MJSAT 3 (3) 158-165

MJSAT

Malaysian Journal of Science and Advanced Technology

journal homepage: https://mjsat.com.my/

Performance Analysis of a 5-DOF Robotic Arm by Implementing a Graphical User Interface

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KEYWORDS

Robotics Arm
Graphical User Interface
Program Algorithm
Wi-Fi connection

ARTICLE HISTORY

Received 28 June 2023
Received in revised form 1 August 2023
Accepted 10 August 2023
Available online 22 August 2023

ABSTRACT

Today, the topic of performance in industrial robotics is being addressed by researchers at a much faster pace than a few years ago. In 2023, there are a variety of applications for industrial robotics, such as agriculture, education, and the film industry. In this paper, the implementation of Graphical User Interface (GUI) as a controller input between an Android smartphone and the Arduino was discussed. This GUI was developed to help the user in controlling the robotic arm. For the movement of 5-degree motion of a robot, the concept of inverse kinematics (IK) was applied to the system. To test the performance of the robot, a simple test had done by drawing the basic shape by putting the pencil into the gripper. Then, these drawings were compared with the original by calculating the percentage error of the dimensions from the center to the outside. The result shows that the robotic arm is capable of performing all the tasks assigned to it and can also be controlled through the graphical user interface of a smartphone. Therefore, implementing Bluetooth Wi-Fi as a communication between smartphone and robot is a good way to study the performance of robots, especially for small and lightweight robotic arms.

1. INTRODUCTION

Nowadays, various types of robots are used in most industries, construction and manufacturing, especially robotic arms, which vary in shape, size, and function according to the needs [1]. A robotic arm is a programmable mechanical arm that has similar functions to a human arm. It is a manipulator with links connected by joints to enable rotational or linear movements and form a kinematic chain [2]. At the end of the kinematic chain is the end effector, which can be equipped with tools or a gripper, analogous to the human arm. The use of robotic arms in industry is very popular due to automation [3], [4]. Repetitive tasks are suitable for robots as they are less prone to errors. Most automated robots are capable of working for a long period of time without interruption as they are faster, more precise and suitable for high accuracy.

For simple tasks such as placing small objects into a container and pouring tea into a cup, it is not practical to use a large sized industrial robot. A smaller robot such as a mini robotic arm is more suited for such purpose. There are many small-sized robotic arms created by robotic engineers and hobbyists, where the robots have a computer or smartphone as the user interface [5]. Smartphones have useful hardware that can be used to wirelessly communicate with another device, such as GPRS, Wi-Fi and Bluetooth [6] [7]. Smartphones usually have a large screen which can be used to display a GUI.

This article is primarily about designing a lightweight robotic arm with five degrees of freedom (DOF) using CATIA software and then manufacturing it from plywood. The proposed controller in this work is a Wi-Fi connection with

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https://doi.org/10.56532/mjsat.v3i3.170
2785-8901/

Android application and Arduino IDE programming via Bluetooth. The purpose of this work is to study the performance of a robotic arm based on the graphical user interface (GUI) of a smartphone connected to Arduino Uno as a microcontroller.

2. Literature Review on the Robotic Arm

Remotely controlled robots are examples of robots that can be controlled over a variety of distances. Most of them are controlled by wireless communication means such as Wi-Fi, Bluetooth, satellite, infrared, radio, and microwave [8]. Each type of wireless communication is different from the other and has its own advantages and disadvantages. The most popular wireless transmitters are radio frequency transmitters/receivers (RF), Bluetooth modules and Wi-Fi modules. For smartphones, the choice is limited to Wi-Fi and Bluetooth only [9].

In [10], a RF transmitter/receiver is used to control a hydraulic robot arm. The robotic arm consists of two parts; the first part is a human arm that captures input from the potentiometers and relays it to the receiver. The second part contains the hydraulic robot arm, which receives the instructions from the first part to control the movement of the robot arm. The resulting movement of the robotic arm matches the movement of the human arm. One advantage of the hydraulic system for actuating the robot arm joints is its strength, making it suitable for lifting heavy loads.

In the paper [11], communication between a robot and a controller was introduced by implementing the RF wireless. This wireless transmission of data from one device to another is used to control and operate applications over a small distance. This method is low cost, easy to decode, low maintenance and user friendly. However, the RF wireless has low security because the frequency band is accessible to almost everyone, then it is not reliable due to errors caused by the environment. The data can be corrupted during transmission and is not suitable for working with scientific experimental components.

