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Economical 3D-Printed Robotic Arm for Educational Training Purpose

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ABSTRACT

The advancement of Engineering technology requires universities as the frontier to educate engineering students with the latest skillset. Fast progress of Artificial Intelligence (AI) shown by the recently released of open AI such as ChatGPT, Genius, etc., has opened a new trend of technological tools. Hence, it is necessary or it can be said a must to train future engineers how to at least use these tools. Robotics and automation have long been used to assist humans in manufacture, logistic, health, and many other areas. Implementing AI into robotics creates intelligent systems which are predicted to be widely used. However, for educational institutions, especially in developing countries, the cost to afford the training robot equipment is still pricy. Here, we present designing and building of an economical robotic arm using 3D printed parts and open sources. The robot arm has six Degrees of Freedoms (DoF) and capable of lifting about 450 grams of maximum load. Some suggestions include future development are presented.

Keywords: Robot arm, Manipulator, Kinematics, Robot Operating System (ROS).

Introduction

The world has been undergoing a fourth industrial revolution that is shown by the implementation of automations, robotics, Internet of Things (IoT), and Artificial Intelligence (AI) [1, 2, 3]. With the growing and development of the technology, the needs of innovations and solutions grow accordingly. Robots play important roles in our live to perform tasks which humans cannot do in term of spectacular speed, repetitive tasks, accuracy and precision, and level of difficulties [4, 5]. Robots also can imitate human behavior, then memorize and learn that leads to deep learning machine [6, 7]. Robots can be programmed and expected to perform a specific and even a complex task since the development of technology are growing fast [8, 9].

In today's rapid advancement and implementation of AI, it may become a necessity for university engineering students to learn robotics [10]. In Indonesia, robotic arms are still considered expensive to be provided by most engineering universities especially for mechanical engineering since most of robotic arms in the market are industrial grade and quite expensive. While for learning purpose, industrial grade is less important but focuses more on how to operate the robot system and its design analysis [11, 12]. In this project, we would like to encourage universities to design and manufacture a low-cost robotic arm for educational purposes. Not only for operating the robot arm but also designing, analyzing and building by ourselves by using open resources

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such as the existing design and operating system. It is an excellent learning experience for engineering students as well as the lecturers since it encompasses many courses such as Statics, Dynamics, Engineering Components Design, Mechatronics, Computer Programming, Additive Manufacturing, etc. [13]. The design of the robot arm in this project aims for low cost and off the shelf availability of the components. Main part material and design of this robotic arm are using 3D printing technology.

A robot arm is a representation of a human arm. The robot arm contains several components, mainly links and joints. The design itself is similar to a human arm which can move in six DoF [14, 15]. Building a robotic arm whose high precision and accuracy are required to ensure the quality of production as well as its safety [16]. Therefore, the calculation of kinematics needs to be done thoroughly. On the other hand, simulation acts as a good practice before operating the real robot arm to avoid any errors and mistakes [17].

In this study, we built a 6-DoF robot arm in terms of its mechanism and application. The kinematics of a 6-DoF robot arm was developed using Robot Operating System (ROS) in a Linux system. The kinematics of the robot arm was analyzed using Denavit-Hartenberg method to be used on forward kinematics to determine the robot pose [18]. A simulation was performed prior to the implementation on the real robot arm in the form of trial and error that will be done during the development process. After successfully finishing the program development, the robot arm can be freely executed using Graphical User Interface (GUI), as well as using it automatically [19].

Methods

Designing Six DoF Robot Arm

A six DoF robot arm is essentially an articulated robot arm that moves similarly to human arm joints [20]. Shown in Figure 1, the first joint is the waist, the second joint is the shoulder, the third joint is the elbow, the fourth and fifth joints are the wrist, which moves the hand up and down about the elbow and also rotates, and the last sixth joint is the rotation for the end-effector. A gripper was chosen to be the end-effector. This combination of links and joints can move the robot in 6 DoF and form a kinematic chain.

