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An Experimental Evaluation of Control Modes for Pneumatic Artificial Muscles Using Fast on/off Valves

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Abstract

Pneumatic Artificial Muscles (PAM) are versatile actuators having many advantages such as high force to weight ratio, soft and flexible structure, extreme safe for human, ease of maintenance and low cost. On the other hand, their inherent nonlinear characteristics yields difficulties in control actions, which is an important factor restricting wide-spread use of PAM. In literature, there are studies to resolve the control issue and their results indicate that there is still requirement for a simple and effective control system. In this work, as a first step of achieving the control goal, three common nonlinear controllers used in literature are selected for an experimental evaluation. The implemented controllers are 'Classical PID controller', 'Fuzzy PID controller' and 'Sliding-Mode Controller' (SMC). The evaluation is performed using a test rig, which is a 1-D robotic arm orthosis actuated by Festo PAMs operated with fast on/off valves. According to experimental results, a model-free Sugeno type combined fuzzy PID controller has yielded most successful performance indicating that it could be a simple and effective solution for PAM control issue.

Keywords: Pneumatic artificial muscle, PID control, Fuzzy PID control, Fast on/off valve

Yapay Pnömatik Kaslar için Denetim Kiplerinin Hızlı Aç/Kapa Valfler Kullanarak Deneysel Bir Değerlendirmesi

Öz

Pnömatik Yapay Kaslar (PAM), yüksek kuvvet/ağırlık oranı, yumuşak ve esnek yapı, insan için aşırı güvenli, bakım kolaylığı ve düşük maliyet gibi birçok avantaja sahip çok yönlü eyleyicilerdir. Öte yandan, doğrusal olmayan karakteristik özellikleri, PAM'ın yaygın kullanımını kısıtlayan önemli bir faktör olarak, kontrol eylemlerinde zorluklar getirir. Literatürde kontrol sorununu çözmek için çeşitli çalışmalar vardır ve o çalışmaların sonuçları hala basit ve etkili bir kontrol sistemine ihtiyaç olduğunu göstermektedir. Bu çalışmada, kontrol hedefine ulaşmanın ilk adımı olarak, literatürde yaygın kullanılan üç doğrusal olmayan kontrolör, deneysel bir değerlendirme için seçilmiştir. Uygulanan kontrolörler, 'Klasik PID denetleyici', 'Bulanık PID Denetleyici' ve 'Kayan Kipli Denetleyicidir' (SMC). Performans değerlendirmesi, hızlı on/off valfleri ile çalıştırılan Festo PAM'lar tarafından sürülen, 1-D robotik kol ortezi olan bir test teçhizatı kullanılarak gerçekleştirilmiştir. Deney sonuçlarına göre, model serbest bir Sugeno tipi kombine bulanık PID kontrolörü, pnömatik yapay kasların (PAM) kontrol sorunu için basit ve etkili bir çözüm olabileceğini göstererek en başarılı performansı vermiştir.

Anahtar Kelimeler: Pnömatik yapay kas, PID denetleyici, Bulanık PID denetleyici, Hızlı aç/kapa valf

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1. INTRODUCTION

In robotic rehabilitation devices, different actuator types are used such as, hydraulic, electric, pneumatic actuators. Actuators operating with hydraulic pressure can produce high powers, but due to their high weight and need for special designs are not widely used in rehabilitation devices. The electric actuators are the most preferred once because of their high power capacity and easy application advantages using electrical energy. However, Caldwell and Tsagarakis [1] claimed that electric actuators are very heavy compared to pneumatic actuators and their impedances are too high to use in rehabilitation devices. As pneumatic actuators, a special type called Pneumatic Artificial Muscle (PAM), is used for rehabilitation purposes since their impedance is low and lighter than electric actuators [2]. PAMs are thought to be more suitable for rehabilitation use since they display a behavior similar to the human muscle due to nonlinear contraction and strength when it is activated [3].

Pneumatic Artificial Muscles (PAM) are type of actuators that mimic behavior of skeletal muscle by contracting and generating force in a nonlinear manner when pressurized. PAM has a radially inflation and axially contraction behavior which produces high pulling(tensile) forces along the longitudinal axis. PAM was invented firstly by Joseph L. McKibben in 1950s and it was used in artificial limbs [4]. In 1980s it was redesigned by Bridgestone Company and it was used for some applications to assist disabled individuals [5]. Nowadays, PAM is produced commercially by Festo Company and it is also called Festo fluidic muscle. The Festo muscle is structurally different from the general McKibben muscles. The fiber of the fluidic muscle is knit into the tube, offering easy assembly and improved hysteric behavior and nonlinearity compared to conventional design [6].

