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An Adaptive Parallel Fuzzy And Proportional Integral Controller (APFPIC) For The Contractor Pneumatic Muscle Actuator Position Control

Heba Ali Al-Mosawi
Computer Engineering Department
University of Basrah
Basrah, Iraq
engpg.heba.ali@uobasrah.edu.iq

Alaa Al-Ibadi
Computer Engineering Department
University of Basrah
Basrah, Iraq
alaa.abdulhassan@uobasrah.edu.iq

Turki Y. Abdalla
Computer Engineering Department
University of Basrah
Basrah, Iraq
turki.abdalla@uobasrah.edu.iq

***Abstract*— Soft robots represent an emerging generation in the robotics research field, these soft robots operate by employing the pneumatic muscle actuator (PMA). Controlling the PMA is a big issue and represents a more complex problem because of the hysteresis behavior and the nonlinearity. So this article proposes a novel adaptive parallel combination of a fuzzy logic controller (FLC) with the conventional proportional-integral (PI) controller; the adaptive parallel fuzzy -proportional-integral controller (APFPIC) shows more adaptability and compliance in response tracking. By utilizing the intelligence embedded in the FLC, an enhancement of the PI controller performance was realized, and a more robust and adaptive control system was obtained.**

Keywords— soft robotics, PMA, control system, PID, fuzzy.

I. Introduction

The design and development of biologically inspired robots that can move, run, climb, and carry out actions by imitating the bio-structure and movement of animals, such as humans or insects, has recently received much attention[1]. These soft robots operate by utilizing the pneumatic muscle actuator (PMA), which serves as the robot's building block. Soft robots have many advantages over traditional rigid robots, including being suitable for close interaction with people, lightweight, environmentally friendly, and cost-effective interms of construction, materials, and energy consumption. Soft actuators such as extensor pneumatic muscle actuators and contractor pneumatic muscle actuators have advantages over conventional electrical and mechanical actuators in addition to soft robotics' advantages. Among all actuators types, PMAs have the best power-to-weight and power-to-volume ratios, typically 100 newtons for several hundred grams. Minimal upkeep, cleanliness, compliance, adaptability, inherent safety, and suitability for severe environments. In contrast, the PMA's hysteresis, low stiffness, and softness demonstrate a high level of nonlinearity and present extra difficulties for controlling and operating these kinds of actuators [2] [3].

The position of the PMA was controlled using a variety of control strategies, among them is the PID controller, which is used for its easy implementation and good response, however; the performance requirements for efficient variable controllers under varying operating conditions or environmental parameter variations frequently exceed the capabilities of linear PID controllers [4]. Additionally, because of the significant nonlinearity found in PMAs, the PID controller is unable to resolve this challenging control issue. So the robustness and performance of the linear PID controller have been improved using numerous techniques, such as fuzzy logic, neural networks, and the self-tuning method of general predictive control [5] [6].

Also, from these studies, an adaptive control strategy for controlling the position and stiffness of an N-degrees of freedom (DOF) robot arm powered by two pneumatic muscle actuators in an oppositional arrangement [7]. Additionally, at various load values, the single extension PMA length and the single self-bending contraction actuator (SBCA) bending angle were controlled using a parallel combination of the neural network controller and the proportional controller (PNNP), which offers a rapid tracking control system and high levels of precision [2]. While a highly nonlinear 2-DOF soft robot manufactured using PMAs for the rehabilitation process is controlled by an adaptive controller consists from fuzzy controller and sliding mode controller [3]. And several effective control schemes were applied in [8] For shape memory alloy (SMA)-based actuators. In cases where P, PI, PD, and PID types of controllers have been implemented and investigated. The SMA-based actuators' high energy density and exceptional flexibility make them popular for soft robotics applications. Also, in the control system of the electro-pneumatic delta manipulator with three degrees of freedom and pneumatic muscle actuators, a standard PID controller was applied. The Ziegler-Nichols approach of the PID tuning parameters based on system evaluation was presented herein [9]. The nonlinear sliding mode controller based on a PID-type sliding surface was created for the management of dynamic response and active vibration dampening of soft robots [10]. Several practical and commercial applications of fuzzy logic have been developed, including the operation and programming of temperature controls for shower heads [11], air conditioners, washing machines, and rice cookers [12]. The pressure and level of drum boilers have also been controlled using a fuzzy controller with genetic algorithm-based optimization [13].