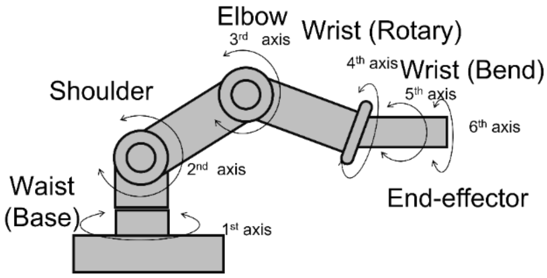

Figure 1. A six DoF Robot Arm

An isometric view of the six DoF robot arm design is presented in Figure 2 below. It was developed using SolidWorks 3D CAD. The base is a fix platform for the robot arm to stand. The first rotary axis is located on top of the base connecting the base to the shoulder. It uses a wide disk thrust bearing to handle the moment caused by the extending movement of the arm. A Nema 17 stepper motor located underneath the base is used to rotate the first axis through an increasing torque planetary gearbox. The shoulder is the second axis and uses a Nema 23 with another planetary gearbox since it handles the most moment load. The elbow is the third axis and uses a Nema 17 and a planetary gearbox as well. The fourth axis is at the rotating wrist. A Nema 17 stepper motor, located in the back of the elbow as a counter balance, used to rotate the wrist. A shaft is used to transmit the rotation from the motor to the wrist which located in the front of the elbow. The fifth axis is using a Nema 11 connected to a belt and a pulley to move the wrist bending up and down. The sixth axis uses a Nema 11 also to rotate the end effector.

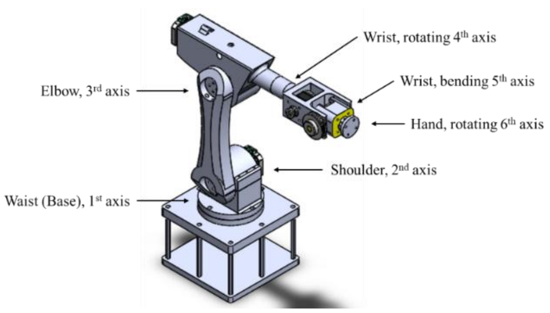

Figure 2. An isometric view of the six DoF robot arm

After rigourous design steps including motor actuator sizes, component weights, torque calculations, etc., including any iterations, the dimension were determined as shown in Figure 3 in the following. Each dimension is in milimeter. A gripper is attached as the end-effector to the rotating sixth axis.

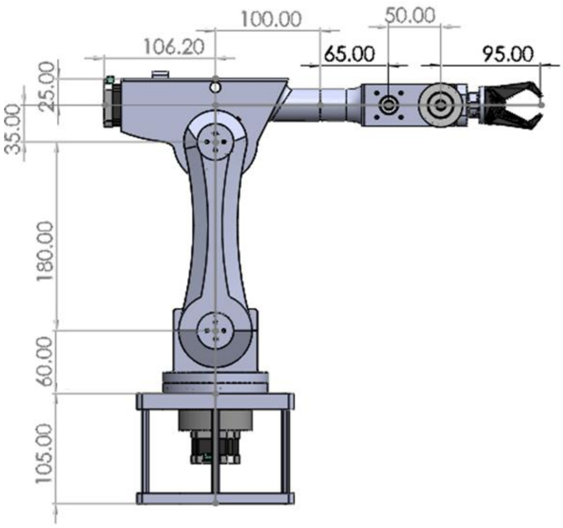

Figure 3. Dimensions of the six DoF robot arm

In calculating the required torque of each joint, a Free Body Diagram (FBD) was made. To simplify the calculations, the robot arm was divided into three sections: a red rectangle section, a blue rectangle section, and a green rectangle section, as presented in Figure 4. The red rectangle section weighs 420 grams, the blue rectangle section weighs 1065 grams, and the green rectangle section weighs 250 grams. The weight in each section includes attached parts, such as stepper motor actuator, 3D printed part, and gearbox transmission. The dimension locates the center of gravity of each section. Additionally, the gripper is designed to lift 1000 grams of weight at 480 mm length.

