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POINT-TO-POINT (PTP) CONTROL PERFORMANCES OF AN UPPER LIMB ROBOTIC ARM

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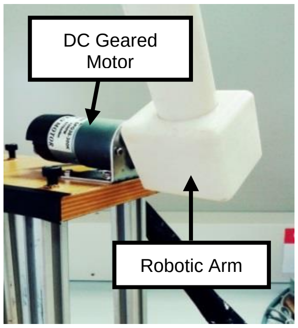
Graphical abstract



Abstract

The objective of this paper is to design a controller which is able to control the output angle for an upper limb of a robotic arm, for precision motion and high speed response. The aim is to optimize the best controller for an upper limb robotic arm system for precision motion, in which improper motion will results in injuries/ fatality and loss of production in manufacturing system. In this research, a robotic arm prototype with a 1 degree-of-freedom (DOF) was designed and fabricated, in which the DC geared motor was implemented. Studies are carried out based on previous research to investigate the suitable type of controller. PID controller and fuzzy logic controller are chosen and compared in terms of their performances such as the steady-state error, settling time, rise time and overshoot. The equipment's used are Micro-Box 2000/2000C, Cytron DC geared motor, motor driver circuit. Micro-Box module acts as the interface between hardware component and MATLAB R2009a. Open-loop simulations are carried out to obtain the transfer function of the motor and substituted into the system for further simulation analysis. Simulation for the uncompensated system is carried out to observe the close-loop system characteristic without the controller. After that, the close-loop point-to-point (PTP) trajectory control for simulations & experiments are carried out for the compensated systems using PID controller based on the Ziegler-Nichols frequency response method. Analyses are made based on the results obtained and the best type of controller is chosen for achieving precise motion control for the upper limb robotic arm. In this paper, the PID controller shows better performances compared to the Fuzzy Logic controller (FLC) with the steady state error of less than 0.01^0 and settling time of 0.5s; for the input reference of 15^0 respectively.

Keywords: Precision motion control, upper limb, robotic arm

Abstrak

Objektif kajian ini adalah untuk merekabentuk pengawal yang mampu untuk mengawal sudut output dengan lengan robot. Model lengan robot dengan darjah kebebasan 1 darjah telah direka dan bangunkan. Perbandingan antara beberapa jenis motor dijalankan dan DC motor dipilih sebagai motor yang akan digunakan dalam kajian ini. Kajian dijalankan berdasarkan kajian sebelumnya bagi menyiasat jenis pengawal yang sesuai. Pengawal PID dan pengawal logik kabur dipilih dan dibandingkan dari segi prestasi seperti ralat keadaan mantap, menetap masa, masa naik dan masa terlajak. Peralatan yang digunakan adalah micro-Box 2000 / 2000C, Cytron DC motor dan litar pemacu motor. Modul Micro-Box bertindak sebagai antara muka di antara komponen perkakasan dan MATLAB R2009a. Simulasi gelung buka dijalankan untuk mendapatkan rangkap pindah motor dan digantikan ke dalam sistem untuk analisis simulasi selanjutnya. Simulasi untuk melihat ciri-ciri sistem gelung-tertutup tanpa pengawal dijalankan. Selepas itu, penutupan gelung titik-ke-titik (PTP) kawalan trajektori menggunakan simulasi & eksperimen dijalankan menggunakan pengawal PID berdasarkan kaedah Ziegler-Nichols. Analisis dibuat berdasarkan keputusan yang diperolehi dan pengawal terbaik dipilih untuk mencapai kawalan pergerakan yang tepat dengan lengan robot. Dalam kajian ini, pengawal PID menunjukkan keputusan yang lebih baik dalam berbanding pengawal Logik Fuzzy (FLC) dengan ralat keadaan mantap kurang daripada 0.01^0 dalam masa 0.5s; untuk rujukan input, 15^0.

Kata kunci: Kawalan gerakan jitu, anggota badan atas , lengan robot

1.0 INTRODUCTION

For accurate servo-positioning of mechanical actuators in realistic engineering systems, high precision motion is required to achieve both high speed and high torque. Once an adequate control loop is designed, the system basically has the ability to achieve the required precise positioning as the errors between the reference and the controlled variables because of fluctuations or disturbances can be discovered and minimized correspondingly [1]. Robotic arm requires precise motion controls which enable it to determine the exact trajectory and the torque needed to achieve a targeted outcome. Currently in robotic assembly cell for small production, there are still some limitations for robots arms. For example, they cannot work efficiently in complicated environments without knowing any environmental information. They often rely on an external sensor system to help with the assembly work [2]. Also, improper motion control results in injuries or fatality. Thus, it is important to improve the capability of robotic manipulator. Table 1 shows the classification and characteristics of robotic arms.

With improved motion control, the robotic arm can be used in wider range applications and with increase efficiency. For example, it can be used in semiconductor industry in which a precise motion is required. The problem faced is in deciding and designing an appropriate controller to control the output angle of the upper limb of robotic arm correspondingly. For actuation, motors are commonly used as a mean of controlling the robotic arm. Motor selection and mechanical design is a crucial part in the process of designing motion control system [2, 3].