Robots can also be controlled remotely via mobile devices such as smartphones. Using smartphones to control robots has been shown to be practical in various studies. Smartphones have high processing power and can perform practical functions such as wireless internet and camera monitoring [12][13]. The built-in hardware such as CPU, buttons or touch screen, graphics, accelerometers, gyroscopes, magnetometers, and wireless networks are useful for robots [14]. For Android devices, the use of the Android API (Application Programming Interface) allows access to the hardware components of Android smartphones [15]. Using a smartphone as the "brain" of a robot is already an active area of research with open opportunities and promising possibilities [16]. In [17], the use of a smartphone to power a Micro Aerial Vehicle is described, which mainly uses smartphone hardware such as gyroscopes, accelerometers, and high-resolution cameras. The use of smartphones with GUI simplifies the task of working with robots, especially for young people.

In the other study, a robot was equipped with a webcam camera for real-time indoor monitoring that is remotely controlled via a smartphone [18]. At the same time, the live video recorded by the webcam is streamed to the smartphone via Wi-Fi. With the help of an image processing algorithm in the smartphone, the robot is able to estimate the distance between itself and a target object in its field of view by using the Wi-Fi hardware, inertial sensors and CMOS sensors. At the same time, the Wi-Fi connection was used to detect the signal strength in a room and determine the robot's position. The accuracy of the estimation can be improved by using inertial sensors and a camera to measure the distance travelled by the robot [19].

Smartphones were used as teaching tools for industrial manipulators [20]. In contrast to the previously mentioned studies, here a two-way communication is established between the smartphone and the robot arm instead of a one-way communication. The feedback data was used for detailed monitoring through OpenGL (Open Graphics Library) based visual drawings displayed on the GUI. In this way, the status of the robot can be better monitored. Similarly, in another study, a smartphone is used to control the humanoid robot Nao by Aldebaran Robotics [21]. The robot interacts with its environment while the user controls it from a remote location. Via a camera installed in the robot's head, the smartphone user can see a live stream of the robot's environment. Communication between the robot and the smartphone is established via Wi-Fi through a bridge server. This allows the robot to be controlled over the internet over a long distance.

3. Methodology

3.1 Designing Five Degree of Freedom (5-DOF) of Robotic Arm

While designing the robotic arm, some factors like payload, height, type of actuators and also end effectors were considered. These factors are crucial for the good performance of the robotic arm. Firstly, the choice of actuator is an important point in the development of the robot. The motor used to turn the joints can support the weight of the robot itself. In practise, high torque is required to move the robot arm precisely and accurately. However, the use of low-cost, low-torque motors for robot arms is possible if a counterweight is used to reduce the torque resulting from the load [22]. To solve the problem of motor torque, a multi-DOF robot arm with counterweight is proposed based on a slider-crank mechanism and bevel gears [23].

In the designing of robot is an essentially about making the robot arm as light as possible to allow fast movements and faster reflections. Fast movements are essential for everyday tasks like moving things from one place to another. The robotic arm was designed using CATIA software and then converted into hardware. The design includes five joints, as shown in Figure 1 (a) and Figure 1 (b) shows the isometric of the robot. All joints are driven by five servo motors, which means that five movements can be interpreted. There are two joints, a base, and a gripper, which are connected to the joints. The dimensions in cm of the robots for each part are given in Figure 1. Table 1 shows the connection between the joints and parts of the robot arm.