From the FBD analysis, the required actuator torque is about 8.26 Nm at the shoulder. Therefore, it is needed to calculate whether the output of the geared stepper motor is enough to hold the load and its body. The formula derived by Corey Rasmussen, can be used to calculate the output torque [21].

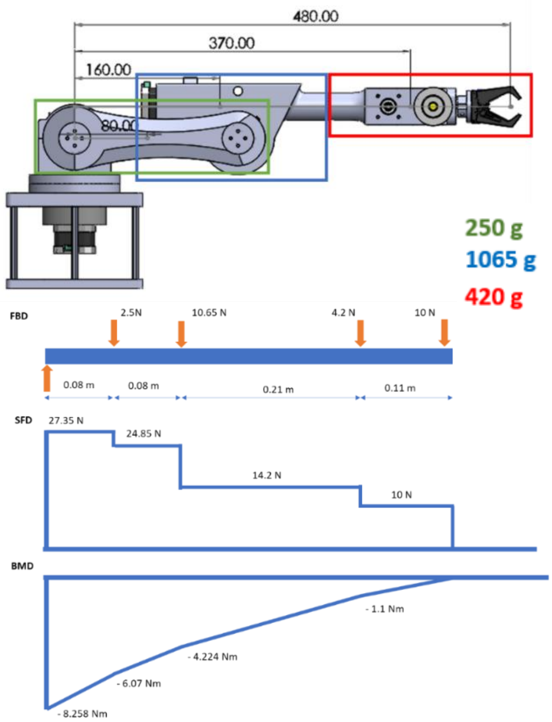

Figure 4. Free Body Diagram (FBD), Shear Force Diagram (SFD), and Bending Moment Diagram (BMD) of the six DoF robot arm

$$\frac{\omega_i}{\omega_o} = R; \quad R = \frac{T_o}{T_i} \qquad (1)$$

Equation (1) shows a ratio calculation of input and output angular velocities, and input and output torques. The speed ratio can be found by using the gear ratio because basically it is the same. For instance, if the gear is 1:16 reduced gear, the input gear will rotate 16 times while the output is only 1. The output torque for each type of stepper motor can be seen from factory data sheet. The gear ratio that will be used is 1:16 with the Nema 23 as the input, which produced 30 Ncm with 12V and 3A electric input power. Therefore, the torque output is:

$$\frac{\omega_i}{\omega_o} = R$$
$$\frac{80}{1} = R$$
$$80 = \frac{T_o}{0.4\ Nm}$$
$$T_o = 24Nm * 50\%\ (efficiency)$$
$$T_o = 12\ Nm$$

The robot arm prototype is shown in the following Figure 5. Most of the custom parts were made of 3D printed materials made of

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PLA. Most of the 3D printed components were printed with 0.2mm layer height, 25% infill density and cubic subdivision infill pattern. However, some parts are printed in 50% infill density to increase strength, such as planetary gears.

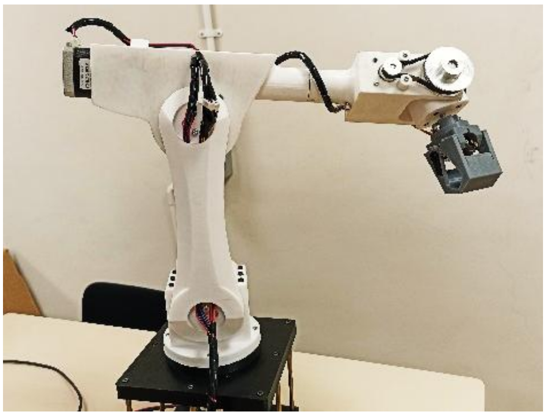


Figure 5. The 3D printed robot arm prototype

Robot Operating System (ROS)

Robot Operating System was used to build the robot movement program. ROS is an open source that can be run in a PC with Ubuntu Operating System. We can make the robot model in ROS in accordance to the Unified Robot Description Format (URDF) [19].

