Tracking Control Performances a Dual-Limb Robotic Arm System

S. P. Tee, M. M. Ghazaly*, P. K. Tan, S. H. Chong, A. C. Amran, M. H. Jamaluddin, M. S. M. Aras

***Abstract*— This paper discuss the tracking control performances of a dual-limb robotic arm system for precision motion and high speed response. In this paper, the focus is to fabricate & analyze the control performances of an upper dual-limb robotic arm system which are able to move in parallel motion. The experimental results are obtained through open-loop and closed-loop test. The system transfer function is evaluated experimentally via system identification method. In this paper the Proportional and Derivative (PD) controller is used to control the trajectory motion of the dual-limb robotic arm system. The PD controller with proportional gain K_p = 169 and derivative gain K_D = 1.1412 shows good performances using step input reference. To further verify the robustness of the controller, tracking control experiments are performed with rectangular & triangular input trajectory. The PD controller shows the dual-limb robotic arm system able to show good performances with the steady state error less than 0.4° for the 15° triangular input references with 0.1Hz frequency, respectively.**

***Index Term*— 1-DOF, PID controller, robotic arm, trajectory tracking control**

I. Introduction

Arobotic arm, by definition is a mimic of human arms' mechanisms that had been developed in a mechanical structure and linked by programmable joint. Manipulators that are connected with joints have allow motion in either rotational (revolute) or translational (prismatic) with a number of Degree of Freedom (DOF) [1]. In such design, robotic arms usually help in conducting activities where environment is hazardous or dangerous to human and activities that required high accuracy and repeatability. Previous research had done on the development of an upper limb robotic arm and its controller had been succeeded [2]. The research is continued by developing an upper dual-limb robotic arm and its controller for position control. A dual-limb robotic arm is able to expand its original workspace and ease operation that requires both arms.

A robotic arm model's transfer function plays a key role in developing a closed-loop controller and it differ from other robotic arm model, depending on the material used, shape, weight, and dimension of model. For approximation of system's model, system identification method is used to identify the most suitable transfer function for the specific robotic arm model. It is merely a grey box model where a few of unknown parameters can be estimated based on the experimental data from this robotic arm model. After obtaining its transfer function, a closed-loop controller is developed to control the movement of 1-DOF robotic arm. The developed controller should have the characteristics of accurate, fast response time and high robustness.

There are various methods used in controlling robotic arm. Few researches were done by using fuzzy logic control (FLC) or PID control or even combine both techniques to improve accuracy of robotic arm. Jiang et al. used FLC and PI as controller for a 9 DOF robotic arm. It found out that FLC has better performance in faster response time and small overshoot than conventional PI controller [1,2]. Besides that, hybrid of FLC and PID controller has advantages over non-fuzzy PID controller. Fuzzy PID adapts the linear structure yet non-constant gain of PID which has the capability of self-tuned in set-point tracking performance. Moreover, control-rule base and deffuzification which are embedded in the fuzzy control law which will ease the process of fuzzification without using look-up tables[3]. Although FLC has more advantages over PID controller such as faster rise time of system and proceed with leap of process of mathematical modeling which lead to easy design and implement, there is a risk on an oscillatory response during the steady-state response of the system [4]. Rosen J. et al stated that proportional derivative (PD) control is the simplest method used to control robot arm yet it has limited robotic system performance unless gravity compensation is applied. PID controller can be an alternative to PD controller where position error caused by gravitational torque can be minimized by introducing integral component to PD controller [5]. Type of controller used is depends on the nature of system. In this paper, PID controller is chose to develop due to the simplicity of tuning algorithm of PID controller and the system itself. Common actuators used in robotic arm are DC motor, servo motor and stepper motor. Won S.C. et al stated that DC motor has coulomb frictions which are the disturbance from gravitational pull and stiff spring effect. High ratio of gear train from DC motor and the linking shaft between motor and manipulator arm are the main cause of stiff spring effect which has increases the order of system by two [6]. To overcome this problem, direct drive system are able to minimize friction and backlash associated with geared drives. However, it produces torque pulsations when operating in low speeds. DSP-based instantaneous

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torque controller is developed to reduce torque pulsations greatly compare to conventional current controllers [7]. DC motors are usually used in speed control as it can supply more than 5 times rated torque. Due to the high ratio of torque to inertia, DC motors can respond to the corresponding changes of control signals. Moreover, the speed of the motor is able to control smoothly down to zero [8].