This article's primary contribution is the development and design of a simulation-based novel adaptive parallel combination of a fuzzy logic controller (FLC) with the traditional proportional-integral (PI) controller (APFPIC) to adjust the length of the pneumatic muscle actuator. The theoretical results were obtained using the Matlab Simulink package.

II. Pneumatic Muscle Actuator (PMA)

Joseph L. McKibben created the McKibben pneumatic artificial muscle during his work on artificial limb research in the 1950s and 1960s. This muscle is made up of an internal bladder (rubber tube) encapsulated in a braided mesh shell (braided sleeve) having extendable threads that aren't expandable and are attached to fittings, or a tendon-like structure at either end [14], a tiny hole for actuated air input and output is located on one of the terminals. A general construction for the PMA is shown in “Fig. 1” with dimensions of "L" length, "D" diameter, and " θ " angle between the braided sleeve threads and the vertical axis, when the value of the braided angle is less than 45.7%, the pneumatic muscle actuator will act as a contraction PMA [15].

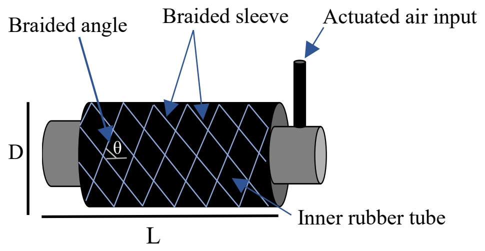


Fig. 1. The pneumatic muscle actuator's general structure

There are different types of McKibben’s muscles, the extensor muscle, whose length increased with the applied pressure, and the contractor muscle, whose length decreased with the applied pressure. Contractor PMAs work at an overpressure, and as the inner elastic tube is inflated, the length of contractor PMAs reduces, they radially expand and exert pressure on the braided sleeve. The fittings on the PMA develop tension within the sleeve, and a force is then transmitted to an external load via the intervening connectors and mechanism [16].

The percentage of contraction varies from muscle to muscle, but it never goes above 35% [17],[18]. The contraction ratio (ε) expression is given by Equation (1):

$$\text{contraction ratio } (\varepsilon) = \frac{L0-L}{L0} \tag{1}$$

L_0 represents the initial length of the PMA and L is the pressurized PMA length. It could be mentioned that the contraction ratio (ε) is highly affected by the PMA diameter, the braided sleeve maximum diameter, and the inner rubber-tube type.

Through the years, various mathematical models have been researched for modeling the dynamics of pneumatic muscle actuators. An improved model is still needed because the current ones do not adequately explain each stage of the mechanical performances, to describe how PMAs behave, several models have been proposed. Two of the most widely used mathematical models are those by Chou and Hannaford [14] and Tondu and Lopez [19]. These models are based on the virtual works of the cylindrical shape and the thinness of the inner tube [14] [13] [15]. For modeling the variation in length according to the applied pressure (p) for the PMA, [15] invented the mathematical sigmoid function represented by eq.(2). While eq.(3) represents the parameters values of (2) which are dependent on the original PMA length (L_0).

$$L = a + \frac{b}{[1+(\frac{p}{c})^d]^e} - 0.009L_0\sqrt{p} \tag{2}$$

$$\text{Where: } \begin{bmatrix} a \\ b \\ c \\ d \\ e \end{bmatrix} =$$

$$\begin{bmatrix} 0.4351 & 0 & 0.0183 & -0.0003 \\ 0.5649 & 0 & -0.0183 & 0.0003 \\ -0.0141 & 0 & 0.0031 & -0.00006 \\ 0.5487 & 0 & -0.0136 & 0.00007 \\ 0 & 0.3694 & 0 & 0 \end{bmatrix} \begin{bmatrix} L_0 \\ L_0^{-0.248} \\ L_0^2 \\ L_0^3 \end{bmatrix} \tag{3}$$

III. Pneumatic Controllers

A. *Ziegler–Nichols-based PI Controller*

PID controller is the most popular feedback-type conventional controller. As process control gained popularity in the 1940s; PID control systems quickly became the common instrument in several applications. Today, PID control loops account for approximately 95 percent or more of all control loops in process control; in fact, PI control loops account for the majority of loops [20]. The tuning procedure is typically used to enhance the overall system performance. The PID parameters have to be modified according to the individual application to achieve the required controller response. “Fig. 2” represent the general block diagram of the PID controller.