The process begins from a reference point of the robot arm, that is the base, as seen Figure 6, shown as a blue color cubic shape. This is connected to the shoulder link by the first joint. In between of every link, there exists a joint so that each link can move. The joints are in accordance with description in Figure 1, which are the waist, shoulder, elbow, two wrist joints, and hand. The gripper, indicated as two blue small cylinders at the top end, uses different joint type, which is prismatic or sliding joint. Other than setting up the robot appearance, the user can also setup the physical parameters for the robot model.

Graphic User Interface (GUI)

In order to simplify the robot operation, a Graphical User Interface (GUI) comes as a handy tool. Before that, a module named "rqt" needs to be installed because it is not included in ROS. The first thing to do is to design a user interface using QT designer. It offers several widgets such as push button, sliders, line edits, and many more, shown in the widget box. Figure 7 shows the interface of the QT designer for designing the GUI.

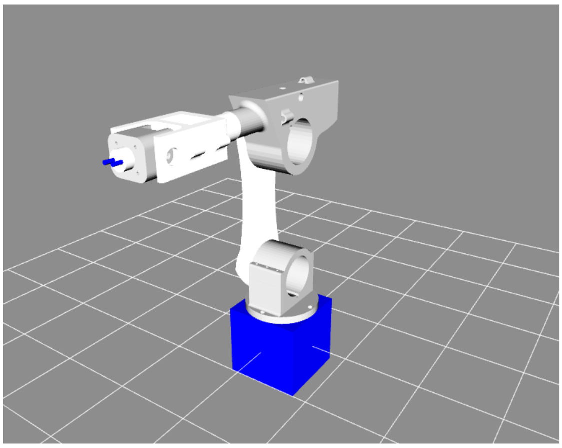


Figure 6. The robot model built upon URDF in ROS

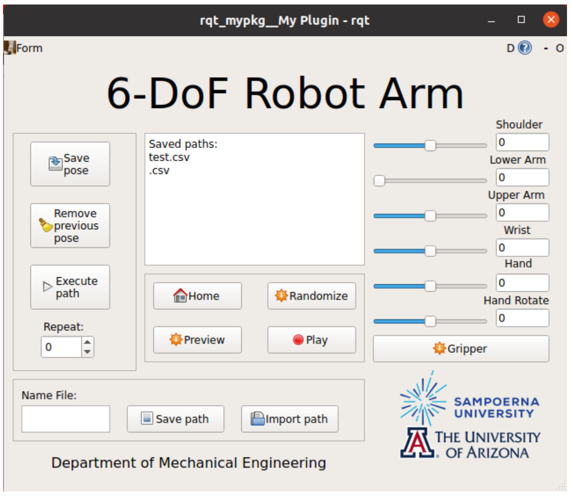
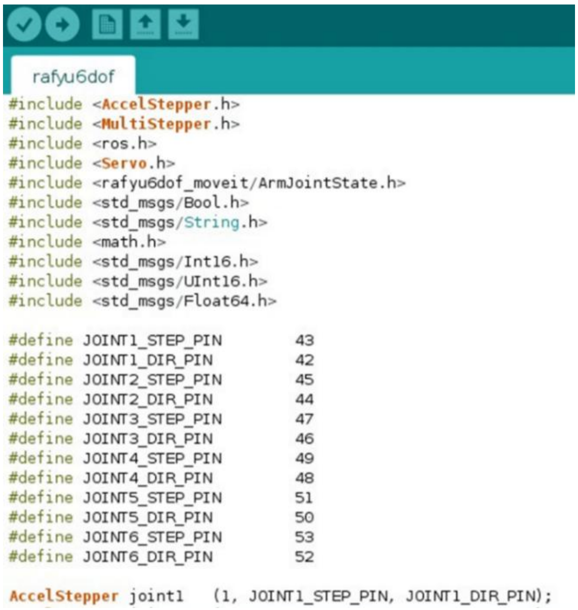