Even though their advantages such as high force to weight ratio, soft and flexible structure, extreme safe for human, cleanliness, ease of maintenance and low cost exist, PAMs have some disadvantages and difficulties in modeling and controlling. These difficulties happen due to the nonlinear characteristics of the actuator like air compressibility, friction, nonlinear airflow through the valves [7], inherent properties of visco-elastic material, geometric structure of PAM and compressibility of the air [8]. Hence, the nonlinear properties of the actuator make it difficult to use in rehabilitation devices. There are several model-free and/or model-based approaches to solve the control problem that restricts the use of Pneumatic Artificial Muscles. The model-free approaches are basically PID control, fuzzy control [9], neural network based PID control [10]. In [11] Andrikopoulos et al. developed the “advanced nonlinear PID control” approach to be used in antagonist study of the Pneumatic Artificial Muscle.

Model-based approaches are basically sliding mode control and model predictive control (MPC). There are numerous works developed sliding mode control [12-14]. Andrikopoluos et al. examined “A Switching Model Predictive Control Approach” in [15]. The main purpose of this approach is to provide different optimal control for each working area of PAM and smooth control transitions between these neighboring regions. In another study, as a combination of both approaches, Chiang and Chen used the “Incremental Fuzzy Sliding Mode” for the Pneumatic Artificial Muscle control in their study [16]. They choose a fuzzy logic based controller for the control problem caused by nonlinear dynamics of PAM and they claimed that they would provide a more successful control compared to the PID controller.

On the other hand, according to a literature review [17], majority of these studies focused only a single control mode with limited experimental conditions and they have not evaluated performance of different control modes. There are very few works implemented multiple different control modes. In addition, proportional valves, servo valves, pressure regulators or on/off valves are used as regulating elements [18]. Proportional valves or pressure regulator has been preferred in the majority of works in the literature. Although proportional valves perform well in PAM control, they are quite costly. Pressure regulators are also not sufficient for the speed range at which PAM can operate. Fast on/off valves are preferred in some works because they are both more economical and faster than others although it becomes more difficult to control PAM. Implementation results indicate that there is still requirement for a simple and effective control system. Hence, modeling and control of the Pneumatic Artificial Muscle are still challenging issues for better utilization of PAM. Although important results were obtained in these studies, there are some points not resolved yet, namely economic actuators and multi-mode control system design.

In order to bring an alternative solution to the above issues, in our implementation, fast on/off valves are preferred since it is more economical and faster than pressure regulator and proportional valves. Moreover, we briefly categorize the control methods used in the literature mentioned above as model-based and model-free controllers. In our opinion, a comparison of both approaches are still required to guide for an effective controller design with fast on/off valves. The comparison of the results is expected to aid for determination of a road map for an efficient and simple controller design. For this purpose, in our work, three nonlinear control methods are experimentally analyzed on our test rig, PID control, fuzzy PID control as model-free ones and sliding-mode control (SMC) as model-based controller. In addition, we have concluded our results with an effective comparison.

The structure of this paper as follows: in section II, our hardware implementation is given, where experimental setup and controllers are explained. In section III, experimental results and discussions are presented. In section IV conclusions are drawn.

2. IMPLEMENTATION

2.1. Experimental Setup

In this work, three nonlinear control modes are investigated using our own designed test rig, which is a 1-D robotic arm orthosis actuated by Festo PAMs operated with fast on/off valves. The controller implementations are performed in MATLAB/Simulink environment on a desktop PC which controls all mechanical, pneumatic and electronics units. The control system block diagram of the test rig is given below in Figure 1. An overview of experimental setup and components of the test rig is given in Figure 2.a and 2.b. In Figure 2.a, part A is the desktop PC where data from sensors can be viewed and processed, part B is 'DC power supply', C is 'Data acquisition unit', D is 'Analog signal amplifier & valve drive unit' and E denotes a constant load.