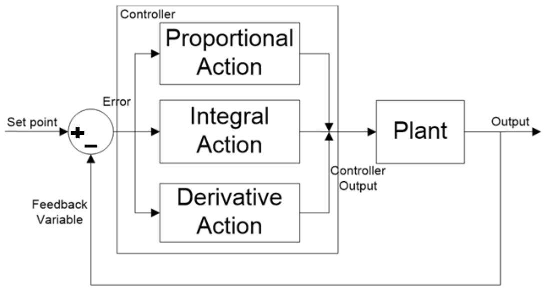


Fig. 2. PID control system block diagram

The following highlights the "three-term" functionalities.

- The proportional term, which uses the all-pass gain factor to provide a general control activity that is proportional to the error signal.
- The integral term, describes how an integrator reduces steady-state errors by compensating for low frequencies.
- The derivative term, enhances transient response with differentiator high-frequency compensation [21].

The PID ideal formula is shown in eq. (4) represent the summation of the three terms, while the output is represented by u(t) as below: -

$$u(t) = k_p e(t) + k_i \int e(t)dt + k_d \frac{d}{dt} e(t) \quad (4)$$

Where the proportional, integral, and derivative gain values of the PID are Kp, Ki, and Kd, and e(t) refers to the error signal. The Ziegler-Nichols(Z-N) method is a well-known approach for tuning P, PI, and PID controllers. This approach starts by bringing the differential and integral gains to zero before progressively raising the proportional gain value until the system reaches the point of sustained oscillation which means the system is unstable, thus K_{max} is the greatest value of K_p at the moment of instability (ultimate gain), and f_0 is the frequency of oscillation (ultimate period). The method then removes a predetermined amount from the proportional gain and sets the differential and integral gains values as a function of f_0. Table 1 shows how to set the values of P, I, and D parameters [22].

TABLE I. SETTING FOR P, I, AND D GAINS ACCORDING TO THE ZIEGLER_NICHOLS APPROACH

Controller type	PID parameters		
	K_P	K_I	K_D
P controller	0.5 K_{MAX}	0	0
PI controller	0.45 K_{MAX}	1.2 f_0	0
PID controller	0.6 K_{MAX}	2.0 f_0	0.125/f_0

The simulation process was performed in Matlab Simulink to design a closed-loop control system; the Z-N method is utilized here for the parameters tuning of the PID controller to adjust the length of the contractor PMA by controlling the air pressure which has been represented by a pulse width modulation (PWM) signal. Initially; the step input signal was used as the set point for the control system, and the sustained oscillation was observed when the value of *Kp* reached (4) as shown in "Fig. 3", so this value will represent the K_{MAX}, the frequency of oscillation f_0 was measured and found to be (2). Finally, a PI-type controller has been designed according to table (1), and the two parameters will be *Kp*=1.8 and *Ki*= 2.4. Due to PWM switching, measurement noise, and set-point variations, the soft actuator pressure control system has high-frequency control errors. As a result, the derivative term produces high control signals and is thus not used in the controller design. The step input signal was used as the set point to the control system and the result of the simulation was shown in "Fig. 4". In conclusion, a good response is obtained from this controller, however; it has some drawbacks that limit its usage, for instance; a frequently retuning for the controller parameters values is needed, which is a time-consuming procedure.