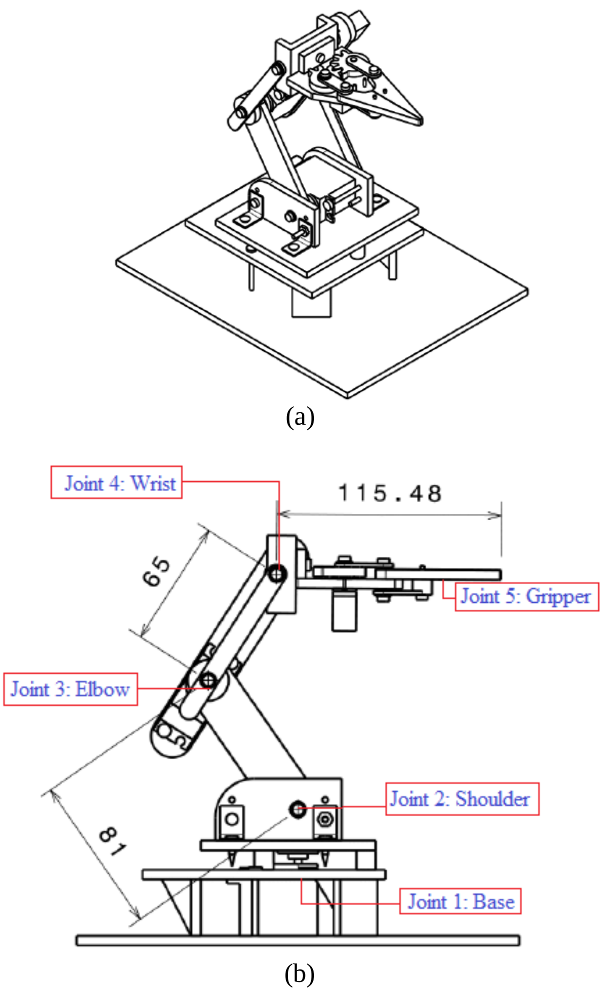


Fig. 1. Robotic arm with 5 degrees of freedom and the joints; (a) isometric of robot (b)) robot joint

The robot arm contains five actuators connected as shown in Table 1. The prototype of the robot arm was made of plywood. The concept of the gear system was applied to the gripper, which acts as an end effector.

Table 1. The connection of the joints with the branch members, the base, and the gripper

Joint	Part	Description
1	Base	Rotate in 360°
2	Link 1 – From shoulder to elbow	Move up and down
3	Link 2 – From elbow shoulder to wrist	Move up and down
4	Wrist to gripper	Move up and down
5	Gripper	Open and close the gripper

3.2 Development the graphical user interface (GUI) system for robot controlling

Controlling a robot is important for the robot to function well. Most robot arms only move in a predetermined motion within the Arduino programme [24][25]. In this project, the robot arm was controlled by moving with commands from a smartphone. The smartphone application served as a graphical user interface (GUI) developed in Android Studio [26]. This application uses the Bluetooth Wi-Fi communication module that connects to the Arduino and displays commands to move the end effector in XYZ coordinates. The control screen of GUI will be displayed when the device is successfully connected as shown in Figure 2.

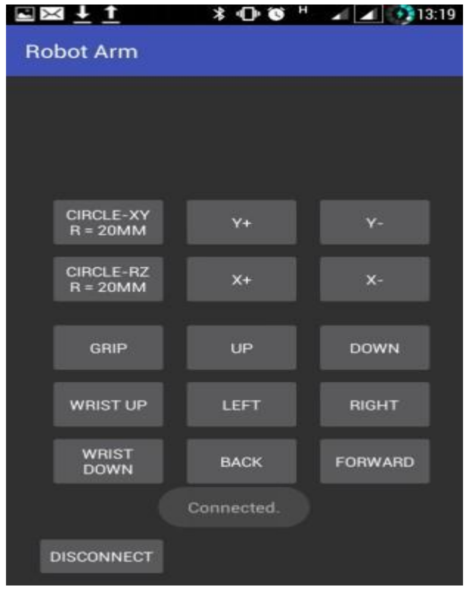


Fig. 2. The GUI display on the smartphone

The smartphone application called Bluetooth terminal can be downloaded from Google Play and was used to communicate between the Arduino and Bluetooth wireless [27]. The application emulates the serial monitor of the Arduino IDE, which can only be accessed with a computer or laptop. The difference of this terminal is that communication can be established via Bluetooth and not via a USB (Universal Serial Bus) cable connected to the computer. The serial monitor can read input from the specific individual ASCII characters [28][29]. When using smartphones, the buttons or inputs are used based on the specific character for the Arduino instead of entering a single character at a time. The character interprets the inputs as a specific decimal code. The code of each character can be looked up in the ASCII character Table 2. The programme reads the character received via the serial interface and executes a specific command. For example, if the character 'w' is sent to the Arduino via the serial interface of the Arduino, the z-coordinate of the gripper is increased at a constant rate. To stop the movement, the character 'x' is sent to the Arduino. Note that any input received from the Arduino is converted to a byte data type.

