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# POSITIONING CONTROL PERFORMANCES OF A ROBOTIC HAND SYSTEM

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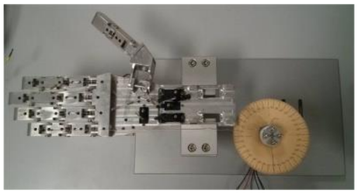
## Graphical abstract



## Abstract

Hazardous environments such as in industry sector with high chemical usage give high risks to the safety of workers. These risks can be reduced by designing robotic hand that is able to replace human works. For the industry purpose, the robotic hand needs to have a higher performance in accuracy, stability and consistency. However, the current robotic hand in industry is not flexible, which means it cannot be used for different tasks. Therefore, a multi-purpose robotic hand was developed. In this paper, the objectives of this research are to design and develop a PID controller for improving the performances of a robotic hand system. The experimental results prove that the PID controller shows good performances with the steady state error less than 0.11$^0$ for the input reference, 30$^0$ respectively.

*Keywords*: DC geared motor, flex sensor, PID controller, open-loop, closed loop

## Abstrak

Persekitaran yang berbahaya seperti dalam sektor industri dengan penggunaan bahan kimia memberi risiko yang tinggi kepada keselamatan pekerja. Risiko ini boleh dikurangkan dengan mereka bentuk tangan robotik yang dapat menggantikan kerja-kerja manusia. Untuk tujuan industri, tangan robotik perlu mempunyai prestasi yang lebih tinggi dalam ketepatan, kestabilan dan konsistensi. Walaubagaimanapun, tangan robotik semasa dalam industri tidak fleksibel, yang bermakna ia tidak boleh digunakan untuk tugas-tugas yang berbeza. Oleh itu, tangan robotik pelbagai guna telah dibangunkan. Dalam kertas ini, objektif kajian adalah untuk mereka bentuk dan membangunkan sebuah pengawal PID untuk meningkatkan prestasi sistem tangan robotik. Keputusan eksperimen membuktikan bahawa pengawal PID menunjukkan prestasi yang baik dengan ralat keadaan mantap kurang dari 0.11$^0$ untuk rujukan 30$^0$ masing-masing.

*Kata kunci*: DC motor menjurus, penderia anjal, pengawal PID, gelung terbuka, gelung tertutup

## 1.0 INTRODUCTION

Robotic hand is a machine mechanism that mimics the motion of human hand. In general, robotic hand plays an important role in any applications which require precision and dexterity. Nowadays, the robotic hand is widely applied especially in rehabilitation technologies [1-2]. Besides that, it is very useful to handle works that are unreachable or dangerous to humans such as in the industrial sectors that utilizes toxic chemicals [3-4]. There are many injury cases reported that occur in hazardous environment. Humans that are exposed to dangerous chemicals can result in various kinds of occupational diseases and disorders. The exposure risks can be reduced by designing a robotic hand that is able to replace humans in performing the human tasks.

Current robotic hand is in open-loop system. The selection of the actuators that used to drive the robotic hand needs to consider some important parameters such as size, efficiency, torque and type of the motor. By using different types of sensors such as flex sensor [5-6], pneumatics force feedback [7] and tactile sensor [8], the human fingers flexion can be detected by the robotic hand.

Other than that, robotic hand needs a controller to reduce the steady state error of the system. A suitable controller is necessary for validating the high accuracy and fast response in order to improve the precision of the robotic hand. However, the difficulty in developing a controller for a robotic hand is deterred due to the nonlinear characteristic of the system. Hence, a suitable controller is needed, so that the finger of the robotic hand could provide and maintain at a specific desired position. In addition, robotic hand with individual actuator at each joint will increase the complexity of the control system design. Since designing a dexterous and high accuracy robotic hand is a difficult task, an underactuated robotic hand at which each finger is actuated by a string or wire is an advantage which will significantly simplifies the robotic hand design. A well-designed controller is important for high adaptability and high precision. Several controllers such as Proportional-Integral-Derivative (PID) controller [9-12], Fuzzy PID controller [9], Artificial Intelligent (AI) controller [13-14] and Nominal Characteristic Trajectory Following (NCTF) controller [15] able to improve the control system performances. The positioning control system of the robotic hand is necessary and requires suitable controller to maintain smooth movement and provide high precision output to the position of the robotic hand. This paper will further discuss about the important element of robotic hand in terms of actuator, sensor and controller used.

