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Experimental Validation for Pneumatic Artificial Muscles using Fuzzy PID Control
Thiết Kế và Kiểm Nghiệm Luật Điều Khiển PID Mờ Cho Cơ Nhân Tạo

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Abstract

Along with the remarkable development of science and technology, recently, robot application in life is quite popular such as robots interacting with humans, rehabilitation robots, etc. Therefore, the pneumatic artificial muscle (PAM) has been studied for application in robot manufacturing. However, the high-performance control system construction is difficult due to the non-linear structure of an artificial muscle. With a classic Proportional-Integral-Derivative (PID) control, the trajectory tracking performance is not high because a fixed set of PID parameters does not solve the enhancing performance problem. Therefore, in this paper, a fuzzy PID control (FPIDC) for a PAM is presented to improve the trajectory tracking performance. The efficiency of the proposed controller has been verified by experiment under different conditions.

Keywords: *Pneumatic Artificial Muscles, Rehabilitation Robot, Fuzzy Proportional-Integral-Derivative Control.*

Abbreviations

PAM	Pneumatic Artificial Muscle
FPID	Fuzzy PID
SISO	Single Input Signle Output
MIMO	Multiple Input Multiple Output
SD	Standard Deviation
NB	Negative Big
NM	Negative Middle
Z	Zero
PM	Positive Middle
PB	Positive Big

Tóm tắt

Cùng với sự phát triển của khoa học và kĩ thuật, gần đây, ứng dụng của robot trong cuộc sống khá là phổ biến. Các ứng dụng được kể đến như là robot tương tác với con người, robot phục hồi chức năng, vv. Do đó, mô hình cơ nhân tạo (PAM) đã được nghiên cứu để ứng dụng trong sản xuất robot. Tuy nhiên, việc xây dựng hệ thống điều khiển với hiệu suất cao gặp nhiều khó khăn do cấu trúc hệ thống cơ nhân tạo là phi tuyến. Với điều khiển PID thông thường, hiệu suất bám quỹ đạo không được cao vì một bộ tham số PID cố định không giải quyết được vấn đề nâng cao hiệu suất. Do đó, trong bài báo này, một bộ điều khiển PID tự điều chỉnh tham số mờ (FPIDC) đã được thảo luận và trình bày để cải thiện hiệu suất bám quỹ đạo. Hiệu quả của bộ điều khiển đề xuất trong bài đã được kiểm chứng bằng thực nghiệm dưới các điều kiện khác nhau.

1. Introduction

In recent years, automated robots have gradually begun to stand out in various industries. Especially in the field of the medicine, making rehabilitation robots is more valuable for assist people in medical tasks. For this field, there has been a lot of recent research related to artificial muscle robots which include modeling and control methods [1, 2, 3, 4, 5, 6, 7, 8] because the PAM flexibility can be used to reduce the risk of injuring users. They have advantages such as compactness, safety and the ability to lift large loads. A construction of artificial muscles consists of a rubber tube on the inside and a sheath on the outside. When the air is supplied to the muscle, the increased volume of the rubber tube means the contracting and inflating muscle. Conversely, when releasing less air, the muscle will deflate and decrease in diameter. This action of artificial muscles has properties similar to human muscles. However, for the application of robots, artificial muscles exist some disadvantages such as hysteresis, non-linearity and low damping ability which cause dynamic delay to the pressure response. Hence, it is extremely difficult to control PAM-based

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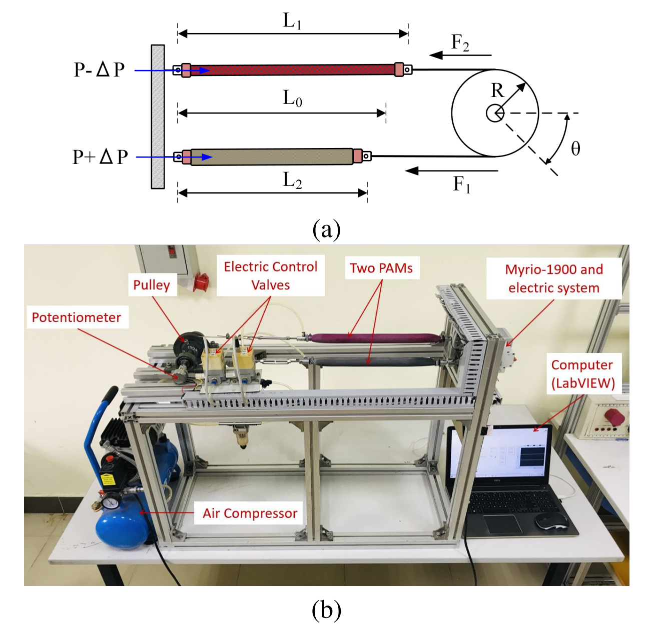

Figure 1: Experimental Platform: (a) working principle of an antagonistic configuration and (b) real image of the system.

robot with high accuracy and speed.