Table 2. ASCII characters and the corresponding gripper movement

ASCII decimal code	ASCII character	Gripper movement
119	W	Move along the +z axis (up)
115	S	Move along the -z axis (down)
122	Z	Left
99	C	Right
121	Y	Forward
116	T	Backward
113	Q	Move along the +y axis (up)
101	E	Move along the -y axis (down)
97	A	Move along the +x axis (up)
100	D	Move along the -x axis (down)
103	G	Open/Close gripper
104	H	Rotate wrist up
106	J	Rotate wrist down
120	X	Stop all movements

4.2 Algorithm and Programming of Arduino and HC-05

There are two different programmes used to control the movement of the robot arm; from the smartphone application the command inputs are set up from the GUI, then the Arduino IDE programme reads the inputs from the HC-05 and sends to the outputs the angle of the servo motor. The flowchart of the algorithm is shown in Figure 3.

This algorithm checked whether the Bluetooth is on or off. If the HC-05 is switched off, a message is displayed prompting the user to switch on the Bluetooth. The user must pair the smartphone with the HC-05. Then the control screen is displayed when the device is successfully connected. When one of the buttons is touched, except for the "DISCONNECT" button, the programme sends a character assigned to the button to the HC-05. The same character is sent as long as the button is pressed. When the key is released, the character "x" is sent to the HC-05. The "DISCONNECT" key simply breaks the connection with the HC-05 and ends the programme. The Arduino programme begins by moving the gripper to the starting coordinates. Then, the programme checks whether the HC-05 has been connected to a smartphone. If this is the case, the programme waits for the HC-05 to receive data from the smartphone's GUI. Otherwise, the programme terminates because there was no input source. The gripper coordinate is incremented at a constant rate in the x, y or z direction depending on the command. The positions of the servo motors are solved from the gripper coordinates with IK and finally rotated according to the solved positions [30].