Usually, servo motor coupled with an encoder is able to sense position and a sophisticated controller is required for controlling its motion and final position. Ramakrishna V. et al stated that servo motors are excellent 'actuator' for imitating fingers, hands or leg movements in terms of resolution and reliability. However, angle of a servo motor's shaft that can turn is limited to different number of PWM pulse width from different sources of motor driver [9]. Since the payload on a robotic arm may vary at all times and a nonlinear system, it is difficult to fix the parameter of robotic arm for trajectory control. Hashimoto H. et al proposed DC servo control system which used DC motor servo system in "self-tuning" algorithm where parameters are tuned online by using recursive least square technique. The characteristic of close-loop system of DC servo motor had provided feedback position of robotic arms and improve the trajectory prediction of robotic arms [10-13]. Stepper motor is one of the actuators that can steps, forward or backward precisely without feedback sensor. It moves and holds at a single time whenever angle and position of rotor is commanded to move. Thus, it can turn in precise angle which depends on the input pulses and its intensity. However, the accuracy of motor's rotation is limited by the gear ratio of motor. In Ahmed F. et al case, the step angle is limited to 1.8º. In addition, controlling a robotic arm with stepper motor as actuator required a dedicated control system such as micro-controller. They drive the stepper motor with single coil excitation in both forward and backward direction with high torque stepping and half-stepping as shown in Figure 1 [11].

As a conclusion, this paper aims to evaluate the tracking control performances of a dual-limb robotic arm system for precision motion and high speed response, where improper motion will results in injuries or fatality and loss of production in manufacturing system. Section 2 discusses the experimental setup of the dual-limb robotic arm system. In Section 3, the analysis result based on the open-loop characteristics and the tracking control using PID controller are discussed in detail. Section 4 will conclude the summary of this paper.

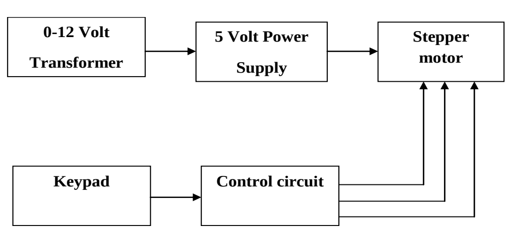

Fig. 1. Block diagram of control system for stepper motor [11]

II. Methodology

The discussion in this paper is separated into two parts: (a) obtaining open-loop system test and (b) close-loop system test. Open-loop system test is aimed to obtain transfer function of the system while close-loop system test is to test the functionality and robustness of the controller. After designing the controller of the system, it is then implemented to the system and the close-loop experiments are validated. The PID controller is tuned in order to obtain desired result. By implementing satisfied tuned PID controller, the system can be tested for real-time application. Figure 2 shows the experiment setup for conducting open-loop test of the dual-limb robotic arm.

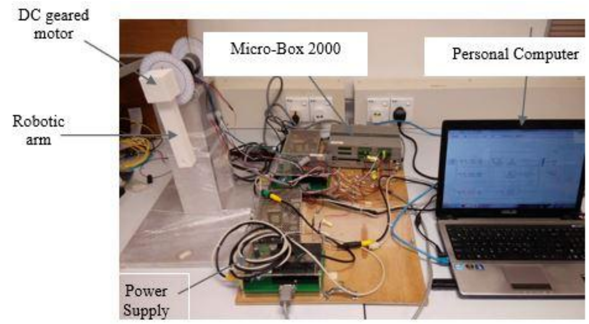

Fig. 2. Dual-limb robotic arm experimental setup

A. Open-loop Experiments

The purpose of implementing open-loop control system is to identify the relationship between reference input and output, a preparation to formulate the transfer function of the system. Figure 3 shows the block diagram for open-loop system. In this research the system identification is used to formulate the mathematical models of a dynamic system from measured input output data. The transfer function is estimated based on the physical system parameters. Thus, the approximate transfer function of system can be obtained. Figure 4 shows the process of system identification.