### 1.1 Related Work

Actuator is a mechanism that converts energy into motion. Based on past research [16], DC geared motor is the most suitable actuator used to operate the robotic hand due to the application of the power which will cause the shaft to rotate continuously. For instance, the shaft only will stop if the power is removed from it [16]. This DC geared motor can be controlled easily via computer with the electronics switches, which is included with the gearbox [16]. The speed of DC motor is similar to servo motor, which is controlled by using Pulse Width Modulation (PWM). PWM is a technique of rapidly pulsing the power to be on or off. The speed of motor is determined by the percentage of time spent. Besides that, servo motor can also be used in robotic hand, which has a good performance in speed control and torque control [17-18]. This motor is available in smaller size that is very suitable if used in the robotic hand. However, servo motor does not include the encoder, hence making it useless to the robotic hand. Other than that, many researchers had developed pneumatics actuator to drive the robotic hand [19-21]. Normally, pneumatics actuator is used in the finger joint which has only one degree of freedom (DOF). By using this actuator, a bigger compressor is needed in order to supply enough air pressure to drive the robotic hand [19]. As a conclusion, DC geared motor has a better performance if it is used as an actuator for robotic hand. This is because DC geared motor can be controlled easily by using the computer [22]. Besides that, DC geared motor has low voltage that is only 12V. High torque of the motor is required in order to perform the movement of robotic hand, so that the robotic hand can operate smoothly, especially in grasping ability and accuracy.

Besides that, there are many sensors that can be used to measure finger flexion. In this section, several types of sensors that are commonly used to develop a master data glove for robotic hand will be discussed. The sensors are the flex sensor [5-6], pneumatics force feedback sensor [7] and tactile sensor [8]. Based on researches, flex sensor is most suitable to be used as an input device that collects and classifies the finger gestures as compared to pneumatics force feedback and tactile sensor [5]. A 4.5 inch flex sensor is used to resemble the length of human fingers and track the bending angle of human fingers. Unlike pneumatics force feedback and tactile sensor, flex sensor behaves like analog resistance and it operates as an analog voltage divider. Acquired data that are relative to the bending angle of fingers can be determined by connecting to an electronic system to the sensor [6]. With the experiments that was performed, the flex sensor shows a better performance in terms of accuracy and repeatability, where it has the accuracy above 90% with 10 samples of gesture [5]. Besides that, flex sensor is also able to detect the minimum bend angle of finger with 5% of sensor value [5]. Pneumatics force feedback is another method that is used to measure the finger gesture. It has a simple structure with a high force to weight ratio and linear control force [7]. Based on [7], the actuator for the pneumatics system is micro-low-friction, while non-contact magnetic sensor is used to measure the gesture of fingers. The maximum for displacement of the piston is 30mm, ranging from the piston rotation angle between upper and lower is in between -25.5° to 40°, while the angle rotation is in the range of -25.5° to 25° for right and left movements. Thus, both pneumatic force feedbacks and flex sensor have better performance in terms of accuracy and repeatability. However, the pneumatic system has a large complicated structure as compared to the flex sensor, which makes it hard to develop. As a conclusion, flex sensor is a better choice to be used in this robotic hand as it has a simple structure with good performance in terms of accuracy and repeatability.

In this system, the robotic hand will be control by using the Point-to-Point (PTP) positioning system. The PTP positioning system is a control system that is used to move the robotic finger to a predefined location. In this paper, the problem that needs to be analyzed is the PTP control performances. The robotic finger operation will be performed at the position when it reaches the desired angle or position. Moreover, the PTP positioning system is required to have fast response, high accuracy and robustness [23]. In designing the controller for robotic hand with PTP positioning system, the nonlinear characteristics of the positioning mechanism will cause changes in the positioning system thus becomes imprecise. The nonlinear characteristic of the positioning mechanism such as frictions between the joints and saturation of the actuators will cause unstable positioning system [24-25].

Thus, a suitable controller is necessary for validating the high accuracy and fast response in order to improve the precision of the non-linear characteristic of the robotic hand system. PID controller is the most vastly control strategy used today due to its simple control structure, easy implementation and it does not required plant model [9-12]. Furthermore, PID controller able to improve the position error in a short period and is suitable for linear system. Proportional gain provides an overall control action proportional to the error signal through the all pass gain factor, while the integral gain reduces the steady state error through low-frequency compensation by an integrator. The derivative gain improves the transient response through high-frequency compensation by differentiator [11]. Besides that, based on past research [9], a self-tuning Fuzzy PID controller is proposed. It does not only keep the advantages of the classical PID controller, but also possesses higher agility and adaptability. The efficient and stable control algorithm is the sticking point for tracking angle fast and smoothly. However, the Fuzzy-PID controller exhibits higher overshoot and slower response time [9]. For the PD controller, it only capable of controlling the finger joints in terms of stability and biomorphic behavior [26]. Furthermore, intelligent controls such as Fuzzy Logic controller, Neural Network controller and Genetic Algorithm controller have been introduced. A Fuzzy Logic controller is a more robust controller for specifying the nonlinear controller that will cause the imprecision of the system [13-14]. However, the design of the AI controller is more complex compared to PID controller. Besides that, NCTF controller has been proved by the previous researchers that it produces a better positioning performances than other controllers due to the robotic hand will always follow the motion of the input [15]. However, this type of controller provides a slower rise time due to the robotic hand will always follow the motion of the input [15].

As a conclusion, the PID controller is the most suitable controller to be used for control the angle of joint for the robotic hand.