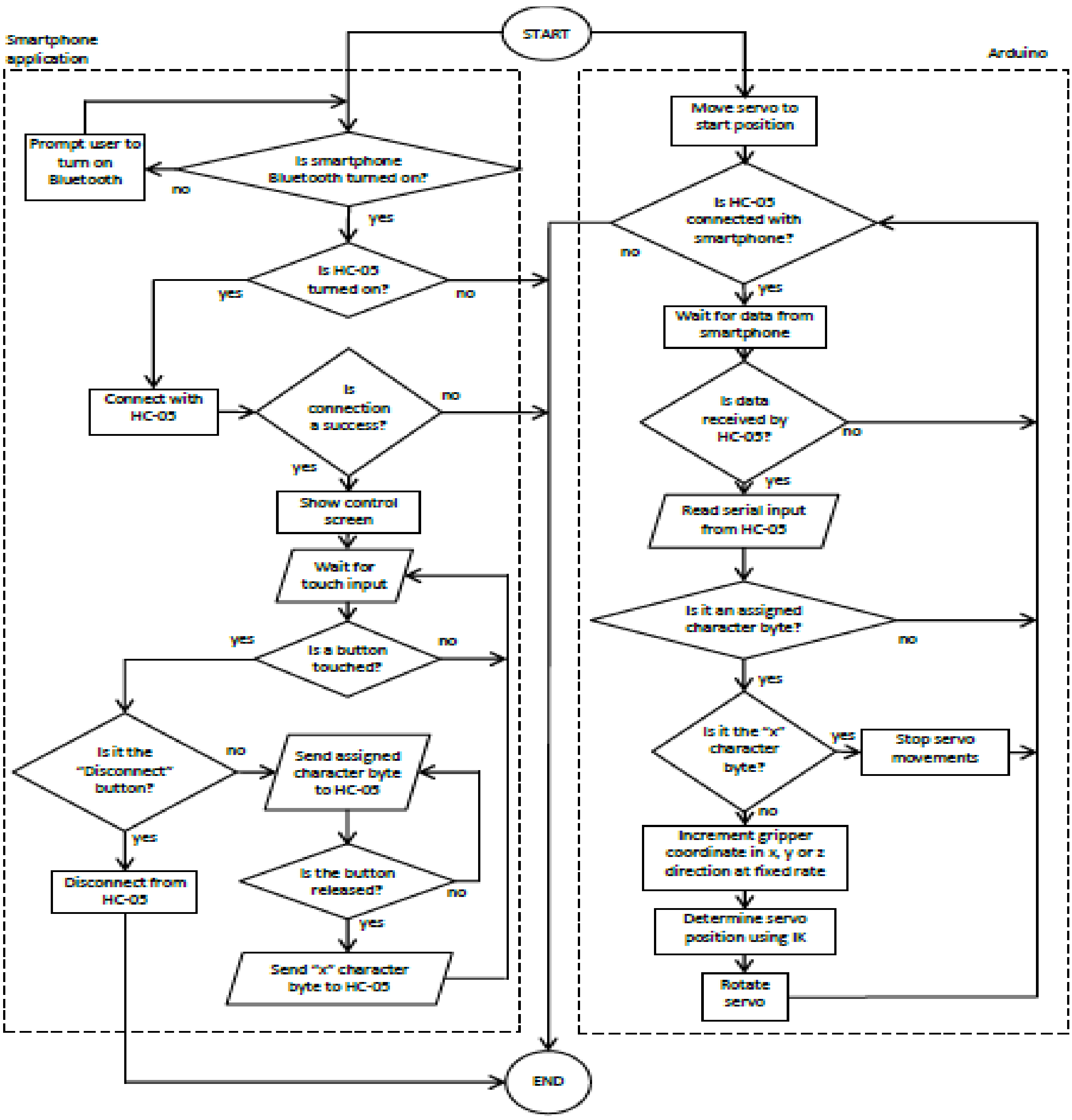
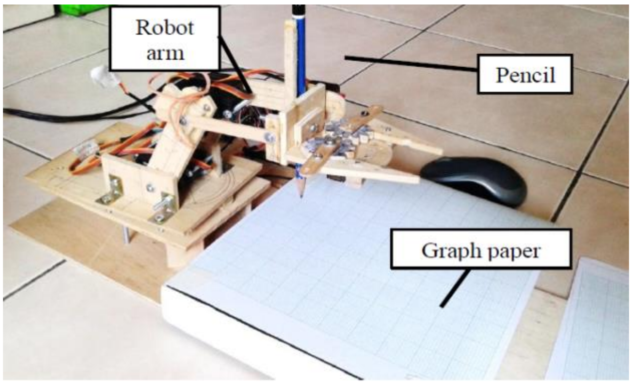


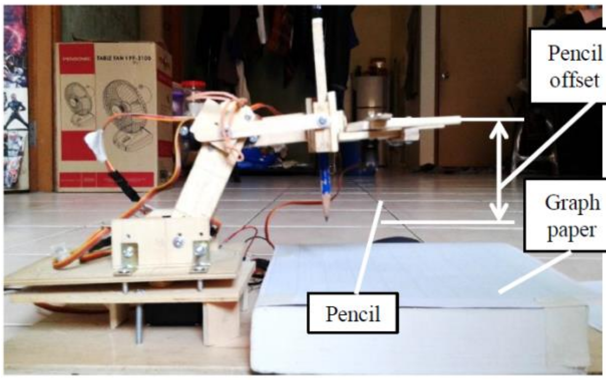
Fig. 3. Algorithm of Bluetooth connection and GUI

4. EXPERIMENT SETUP FOR ROBOTIC ARM SYSTEM

In one of the tests, the robot arm was connected to a pen at the base of the gripper to draw various basic geometric shapes such as triangle, square and circle in a certain dimension based on the original drawing. The aim of this test is to evaluate the accuracy of the robot arm's movement by implementing GUI. The pencil was placed on the wrist and not held by the gripper, as the coordinates of the gripper are on the wrist, as shown in Figure 4. The angle of the gripper was set to zero so that the pencil was perpendicular to the paper. Meanwhile, the graph paper was placed so that the grid lines of the paper coincided with the x and y axes of the robot arm. The same shape was drawn five times on different sheets of paper. The drawing of the shapes is evaluated in terms of the quality of the lines and the dimensions of the shapes. The block diagram for this system is illustrated in Figure 5.