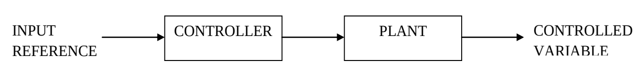

Fig. 3. Open-loop system

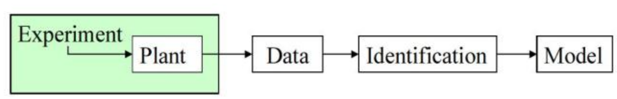

Fig. 4. System identification model

In order to evaluate the robustness of the design controller, the PID controller was applied. The feedback signal of the system enables the close-loop system to meet the desired requirement. Figure 5 shows the close-loop control system block diagram.

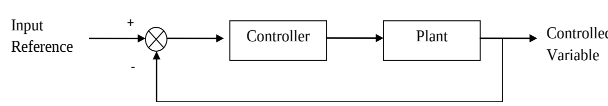

Fig. 5. Close-loop control system

B. Close-loop Experiments

The aim of this experiment is to verify robustness and compatibility of designed controller. The output of the system determines the suitability of designed controller in the system. In this part, point to point trajectory (PTP) and triangular trajectory are chose as trajectory tracking control. For PTP trajectory, the signal amplitude is set at 15º whereas for triangular trajectory, the signal amplitude is set at 15º and 30º with frequency of 0.1Hz and 1Hz. For the tuning process, Zieglar-Nichols tuning method is used for approximation tuning value. Then, it is completed by manual tuning for optimizing output as desired input. Zieglar-Nichols tuning method is a heuristic method of tuning a PID controller. It is done by settling *I* (Integral) and *D* (Derivative) gains to zero while increase *P* (proportional) gains until it reaches ultimate gain, K_u where the output of the control loop has stable and consistent oscillation. The period of the oscillation is known as T_u. Table I shows the evaluation of each gains of PID controller.

TABLE I
GAINS FOR PID CONTROLLER USING ZIEGLER-NICHOLS METHOD

Control Type	K_p	T_i	T_d
P	$0.5K_u$	-	-
PI	$0.45\ K_u$	$T_u/1.2$	-
PD	$0.8\ K_u$	-	$T_u/8$
PID	$0.6\ K_u$	$T_u/2$	$T_u/8$

III. Results and Discussions

Open-loop experiments are carried out to determine the relationship between input voltage and angle of rotation. From Figure 6, it shows that the input voltage is proportional to angle of rotation. In other words, the higher the input voltage, the higher the torque and angular speed produced. For open-loop test, the input voltage signal is set as square wave function signal with pulse width of 50% where the rotation of DC motor will stop in a period of time as shown in Figure 7. It is to investigate the accuracy of encoder by comparing the data shown in simulation and actual angle rotated by the robotic arm. Figure 6 shows that the angle of rotation increase proportionally with input voltage until it reaches input voltage of 8V which reaches maximum angular speed of the DC geared motor.

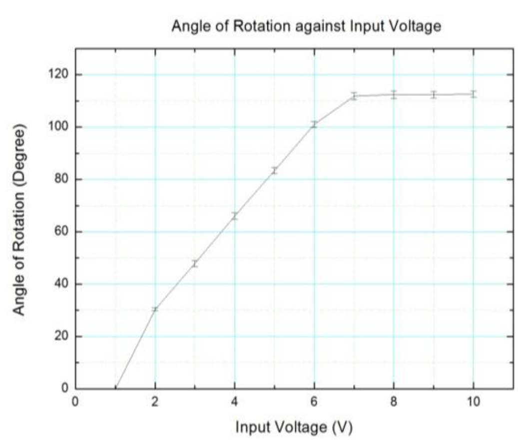

Fig. 6. Relationship between angle of rotation against input voltage and its standard deviation