## 1.2 The Developed Prototype

The developed prototype consists of two major components that are Robotic Hand (RH) and Master Data Glove (MDG). The description of each component is described as follows.

### *1.2.1 Robotic Hand (RH)*

The RH has been developed in our laboratory as shown in Figure 1. The material used for the RH is aluminum 6061. DC geared motor is assembled together with base by using the L-shape bracket. Furthermore, the DC geared motor rotates and a coupling is used to pull the RH finger by using a wire. The wire that is used to pull the RH finger is called nylon coated wire. This nylon coated wire is very flexible, soft and strong as the thickness of this wire is 0.25mm to sustain load up to 10lb (4.536kg).

The base is designed to grip the RH. The material used for the base is aluminum. For this base, it consists of two holders and two grippers, whereby the holders and grippers are assembled together by using M6 screw and a bolt is used to tighten it. Figure 1 shows the top view, while Figure 2 shows the side view of experiment setup of RH with fully assembled together with the actuator system.

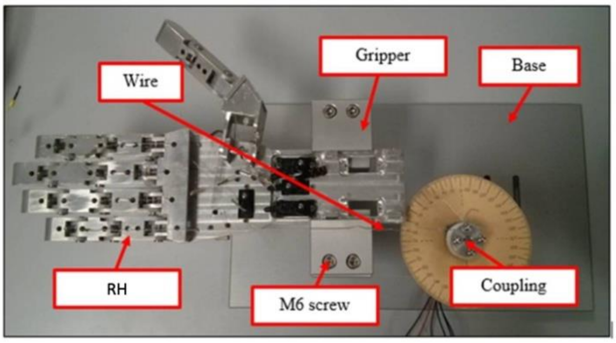


**Figure 1** Experiment setup for RH (top view)

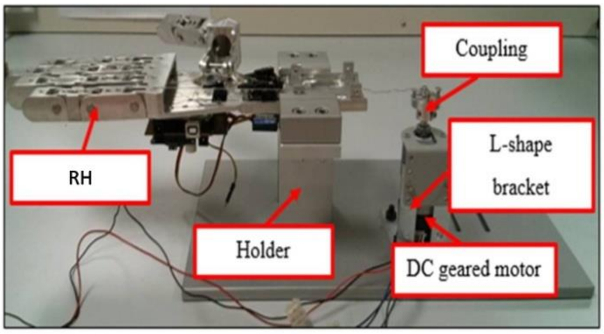


**Figure 2** Experiment setup for RH (side view)

### *1.2.2 Master Data Glove (MDG)*

From Figure 3, there are five sensors attached to the MDG. These sensors are bent to measure the input signal from actual human fingers flexion. There are ten (10) different values of input voltages selected which are 0.5V until 5.0V. The angle measured is based on the fingers flexion. Next, the signal produced by the flex sensors of the MDG is then transmitted to RH through XBee module. The RH then receives the signal and processes it by using Arduino microcontroller which later operates the DC geared motors. These motors will move the RH to mimic the motion of the MDG. This RH prototype employs feedback signals to reduce any steady state errors. There are three different values of angle selected for RH which are 30°, 60° and 90° for the closed-loop experiment.

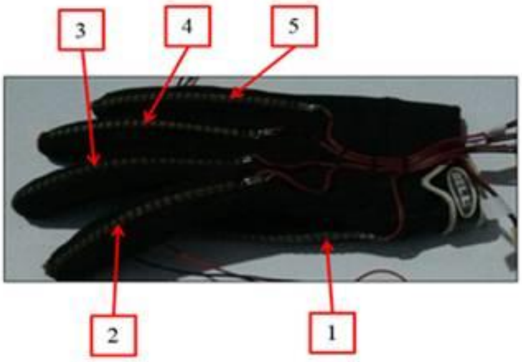


**Figure 3** Flex sensor mounted on MDG

### 1.3 The Developed Prototype System Description

This section explains how the prototype works. The whole prototype includes a RH and MDG. Figure 4 and 5 shows the schematic diagram of developed prototype and system flow chart of the robotic hand prototype. The system starts when both XBee transmitter and receiver modules are switched on. After that, the protocol communication between MDG and RH is established through the wireless system. After measuring the finger flexion, the input signal of flex sensors will be obtained and transmitted to RH through XBee module. Next, DC geared motor that is used as an actuator for the RH finger is then operated and the rotation of DC geared motor depends on input value of the flex sensor, which is in degree. RH will therefore operate as the motion of actual human finger and there will be a feedback if the angle detected is an undesired angle.