Table 1 Classification and characteristics of robotic arms

Type	Number of Joint	Characteristic
Rectangular Coordinate Robot	2 prismatic joints	Principal axes of control are linear
Spherical Coordinate Robot	1 prismatic joint & 2 revolute joints	Allow full rotation throughout a spherical range
Cylindrical Coordinate Robot	2 prismatic joints & 1 revolute joint	Operate on a cylindrical axis
SCARA Robot	2 parallel revolute joints & 1 additional prismatic joint	For pick-and-place work
Cartesian/ Gantry Robot	3 cylinder joints	Coincident with the standard X-Y-Z Cartesian axis
Articulated Robotic Arm	All revolute joints	Used for complex assembly operations

Table 2 shows the comparison between several types of motors in terms of their advantages and disadvantages [1-6]. Actuation of the robotic arm requires high torque, relatively moderate speed and to achieve accurate positioning. After comparing these motors with each other, brushless DC motor is chosen to be used in this paper due to its excellent torque performance and the least disadvantages.

For the implementation of this paper, the aim is to optimize the best controller for the upper limb robotic arm system for precision motion, where improper motion will results in injuries or fatality and loss of production in manufacturing system. The PID controller and fuzzy logic controller are chosen to be compared in terms of their performance such as steady-state error and settling time [7 –10]. This is to verify that the advanced technique might achieve more precise motion control as compared to conventional control technique for the robotic arm.

Table 2 Comparison between different types of motors [1–6]

Type	Advantages	Disadvantages	Applications
Stepper Motor	✓ Inexpensive ✓ No feedback is required ✓ Good low-end torque ✓ Clean rooms	× Noisy and resonant × Rough performance at low speeds × Poor high-speed torque × Not for hot environments × Not for variable loads	Positioning, micro-movement
Brushed DC Servo Motor	✓ Inexpensive ✓ Moderate speed ✓ Good high-end torque ✓ Simple drives	× Maintenance required × No clean rooms × Brush sparking causes EMI and danger in explosive environments	Velocity control, high-speed position control
Brushless DC Motor	✓ Excellent torque at low speed ✓ Don't need complex power supply ✓ Low maintenance ✓ High efficiency ✓ Long lifespan	× High initial cost	Position control
Brushless Servo Motor	✓ Maintenance free ✓ Long lifetime ✓ No sparking ✓ High speeds ✓ Clean rooms ✓ Quiet	× Expensive × Complicated drives × Require tuning of control loop parameters	Robotics, pick-and-place, high-torque applications

2.0 EXPERIMENTAL SETUP & SYSTEM OVERVIEW

In this section, the research setup & procedures during research are discussed. The experimental setup of the position control system is presented in Figure 1, which consists of the xPC Target Machine (Micro-Box 2000/2000C), the robotic hand upper limb and the DC geared motor with encoder.

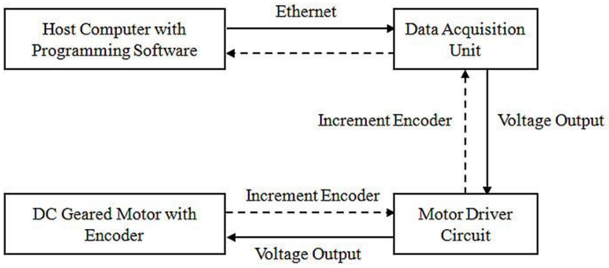
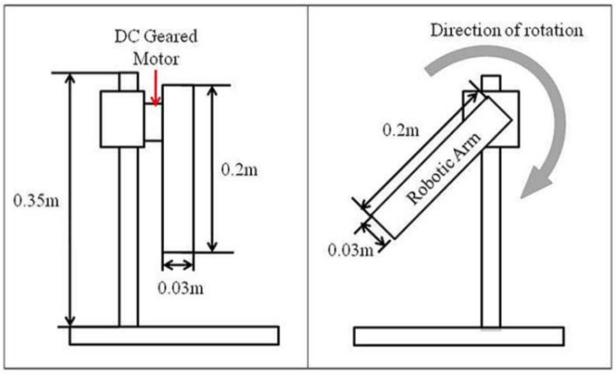


Figure 1 System concept of the upper limb robotic arm system

The objective of this research is to control the output angle of the robotic arm via the Cytron 12V DC geared motor as shown in Figure 2.



(a) Side view (b) Front view

Figure 2 The structure of upper limb robotic arm

Figure 3 shows the DC geared motor with the encoder that was used in this research. The robotic arm is connected to the Micro-box, where the Micro-box module acts as the interface between the hardware and the host computer. Figure 4 shows the components of the Micro-Box 2000/2000C module. The Micro-box also acts as a data acquisition unit, which obtains data from the host computer and transfers the information as voltage output to the motor driver circuit. The driver circuit will then actuate the motion of the robotic arm as shown in Figure 2.