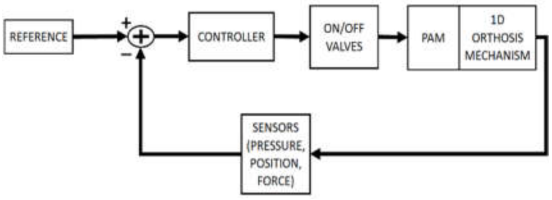

Figure 1. Control system block diagram of the test rig

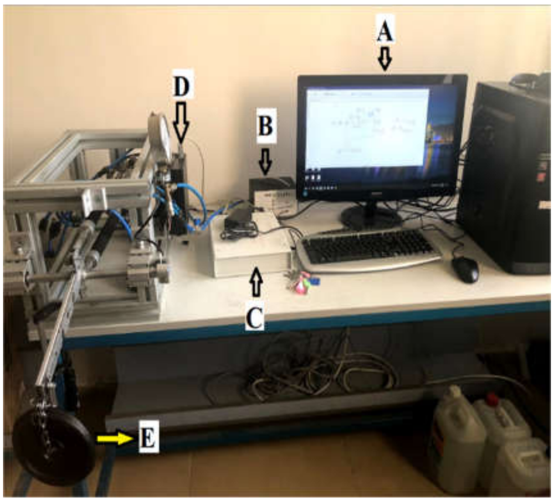

Figure 2.a. Overview of experimental setup

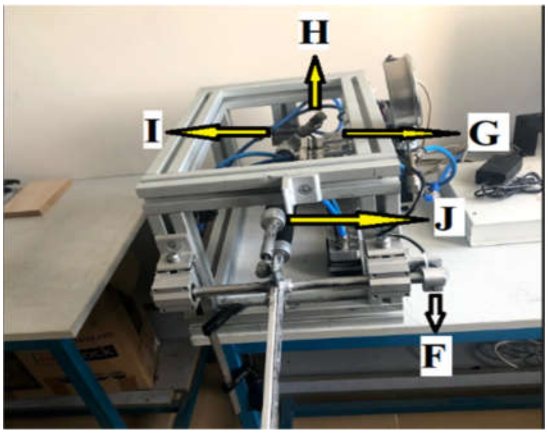

Figure 2.b. Components of the test rig

In Figure 2.b, the pneumatic artificial muscle (PAM) is indicated with J, that can work in the range of 0-6 bars, with a length of 250 mm, from the DMSP 20 series of FESTO (FESTO DMSP-20-250). Label G shows MATRIX MX890 series very fast on/off valves of used with PWM method. Label H marks HONEYWELL 24PCFFM6G series pressure sensor operating in the range of 0-100 psi. For the force measurement, ZEMIC H3-P3 type load cell of S-type with 0-100 kg range is used and marked with I. For the position measurement, BOURNE AMS22 type encoder is used and labeled with F.

During the experiments, MATLAB/Simulink blocks are used to implement controllers as well as sensors and actuator configurations. The Simulink blocks are compiled and sent to a microprocessor running in "Data Acquisition" unit. In the test rig, ATMEL Arm Cortex M3 microprocessor card included in the “Data Acquisition” unit is used to control the system.

2.2. Pneumatic Muscle Actuator Modeling

In order to implement model-based control methods, we first analyzed main modeling approaches developed for PAM. In the modeling works, the main purpose is to establish a relationship between pressure, extension of the muscle along the entire axis (displacement) and force. Pulling force, air pressure, diameter and length of the muscle, material properties play an important role in modeling approaches. PAM’s mathematical models relate these factors [19]. In general, modeling approaches depend on the static and dynamic behavior of PAM.

When developing a static model of the muscle, the basic approach is based on energy modeling. That approach provides a relationship between "actuator force, pressure and length", showing the length or degree of contraction and the diameter of the muscle formed by the forces, the actuator performance, taking into account virtual work and energy savings [18]. The Chou and Hannaford model is the simplest geometric model for the static performance of a PAM [20]. In this approach PAM actuator is modeled as a cylinder and the equation showing the expression between force, pressure and position according to this model is as follows (Equation 1).

$$F=P'\frac{b^2}{4\pi n^2}\left(3\cos^2\theta-1\right) \tag{1}$$

where b is the thread length, n indicates the number of turns of a thread, θ angle is defined as the angle between longitudinal axis and thread.

The aim of the dynamic model, also known as the phenomenological model of PAM, is to best evaluate the dynamic behavior of the pneumatic muscle. In dynamic modeling, as seen in Figure 3, the parallel configuration of the muscle, spring, damper and contractile element is used. The coefficients corresponding to these three elements depend on the input pressure of the PMA [21].

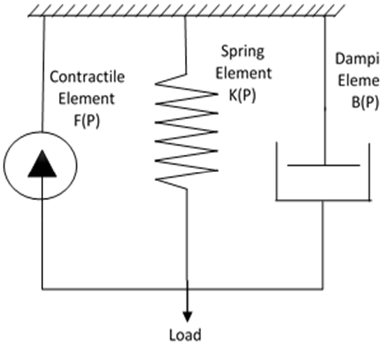

Figure 3. Three element phenomenologic model of pneumatic artificial muscle

The equations for the phenomenological model are written as follow (Equations 2-6):

$$M\ddot{x}+B(P)\dot{x}+K(P)x=F(P)-Mg \tag{2}$$

$$K(P)=K_0+K_1P \tag{3}$$

$$B(P)=B_{0i}+B_{1i}P \quad \text{(inflation)} \tag{4}$$

$$B(P)=B_{0d}+B_{1d}P \quad \text{(deflation)} \tag{5}$$

$$F(P)=F_0+F_1P \tag{6}$$

where M is the mass, *g* denotes the acceleration of gravity. K(P) indicates the spring coefficient. B(P) is damping coefficient and it depends on whether the PMA being inflated or deflated. F(P) is the effective force provided by the contractile element. The coefficients in the equation are determined as in the Xing et al. study [14]. In our implementation, we used that phenomenological modeling.

2.3. Sliding Mode Controller Implementation

Sliding mode control (SMC) is a variable form of structure control that uses a plane in the state space. This plane is called the sliding surface, and the aim is to keep state values close to this surface by minimizing state errors. Ideally, if the state value is away from the surface, a switching gain is used to push the state value towards the sliding surface. Once on the surface, the states slide along the surface in what is called the sliding mode [22]. The switching brings inherent stability and robustness to the control strategy, while also introducing chattering (high frequency switching) that is undesirable in practice and can excite un-modeled dynamics.