**Figure 4** Schematic diagram of developed prototype

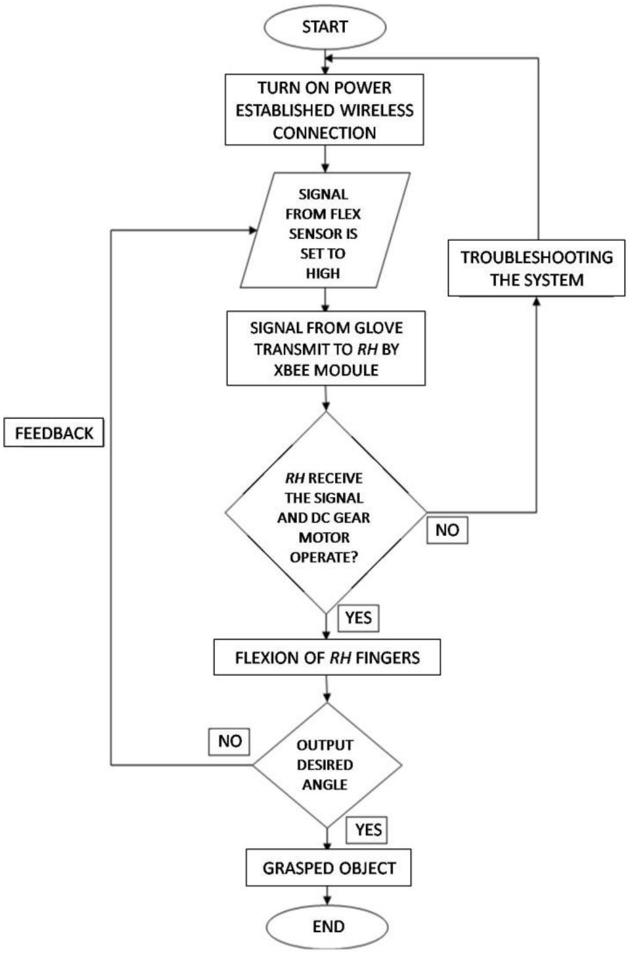


**Figure 5** The developed prototype system flow chart

## 2.0 METHODOLOGY

### 2.1 MDG Experiment Setup and Procedures

The objective for this setup is to measure the output voltage of each of the flex sensor on the MDG by giving different value of input voltages and the second objective is to simulate the performance of flex sensors.

The parameter of this experiment is the different values of input voltages. There are 10 different values of input voltages selected namely 0.5V until 5.0V. This experiment setup is done by connecting a 10k potentiometer and a 10kΩ resistor with the Arduino microcontroller as shown in Figure 6. In addition, the value of the input voltages can be adjusted by using the potentiometer. The flexion angle is measured based on the finger flexion via flex sensors. Figure 6 shows that Arduino microcontroller is used to read the output of flex sensor through analog port and this output of flex sensor is converted to voltage.

First of all, the experiment is conducted by taking the output voltage when the flex sensor for Finger 1 is in a normal position, which is at 0° of the flex flexion and the input voltage given is 0.5V. To obtain more reliable results, the experiment is tested 10 times and results obtained are recorded in the table. After that, the experiment proceeds with different values of input voltages which are 1.0V, 1.5V, 2.0V, 2.5V, 3.0V, 3.5V, 4.0V, 4.5V and

5.0V. Next, all the steps are repeated by using the same input voltages but continued with the flex sensor for Finger 2, Finger 3, Finger 4 and Finger 5 as shown is Figure 7.

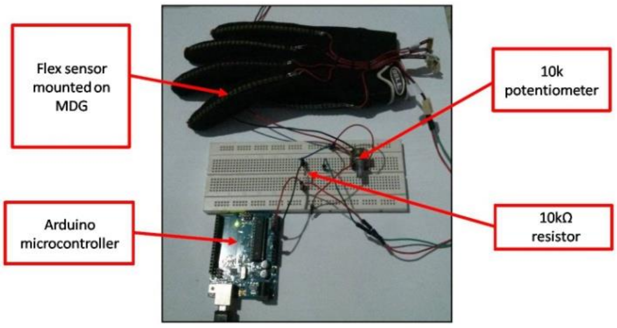


**Figure 6** MDG experiment setup

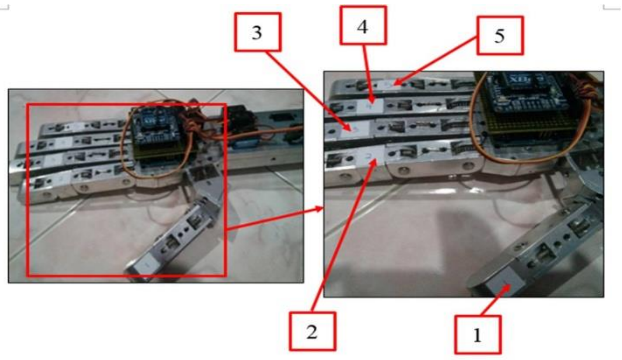


**Figure 7** RH fingers with label

## 2.2 RH Experiment Setup and Procedures

### 2.2.1 *Open-loop System*

The objective for this setup is to understand the open loop system of DC geared motor by using MATLAB software. Second objective is to obtain the transfer function and compare to mathematical model as well as with the real time system by using Random White Noise and System Identification Tool. Figure 8 shows the open-loop system diagram used in this experiment.