Figure 3 DC geared motor with encoder and its removable cover [9]

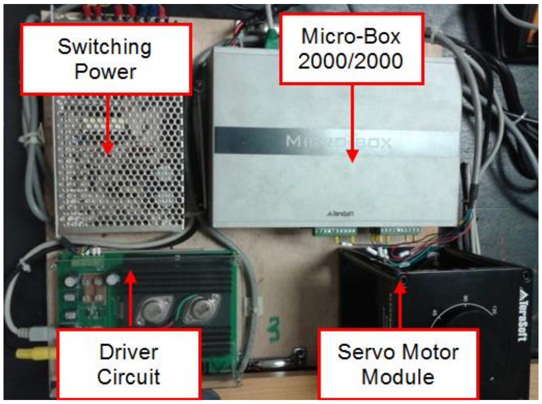


Figure 4 Components of Micro-Box module. Micro-Box 2000/2000C (xPC Target Machine)

3.0 OPEN-LOOP CONTROL & SYSTEM IDENTIFICATION

The purpose of open-loop control is to study the dynamic system behavior. In this paper, the open-loop experiments are done in order to characterize the upper limb robotic arm system by obtaining the system transfer functions. The System Identification MATLAB toolbox is used to obtain the system transfer functions by evaluating the input and output data. Further analyses are done using the system transfer function; i.e verification of the open-loop characteristics & the close-loop performances with the experimental results. The simplified transfer function of the motor is a second order transfer function as shown in Eq(1).

$$G(s) = \frac{As + B}{Cs^2 + Ds + E} \tag{1}$$

The System Identification experiments were carried out in an open-loop condition using the System Identification MATLAB toolbox. The procedures were repeated 10 times for repeatability. The parameter value closest to the mean value with the smallest standard deviation was chosen as the transfer function of robotic arm system. Figure 5 shows the block diagram of the open-loop block diagram.

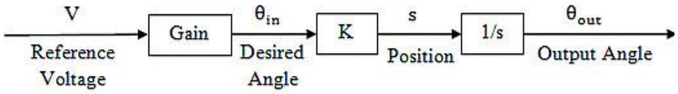


Figure 5 Block diagram of the open-loop system.

The open-loop control was carried out to observe the system characteristics. The sampling time was set to 1ms. In addition, a delay of 0.1 second was set to enable a clearer view of the input and output signals. The input voltage was varied, ranging from 1V to 5V. The output data were obtained in angle (°0). Table 3 shows the parameters and each of their numerical values set for the open-loop tests.

Table 3 Parameters of the open loop simulation

Parameter	Numerical Value
Input Voltage	1 ~ 5Volt
Simulation time	1s
Delay	0.1s
Sampling time	1ms
Input type	Step input

Figure 6 shows the method used to determine the output angle, which is compared with the data from Microbox. The card board is used as inspection method, to confirm the rotation angle manually.

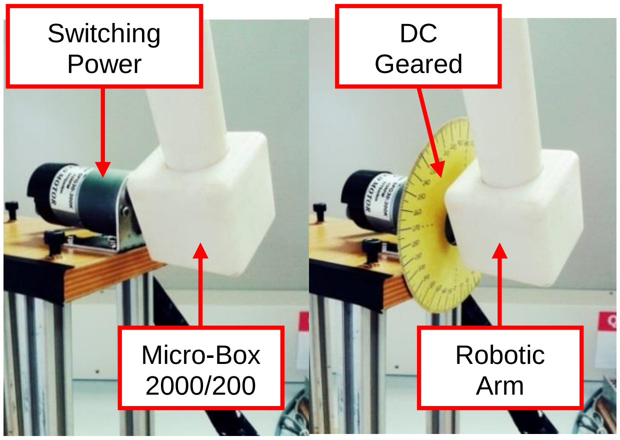


Figure 6 The experimental setup of the robotic arm (a) before the card board is attached and (b) after the card board is attached

Several input voltages, from 1V to 5V are applied to the system. The purpose of varying the voltage is to observe the difference between the simulation value and experimental value. Table 4 shows the results of system identification for robotic arm system, when the input voltage is set at 5V, with 10 times repeatability. Figure 7 shows the graphs of input voltage and output angle for 5V, when the system transfer function is set to $G_5(s)$. It can be depicted that the maximum output angle achieved is about 75° when 5 volts is applied to the system, and that the simulation and experiment results show similar response. From Table 4, the third experimental values were chosen as the transfer function for the system as it has the smallest standard deviation. Therefore, based on the results shown in Figure 7, Eq. (2) was selected as the transfer function of the robotic arm system by substituting parameters A to E of Table 4 into Eq. (1). The transfer function $G_5(s)$ will be used in further analysis for evaluating the PTP control performances in Section 4.0.

$$G_5(s) = \frac{-0.06382s + 15.37}{s^2 + 53.39s + 0.3334} \tag{2}$$

Table 4 Results of system identification for DC motor (V_{in} = 5V)

Repeatability	A	B	C	D	E
1	-0.088	19.58	1	72.25	-1.037
2	-0.056	14.14	1	51.85	-0.608
3	***-0.063***	***15.37***	***1***	***53.39***	***0.333***
4	-0.070	17.95	1	64.09	-0.331
5	-0.086	18.16	1	66.49	-0.925
6	-0.053	13.95	1	50.02	-0.285
7	-0.059	14.69	1	51.21	0.304
8	-0.078	18.11	1	63.55	0.131
9	-0.068	17.23	1	62.21	-0.614
10	-0.027	12.72	1	45.32	-0.075
Mean	-0.065	16.19	1	58.038	-0.311
Std. Dev	0.018	2.295	0	8.758	0.486