Sliding mode is separated into two parts: the equivalent control term u_{eq} and the switching control term u_{sw} [23]. While the switching control term aims to push the state variable away from the sliding surface to the sliding surface; the term "equivalent control" aims to keep the state variable reaching the sliding surface on the sliding surface by using the system model.

Consider as a class of n-th order nonlinear systems of the form (Equations 7-8):

$$x^n=f(x,t)+g(x,t)u(t) \tag{7}$$

$$x=\left[x,\dot{x}\cdots x^{(n-1)}\right]^T \ , \ y=x \tag{8}$$

where $x=\left[x,\dot{x}\cdots x^{(n-1)}\right]^T \in R^n$ is the state vector of the system which is assumed to be available for measurement, f(x,t) and g(x,t) are unknown continuous nonlinear functions of the system, $u \in R^n$ and $y \in R^n$ are the input and output of the system, respectively. The control objective is to obtain state x for tracking a desired state $x_d=\left[x,\dot{x}\cdots x^{(n-1)}\right]^T$

The tracking error has the following form generally (Equation 9):

$$e=x-x_d=\left[e,\dot{e}\cdots e^{(n-1)}\right]^T \tag{9}$$

The switching function for the sliding mode called 'sliding surface' can be chosen as below (Equation 10):

$$s(x,t)=Ce=c_1e+c_2\dot{e}+\cdots+c_{n-1}e^{(n-2)}+e^{(n-1)} \tag{10}$$

SMC is divided into 2 phases as approaching phase with $s(x,t)\neq 0$ and sliding phase with $s(x,t)=0$. In the sliding phase, we have $s=0$ and $\dot{s}=0$, then the equivalent control u_{eq} which will force the system dynamics to stay on the sliding surface.

According to the dynamic behavior of PAM is actually described as in [24] (Equations 11 and 12):

$$\ddot{x}=\frac{1}{M}\left(F_0-B_0\dot{x}-K_0x-Mg\right)+\frac{1}{M}\left(F_1-B_1\dot{x}-K_1x\right)P \tag{11}$$

$$y=x \tag{12}$$

where y is the trajectory of the PAM, P is the pressure of the PAM, $\ddot{x}$ and $\dot{x}$ are the desired acceleration and speed of the system, respectively.

According to these equations, f(x,t) and g(x,t) are, (Equations 13 and 14)

$$f(x,t)=\frac{1}{M}\left(F_0-B_0\dot{x}-K_0x-Mg\right) \qquad (13)$$

$$g(x,t)=\frac{1}{M}\left(F_1-B_1\dot{x}-K_1x\right) \qquad (14)$$

The control input u is the sum of the equivalent control term u_{eq} and the switching control term u_{sw} (Equation 15),

$$u=u_{eq}+u_{sw} \qquad (15)$$

where (Equations 16-17),

$$u_{sw}=-\eta\,\mathrm{sgn}(s)\ ,\ \eta\geq D \qquad (16)$$

$$u_{eq}=\frac{1}{g(x,t)}\left(-f(x,t)+\ddot{x}-c\dot{e}\right) \qquad (17)$$

We have implemented above SMC control mode for both pressure and position control in MATLAB/ Simulink.

2.4. PID Controller Implementation

The PID algorithm is given by following control law with three terms (P, I, D), to reduce the error value in a closed loop control (Equation 18).

$$u(t)=K_p\left[e(t)+\frac{1}{T_I}\int e(\tau)d\tau+T_D\frac{d}{dt}e(t)\right] \qquad (18)$$

Intuitively, these values can be interpreted as follows in terms of time considering the current change; P depends on the current error, I is the sum of past errors and D is an estimate of future errors. The process controlled through the weighted sum of these three actions is used to set the desired level. In our work, PID method has been applied for both pressure control and position control. For PID tuning, Ziegler-Nichols reaction rate method is used [25].

While applying Ziegler Nichols reaction rate method using the step response of the system, P, I and D parameters were calculated as K_p=3, T_I=0.2 and T_D=0.8 for pressure control. For position control, K_p=2, T_I=1 and T_D=0.19 for the position feedback section in the cascade structure, K_p=4, T_I=1.2 and T_D=0.7 for the pressure feedback section.

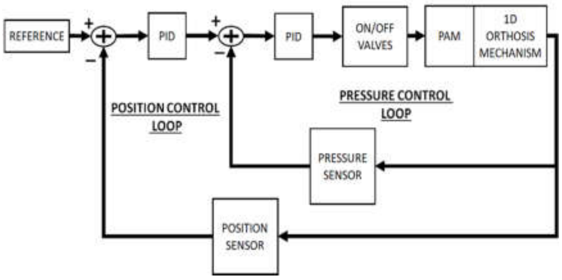

Figure 4. PID cascade controller

We have implemented a single loop PID for the pressure control and cascade PID control for the position control. We observed that single loop position control did not yield a successful result. Hence, we have used the cascade PID approach. For the position control, inner loop is chosen as pressure control since the primary control input of PAM is pressure. Performance of the implementation is given in results section.