(a)



(b)

Fig. 4. Experiment setup for drawing the shape: (a) front view, (b) side view

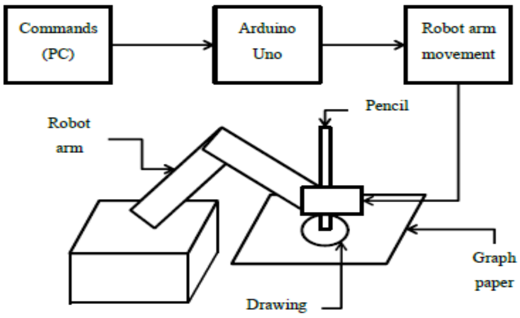


Fig.5. Block diagram for experiment setup

4.1 Test and evaluate robot arm performance

In this case the original forms had their own centre. The distances from the outside to the centre were divided by eight straight lines, which can be seen in Figure 6. D1 is the distance from the outside to the centre for the original shape, while D2 is the distance from the drawing through the robot arm to the centre. To determine the accuracy, the equation for the percentage error formulated in (1) was used.

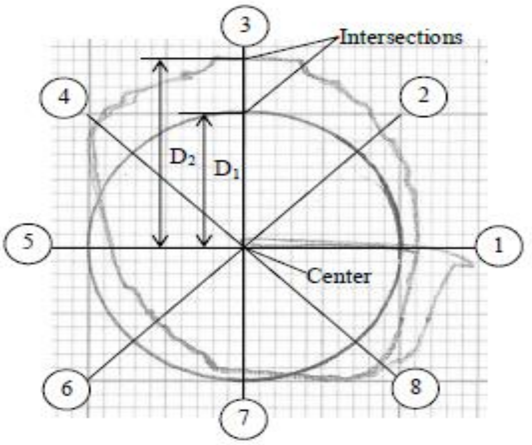


Fig. 6. The distance between the centre and the original shape of drawing by the robot arm

$$\text{Percentage error, \%} = \frac{D_1 - D_2}{D_1} \quad (1)$$

where: -

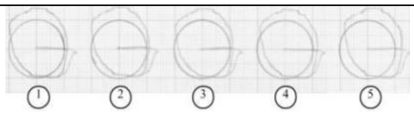
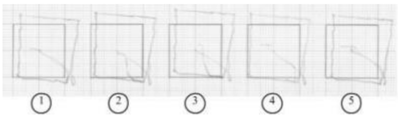
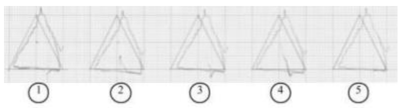
D1: Distance between centre and intersection between straight line and original drawing
D2: Distance between centre and intersection between straight line and robot arm drawing

The same procedure was repeated for the rest of the lines to obtain a total of eight errors. The errors were then tabulated.

5. RESULTS AND ANALYSIS

In this project, the prototype was fabricated based on the design that developed by CATIA. Then a simple test was carried out to evaluate the performance of controller using the smartphone graphical user interface with connection of Wi-Fi. In this experiment, there are three shapes of drawing had been done to compare with the original drawing; circle, square and triangle shapes. Table 3 shows the drawings of five circles, five squares and five triangles with a diameter of 40 mm and a height of 40 mm.

Table 3. The drawings of five circles, five squares and five triangles with a diameter of 40 mm and a height of 40 mm.

Shape	Sketch of drawing	Description
Circle		diameter (D) = 40 mm
Square		width (W) = 40 mm height (H) = 40 mm
Triangle		width (W) = 40 mm height (H) = 40 mm

Based on the drawing, the circles drawn by the robot arm were not round but elliptical. Meanwhile, the square drawings were slightly shifted to the right, rotated clockwise and had a slightly larger width and height compared to the original square drawings, but the shapes were the same. The triangles drawn by the robot arm were also shifted to the right and rotated clockwise, but have almost the same dimensions and shapes as the original triangular drawings.

To analyze the performance of the robot, the following detail is calculated for the sample in Figure 7. The drawing of the circle has been enlarged and labelled for clarity. The "O" mark indicates the intersection between the circle drawn by the robot arm and the straight lines, while the "X" mark indicates the intersection between the original circle and the straight lines. The measurements and errors were calculated and tabulated in Table 4.