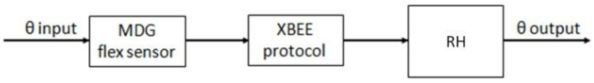


**Figure 8** Open-loop system diagram

The experiment is set up by connecting the DC geared motor with micro-box 2000/2000C. The connection is done by using four pins and six pins DIN female connector as shown in Figures 9 and 10. From Figure 9, the pins that need to be connected are pins 1 and 2 only, where pin 1 represents the ground (-) and pin 2 represents VCC (+). By conducting this connection, power can be supplied.

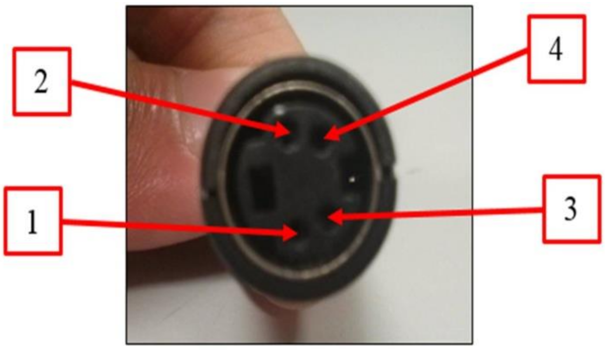


**Figure 9** Four pins DIN female connector

Figure 10 shows the pins number of the six pins from the DIN female connector. The pins number that need to connect are pins 1 and 2, which 1 represents ground (-) while 2 represents VCC (+). For the connection of encoder, pins 4 and 6 are needed. Pin 4 is for encoder phase B while pin 6 is for encoder phase A.

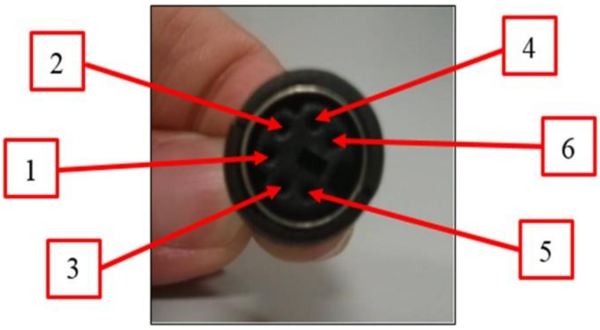


**Figure 10** Six pins DIN female connector

In this setup, the experiment is conducted by drawing a block diagram for Random White Noise in Simulink as shown in Figure 11. The simulation stop time set is 300s to run the block diagram. The saturation block is needed to avoid excess voltage flow into the system. Besides that, the value settings of upper and lower limits for the saturation block are ±10. Noise produced is then monitored by connecting a scope to ensure that the noise is in the range of ±10. The noise produced will thus cut off if exceeds the range of ±10 and this will cause the result of transfer function

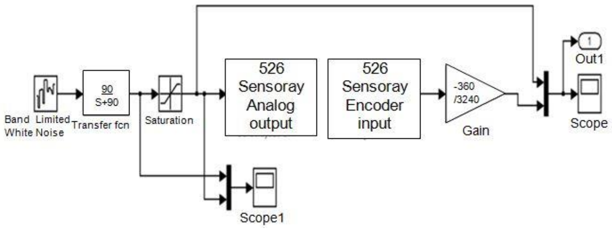


**Figure 11** Block diagram for Random White Noise

System Identification Tool is used to obtain the transfer function of the DC geared motor. The noise produced by Random White Noise is then straight imported into System Identification Tool. After all the data needed are inserted step by step, state space matrices A, B, C and D are shown. Furthermore, the state space matrices are then converted to S-domain from state space to transfer function by using the commands. The transfer function obtained is recorded and then is inserted in the block diagram as shown in Figure 12 for the purpose of comparing with the real-time system. To obtain a more reliable result, the experiment is tested three times. Eq. (1) shows the obtained transfer function of the system,

$$G(s) = \frac{0.7756s - 707.5}{s^2 + 48.51s - 0.08472} \qquad (1)$$

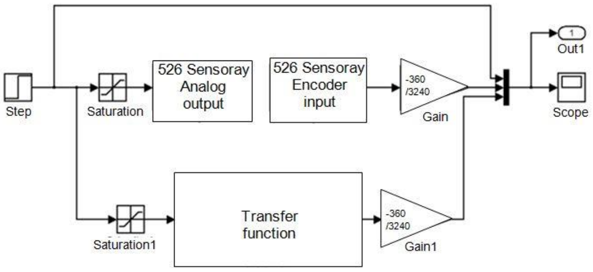


**Figure 12** Block diagram for compare with real time system

### 2.2.2 Closed-loop Compensated System using PID Controller

For this experiment, the objective covered is to design and develop a suitable controller for RH. Figure 13 shows the closed-loop system diagram used in this experiment.

