Tracking Control of Vertical Pneumatic Artificial Muscle System using PID

M.H. Tan, S.H. Chong, T.F. Tang, A.Z. Shukor, V. Sakthivelu, T.C. Ma, M.R. Md. Nawawi
Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.
horng@utem.edu.my

***Abstract*—The advantages of pneumatic system such as compactness, high power to weight ratio, ease of maintenance, cleanliness and inherent safety led to the development of McKibben muscle and pneumatic artificial muscle (PAM). However, the air compressibility and the lack of damping ability of PAM bring dynamic delay to the pressure response and causes oscillatory motion to occur. It is not easy to realize the motion with high accuracy and high speed due to all the non-linear characteristics of pneumatic system. In this paper, we present a vertical PAM system with a simple PID controller to control the motion of the PAM. The experiment setup is explained and Ziegler Nichols tuning method is used in getting the approximation PID parameters. The effectiveness of the proposed control algorithm is demonstrated through experiments.**

***Index Terms*—Pneumatic Artificial Muscle; Pneumatic Muscle Actuator; PID.**

I. INTRODUCTION

The motion of robots and machines depends on its own actuation system as it provides forces, torque or any form of mechanical motion to the system in order to move. Electric system is commonly used as the actuator technology for most of the robotic applications nowadays. Meanwhile, due to the low power to weight ratio of electric actuator system as compared to pneumatic system, some industries prefer to use pneumatic system as their machine actuator. This is because pneumatic systems have the advantages of compactness, low cost, east of maintenance, and most importantly the high power to weight ratio characteristic. Therefore, these advantages have led to the development of novel actuator such as McKibben Muscle and Pneumatic Artificial Muscle (PAM).

PAM is a rubber tube clothed with a sleeve made of twisted fiber-code, and is fixed at both ends by fixtures. It is an actuator that is able to expand its muscle in radial direction when pressure is supplied and vice versa. PAM has a property like a spring, which enables it to change its own compliance by the inner pressure. The development of actuator system using PAM has been applied to some of the therapy robot and industrial machines. However, PAM has the characteristics such as hysteresis, non-linearity and low damping ability. The air compressibility and lack of damping ability of PAM system causes dynamic delay to the pressure response, which will results in oscillatory motion. Hence, it is not easy to realize the motion with high accuracy and high speed.

There are many intelligent control algorithms have been proposed up to now to control the motion of PAM. A simple PID control [1] is designed and applied on a 7 degree of freedom PAM system to power up exoskeleton, in which it had its effectiveness to replicate contact forces. Not only that, a fuzzy PD+I learning control for a single PAM is done in [2], with an adjustable PD fuzzy part and a parallel non-fuzzy integral branch. However, this controller has the limitation of low accuracy for tracking motion during the starting of operation. Fuzzy + PID control that is being proposed in [3] causes the PAM system to be vulnerable to parameter changes over time. Tetsuya Kimura applied a method of feedback linearization for a PAM system to handle the non-linear characteristics based on a non-linear model in [4] and [5]. Besides, Kyoung Kwan proposed a switching algorithm of control parameter using learning vector quantization neural network (LVQNN) on a PAM system in [6]. The position control was successfully implemented using proportional valve in place of expensive servo valve. Kyoung Kwan also further improved the system by adding a magneto-rheological brake (MRB) to the joint of manipulator to greatly improve the stability in a high gain control regardless of the changes of external inertia loads in [7]. Furthermore, sliding mode control for the PAM system was proposed in [8]. Wang proposed a practical controller to achieve precise positioning of PAM systems in [9]. In the paper, the point-to-point motion of the PAM system was examined with a practical controller that emphasized the simplicity in the design procedure. Furthermore, a nonlinear PID control was proposed by Thanh and Kyoung for an antagonistic based PAM system [10,11]. These papers used superb mixture of conventional PID controller and the neural network, which has powerful capability of learning, adaption and tracking nonlinearity, bring to a novel controller. Besides that, classic controller is still further researched for PAM system. Sakthivelu et. al. has proposed a classic PI controller to examine the 1-DOF pneumatic muscle actuator system after a complete phenomenological modeling has been done [12,13]. The experimental dynamic model of the system agreed well with the simulation one.

II. EXPERIMENTAL SETUP

A new setup on vertical PAM system in antagonism configuration is designed and constructed. A classical controller, PID is selected as the startup controller to be applied on the system for its tracking performance. Two parts are discussed in this section, first part is started by designing and constructing the vertical PAM experiment setup, and the second part is the PID controller design.