2.5. Fuzzy PID Controller Implementation

While designing a fuzzy controller for PAM, we have chosen a direct fuzzy PID controller that is composed of fuzzy PI and fuzzy PD controllers. Figure 5.a shows the overall block diagram of the fuzzy PID control. Both fuzzy blocks are Sugeno type controllers. The fuzzy PI and fuzzy PD controllers performed simultaneously and separately; hence, their results are combined as the final output of controller. The internal structure of each fuzzy block is also given in Figure 5.b. The inputs for fuzzy PD are the error, derivative of the error and the inputs for fuzzy PI are the error, integral of the error, all with appropriate gains. The amount of error is calculated from the difference between the reference value and data from sensors. The gains are indicated by K_e for the error, K_{de} for the derivative of the error and K_{ie} for the of the integral of the error. In the Table 1, fuzzy rules are given and f(e) demonstrates rule function used for both PD and PI implementation. Similar logic is used for pressure control and position control. [26].

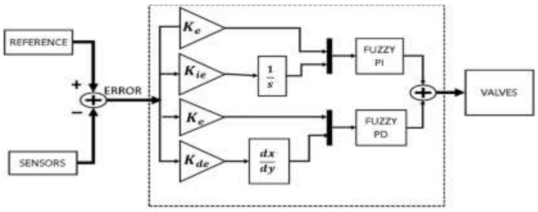

Figure 5.a. Fuzzy PID controller

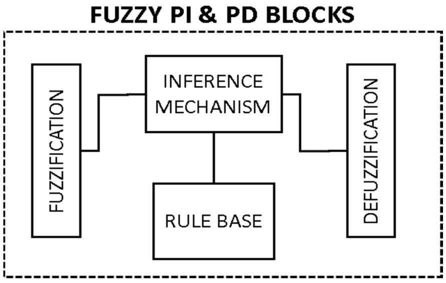

Figure 5.b. The Internal structure of fuzzy PI & PD blocks

Fuzzy PID controller implementation, error, derivative of error and integral of error are evaluated as fuzzy inputs using fuzzy memberships, and the inference mechanism yields the fuzzy output. The fuzzy output is defuzzified and resultant PWM signal is sent to the valves to provide system control with feedback. As shown in Figure 6, trapezoidal membership functions are selected for inputs in the range of [-1 1]. The seven membership functions are represented as follows: NB: Negative Big, NM: Negative Medium, NS: Negative Small, Z: Zero, PS: Positive Small, PM: Positive Medium and PB: Positive Big. Figure 7 indicates the output membership functions which use Sugeno zero-order type. In Figure 8, the control surface for the fuzzy PID controller is given.

Table 1. Fuzzy Rules for PD and PI blocks

f(e) e	NB	NM	NS	Z	PS	PM	PB
NB	-0.8	-0.67	-0.53	-0.4	-0.26	-0.13	0
NM	-0.67	-0.53	-0.4	-0.26	-0.13	0	0.13
NS	-0.53	-0.4	-0.26	-0.13	0	0.13	0.26
Z	-0.4	-0.26	-0.13	0	0.13	0.26	0.4
PS	-0.26	-0.13	0	0.13	0.26	0.4	0.53
PM	-0.13	0	0.13	0.26	0.4	0.53	0.67
PB	0	0.13	0.26	0.4	0.53	0.67	0.8

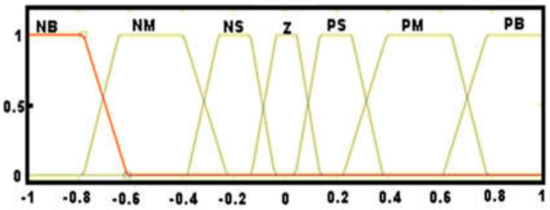

Figure 6. Membership functions for inputs (error, derror and ierror)

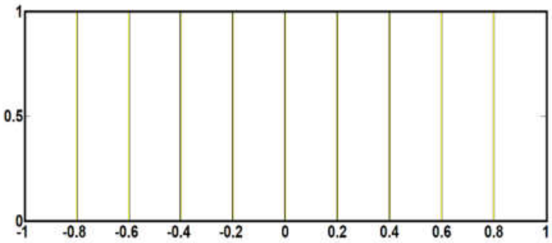

Figure 7. Membership functions for output

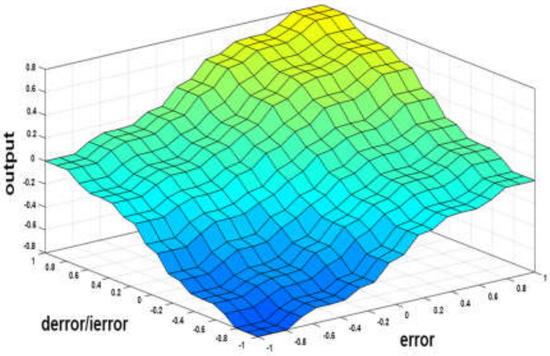

Figure 8. Control surface for fuzzy PID

3. RESULTS AND DISCUSSIONS

In this study, the responses of a pneumatic artificial muscle operated with fast on/off valve to three common nonlinear control methods are investigated. Among the nonlinear control methods, as model-free ones, conventional PID control and fuzzy PID control are implemented. As model-based method, sliding mode control (SMC) is implemented. The performance of the control methods is evaluated using step response and reference sine signal tracking. The controllers are implemented for both pressure control of PAM and position control of 1-D orthosis. Range of motion