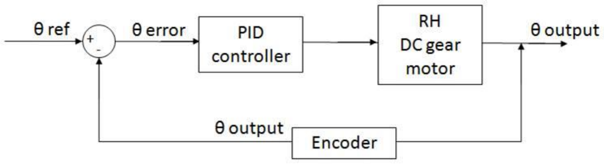


**Figure 13** Closed-loop system diagram

In this experiment, the PID gain; i.e; $K_p$, $K_i$ and $K_d$ are added into the block diagram of closed loop system as shown in Figure 14. The values of $K_p$, $K_i$ and $K_d$ are changed by using the manual tuning method. Other than that, the variable of the experiment contains different values of degree. In this experiment, there are three different references input that are selected which are 30°, 60° and 90°. First, the values for $K_p$ which are 1.0 and 1.1 are tuning for reference angle 30°. Next, by using $K_p$=1.1, the values for $K_i$ are tuned. Three values of $K_i$ were tuned which are $1x10^{-3}$, $0.01x10^{-3}$ and $1x10^{-6}$.

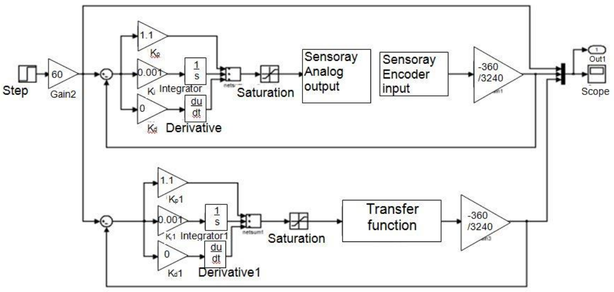


**Figure 14** Implementation of PID compensator in closed-loop system

## 3.0 RESULTS AND DISCUSSION

### 3.1 MDG Experiment Results

This experiment is to simulate and analyze the performance of flex sensor for each finger. The experiment is performed with Arduino microcontroller where the output voltages of flex sensors are obtained by using Arduino serial monitor. Arduino microcontroller will read the analog input data from sensor in Bytes and is converted to voltage by using the command. From the command, values for output voltage are obtained. Data obtained from the experiments are compiled into a graph according to the different value of input voltages that applied to each of the finger. The experiment is done by measuring the angle of finger flexion which depends on the bending angle of the finger. Figures 15 to Figure 19 show the graph results of output voltage against input voltage for Finger 1, Finger 2, Finger 3, Finger 4 and Finger 5. It can be depicted that the output voltage increases when the input voltage applied increases. Other than that, it can be concluded that the greater the bending angle, the smaller the output voltage that is produced. Since the voltage is used to operate the DC geared motor, a higher value of input voltage which is more than 5.0V is needed so that the time taken to reach the desired angle is shorter. Besides that, from the calculation, the standard deviation for all the output voltages is smaller. Thus, the smaller the values of standard deviation, the more consistencies the values of the output voltage for DC geared motor are obtained. Therefore, from the graph, it can be inferred that the flex sensors are linear.