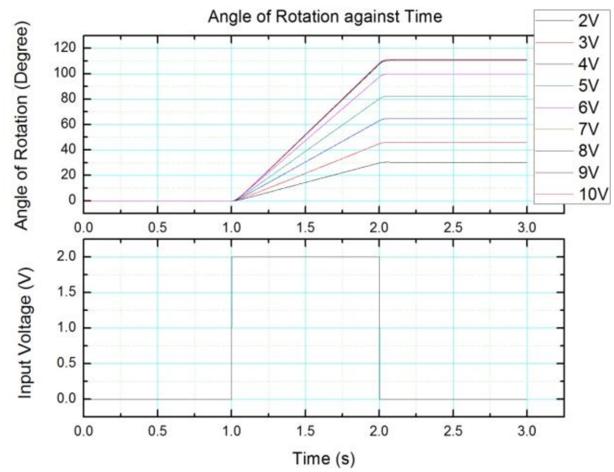

Fig. 7. Relationship of angle of rotation against time with different input voltage

System Identification Tool is used to generate mathematical formulae for each corresponding input and output data. Each mathematical formula, also known as transfer function is simulated with similar input voltage, ranging from 1V until 10V. The comparison of experimental result and simulation result will determine the most suitable transfer function for robotic arm system. Second order transfer function is chose as transfer function for the system as shown in (1).

$$\mathrm{TF} = \frac{\mathrm{As+B}}{\mathrm{Cs^2+Ds+E}} \quad (1)$$

Simulated of input voltage representative transfer function that has the lowest error is selected as transfer function for the system. Figure 8 shows the representative transfer function of input voltage 2V has smallest and acceptable error. Thus, the selected transfer functions for this system shown in (2).

$$\mathrm{TF} = \frac{-7.94s+1698}{s^2+113.1s-1.331} \quad (2)$$

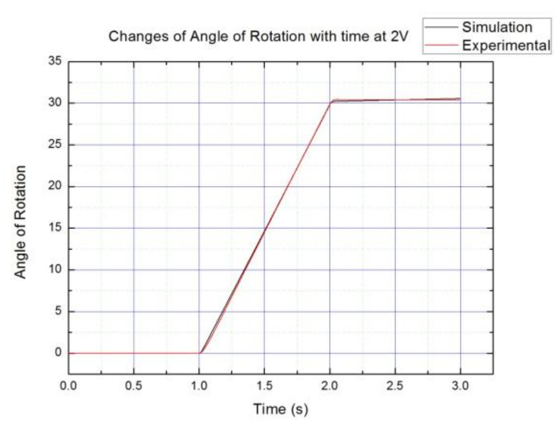

Fig. 8. Comparison of experimental and simulation result at 2V

Then, the close-loop uncompensated system is proceed with input PTP trajectory of 15°, 30°, 45° and 60° as shown in Figure 9 until Figure 12. It is to determine the error between both output data (experimental and simulation) and desired input. Before designing PID controller, error between desired input and experimental result is determined in order to clarify the parameters that should be improved in the system. Figure 9 until Figure 12 show that the steady-state error is ranging from 5° to 7° and has high rise time and settling time.

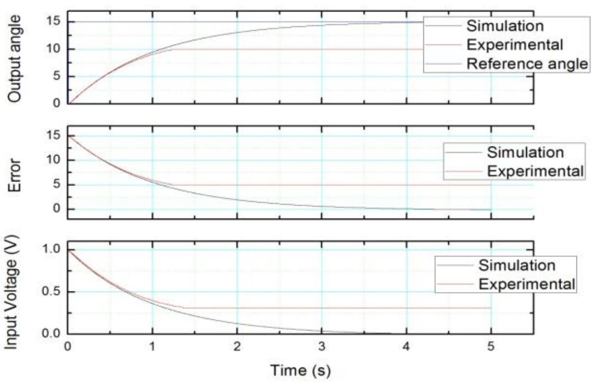

Fig. 9. Comparisons of output data with reference angle (15°)

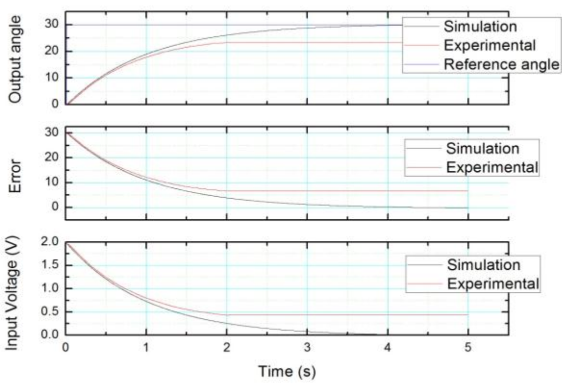

Fig. 10. Comparisons of Output Data with Reference Angle (30°)