(ROM) for most of the human main extremity joints are limited to maximum 1100. The velocity of the human muscles for articulated joints are also less than 1000/sec. Hence, for a rehabilitation device, maximum 1 Hz cycling frequency for exercise is more than the required physiotherapy exercise ranges. Therefore, in our case, we have chosen 0.1 Hz and 0.5 Hz for reference sine signals to represent, passive cyclic exercise patterns. The range of motion (ROM) of the arm orthosis for rehabilitation is selected between -15 to 70 degrees for cyclic passive exercise which corresponds to the pressure range of 5-75 psi in PAM, approximately. Experiments are carried out with a fixed weight of 15 kg and flow throttling valves are used to reduce the pressure flow to prevent swing. In following text, performance test results are given as grouped for pressure control and position control, for all the control modes.

In Figure 9, step response results for PID, fuzzy PID and sliding mode control are given, respectively, for pressure control of PAM. As seen in Figure 9 and Table 2, although there is no overshoot in the traditional PID control and fuzzy PID control, an 8 % overshoot occurred in the sliding mode control. In the step response for pressure control with conventional PID an oscillation in the range of about ±0.8 psi is observed while in SMC an oscillation in the range of about ±3 psi is observed. Although there is a negligible small steady state error in fuzzy PID and there is no oscillation as compared to traditional PID and SMC.

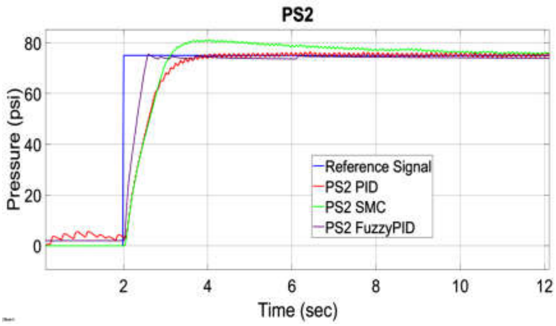

Figure 9. Step responses for pressure control using PID, fuzzy PID and SMC

Table 2. Results of applied controllers for pressure control

Controller	Overshoot (%)	Rise Time (sec)	Steady State Error (psi)
PID	~0	3.6	0.8
Fuzzy PID	~0	1.1	1.3
Sliding Mode Control SMC)	8	2.1	3

In Figure 10, PID, fuzzy PID and Sliding mode control 0.1 Hz sine tracking results are given for pressure control, respectively.

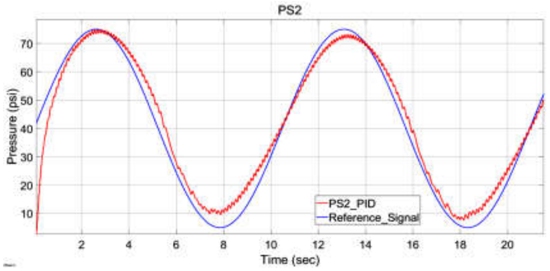

Figure 10.a. 0.1 Hz Sine tracking with PID control

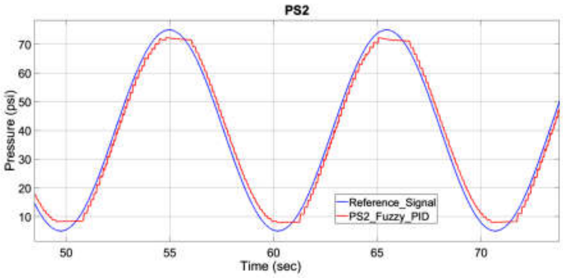

Figure 10.b. 0.1 Hz Sine tracking with fuzzy PID control

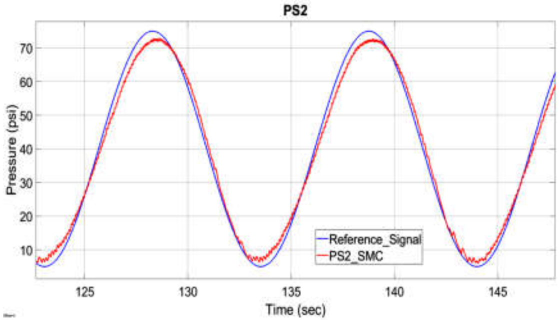

Figure 10.c. 0.1 Hz Sine tracking with SMC

In Figure 11, PID, fuzzy PID and Sliding mode control 0.5 Hz sine tracking results are given for pressure control, respectively.