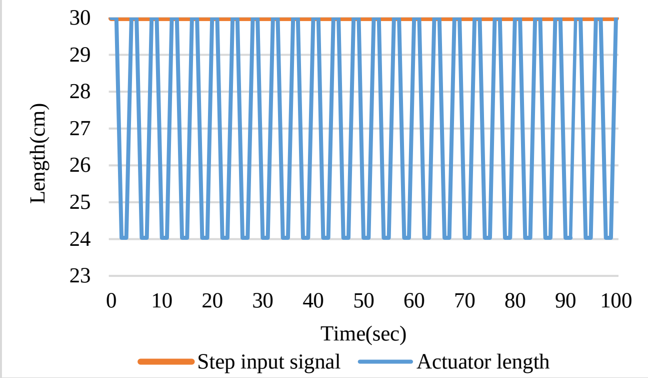


Fig. 3. the oscillatory behavior of the Z-N PID control system

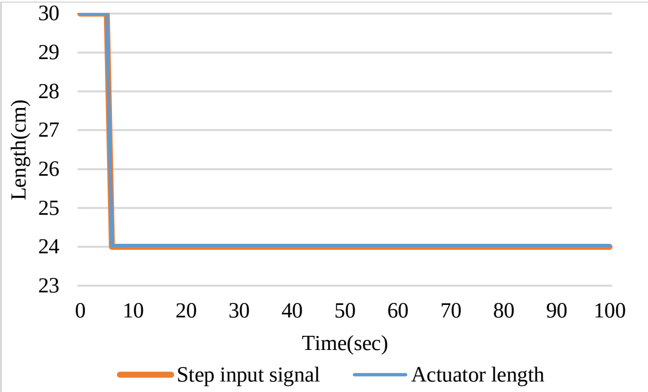


Fig. 4. Step input response for the Z-N PI controller

B. Adaptive parallel fuzzy proportional-integral controller(APFPIC)

As an extension of boolean logic, Lotfi Zadeh developed fuzzy logic in 1965. It is based on the mathematical theory of fuzzy sets, which is a generalization of classical set theory. Alternatively, one could say that classical set theory is a subset of fuzzy set theory. With the introduction of the concept of degree in the conditions verification, they can now exist in a state other than false or true. Furthermore, the FLC added a lot of flexibility in solving uncertainties and inaccuracies in a variety of difficult problems [23]. Informational environments are full of ambiguity and imprecision. Human reasoning is capable of making sense of imprecise, unreliable, and foggy concepts. Human thought, reasoning, and perception are typically difficult to describe precisely. These experiences rarely can be described or quantified using statistical or probability theory. A framework for modeling uncertainty, human thought, reasoning, and perception is provided by fuzzy logic [24]. For complex, uncertain, and nonlinear systems, it can track intended control activities without the use of parameter estimation or mathematical models. [25]. This section will demonstrate the design procedure of a Mamdani model FLC system laid in parallel with the PI controller. The PWM control signal u(t) represents the summation of the signals coming from the two controllers, the block diagram of the suggested controller is illustrated in "Fig. 5".

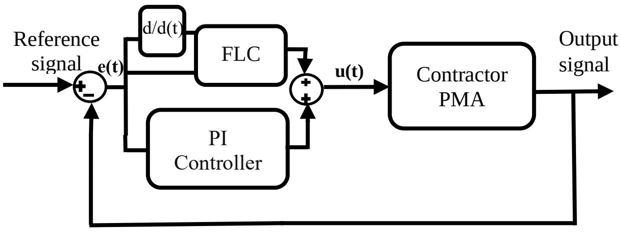


Fig. 5. Block diagram of the Adaptive Parallel Fuzzy Proportional Integral Controller (APFPIC)

It is well known that the traditional technique for designing an FLC system consists of a fuzzification process, a fuzzy rule base with a fuzzy inference engine, and a defuzzification process as in "Fig. 6".