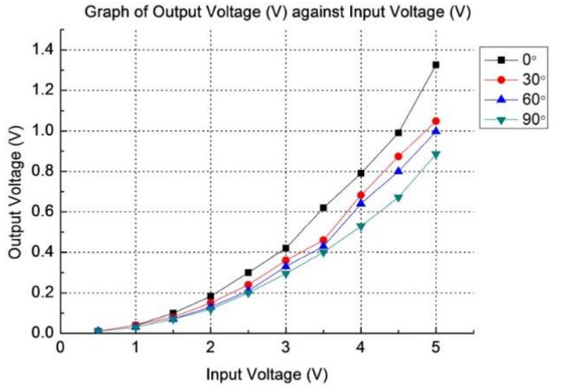


**Figure 15** Graph of Output Voltage (V) against Input Voltage (V) for Finger 1

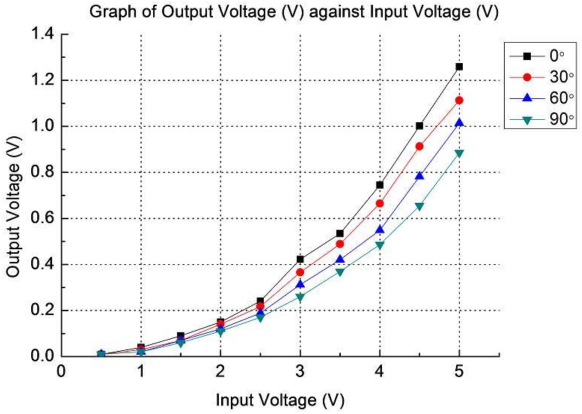


**Figure 16** Graph of Output Voltage (V) against Input Voltage (V) for Finger 2

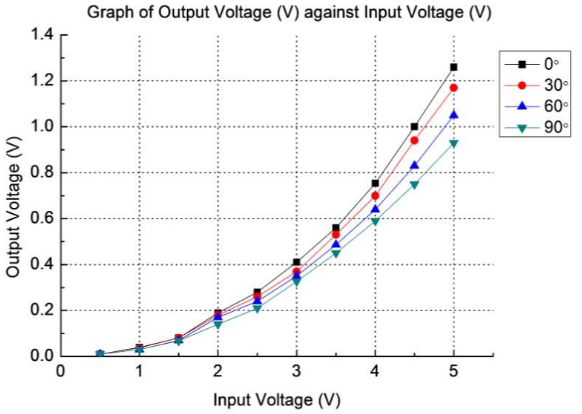


**Figure 17** Graph of Output Voltage (V) against Input Voltage (V) for Finger 3

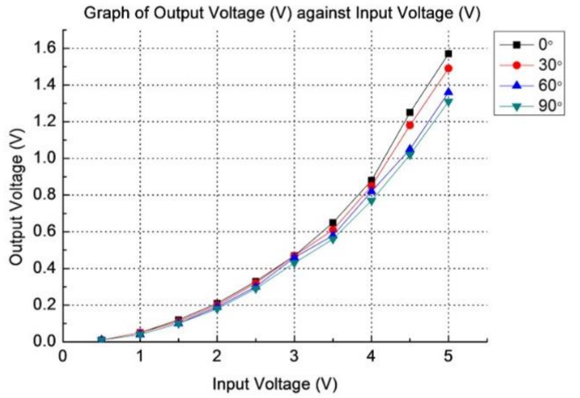


**Figure 18** Graph of Output Voltage (V) against Input Voltage (V) for Finger 4

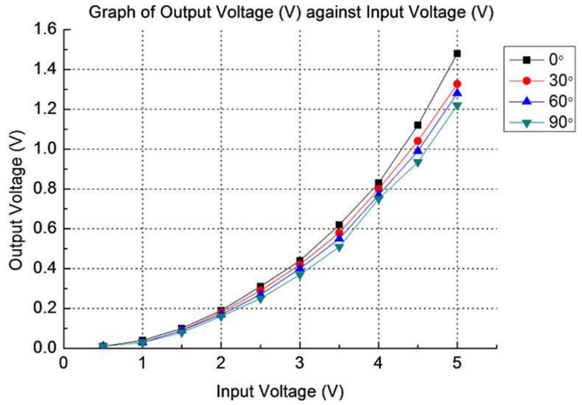


**Figure 21** Graph of Output Voltage (V) against Input Voltage (V) for Finger 5

## 3.2 RH Experiment Results

### *3.2.1 Open-loop System*

Figure 20 shows the time response of experimental and simulation. From Figure 20, it can be seen that when a voltage given is 1.0V, the degree of simulation and experimental is increasing according to time. The degree in experimental increases in a higher gradient compared to the simulation. This result happened because of the transfer function from the System Identification Tool is inaccurate according to gross error. Gross error is mainly due to human mistakes in reading or in using instruments or error in recording observations. When using Random White Noise Tool, the values of noise produced must be monitored every single second to ensure that the noise produced are in the range of ±10. The noise produced will cut off by filter if exceed the range of ±10 and this cause the result of transfer function to be incorrect or inaccurate. Error may also occur due to incorrect adjustment of instruments or computational mistakes. These errors cannot be treated mathematically. Except from gross error, dynamic errors also occur because of the instrument not responding fast enough to follow the change in a measured variable.

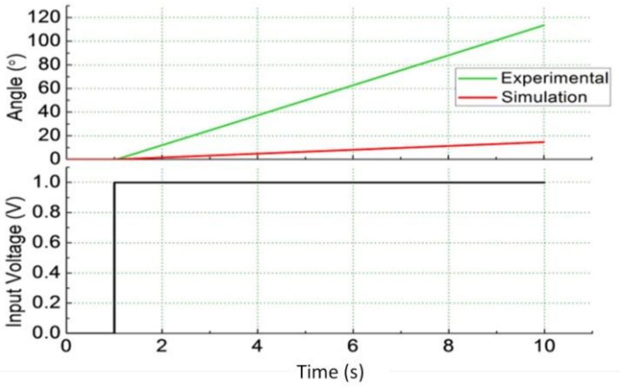


**Figure 22** Time response of experimental and simulation

### *3.2.2 Closed Loop Compensated System using PID Controller*

In this section, the positioning control experiments with PID controller were carried out with several reference angles; i.e. 30°, 60° and 90° respectively. The rectangular input is the reference signal that is implemented in this experiment. Figures 21 to Figure 23 show the results of positioning control experiments for input angles of 30°, 60° and 90°. Table 1 shows the percentage of steady state error with the changed of the PID gain values; i.e. $K_p$, $K_i$ and $K_d$. It can be conclude that the value of $K_p$=1.1, $K_i$=1x10$^{-6}$, $K_d$=0 is suitable for reducing the steady state error. From these results, it was proven that the PID controller gave satisfactory performances. From the simulation evaluations, the time taken for output to reach the desired angle is longer as the angle increases. In addition, the steady state error for both the experiments and simulations increases by the applied reference angle.