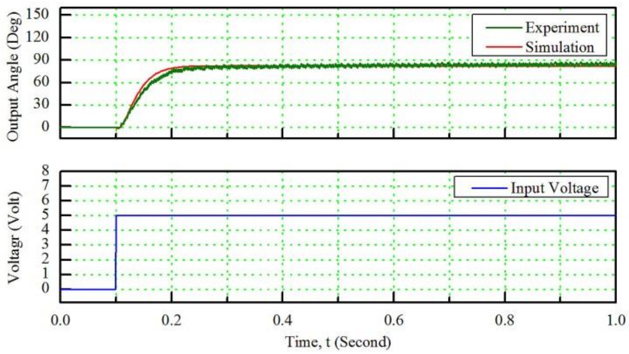


Figure 7 Graph of input voltage (5V) and output angle against time

4.0 CLOSE-LOOP CONTROL

In this paper, the output angle of the motor is the parameter that needs to be controlled, namely the point-to-point (PTP) control. Thus, the controller must be able to achieve small steady-state error and fast response. Initially the uncompensated closed-loop experiments were carried out with different input angles; i.e.: 15°, 30° and 60° respectively. After that, the PID controller and fuzzy logic controller were implemented to observe the changes in the system for the same batch of input angles. In this section, the closed-loop uncompensated system was designed where the reference input is a step input waveform, namely as the point-to-point control.

4.1 Uncompensated System

Table 5 shows the parameters being fixed and also varied in this uncompensated system. Figures 8 and 9 show the results of point-to-point trajectory control for input angles of 15° and 30°.

Table 5 Parameter for point-to-point trajectory control experiments

Parameter	Numerical Value
Input Angle	15°, 30°
Simulation Time	1s
Delay	0.1s
Sampling Time	1ms
Input Type	Step Input
Controller	None

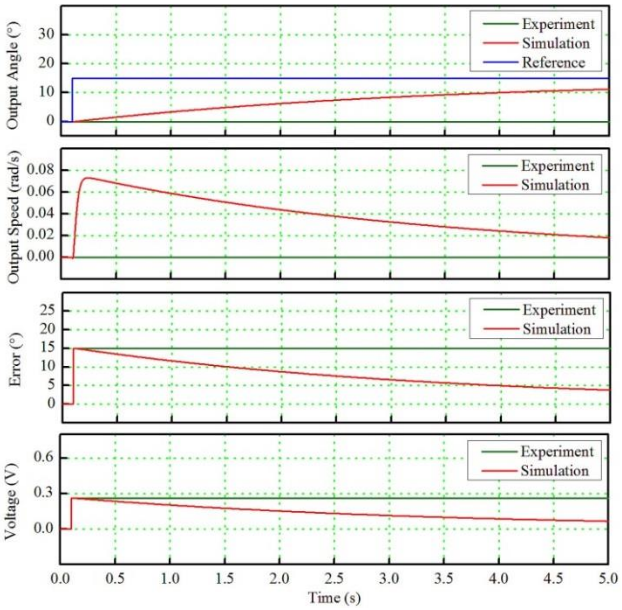


Figure 8 Results of point to point trajectory control for an uncompensated system with input angle of 15°

From both figures, the experimental signal shows that the robotic hand does not exhibit any motion (almost 0^0). This is due to large friction at the motor shaft. When the input angle increased from 15° to 30°, the robotic arm was still in stationary position. In short, the uncompensated system in this experiment did not produce satisfactory results as the output signals did not follow the input signals, where large errors were found in both cases.

4.2 Compensated System Using PID Controller

This section explains the system being implemented with PID controller based on the Ziegler-Nichols frequency response method. The experiments were conducted to test the capability of the robot manipulator as well as to control its motion precisely using PID controller. To determine the suitable Kp value, simulation was run with Ki & Kd set to zero value. The gain was increased slowly until the system started to oscillate. Table 6 shows the parameters being fixed and also varied in this compensated system with PID controller. Figures 10 and 11 show the results of simulation with a constant input angle of 15° and varying Kp values to; Kp=1 and Kp = 14.6.

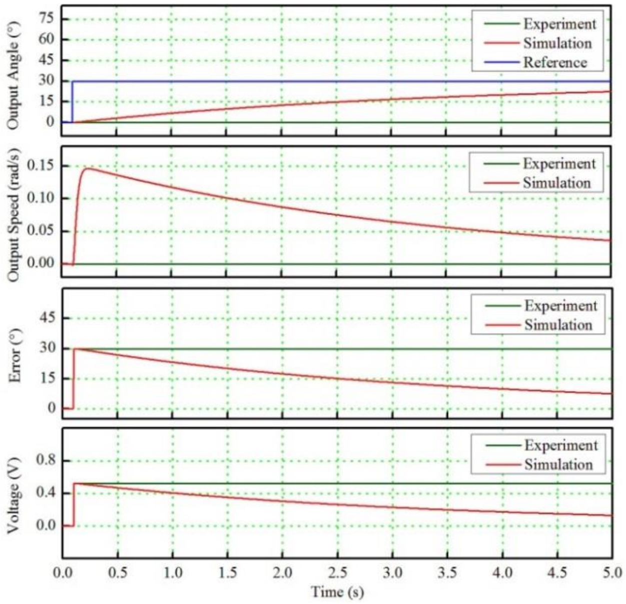


Figure 9 Results of point to point trajectory control for an uncompensated system with input angle of 30°