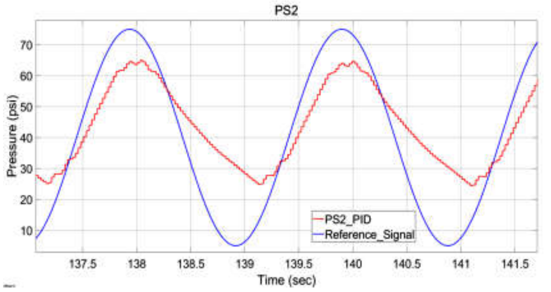

Figure 11.a.0.5 Hz Sine tracking with PID control

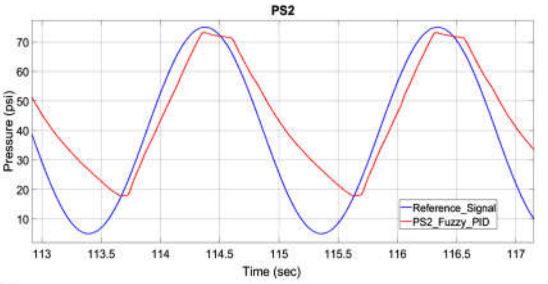

Figure 11.b. 0.5 Hz Sine tracking with fuzzy PID control

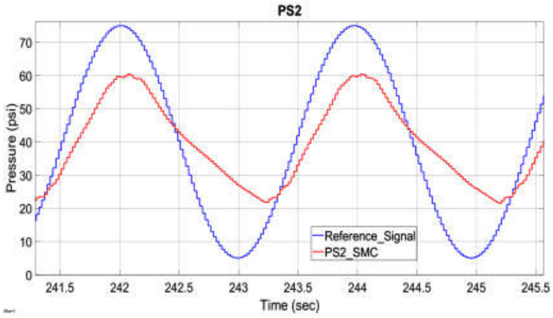

Figure 11.c. 0.5 Hz Sine tracking with SMC

When the results of the sine signal tracking in the pressure control are examined, it is seen that the error increases while the frequency increases. As seen in Figure 11, 3 controllers have good performances in 0.1 Hz frequency sine tracking. However, with the frequency rising to 0.5 Hz, as seen in Figure 11, fuzzy PID shows the best performance despite a negative error caused by the flow throttling valve.

Let's consider similar results for position control. Cascade PID control is used for position control using both pressure feedback and position feedback. The reason for using the cascade structure is that the air in-taking and releasing the muscle is provided by pressure control while the muscle contracts and relaxes, i.e. the pressure is the primary controlled system input.

In Figure 12, step response results for PID, fuzzy PID and sliding mode control are given, respectively, for position control of PAM.

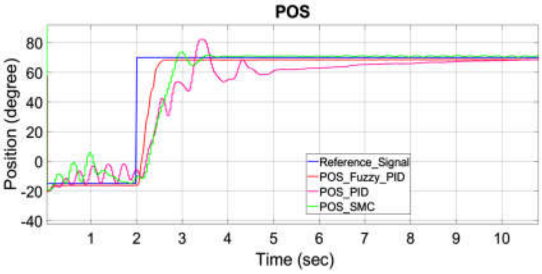

Figure 12. Step Responses for Position Control using PID, fuzzy PID and SMC

As seen in Figure 12 and Table 3, although there is no overshoot in the fuzzy PID control, a 17.85 percent overshoot occurred cascade PID control and a 5.71 percent overshoot occurred in the sliding mode control. In the step response for position control with conventional PID an oscillation in the range of about 0.8° is observed while in SMC an oscillation in the range of about 1.0° is observed. Eventually, a steady state error for fuzzy PID is 0.5°, which is a much better performance as compared to cascade PID and SMC.

Table 3. Results of applied controllers for position control

Controller	Overshoot (%)	Rise Time (sec)	Steady State Error (deg)
PID_Cascade	17.85	3.27	0.8°
Fuzzy PID	~0	2.6	0.5°
SMC	5.71	2.89	1.0°

In Figures 13 and 14, the results of sine signal tracking with 0.1 Hz and 0.5 Hz for position control with cascade PID, fuzzy PID and sliding mode control (SMC) are given respectively.