Currently, many methods used to control artificial muscles. The Proportional–Integral–Derivative (PID) controller is one of the most important one in any process industry [9] because of its simple structure and robust performance in a wide range of operating conditions. The fuzzy controller [10] has been the most successful application field in fuzzy logic and are being used in a wide variety of engineering applications. Many applications show that results obtained by fuzzy controllers are better than those by the conventional control algorithms [11, 12]. In this paper, the PID controller is combined fuzzy controller to tune parameters of controllers [13]. This paper is devoted to study the performance of Fuzzy PID controller in the experiment. The FPID controller is designed with the help of LabView.

The remains of this paper are organized as follows. Section 2 introduces the system structure and parameters identification of a PAM-based actuator. In Section 3, the design of FPID is presented. Some experiment results are given in Section 4 showing the interests of the proposed controller. Conclusion is reported in Section 5.

2. Experimental Platform And Parameters Identification

2.1. Experimental Platform

This research is carried out base on an experiment platform of two PAMs in an antagonistic configuration which has working principle as 1a. As shown in 1a, two PAMs connected together through a pulley that allows converting the longitudinal direction of PAMs to its rotating motion. The used PAMs have 25.4 (mm) of diameter, 400 (mm) of length.

In the initial state, two PAMs are supplied with compressed air at the same pressure P_0 = 0.2 (MPa). The equalizer in lengths of both PAM leads to the actuator angle is zero. The joint angle θ is created when having a different pressure ΔP in both PAMs.

2.2. Parameters Identification

In this work, the chosen method is based on a parametric identification of an ARX model which decribes the input effects on the output [14]. This model is represented by the following expression:

$$y_{k+1} = -a_1 y_k - a_2 y_{k-1} + b_1 u_k + b_2 u_{k-1} \tag{1}$$

where u_k is the control signal ΔP; y_k is the joint angle output θ; $a_i, b_j (i, j = 1, 2)$ are the model parameters.

To obtain the model parameters, firstly, setting the initial value of pressure at $P_0 = 0.2$ (MPa) for each PAM so that the actuator's initial position is in a position where the actuator angle $\theta = 0°$.

Then, change the joint angle by sending control signals to the electrical control valves. In this experiment, the control signal is used as a sine wave signal with a combination of four sine waves with different frequencies and amplitudes. The sine wave signal is expressed as follows:

$$u(t) = Acos(\pi/2 - 2\pi ft) + 0.3Acos(\pi/2 - 2\pi 0.2ft)$$
$$+0.7Acos(\pi/2 - 2\pi 1.5ft) + 0.1Acos(\pi/2 - 2\pi 3ft)$$

where $A = 0.05$ (MPa) and $f = 0.5$ (Hz) are the amplitude and frequency of the control signal, respectively.

All the data, including the control signal and the actuator angles, are recorded with sampling time $T_s = 5$ (ms) to proceed to the next steps.

The model parameters a_i, b_j are estimated by the Least Square method and provided in Table 1.

Table 1: Identified parameters of the model.

Parameters	Value($Mean \pm SD$)
a_1	-1.9345 ± 0.0092
a_2	0.9249 ± 0.0128
b_1	0.0214 ± 0.0053
b_2	-0.0207 ± 0.0049

After the system identification process, we obtain model recognition results, see Figure 2.