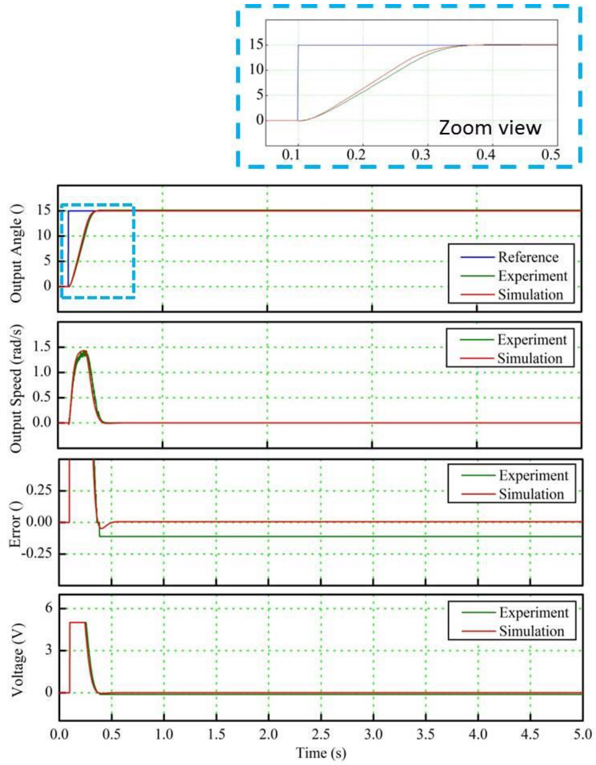


Figure 10 Results of point to point trajectory control experiment for a PID control system with input angle of 15° and Kp value of 1 (Ki = 0, Kd = 0)

Table 6 Parameter for point-to-point experiments using PID controller

Parameter	Numerical Value
Input Angle	15°, 30°, 60°
Simulation Time	5s
Delay	0.1s
Sampling Time	1ms
Input Type	Step Input
Controller	PID Controller

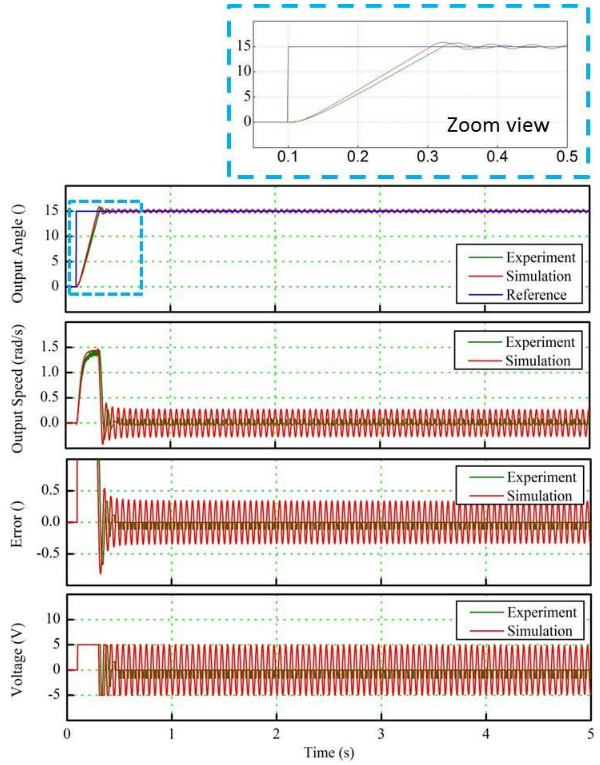


Figure 11 Results of point to point trajectory control experiment for a PID control system with input angle of 15° and Kp value of 14.6 (Ki = 0, Kd = 0)

Figures 12 and 13 show the results of simulation with a constant input angle of 30° and varying Kp values. From Figure 13, it can be depicted that when the system started to oscillate, the value of Kp is increased continuously until Kp = 14. Furthermore, the oscillation of system increased too. When the Kp value in increased to 14.6, the system reached complete oscillation. Figures 14 to 15 show the results of simulation with a constant input angle of 60° and varying Kp values. The results are similar to the previous experiments. When the Kp value increased to 14.6 as in Figure 15, the system reached complete oscillation.

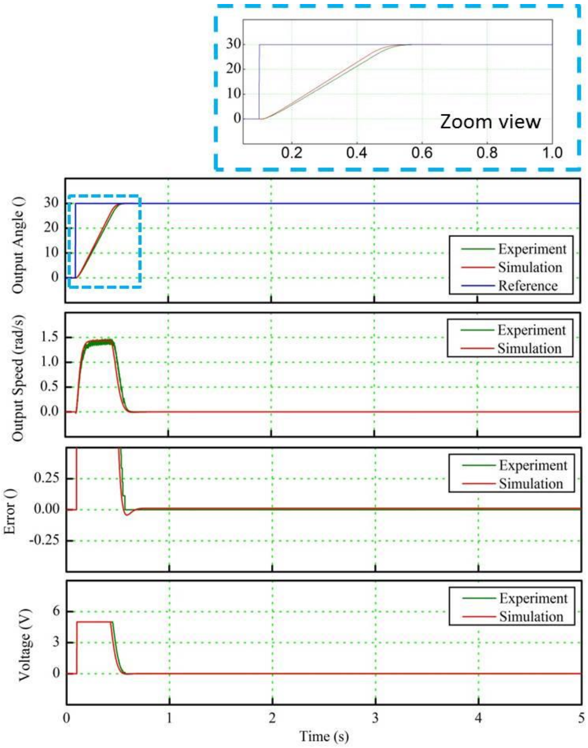


Figure 12 Results of point to point trajectory control experiment for a PID control system with input angle of 30° and Kp value of 1 (Ki = 0, Kd = 0)

