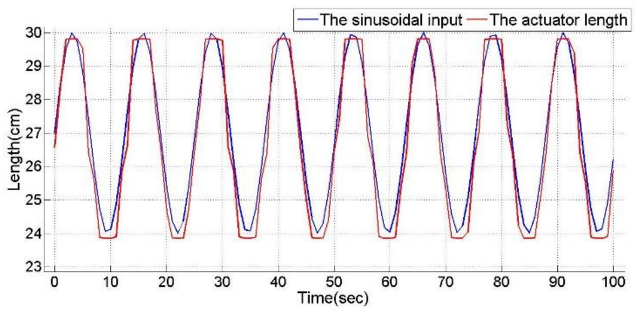

Figure 11. The fuzzy controller response for the sinusoidal wave signal

In order to compare the various control strategies, the root mean square error (RMSE) of each method has been calculated for both signals. As shown in Table I below, RMSE values vary for different control methods.

TABLE I. The RMSE for The Control Methods

Control Method	RMSE for Sinusoidal Wave Signal	RMSE for Step Input Signal
Bang-Bang	2.03459	0.02633
PID	3.70030	0.20803
Neural Network	3.25809	0.58240
Fuzzy	0.46621	0.17677

We conclude that the fuzzy control system has the smallest RMSE as well as the highest accuracy, which makes it suitable for a variety of medical applications. While the PID control method shows lower accuracy than other strategies, however, the simplicity of the PID implementation makes it suitable for applications that do not need high accuracy.

IV Conclusion

Several different types of control systems have been implemented theoretically in this paper to control the contraction length of the contraction PMA using MATLAB/SIMULINK. By representing the actuator dynamics with two different signals, the step input signal and the sinusoidal wave signal, after that the control action implementation have been performed to adjust the PMA length. Also the RMSE have been calculated for the different control methods in order to analysis their performance.

As a future work different signals may be applied to the proposed controllers, also hybrid control systems may be designed and implement on the same mathematical model.

Acknowledgment

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