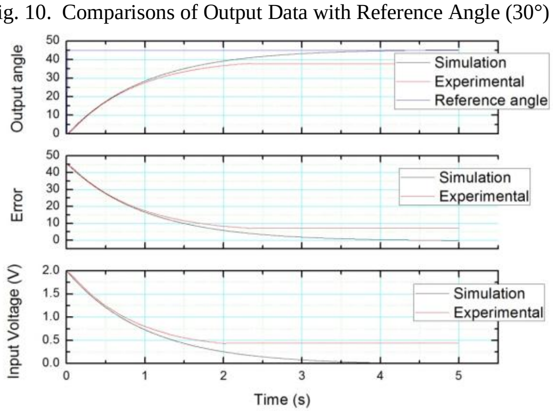

Fig. 11. Comparisons of output data with reference angle (45°)

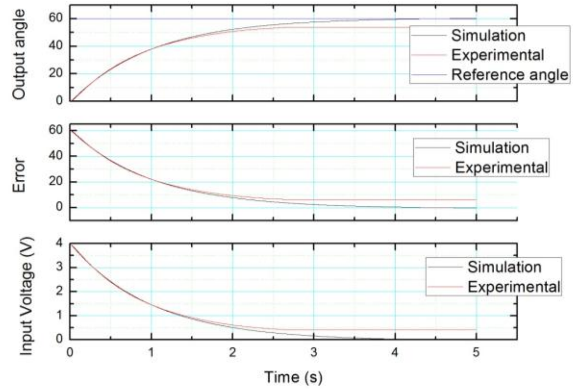

Fig. 12. Comparisons of output data with reference angle (60°)

After analyzing the system performance of close-loop uncompensated system, a PID controller is designed by using Zieglar-Nichols method. As the ultimate gain, $\boldsymbol{K_u}$ for the system is varies with different input angle, only the smallest ultimate gain is used to design PID controller. As a result, the input angle 15º shows the smallest ultimate gain, K_u = 356 and oscillation period T_u = 0.042s. By substituting these data into Table 1, the gains for K_p, K_I, and K_D can be obtained. Since Zieglar-Nichols method is an approximation method, it is then fine-tuned to optimize the system performance based on Table II.

TABLE II
EFFECT OF TUNING EACH GAIN TO THE SYSTEM PERFORMANCE

Parameter	Rise Time	Settling Time	Overshoot	Steady-state Error
K_p	Decrease	Small Change	Increase	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Minor Change	Decrease	Decrease	Decrease

After fine tuning of PID controller, PD controller is performed with best system performance among P controller and PI controller as shown in Figure 13 and Table III. As a conclusion, the PD controller gain used for the dual-limb robotic arm system is K_p = 169 and K_D = 1.1412.

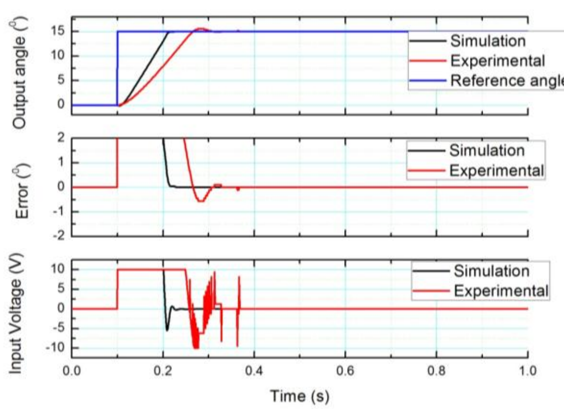

Fig. 13. System response after PD controller is applied. (K_p = 169 and K_D = 1.1412)

TABLE III
SYSTEM PERFORMACES AFTER APPLICATION OF PD CONTROLLER

Type of Controller	Rise Time	Settling Time	%OS	Steady-state Error
PD (Experimental)	0.12	0.21	3.73	0
PD (Simulation)	0.08	0.15	0.10	0

In order to verify the robustness of the PD controller and its suitability, trajectory tracking reference input is applied; i.e. triangular trajectory of amplitude 15^o and 30^o with frequency 0.1Hz and 1Hz, respectively. Figure 14 and Figure 15 shows tracking control with amplitude 15^o of triangular trajectory while Figure 16 and Figure 17 shows tracking control with amplitude 30^o of triangular trajectory. Based on the trajectory tracking control result, the movement of robotic arm can tracks and follows the input trajectory with acceptable error as shown in Table IV.