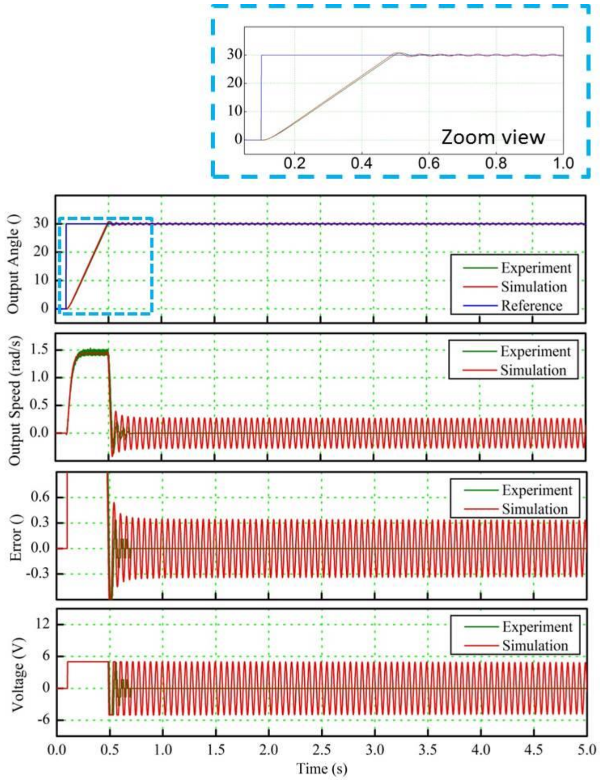


Figure 13 Results of point to point trajectory control experiment for a PID control system with input angle of 30° and Kp value of 14.6 (Ki = 0, Kd = 0)

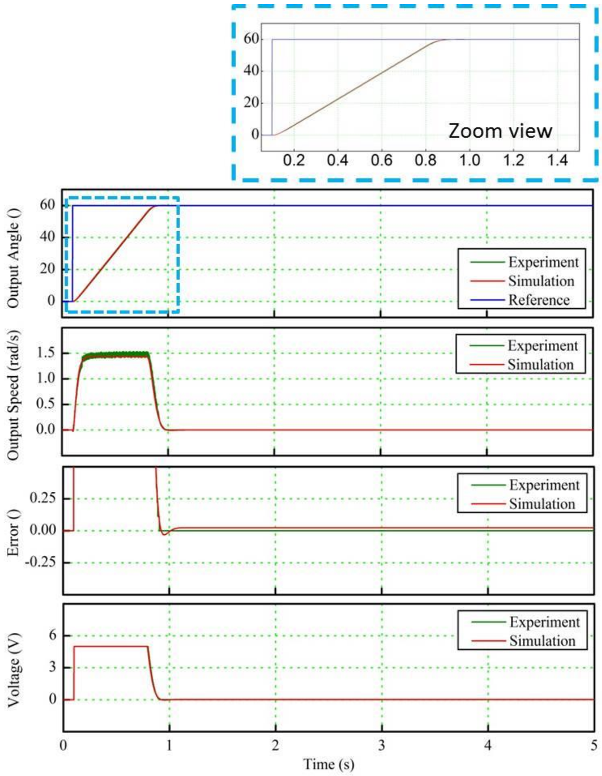


Figure 14 Results of point to point trajectory control experiment for a PID control system with input angle of 60° and Kp value of 1 (Ki = 0, Kd = 0)

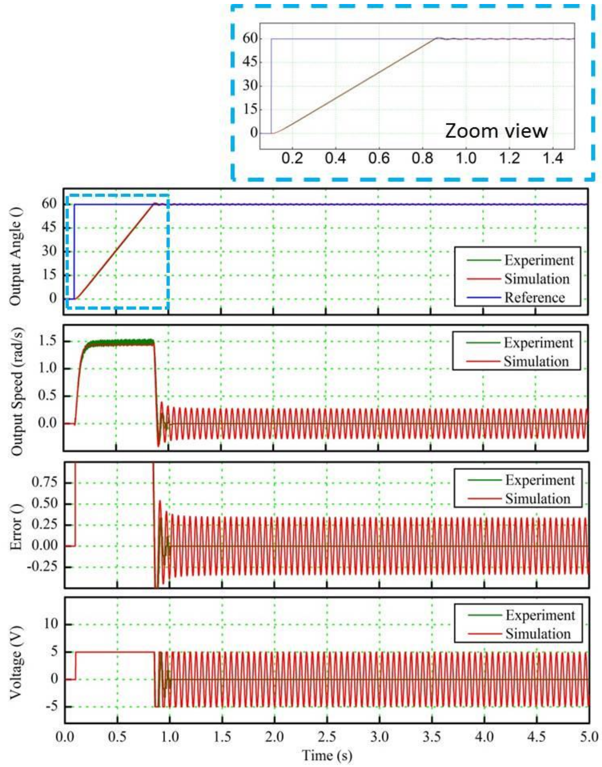


Figure 15 Results of point to point trajectory control experiment for a PID control system with input angle of 60° and Kp value of 14.6 (Ki = 0, Kd = 0)

For all the experiments, when the Kp value increased to Kp = 14.6, the system reached complete oscillation. The gain value during this condition is named as ultimate gain (Ku) whereas the period of oscillation is named as Tu. Then, the Kp and Ki values are calculated from the Ku value based on the Ziegler-Nichols frequency response method. Thus from the results of simulation of input angle 15°, the following PID controller gain using the Ziegler-Nichols frequency response method are obtained as shown in Table 7.