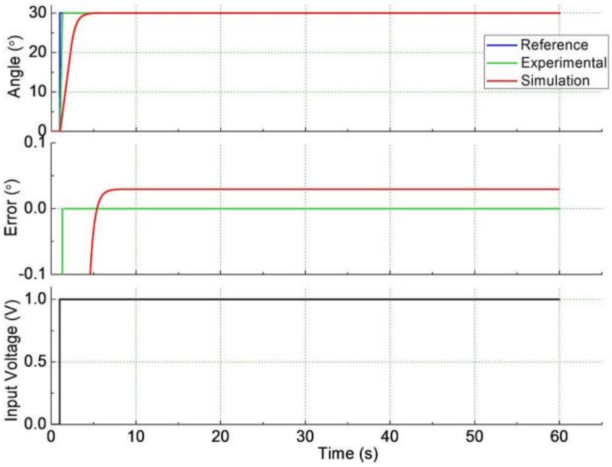


**Figure 23** When $K_p$ = 1.1, $K_i$ =1×10$^{-6}$, $K_d$ = 0 for reference angle 30°

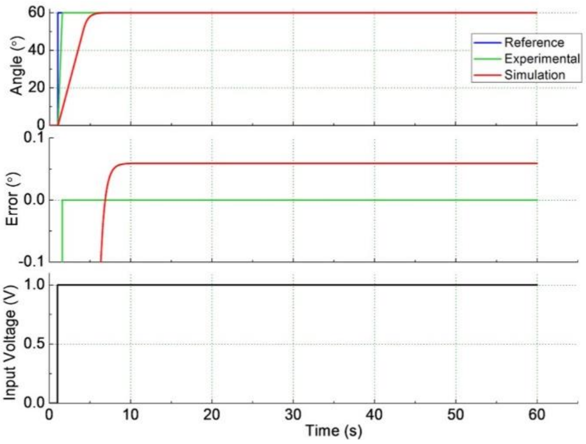


**Figure 24** When $K_p$ = 1.1, $K_i$ =1×10$^{-6}$, $K_d$ = 0 for reference angle 60°

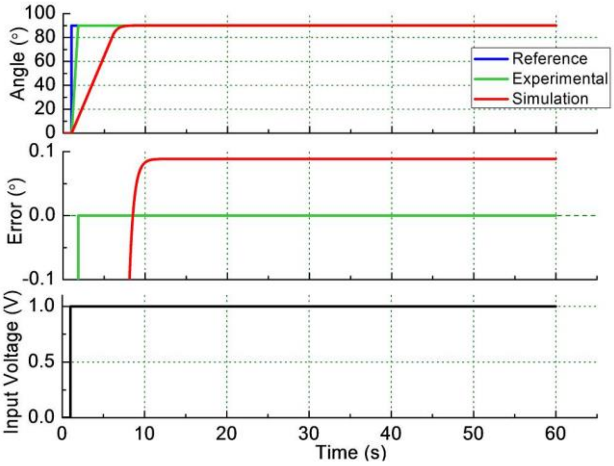


**Figure 25** When $K_p$ = 1.1, $K_i$ = 1×10$^{-6}$, $K_d$ = 0 for reference angle 90°

**Table 1** $K_p$, $K_i$ and $K_d$ values for experimental and simulation

| Angle (°) | Values of compensator |  |  | Steady state error |  | Settling time |
|---|---|---|---|---|---|---|
|  | $K_p$ | $K_i$ | $K_d$ | Simula-tion (°) | Experi-mental (°) |  |
| 30 | 1.1 | 0 | 0 | 0.03 | -0.11 | 0.001 |
|  | 1.1 | 0 | 0 | 0.029 | -0.11 | 0.001 |
|  | 1.1 | 1x10$^{-3}$ | 0 | 0.06 | 0 | 0.001 |
|  | 1.1 | 0.01x10$^{-3}$ | 0 | 0.03 | 0 | 0.001 |
|  | 1.1 | 1x10$^{-6}$ | 0 | 0.029 | 0 | 0.001 |
| 60 | 1.1 | 1x10$^{-6}$ | 0 | 0.058 | 0 | 0.001 |
| 90 | 1.1 | 1x10$^{-6}$ | 0 | 0.088 | 0 | 0.001 |

## 4.0 CONCLUSION

This paper has presented the implementation of the robotic hand with PID controller to improve the system performance of the robotic hand. The MDG was equipped with flex sensor and XBee module to transmit the signal to the RH. For RH, it was equipped with XBee module and DC geared motor to receive the signal from the MDG. The results showed that the PID controller was able to reduce the steady state error of system performance of robotic hand to less than 0.11$^0$. For future research, the transfer function needs to be reconfirmed using mathematical modeling method instead of system identification tools in order to improve the performances of robotic hand system. In addition, another type of controller such as Fuzzy Logic controller can be implemented for comparison of the controller performances, besides using the conventional controller; i.e. PID controller.

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