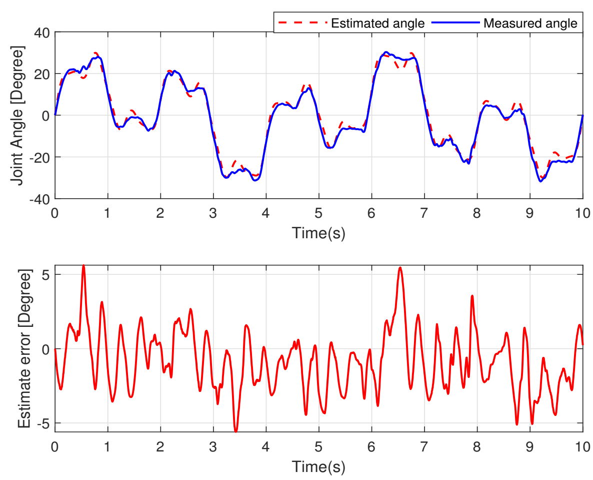

Figure 2: Identification results of the model: The sine wave signal with time-varying amplitude and frequency, amplitude 0.05 (MPa), frequency 0.5 (Hz).

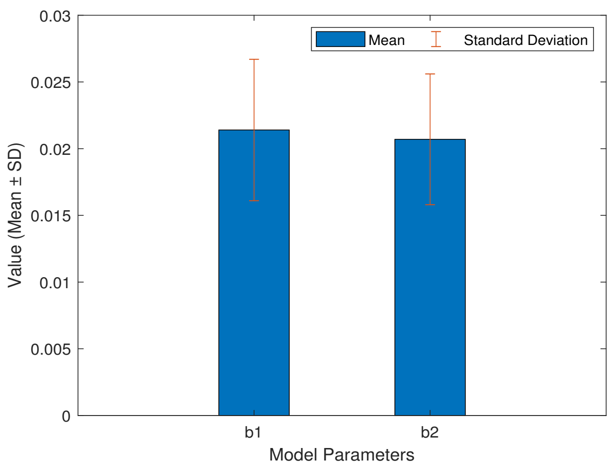

Figure 3: The means and standard deviations of the model parameters b_j.

The mean values and SD of the parameters are summarized in Table 1. As we can see in Figure 3, the b_j elements of model's parameters are not constant. In details, the standard deviation (SD) of b_1 and b_2 are 24.77% and 23.67%, respectively. It observe that PAM is highly uncertainty and nonlinear. To solve this problem, we proposed a Fuzzy PID controller which is based on Fuzzy logic with a PID struture. This is helpful in controlling the systems if the exact model of the system is not available.

3. Fuzzy PID Controller Design

The PID control is one of the most utilized model-free control algorithms including three control parameters: a Proportional, an Integral, and a Derivative operation [15]. The PID control input u_k is shown in Equation 2:

$$u_k = u_{k-1} + K_r \left[e_k - e_{k-1} + \frac{T_s}{T_c} e_{k-1} + \frac{T_v}{T_s} (e_k - 2e_{k-1} + e_{k-2}) \right] \tag{2}$$

where K_r is the proportional gain, T_c is the integral time, T_v is the derivative time of the PID control law, and T_s is sampling time. PID controller is the best-known industrial process one because of its simple structure and robust performance in a wide range of operating conditions. On the other hand, fuzzy logic controllers have been successfully applied for control of various physical processes. So the goal of this paper is to a design a Fuzzy PID (FPID) based on fuzzy logic with a PID structure for studying the performance in application.

Figure 4 illustrates the block diagram of the proposed control system, by using a fuzzy controller for tuning a PID controller parameters. The first input being the tracking error e_k of the system and the second input is the derivative of the tracking error d_{e_k}. With the input of the system, two gain factors k_{e_k} and kd_{e_k} are used to control and adjust the input, making the system stable and improving performance. The output of the fuzzy controller includes parameters of a PID controller such as K_r, T_c, T_v. The value u_k is the gas pressure introduced into the PAMs system determined during the experiment.

Fuzzy controller includes [16, 17] a set of fuzzy rules, a fuzzifier, a fuzzy inference engine and a defuzzifier. Fuzzy rules will be formed based on the experimental and research process of experts. The fuzzifier converts the explicit values of the input language variable into the vector μ. Depending on the input values, the fuzzy inference engine will generate a fuzzy set for the output variables based on the control law. The defuzzifier converts the output fuzzy set into a clear value corresponding to the input to control the object. An element in fuzzy logic can belong to more than one set. A fuzzy set is characterized by a language variable, which is a word or phrase whose value is the word or phrase associated with a particular fuzzy set. The values of language variables are attached to membership functions (triangular, trapezoidal, generalized bell, gaussian, etc.). The membership functions can be superimposed on each other and that is also the strength of fuzzy control. Like classical controllers, fuzzy controllers can be classified according to the number of inputs and outputs: SISO, MIMO.