Table 7 PID controller gain parameters

Parameter	Symbol	Numerical Value
Proportional gain	K_p	8.76
Integral gain	K_i	156.4
Derivative gain	K_d	0.06

To validate the reliability of the results, the Kp value is fixed on the next experiment and the Ki value is varied to reduce the steady-state error of the system. Figure 16 and 17 shows the results of tuning Ki values. From Figure 17, it can be observed that when Ki =1, there are some vibrations of the movement of robotic arm. The vibration is not necessary thus; the value of Ki is kept constant at zero. The performances of the PID controller are shown in Table 8, with Kp = 8.76; Ki = 0; Kd = 0.

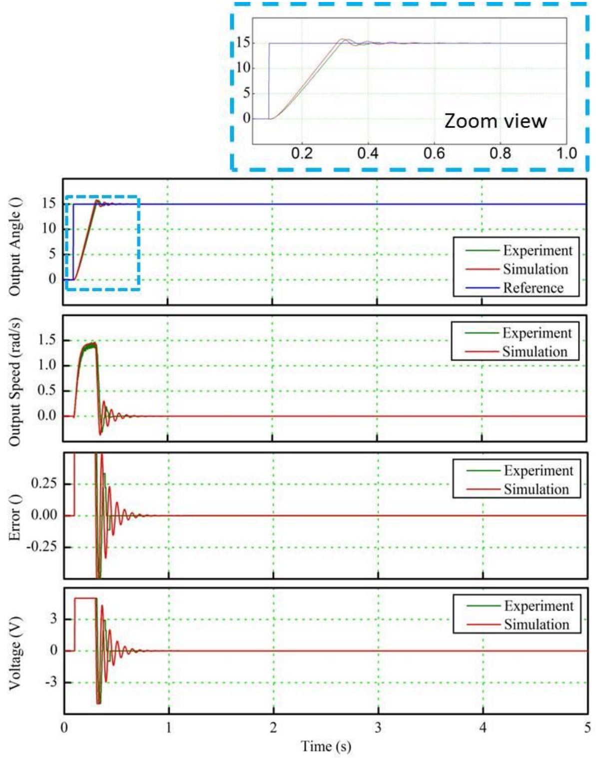


Figure 16 Results of point to point trajectory control experiment for a PID control system with input angle of 15° and Kp = 8.76; Ki = 0; Kd = 0

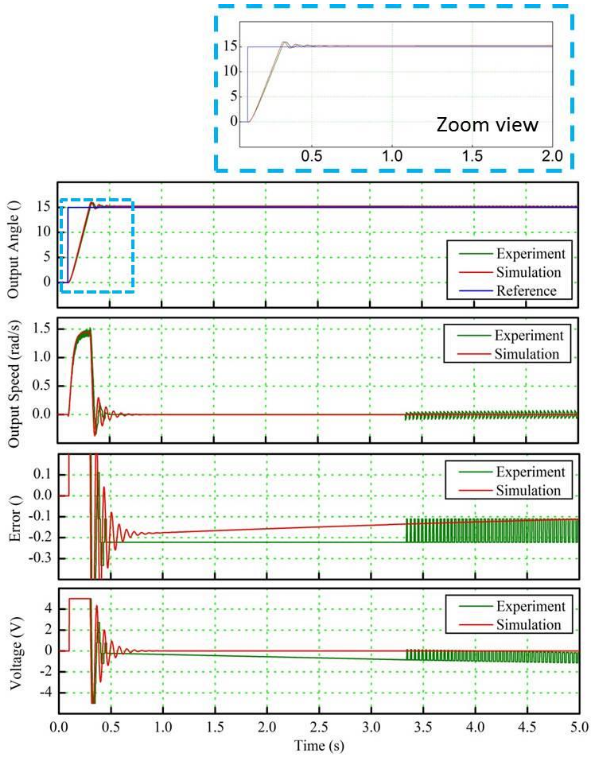


Figure 17 Results of point to point trajectory control experiment for a PID control system with input angle of 15° and Kp = 8.76; Ki = 1; Kd = 0

Table 8 Summary of PID controller performances

Performance	Point to Point Trajectory Control		
	15°	30°	60°
Steady-state Error (°)	0.01	0.01	0.02
Settling Time (s)	0.5	0.7	1.1
Rise Time (s)	0.25	0.4	0.8
Overshoot (%)	13.33	6.67	3.33

4.3 Compensated System using Fuzzy Logic Controller

For the compensated with fuzzy logic controller, a two-input and two-output (TITO) system was implemented. The inputs of the system are steady-state error and rate of change of error, whereas the output is the angle of the robotic arm. Table 9 shows the parameters being fixed and also varied in this compensated system with fuzzy logic controller (FLC), whereas Figure 18 shows the results of output angle, steady-state error and input voltage when the input angle is 15°.