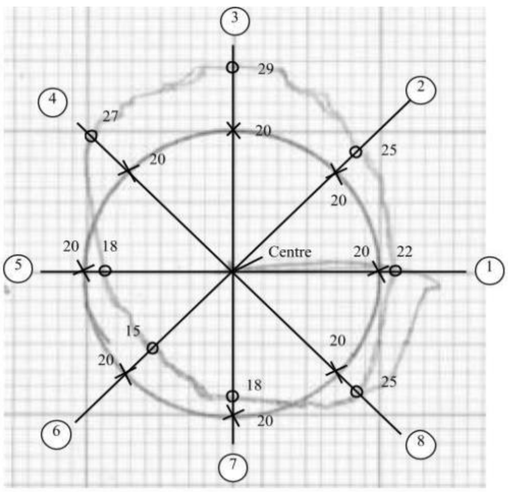


Fig. 7. Scaled drawing of Circle #2

Table 4. Measurements between centre of circle and intersections of original drawing and robot arm drawing

Measurement (mm)	Line 1	2	3	4	5	6	7	8
Original, D1	20	20	20	20	20	20	20	20
Robot arm, D2	22	25	29	27	18	15	18	25
Difference (D1- D2)	2	5	9	7	-2	-5	-2	-5
% Error	10	25	45	35	-10	-25	-10	25

As far as the errors are concerned, the results obtained are too large, more than 10%. This is because the error is mainly due to the fact that the shapes drawn by the robot are not centred on the original shapes. The movement of the robot was not smooth due to the jagged lines drawn by the robot. This is due to the poor quality of the servo motor used for the foot, shoulder and elbow. The problem with the servo motor is that the actuator rotates at a slightly greater angle than intended before returning to the correct position. This is called overshoot. The overshoot can be corrected with the help of a PID controller. To do this, the servo motor's shaft position must be read by the Arduino. However, the feedback loop in the servo motor is closed. Therefore, there is no way to read the servo motor's shaft position. The percentage error for three drawing shapes are presented in Table 5, Table 6 and Table 7.

Table 5. Percentage error for five circles between original and drawn by robot arm

Circe	Line 1	2	3	4	5	6	7	8
1	12.5	22.5	42.5	35	-15	-20	-5	25
2	10	25	45	35	-10	-25	-10	25
3	10	25	40	30	-15	-20	-10	25
4	20	25	40	20	-20	-25	-5	30
5	25	30	40	20	-30	-35	-10	30

Table 6. Percentage error for five squares between original and drawn by robot arm

Square	Line 1	2	3	4	5	6	7	8
1	25	25	35	-18	-15	-10	5	3
2	25	42	5	-25	-20	-21	-10	3
3	20	21	30	-14	-10	-7	5	0
4	35	18	30	-29	-25	-21	22	7
5	27	18	25	-25	-25	-18	21	7

Table 7. Percentage error for five triangles between original and drawn by robot arm

Triangle	Line 1	2	3	4	5	6	7	8
1	40	67	-45	-33	-40	-11	-5	-14
2	40	44	-60	-44	-50	-21	5	-11
3	50	67	-55	-44	-50	-32	0	0
4	40	56	-55	-44	-50	-29	0	-7
5	50	78	-50	-33	-50	-36	-5	-4

Eventhough the percentage is quite high, but this robot arm still capable to draw and complete the shape based on a given sketch using GUI. In addition, from the Table 4 to Table

6, it can say that the readings are consistent for five drawing for each shape.

6. CONCLUSION

In conclusion, the robot arm with five independent movements was successfully developed, which can be controlled via Bluetooth Wi-Fi communication that connected to the smartphone. It can move freely from one joint to another based on the command from the GUI of the smartphone.

To ensure good functioning of the robot, the choice of drive is very important. A good resolution affects the positioning accuracy of the gripper and the quality of the drawing of the shapes. Therefore, using a high torque stepper motor can give the robot more accuracy and balance. In terms of control, fuzzy PID technology can also be developed to improve the performance of the robot.

Moreover, the implementation of IoT in this system also can be introduced in order to use in huge applications, especially in manufacturing industries. Furthermore, it is not just for the hobbyist, but it also can be used for any small industry like picking and placing the toys in the kindergarten and mini library.

ACKNOWLEDGEMENT

This project is supported by Universiti Teknologi MARA, Cawangan Pulau Pinang, Kampus Permatang Pauh.

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