PAM operates by means of overpressure and contract when it is pressurized. The pair of PAM arranged into antagonism structure imitate a bicep-tricep system and emphasize the analogy between this artificial muscle and human skeletal muscle as shown in Figure 1. The schematic diagram of the vertical PAM system is shown in Figure 2. The hardware includes a personal computer (i7 4GHz), which calculates the control input and controls the 5/3 proportional directional valve (FESTO MPYE-5-1/8HF-710B) and two PAM (FESTO DMSP-10-150N-RM-CM) through a data acquisition unit. The pressures in both the PAM are measured using the pressure sensors (FESTO SDE-10-10). A joint angle θ is detected by using a rotary encoder with the resolution is 3600 pulse/rev. All the signals are fed back to the computer through the data acquisition unit. Two ends of the PAM are connected to the fabricated base, while the other two ends are connected to each other through a timing belt. The timing belt is attached to a timing pulley attaching to a shaft to perform rotational motion. The experiments are conducted under a temperature of 20°C and supply pressure of 5 bar. A photograph of the experiment setup is shown in Figure 3. When air is supplied, the input voltage controls the 5/3 proportional directional valve in order to alter the amount of pressure flowing into the PAM. This causes the two PAM to expand and contract simultaneously, and hence causing the shaft connecting to the PAM to rotate in clockwise and anticlockwise directions.

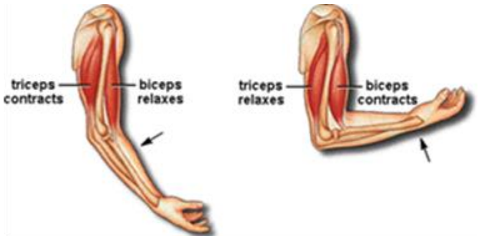

Figure 1: Working principle of human arm muscle

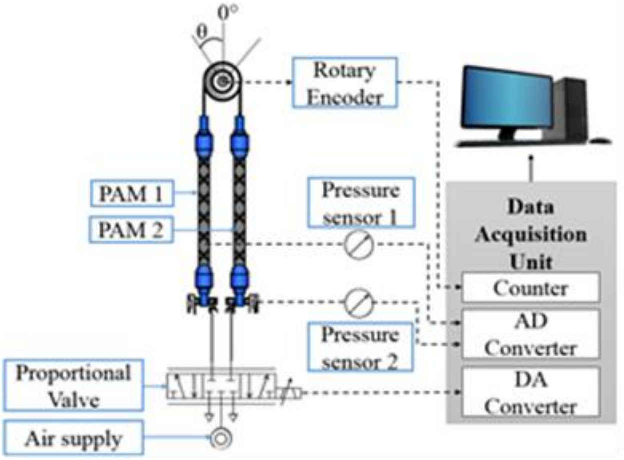

Figure 2: Schematic diagram vertical PAM system

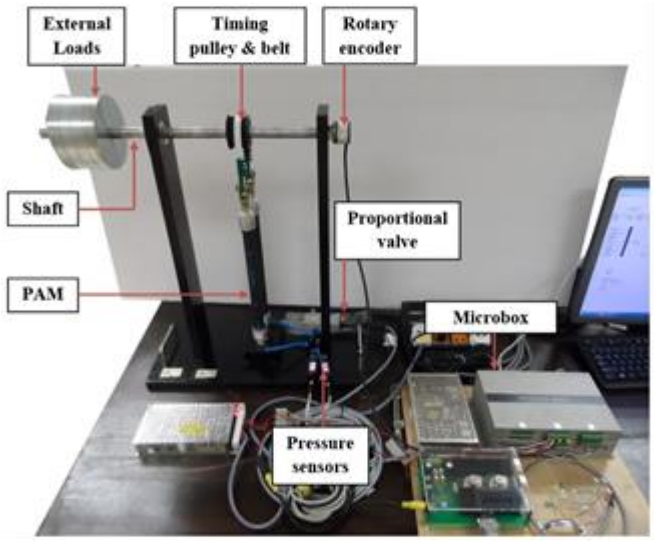

Figure 3: Photograph of the experiment setup.