Table 9 Parameters for PTP control using FLC control

Parameter	Numerical Value
Input Angle	15°, 30°, 60°
Simulation Time	5s
Sampling Time	1ms
Input Type	Step Input
Controller	Fuzzy Logic Controller

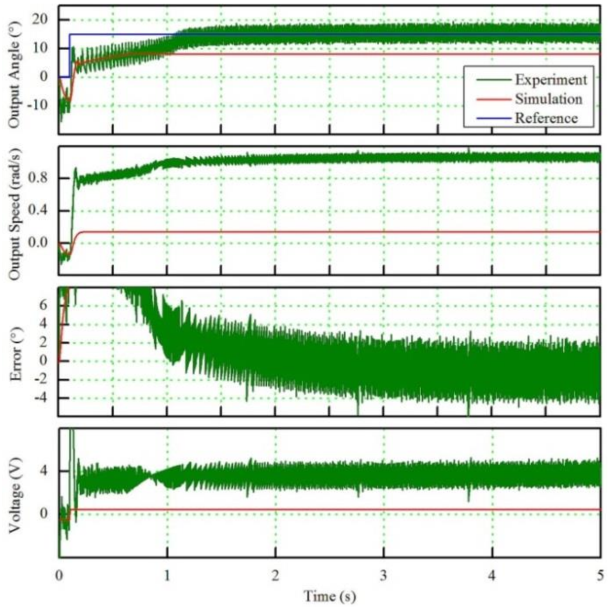


Figure 18 Graph of input voltage, output angle and steady-state error against time for a compensated system with input angle of 15°

Figure 18, 19 and 20 show the performances of the Fuzzy logic controller with the two-input two-output (TITO). In all figures, the fuzzy logic controller is able to produce better results for the experimental work in compared to the simulations work. The performances of the Fuzzy Logic controller are shown in Table 10.

Table 10 Summary of the Fuzzy Logic controller performances

Performance	Point to Point Trajectory Control		
	15°	30°	60°
Steady-state Error (°)	0.03	0.03	0.04
Settling Time (s)	0.6	0.4	1.0
Rise Time (s)	0.8	0.8	0.9
Overshoot (%)	33.33	42.86	25

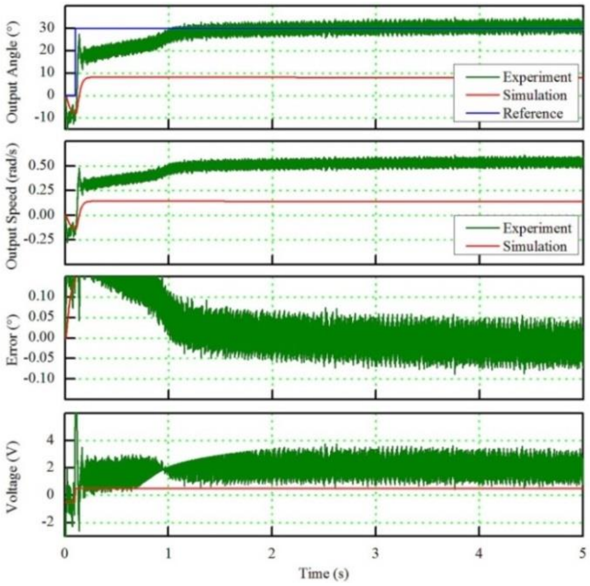


Figure 19 Graph of input voltage, output angle and steady-state error against time for a compensated system with input angle of 30°

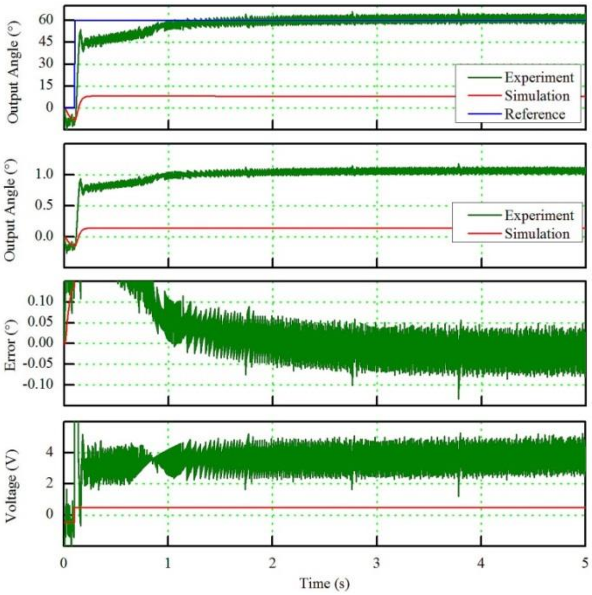


Figure 20 Graph of input voltage, output angle and steady-state error against time for a compensated system with input angle of 60°

5.0 CONCLUSION

This paper presents the PTP control performances of an upper limb of robotic arm using PID controller and fuzzy logic controller. Several types of experiments were carried out involving open-loop systems, uncompensated systems and compensated systems. Besides that, two types of experiments were carried out to control the motion of the robotic arm, namely point to point trajectory control. It can be concluded that the PID controller is more capable in eliminating the steady-state error, whereas the fuzzy logic controller demonstrates shorter settling time compared to the PID controller. However, the rise time of the fuzzy logic controller is higher as compared to the PID controller. In short, PID controller (Kp = 8.76; Ki = 0; Kd = 0) is a better choice in precision motion control as compared to fuzzy logic controller, where the result shows that the steady state error was less than 0.01^{0} and settling time of 0.5s; for the input reference, 15^{0} respectively. For future research, the robustness of the proposed controller can be further verified by evaluating the tracking control performances of the upper limb of robotic arm system.

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