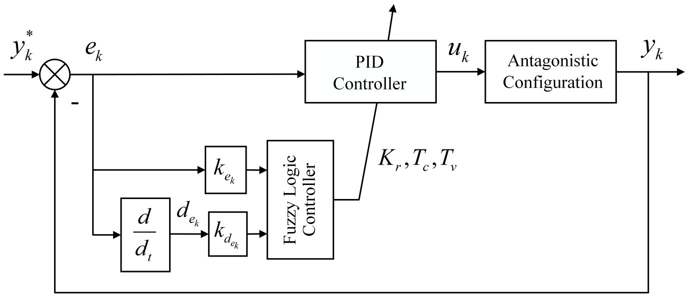

Figure 4: System diagram.

In this paper, the MIMO fuzzy controller is used with the first input being the tracking error e_k of the system and the second input being the derivative of the tracking error d_{e_k}. The output of the fuzzy controller is parameter of a PID controller including K_r, T_c, T_v. Figure 5 shows the diagram of Fuzzy Controller.

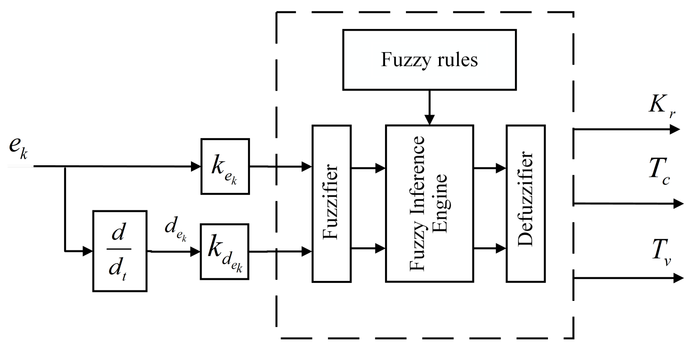

Figure 5: The details of fuzzy controller.

The design of a fuzzy logic controller requires the following steps (fuzzification, inference and defuzzification) which are detailed in the following sections.

3.1. Fuzzification

We define the language variable values of the e_k input as : PB (Positive Big), PM (Positive Middle), Z (Zero), NM (Negative Middle), and NB (Negative Big). We perform symmetric membership functions on the universe set of language variables of controller. The universe of language variables for $e_k \in [-3, +3]$ is shown in Figure 6. The values of language variables

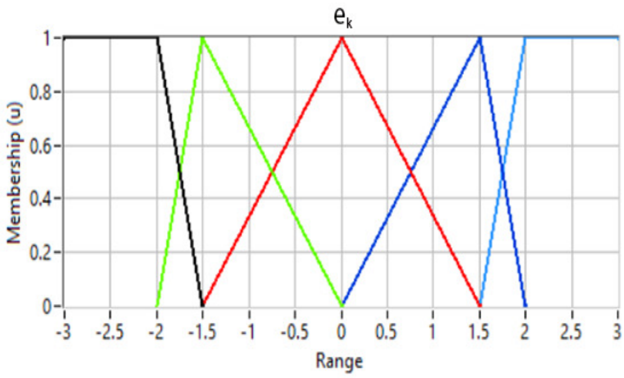

Figure 6: Input fuzzy controller e_k.

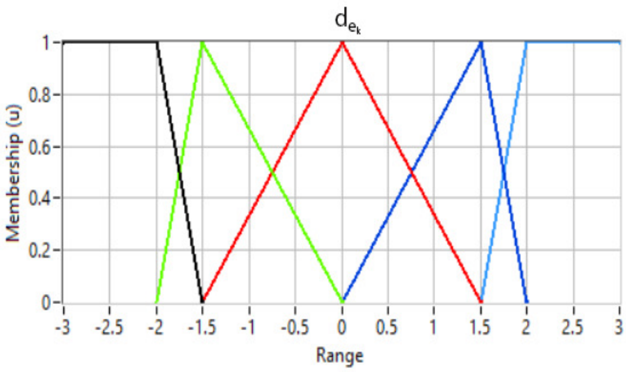

Figure 7: Input fuzzy controller d_{e_k}.