Figure 7. GUI for operating the robot arm

The GUI provides several functions and buttons that command the robot to move as desired. It provides two controlling methods: manual and automatic. Using the manual control, a user can operate each joint using slider on the left side of the GUI. The number on the rightmost shows the angle from initial position, which is upright. The maximum and the minimum angle for all the joints are set to 90 degrees and -90 degrees respectively, except for the second joint or the shoulder where the minimum angel is set to 0 degree. After deciding the angle of each joint, the user may preview the robot path and pose shown in RVIZ. Finally, the robot can be executed by pressing the play button. For the automatic control, the user can define the robot pose manually using the slider, then save the robot pose using “save pose” button. The button can be used consecutively to save several poses. With the saved poses, the robot can be operated automatically according to the save order.

Arduino IDE

The communication between the robot arm and the controller, in this case the PC, is connected by an Arduino microcontroller. In Arduino, a user can assign the direction and step pin number and the servo pin number, as well as set the maximum stepper speed. Since the program is built over ROS, rosserial_arduino needs to be installed and used, so that ROS can communicate with the Arduino. In Arduino IDE, it can be done by including *#include <ros.h>* and *#include <std_msgs/String.h>* so that the rosserial_arduino library can be loaded. Figure 8 shows the Arduino program to connect ROS and the robot arm.



```
rafyu6dof
#include <AccelStepper.h>
#include <MultiStepper.h>
#include <ros.h>
#include <Servo.h>
#include <rafyu6dof_moveit/ArmJointState.h>
#include <std_msgs/Bool.h>
#include <std_msgs/String.h>
#include <math.h>
#include <std_msgs/Int16.h>
#include <std_msgs/UInt16.h>
#include <std_msgs/Float64.h>

#define JOINT1_STEP_PIN      43
#define JOINT1_DIR_PIN       42
#define JOINT2_STEP_PIN      45
#define JOINT2_DIR_PIN       44
#define JOINT3_STEP_PIN      47
#define JOINT3_DIR_PIN       46
#define JOINT4_STEP_PIN      49
#define JOINT4_DIR_PIN       48
#define JOINT5_STEP_PIN      51
#define JOINT5_DIR_PIN       50
#define JOINT6_STEP_PIN      53
#define JOINT6_DIR_PIN       52

AccelStepper joint1  (1, JOINT1_STEP_PIN, JOINT1_DIR_PIN);
```

Figure 8. Arduino program ROS to robot arm

Kinematic Analysis Using Denavit – Hartenberg Method

In order to build the mathematical model of robot kinematics, the parameters of the robot, such as the link and the joints, need to be known. Denavit-Hartenberg (DH) is commonly used to calculate the robot movement and provides the robot parameters. DH contains four parameters, which are link length (a), link twist (α), link offset (d), and joint angle (θ). Link length is described as the distance from $z_{i-1}\ to\ z_i$ along x_i. Link twist measures the angle from $z_{i-1}\ to\ z_i$ about x_i. link offset expresses the distance from $x_{i-1}\ to\ x_i$ along z_{i-1}. Finally, joint angle describes the angle from $x_{i-1}\ to\ x_i$ about z_{i-1} [22]. Constructing DH parameters requires to follow the convention as follows: a z-axis as the rotation axis, an x-axis is perpendicular to z-axis, and a y-axis follows according to right-hand rule with respect to the z-axis and the x-axis.

The kinematic analysis starts by analyzing the robot dimension, especially the distance between each joint. Then, assign frames to the joints of the robot arm. This is shown in Figure 9.

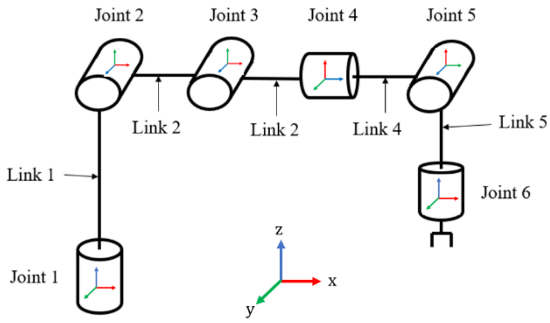


Figure 9. Robot arm frame and axis assignments

The DH parameters are shown in Table 1.