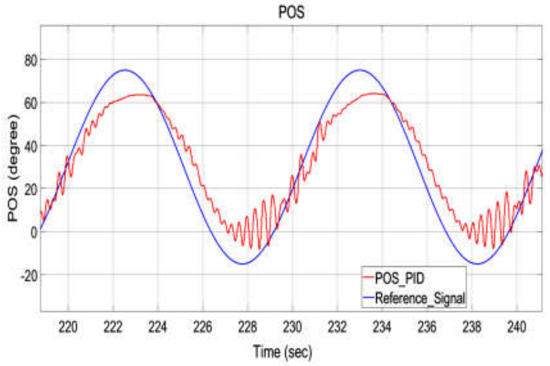

Figure 13.a. 0.1 Hz Sine tracking with PID control

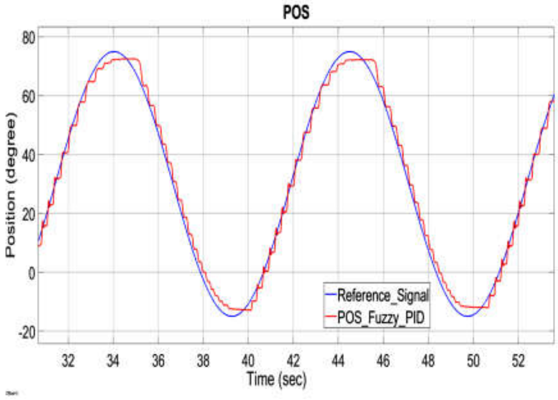

Figure 13.b. 0.1 Hz Sine tracking with fuzzy PID control

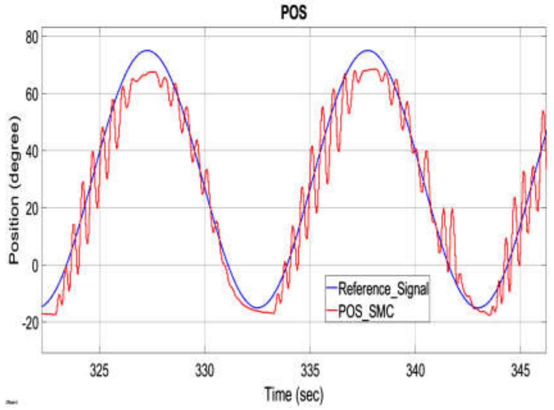

Figure 13.c. 0.1 Hz Sine tracking with SMC

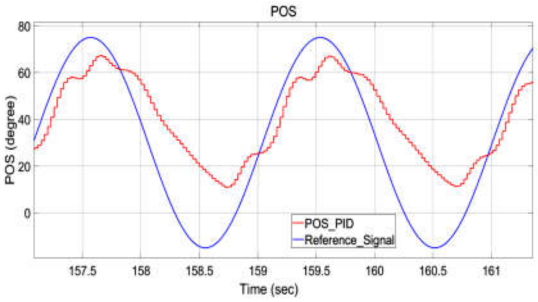

Figure 14.a. 0.5 Hz Sine tracking with PID control

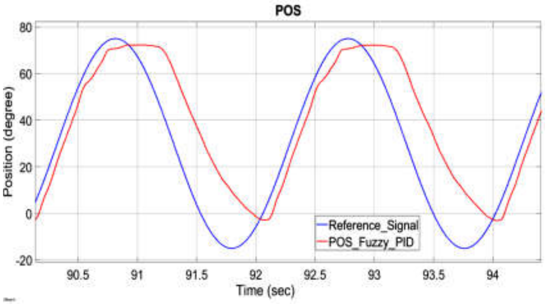

Figure14.b. 0.5 Hz Sine tracking with fuzzy PID control

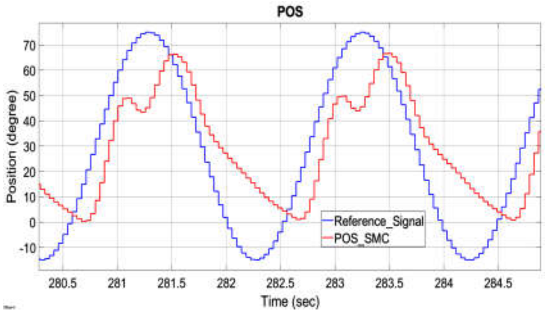

Figure14.c. 0.5 Hz Sine tracking with SMC

When looking at the results of position control in signal tracking, as in the pressure control, it is seen that the error increases while the frequency increases. In addition, a higher error value than expected occurred during the monitoring of the sine signal at all frequency values during position control. It is thought that this is due to both the throttling valves affecting the pressure inlet and outlet, and the position is not a directly controllable parameter in the system. In addition, fuzzy PID has the smoothest following performance.

4. CONCLUSIONS

In this work, we performed an experimental evaluation of common nonlinear control modes, in order to search for simple and effective methods that is going to be used in Pneumatic Artificial Muscle rehabilitation applications. The main contribution of this work is to find an alternative method using economic actuators and a multi-mode control system approach. Fast on/off valves are preferred in some works because they are both more economical and faster than others although it becomes more difficult to control PAM.

As a first step of searching a better control method, three common nonlinear controllers used in literature are selected for an experimental evaluation. In this work, three nonlinear control methods are PID control, fuzzy PID control as model-free ones and sliding-mode control (SMC) as model-based controller. The evaluation is performed using a test rig, which is a 1-D robotic arm orthosis actuated by Festo PAMs operated with fast on/off valves. Based on our experimental results, a comparison of both approaches helps us to guide for an effective controller design with fast on/off valves. The comparison of the results enlightens the determination of a road map for an efficient and simple controller design.

In conclusion, our experimental results demonstrate that a model-free Sugeno type combined fuzzy PID controller has yielded most successful performance indicating that it could be a simple and effective solution for PAM control issue.

5. ACKNOWLEDGMENTS

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