III. CONTROLLER DESIGN

A classic control, PID compensator is proposed to improve the tracking performance of the vertical dual-axis PAM system. PID controller continuously calculates the error values as the difference between the output value and the desired value. The PID controller for the system is designed using Ziegler Nichols closed-loop tuning method. A performance comparison between P, PI and PID controller is done to select the best and simplest controller for the system. The value of K_c is calculated by obtaining the ultimate gain value, K_u, and the ultimate period of oscillation, P_u. It is a simple method of tuning the PID controller and can be refined to give a better approximation of the controller parameters. The controller constants K_c, T_i and T_d in the system with feedback are obtained.

The obtained gain value K_u is 40, and period of oscillation P_u is 0.6. These values are substituted into the Ziegler Nichols closed-loop equations and the approximated parameters are obtained.

The general equation for PID controller is

$$C(s) = K_c(1 + \frac{1}{T_i s} + T_d s) \quad (1)$$

By substituting the calculated parameters into Equation (1), yields

$$C_P(s) = 20 \quad (2)$$

$$C_{PI}(s) = 18 + \frac{36}{s} \quad (3)$$

$$C_{PID}(s) = 24 + \frac{80}{s} + 1.8s \quad (4)$$

$$C(s) = K_p + \frac{K_p}{s} + K_d s \quad (5)$$

The parameters are fine-tuned at point-to-point positioning experiment to achieve better results. At the step height of 20°, the positioning performance of compensator P, PI and PID are examined and compared. The fine-tuned parameters are shown in Table 1 and their performances are depicted in Figure 4. As can be seen clearly, the PID controller has demonstrated better positioning performance with small (nearly zero) overshoot and small steady-state error as compared with others. Hence, the PID controller is selected as the controller for the rest of the experiments.

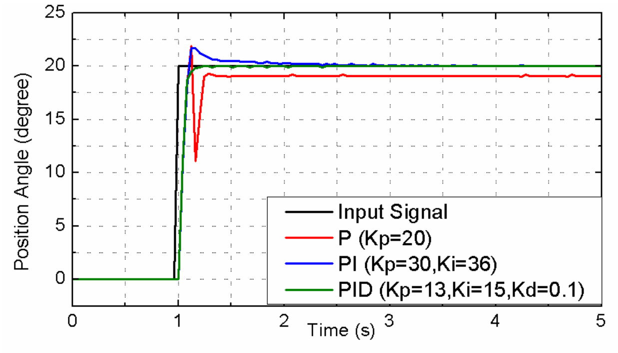

Figure 4: Closed-loop step input experiment

Table 1
Calculated and tuned PID parameters

Parameters	K_c	K_i	K_d
P	20	0	0
PI	30	36	0
PID	13	15	0.1

IV. PERFORMANCE EVALUATION

In this paper, the tracking performance of the vertical dual-axis PAM system is validated at slow velocity, with the frequency of 0.1-Hz. The experiment is carried out for 60-s, with the variation of amplitude. The working range is from 5° to 23°, which are 5°, 11°, 17° and 23° (incremental of 6°).

Figures 5 to 8 illustrate the tracking responses of PID controller for rotary amplitudes of 5°, 11°, 17° and 23°, as compared to the uncompensated performance. It is shown that the uncompensated system does not reach the desired position angle with very large errors regardless of the amplitude variation. Meanwhile the PID controller is able to overcome it and enable the system to track the desired input rotary angle with minor errors.

As can be seen in Figure 5, the maximum tracking error of PID controller is approximately 0.3°, which is 91.5% better than that of uncompensated system. At amplitude of 11° as shown in Figure 6, the tracking response for PID controller demonstrates an approximately 0.6° of maximum tracking error, which is 92.5% better than that of uncompensated system. The PID controller has succeeded to compensate the tracking error with 92.5% better than that of the uncompensated system (see Figure 7). When the rotary amplitude is increased to 23°, the PID controller has achieved high tracking with tracking error approximately 1.3°, which is 92% better than that of uncompensated system.