Table 1. DH parameters

Axis (i)	$a_i\ (mm)$	$\alpha_i\ (deg)$	$d_i (mm)$	$\theta_i\ (deg)$
1	0	90	165	θ_1
2	180	0	0	θ_2
3	35	90	0	θ_3
4	0	−90	215	θ_4
5	0	90	0	θ_5
6	0	0	95	θ_6

$$T_i^0 = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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After completing the DH parameter table, the kinematic analysis continues to the calculation of transformation matrix for link i as follows:

For T_1^0 where $i = 1,\ a_1 = 0,\ \alpha_i = 90°$, and $d_1 = 165$,

$$T_1^0 = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & 165 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For T_2^1 where $i = 2,\ a_2 = 180,\ \alpha_2 = 0$, and $d_2 = 0$,

$$T_2^1 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 180\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & 180\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For T_3^2 where $i = 3,\ a_3 = 35,\ \alpha_3 = 90$, and $d_3 = 0$,

$$T_3^2 = \begin{bmatrix} \cos\theta_3 & 0 & \sin\theta_3 & 35\cos\theta_3 \\ \sin\theta_3 & 0 & -\cos\theta_3 & 35\sin\theta_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For T_4^3 where $i = 4,\ a_4 = 0,\ \alpha_4 = -90$, and $d_4 = 215$,

$$T_4^3 = \begin{bmatrix} \cos\theta_4 & 0 & -\sin\theta_4 & 0 \\ \sin\theta_4 & 0 & \cos\theta_4 & 0 \\ 0 & -1 & 0 & 215 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For T_5^4 where $i = 5,\ a_4 = 0,\ \alpha_4 = 90$, and $d_4 = 0$,

$$T_5^4 = \begin{bmatrix} \cos\theta_5 & 0 & \sin\theta_5 & 0 \\ \sin\theta_5 & 0 & -\cos\theta_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For T_6^5 where $i = 6,\ a_4 = 0,\ \alpha_4 = 0$, and $d_4 = 95$,

$$T_6^5 = \begin{bmatrix} \cos\theta_6 & -\sin\theta_6 & 0 & 0 \\ \sin\theta_6 & \cos\theta_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Multiplying all the matrices using the formula below:

$$T_6^0 = T_1^0 \times T_2^1 \times T_3^2 \times T_4^3 \times T_5^4 \times T_6^5 \qquad (2)$$

And taking only the coordinates of the end effector results in:

$$\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} 180ac + 215acf - 35adf + 35ace + 215ade \\ 180bc + 215bcf - 35bdf + 35bce + 215bde \\ 180d + 215cf - 35df + 35ce + 215de + 165 \end{bmatrix}$$

where

$a = cos\,\theta_1$ $\quad d = sin\,\theta_2$
$b = sin\,\theta_1$ $\quad e = cos\,\theta_3$
$c = cos\,\theta_2$ $\quad f = sin\,\theta_3$

Kinematics Simulation

The DH parameters can be used in MATLAB to simulate robot poses using Robotics Toolbox. Here, the parameters are written on each link, and the joint angle can also be adjusted. One example of the robot pose in simulation and implementation is shown in Figure 10.