are attached to fuzzy sets as follows:

$$\mu_{NB}(x) = trapmf(x, [-4 \quad -3 \quad -2 \quad -1.5]) \tag{3}$$

$$\mu_{NM}(x) = trimf(x, [-2 \quad -1.5 \quad 0]) \tag{4}$$

$$\mu_{Z}(x) = trimf(x, [-1.5 \quad 0 \quad 1.5]) \tag{5}$$

$$\mu_{PM}(x) = trimf(x, [0 \quad 1.5 \quad 2]) \tag{6}$$

$$\mu_{PB}(x) = trapmf(x, [1.5 \quad 2 \quad 3 \quad 4]) \tag{7}$$

Similar to the input e_k, we define the language variable values of input d_{e_k} as: PB (Positive Big), PM (Positive Middle), Z (Zero), NM (Negative Middle), and NB (Negative Big). The universe of language variables for $d_{e_k} \in [-3, +3]$ is shown in Figure 7 . The values of language variables are attached to fuzzy sets as follows:

$$\mu_{NB}(x) = trapmf(x, [-4 \quad -3 \quad -2 \quad -1.5]) \tag{8}$$

$$\mu_{NM}(x) = trimf(x, [-2 \quad -1.5 \quad 0]) \tag{9}$$

$$\mu_{Z}(x) = trimf(x, [-1.5 \quad 0 \quad 1.5]) \tag{10}$$

$$\mu_{PM}(x) = trimf(x, [0 \quad 1.5 \quad 2]) \tag{11}$$

$$\mu_{PB}(x) = trapmf(x, [1.5 \quad 2 \quad 3 \quad 4]) \tag{12}$$

The language variable values of output K_r, T_c and T_v as : NB, NM, Z, PM, PB are defined and shown in Figure 8, 9 and 10.

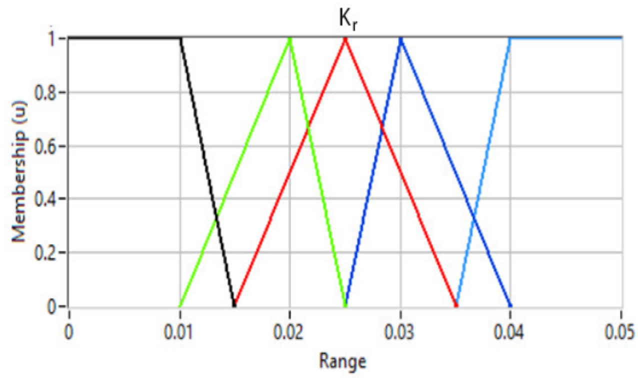

Figure 8: Output fuzzy controller K_r.

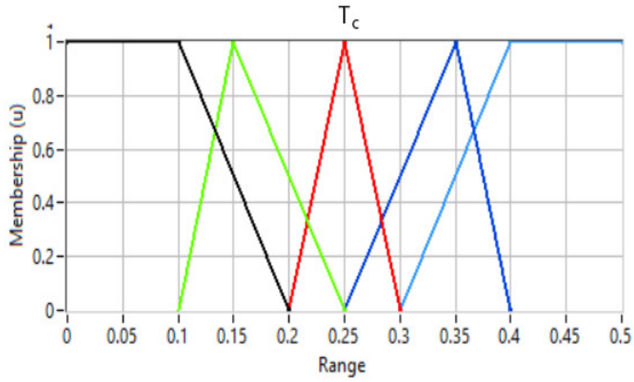

Figure 9: Output fuzzy controller T_c.

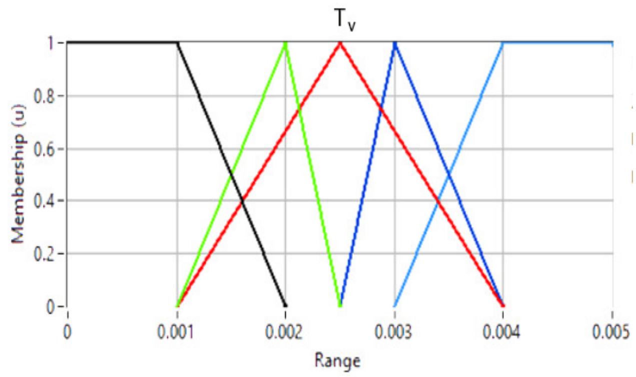

Figure 10: Output fuzzy controller T_v.