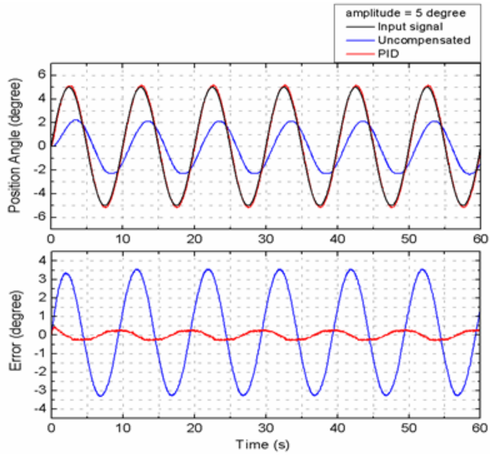

Figure 5: Experimental sinusoidal input tracking performance at amplitude of 5°

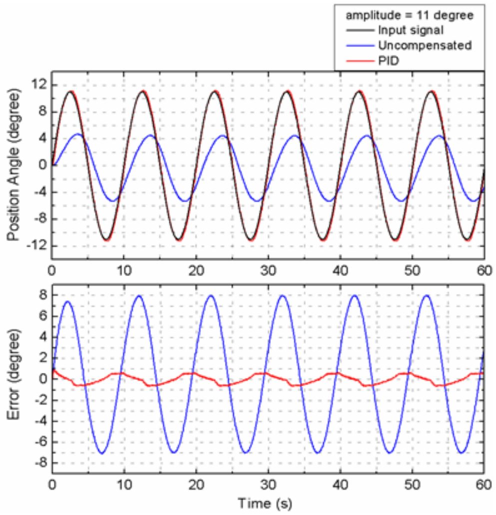

Figure 6: Experimental sinusoidal input tracking performance at amplitude of 11°

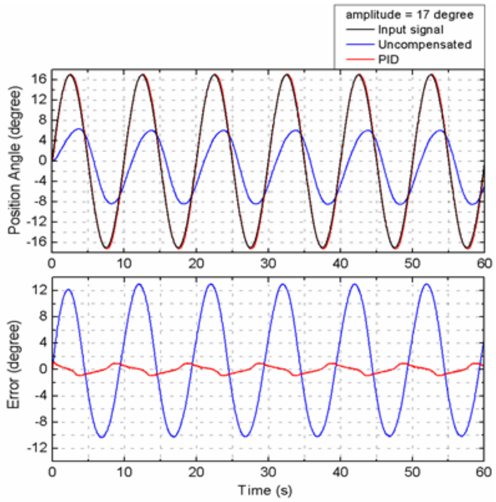

Figure 7: Experimental sinusoidal input tracking performance at amplitude of 17°

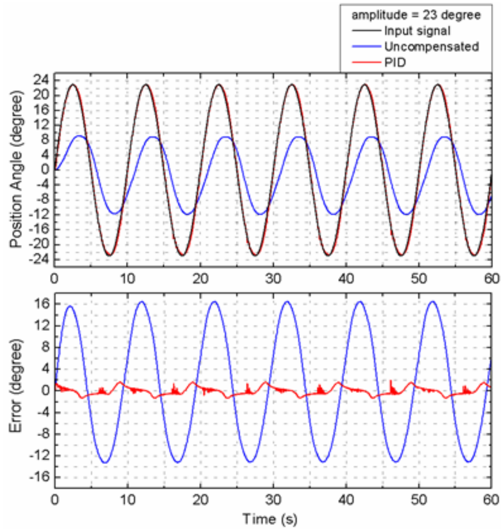

Figure 8: Experimental sinusoidal input tracking performance at amplitude of 23°

We can conclude that PID controller is capable to demonstrate high tracking performance at slow velocity (low frequency) with the small tracking errors are approximately within 1.3° for all the amplitudes applied to the system. It is clearly shown that by adding PID controller to the system, the vertical dual-axis PAM system is able to be controlled in slow velocity with minor error.

However, a fast tracking performance is always required in industrial application. Therefore, the PID controller for vertical dual-axis PAM system will be validated for fast velocity (higher frequency) as the future work. It is predicted that the PID controller is needed to be improved or a high bandwidth controller should be proposed, so that the PAM system is capable to demonstrate high tracking performance in fast velocity.

V. CONCLUSION

PID controller is designed for tracking control of a vertical dual-axis pneumatic artificial muscle system. The Ziegler Nichols closed-loop tuning method is used to determine the parameters in designing a PID controller. Then, the parameters are tuned iteratively. The experimental tracking results show that the PID controller is capable to demonstrate high tracking performance with the tracking errors 90% better than the uncompensated system regardless of the input amplitude at low frequency of 0.1Hz. The proposed control algorithm is simple and gives satisfactory trajectory tracking. PAM system has non-linear characteristics due to frictions, air compressibility of the supply input, and also the lack of damping ability of the muscle. Since PID controller has the limitation in dealing with high precision performance, a high bandwidth control strategy will be proposed to control the PAM system in tracking motion as a future work in order to perform high tracking responses in fast velocity. Besides, a proposed approach will be extended to examine the robust performance in the presence of load change to the PAM system.

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