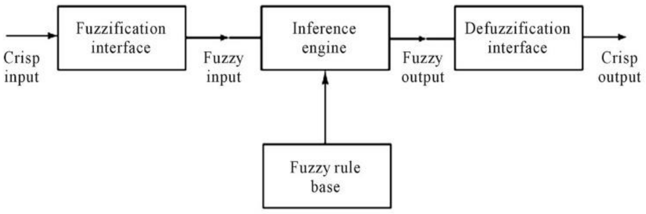


Fig. 6. the steps of the fuzzy logic controller

1) *The fuzzification Process*: the membership functions have been defined for both the input and output variables, and these variables will be converted to linguistic variables in the first phase, the transformation of the crisp variables (inputs and outputs) from classical variables to fuzzy variables is done here. The error e(t) and the derivative of the error de(t)/d(t) are both inputs to the FLC, the number of fuzzy sets for each variable typically depend on the application of the PMAs and can be from 2 to 17, the universe of discourse of the 2 inputs is partitioned into 3 fuzzy sets for each variable [low, medium, height] labeled as [L, M, H] and characterized by a gaussian membership function and defined in the range between [-6 6], in order to bring the system to the stability zone, the error signal was limited in that range.
2) *fuzzy inference system(FIS)*: this stage is connected to the rule base, the fuzzy variables are processed here to provide the appropriate output, and nine fuzzy rules will be created in the form of (if x is A_1 and y is B_1 then $z_1 = C_1$) where x and y are the antecedents and z_1 is the consequent, these rules represent professional expertise in any applicable field of application. "Fig. 7" shows the FIS decisions representation.
3) *defuzzification*: the fuzzy outputs must be transformed into crisp variables, to achieve the necessary control goals, three fuzzy sets for the output variable representing as [low-pressure, medium-pressure, height-pressure] labeled as [L, M, H], and characterized by a triangular membership function and defined in the range between [0 2.2] to represent the amount of the air pressure, the center of gravity (COG) method is used here to defuzzify these fuzzy sets by calculating the centroid of the area under the membership function as in eq. (5), the output from this stage is the pressurized air represented by the PWM signal.

$$COG(X) = \frac{\sum_{i=1}^{\mu} \mu_i(x) X_i}{\sum_{i=1}^{\mu} \mu_i} \qquad (5)$$

$\mu_i(x)$ is the aggregated output membership function.

In the proposed controller, the tracking performance is further enhanced in a steady-state using an integrator, and the nonlinearity and complexity of the PMA dynamic behaviors are handled by the FLC. The PWM duty cycle from the two controllers (PI and FLC) will represent the output signal of the APFPIC controller that is used to adjust the amount of the pressured air from 0 kPa to 5 kPa which in turn is used for inflating the 30cm contractor PMA, after theoretically simulating the control system; the results were obtained in "Fig. 8", "Fig. 9" and "Fig. 10" for the square wave signal, the sinusoidal wave signal and the repeating sequence with the error signals respectively. Adaptive and accurate responses have been accrued from this controller for a wide range of control input signals.

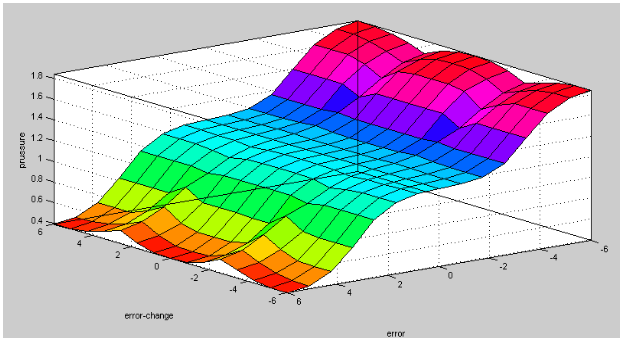
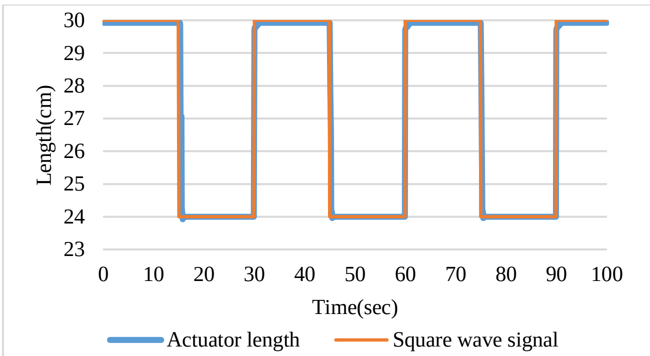
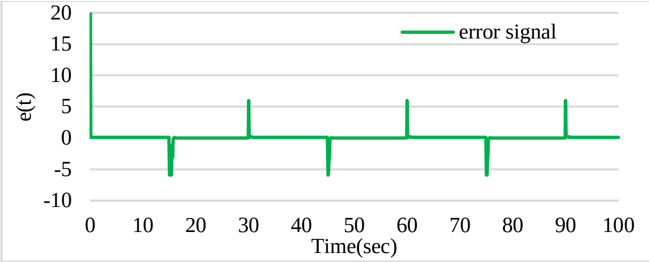