3.2. Control law

A typical structure for a Fuzzy logic controller is to have two inputs, the first input is the error e_k and the second input is the derivative of the error d_{e_k}. A set of membership functions has to be designed of the input and output and the associated set of rules are generated to govern the membership functions of the input/ output relationship. The fuzzy rules for the self-tuning PID are listed in the Tables 2, 3, and 4. They are interpreted as follows:

For K_r in Tables 2,
Rule i: if e_k is $A^i_{e_k}$ and d_{e_k} is $A^i_{d_{e_k}}$ then K_r is $B^i_{K_r}$; i=1, ... ,25

For T_c in Tables 3,
Rule j: if e_k is $A^j_{e_k}$ and d_{e_k} is $A^j_{d_{e_k}}$ then T_c is $B^j_{T_c}$; j=1, ... ,25

For T_v in Tables 4,
Rule l: if e_k is $A^l_{e_k}$ and d_{e_k} is $A^l_{d_{e_k}}$ then T_v is $B^l_{T_v}$; l=1, ... ,25

Table 2: Fuzzy control laws for K_r.

d_{e_k} / e_k	NB	NM	Z	PM	PB
NB	PB	PB	PM	PM	Z
NM	PB	PM	PM	Z	NM
Z	PM	PM	Z	NM	NM
PM	PM	Z	NM	NM	NB
PB	Z	NM	NM	NB	NB

A_{e_k} and $A_{d_{e_k}}$ are the input linguistic variables of the error e_k and derivative of the error d_{e_k}, respectively. B_{K_r}, B_{T_c} and B_{T_v} are the output linguistic variables of three output K_r, T_c and T_v.

Table 3: Fuzzy control laws for T_c.

d_{e_k} / e_k	NB	NM	Z	PM	PB
NB	PB	PB	PB	PM	Z
NM	PB	PM	PM	Z	NM
Z	PB	PM	Z	NM	NB
PM	PM	Z	NM	NM	NB
PB	Z	NM	NB	NB	NB

Table 4: Fuzzy control laws for T_v.

d_{e_k} / e_k	NB	NM	Z	PM	PB
NB	PB	PB	PM	Z	Z
NM	PB	PM	PM	Z	Z
Z	PM	PM	Z	NM	NM
PM	Z	Z	NM	NM	NB
PB	Z	Z	NM	NB	NB

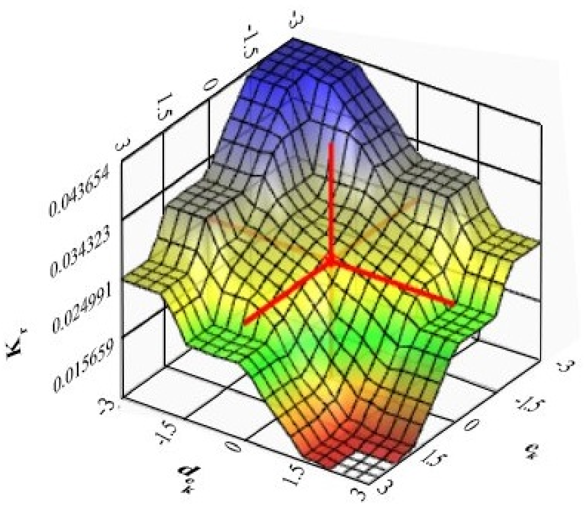

Figure 11: Surface presents the relation between inputs and output K_r of fuzzy controller.

Defuzzification process converts the degrees of membership of output linguistic variables K_r, T_c and T_v within their linguistic terms into crisp numerical values. Result gains are obtained by LabView Fuzzy Logic Toolkit, see Figure 11, 12, 13.

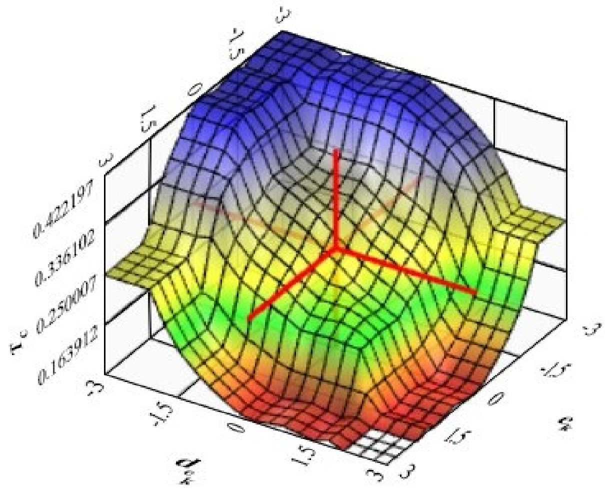

Figure 12: Surface presents the relation between inputs and output T_c of fuzzy controller.