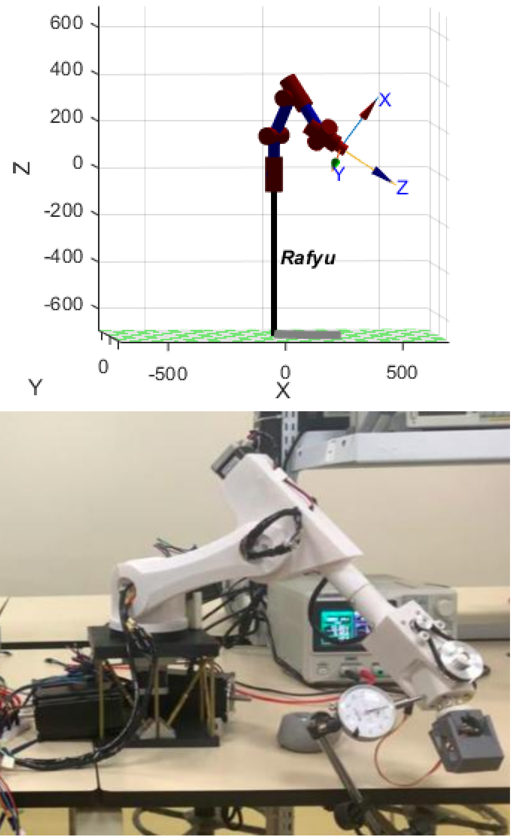


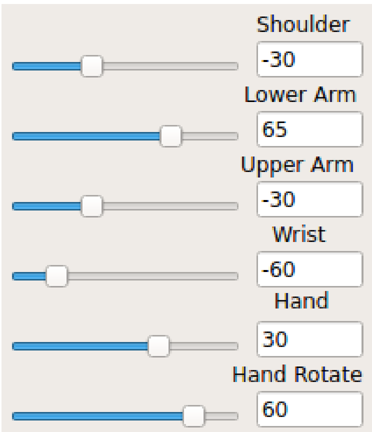
Figure 10. An example of a robot pose on simulation and experiment

Repeatability Test

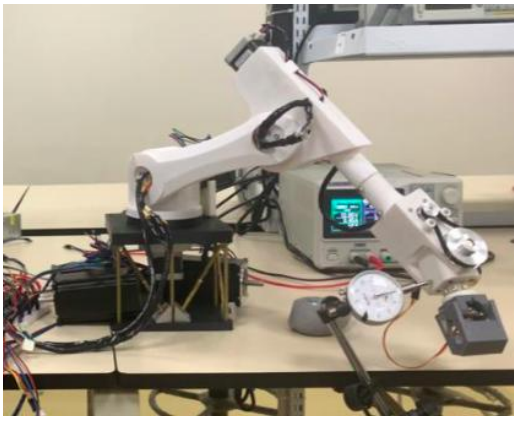
The repeatability test is meant to measure how well the robot arm maintains its accuracy throughout several works. The measuring tool used was a dial indicator which has an accuracy up to 0.01 mm, as shown in Figure 11. This test was conducted two times where the robot arm was executed in two different poses. The first pose was the robot arm going downward, and the second pose was the robot arm going upward.

Figure 11. Dial indicator used to measure the repeatability of the robot arm

The first robot pose was moving the end effector downward. It started from the initial position, then set the angle of each joint so that the robot moved to desired position. This position cycle was repeated for 11 times during the test. The angle for each joint is shown in Figure 12 (a), while the robot pose for the first test is shown in Figure 12 (b).



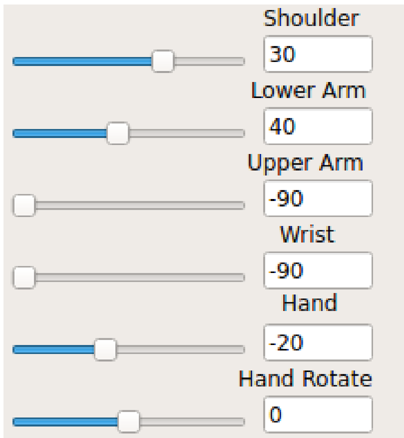
(a)



(b)

Figure 12. (a) Joint angles, and (b) The robot pose, for the first repeatability test

The second test was about moving the end effector upward. It started from the initial position, then set the angle of each joint so that the robot moved to desired position. This position cycle was repeated for 11 times during the test. The angle for each joint is shown in Figure 13 (a), while the robot pose for the first test is shown in Figure 13 (b).