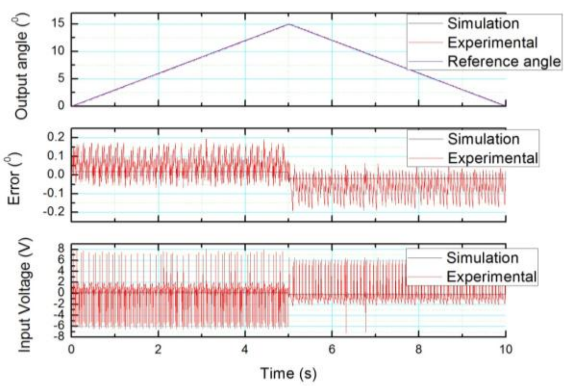

Fig. 14. Tracking control of triangular trajectory with amplitude 15^o and 0.1Hz

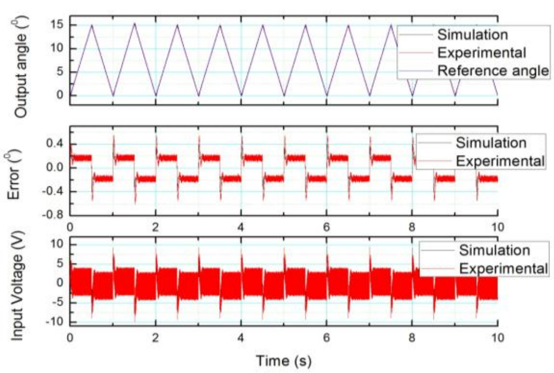

Fig. 15. Tracking control of triangular trajectory with amplitude 15^o and 1Hz

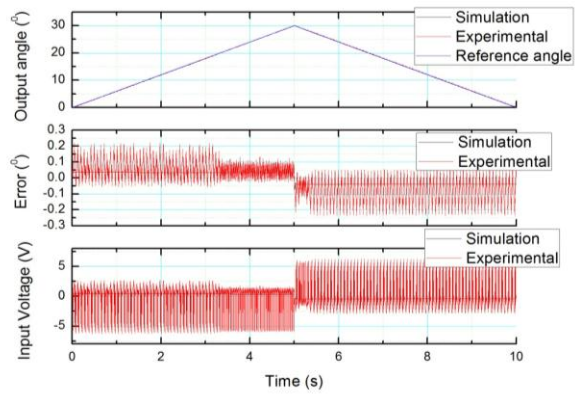

Fig. 16. Tracking control of triangular trajectory with amplitude 30^o and 0.1Hz

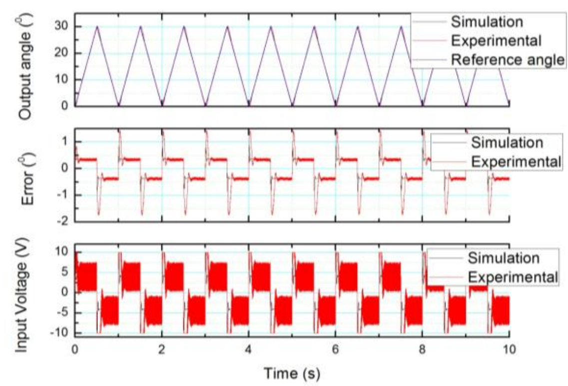

Fig. 17. Tracking control of triangular trajectory with amplitude 30^o and 1Hz

TABLE IV
SYSTEM PERFORMANCE FOR TRAJECTORY TRACKING CONTROL

Amplitude	Frequency	Error
15	0.1	0.4
	1.0	1.1
30	0.1	0.5
	1.0	3.0

IV. CONCLUSION

This paper presents the tracking control performances of a dual-limb robotic arm system for precision motion and high speed response using PD controller. The relationship between the input voltage and the output angle rotation is verified proportional. The linearity of DC geared motor with input voltage is verified. System identification method is an alternative method of mathematical modeling. It is useful in estimating transfer function of system which can be a reference system for developing a PID controller for the system. The selected transfer function is a second order transfer function as shown in (2). From the analyzed result, PD controller is suitable to control the robotic arm system with proportional gain, $K_p = 169$ and derivative gain $K_D = 1.1412$. The PD controller had greatly improved system performance and the robotic arms are working as desired.