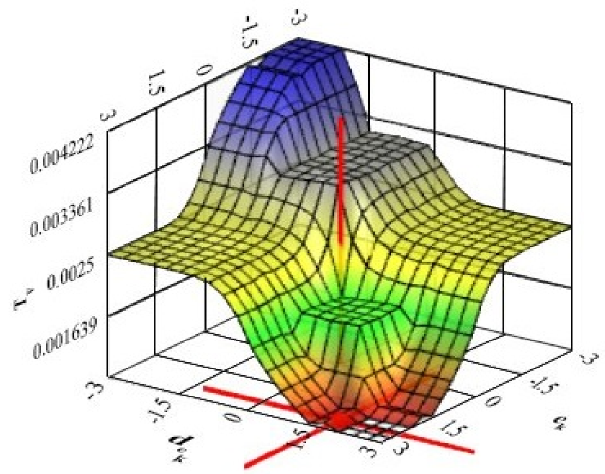

Figure 13: Surface presents the relation between inputs and output T_v of fuzzy controller.

4. Experimental Results

In order to verify the efficiency of proposed control method, multiple scenarios are tested with different trajectories. The experiment is carried out with sinusoidal signals which have amplitudes 20° and frequencies 0.2 (Hz) or 0.5 (Hz). In all experimental scenarios, the sampling cycle of the controllers T_s is set at 5 (ms).

From experiment results, we can conclude that the parameters of fuzzy PID controller is time-varying. For example, Figure 16 illustrates the values of K_r, T_c and T_v when tracking the 0.2Hz sinusoidal signal in the first experiment scenarios.

Figure 14 shows the experimental results when the actuator tracks 0.2Hz-frequency sine wave signal without a load. The upper sub-figure includes desired (blue line), PID-measured (dash red line), and Fuzzy PID-measured (blue dash line) signals, the lower one are their deviations from the desired signal. In all experiment conditions, both PID and FPID controllers can track the desired signals. As illustrated on Figure 15, the control performances of both controllers are slightly decreased when the desired signal's frequency increases, but still reach good accuracy. The control performance of the FPID controller

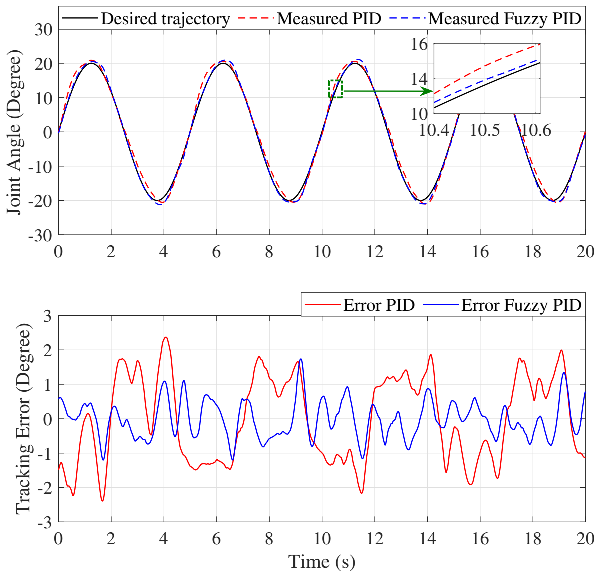

Figure 14: Experiment result when tracking a 0.2Hz without a load.

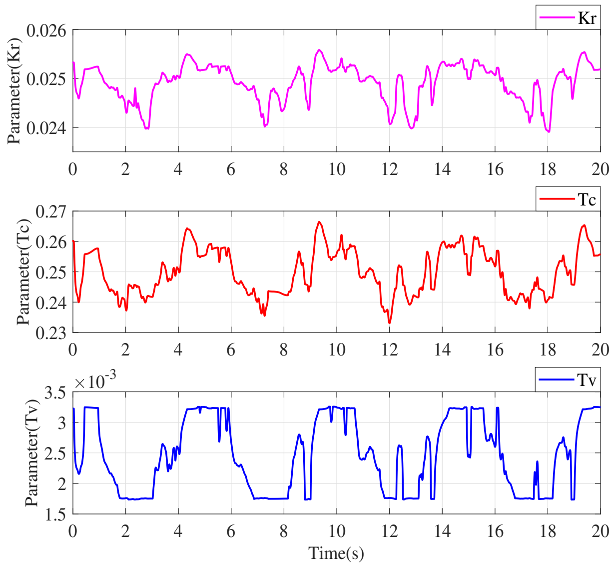

Figure 16: The Fuzzy PID's parameters in experiment of tracking a 0.2Hz sine wave signal.