Fig. 7. The rules surface of the fuzzy logic controller

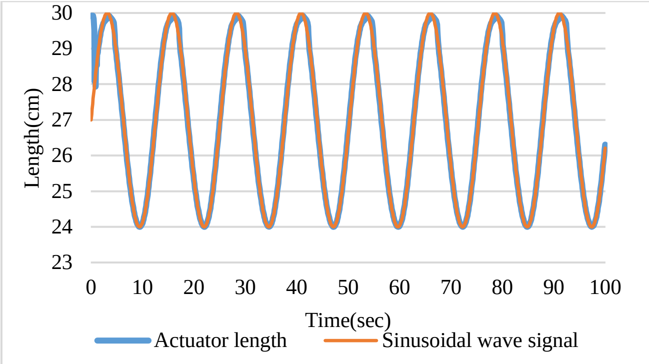


(a)

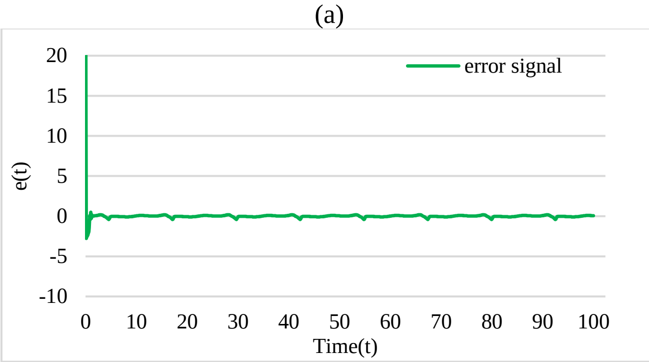


(b)

Fig. 8. (a) square wave signal response for the Adaptive Parallel Fuzzy Proportional Integral Controller. (b) error signal.

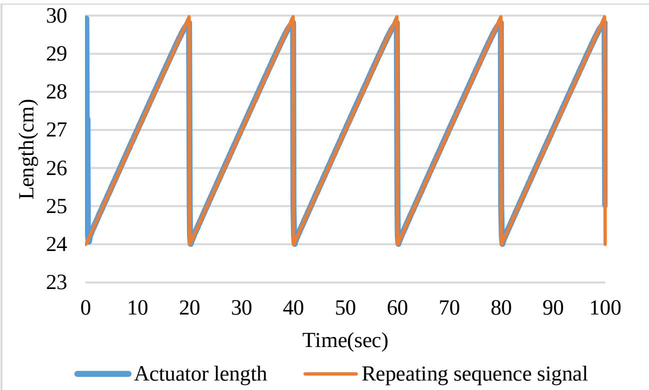


(a)

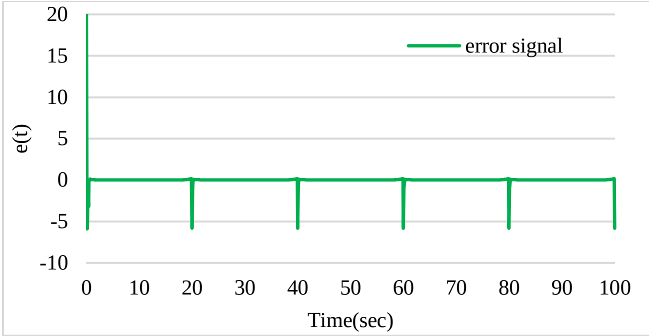


(b)

Fig. 9. (a) sinusoidal wave signal response for the Adaptive Parallel Fuzzy Proportional Integral Controller. (b) error signal.



(a)



(b)

Fig. 10. (a) repeating sequence signal response for the Adaptive Parallel Fuzzy Proportional Integral Controller. (b) error signal.

IV. CONCLUSIONS

In this article, the development and design of a novel adaptive parallel structure consisting of a fuzzy logic controller and proportional-integral controller (APFPIC) have been presented to adjust the length of a highly nonlinear contractor pneumatic muscle actuator, the proposed control scheme shows an adaptive and robust tracking to different reference signals, as well; reducing the steady state error and enhancing the transient performance. Initially, the Z-N method was used for the PID parameters tuning, which is effective for determining the PID values as a starting point, as a result, the FLC methodology is observed as a complementary solution for improving the performance of the linear PID controller created using the standard way. Of course, there are other artificial intelligence approaches available, and the FLC is one of the most modern and efficient artificial intelligence techniques.

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