Trajectory tracking control is used to verify the robustness of PD controller. As conclusion, the robotic arm able to track and follow the input trajectory with 10% error. For future work, the recommendation is to apply other types of controllers to improve the controller accuracy. In addition, higher DOF of robotic arm is recommended to increase the flexibility and application of the robotic arm.

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REFERENCES

[1] X. Jiang, C. Xiong, R. Sun, and Y. Xiong, "Fuzzy Hybrid Force-Position Control for the Robotic Arm of an Upper Limb Rehabilitation Robot Powered by Pneumatic Muscles," *2010 Int. Conf. E-Product E-Service E-Entertainment*, pp. 1–4, 2010.

[2] M. M. Ghazaly**,** T. H. Teo, V. Regeev, K. Vijayan, S. H. Chong, A. C. Amran, Z. Abdullah, M. A. M. Ali, "Point-To-Point (PTP) Control Performances of an Upper Limb Robotic Arm", *Jurnal Teknologi*, vol. 78 (10), 2016.

[3] H. A. Malki, D. Misir, D. Feigenspan, and G. Chen, "Fuzzy PID control of a flexible-joint robot arm with uncertainties from time-varying loads," *IEEE Trans. Control Syst. Technol.*, vol. 5, no. 3, pp. 371–378, 1997.

[4] R. Ketata and J. Ibafiez-Guzman," A Robotic Test-rig for the experimentation with Fuzzy Logic Controllers", 21-24 March 1994 Conference Publication No. 389.

[5] W. Yu and J. Rosen, "A Novel Linear PID Controller for an Upper Limb Exoskeleton," pp. 3548–3553, 2010.

[6] C. Won and I. City, "DC Motor Driven Robotic Manipulator Control", 24th Conference, "Wp1 2:30," pp. 2–5, December 1985.

[7] K. J. Tseng, "DSP-based control of brushless DC drives for direct-driven robotic arms," *Microprocess. Microsyst.*, vol. 19, no. 10, pp. 581–589, 1995.

[8] E. Kayacan, O. Kaynak, R. Abiyev, J. Torresen, M. Hovin, and K. Glette, "Design of an adaptive interval type-2 fuzzy logic controller for the position control of a servo system with an intelligent sensor," *Int. Conf. Fuzzy Syst.*, pp. 1–8, 2010.

[9] V. Ramakrishnan, N. S. Gopal, R. Ashok, and S. Moorthi, "FPGA based DC servo motor control for remote replication of movements of a surgical arm," *Tencon 2011 2011 IEEE Reg. 10 Conf.*, pp. 671–675, 2011.

[10] H. Hashimoto, O. Kaynak, H. Kuroyanagi, Y. Deguchi, and F. Harashima, "Prediction based DC servo control system in robotic arm," *[Proceedings] IECON '90 16th Annu. Conf. IEEE Ind. Electron. Soc.*, vol. 110, pp. 294–299 vol.1, 1990.

[11] F. Ahmed, M. A. Safiullah, S. H. Khan, A. Moinuddin, and A. M. Farhan, "Assembly of Robotic Arm Based on Inverse Kinematics Using Stepper Motor," *2012 Sixth UKSim/AMSS Eur. Symp. Comput. Model. Simul.*, pp. 285–290, 2012.

[12] M. F. Rahmat, M. M. Ghazaly, "Performance comparison between PID and fuzzy logic controller in position control system of dc servomotor," *Jurnal Teknologi*, vol. 45, pp. 1-17, 2006.

[13] M. M Ghazaly and K. Sato, "Characteristic switching of a multilayer thin electrostatic actuator by a driving signal for an ultra-precision motion stage," *Precision Engineering*, vol. 37, no. 1, pp. 107–116, 2013.