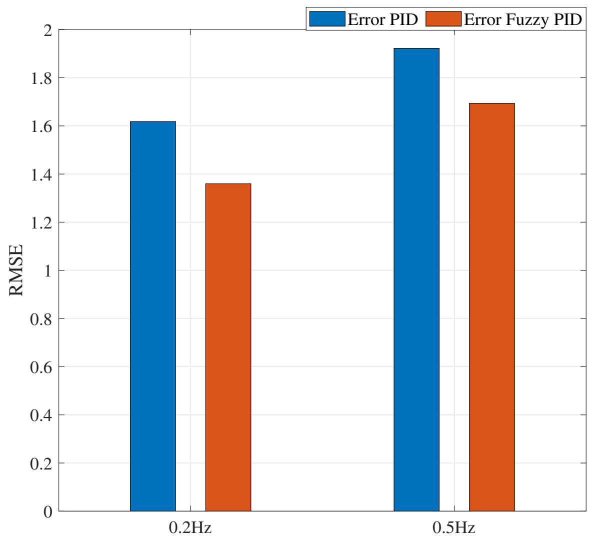

Figure 15: Graph bar indicator of controllers' root mean square error in the first scenarios.

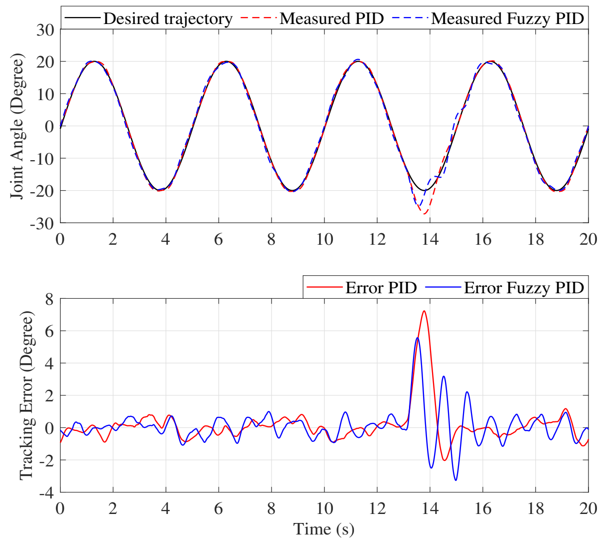

Figure 17: Experiment result when tracking a 0.2Hz sinusoidal signals and carrying a load m = 5 (kg).

is better than PID's, for example RMSEs (Root Mean Square Error) of the PID and FPID are 1.618° and 1.357° while tracking the 0.2Hz sinusoidal signal. The RMSEs of both controllers in the first scenario are given in Table 5.

In the second scenario, the load (m=5kg) is added to the system when the system reaches stable state. The experiment is also carried out with sinusoidal signals which have amplitudes 20° and frequencies of 0.2 (Hz) and 0.5 (Hz). Figure 17 shows experiment results of the system when tracking the 0.2Hz signal and carrying a 0.5 (kg) of load. The similar legend is used in Figure 17 and Figure 14. As shown in Figure 17, when the load is added to the system, the tracking performance is degraded. However, it quickly returns stable and still achieves a good tracking accuracy with RMSE is less than 2.5 (°).

Table 5: RMSE values of two controllers.

Frequency	RMSE (°) (No load)		RMSE (°) (m = 5kg)	
	PID	FPID	PID	FPID
0.2 Hz	1.618	1.3597	2.072	1.6691
0.5 Hz	1.922	1.6935	2.397	2.1485

5. Conclusion

In this paper, the PID controller is combined with a fuzzy controller for tuning parameters of controller. The proposed fuzzy controller designed in Labview software. The tracking of the trajectory with the sinusoidal signal has brought high efficiency with small error. The modeling and computational construction of PAM model have been verified with the experiment under different conditions. The experimental results illustrate the applicability of the proposed model and controller to the robot's motion system to human motion.

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