(a)

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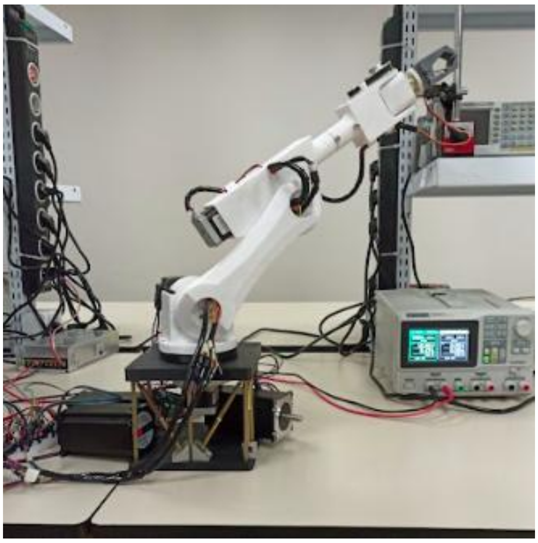

(b)

Figure 13. (a) Joint angles, and (b) The robot pose, for the second repeatability test

Results and Discussions

The repeatability test results show the difference between the initial set up and each test. The dial indicator readings display the minimum value for the first test is 0.04 mm, while the maximum value is 0.6 mm. For the second test, the minimum difference value is 0.1 mm, and the maximum value is 0.36 mm. The complete result for the repeatability test is shown in Table 2.

Table 2. Repeatability test results

Number of Test	1st test (mm)	2nd test (mm)
1	0.22	0.2
2	0.6	0.13
3	0.05	0.15
4	0.1	0.15
5	0.05	0.28
6	0.1	0.1
7	0.06	0.26
8	0.18	0.2
9	0.04	0.22
10	0.32	0.36
11	0.48	0.3

After calculating the average value, it can be concluded that the average repeatability for the first test is 0.2 mm, while for the second test is 0.21 mm. Compared to industrial grade robot arm, these repeatability valueas are about 1 order higher. But considering for educational training purpose, these are quite good results. Besides, the standard deviation for the first test is 0.19 mm, while the standard deviation for the second test is lower, that is 0.08 mm.

Conclusions

The robot arm was designed and built using mostly 3D printed PLA parts and off the shelf easy to find parts such as stepper motors, bearing, bolts, and nuts. It has six degrees of freedoms robot arm, controlled by ROS which is an open source and easy set and operate with simple GUI and interactive model simulation. It also employs an Arduino microcontroller for connecting the robot arm and ROS. The combinations of these put the budget to build a training robot arm at an economically low cost. The kinematics of the robot arm is based on forward kinematics, where it was constructed by Denavit-Hartenberg parameters. Building DH parameters was done by analyzing each link and joint of the robot and completing the DH table containing link length, link twist, link offset, and joint angle. The forward kinematics analysis was done by applying the parameters to transformation matrices to find the coordinates of end effector. The robot arm was evaluated for its repeatability. The test was done in two poses, where the end effector was upward and downward. The repeatability tests ranges from 0.04 to 0.6 mm for the first test, and 0.1 to 0.36 mm for the second test.

Future recommendations include using stronger materials for 3D printed parts such as ABS instead of PLA especially for planetary gears inside the gearbox. Metal gearbox will perform better in term of long run durability.

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Author Contributions
"Conceptualization, Wahyu Nur Budiarta and Raffy Frandito, Budi Hadisujoto; methodology, Wahyu Nur Budiarta, Raffy Frandito, Budi Hadisujoto, Farid Triawan, Kushendarsyah Saptaji and Djati Wibowo; software, Raffy Frandito, Djati Wibowo; validation, Wahyu Nur Budiarta, Raffy Frandito and Budi Hadisujoto; formal analysis, Wahyu Nur Budiarta, Budi Hadisujoto, Farid Triawan; investigation, Wahyu Nur Budiarta and Raffy Frandito, Budi Hadisujoto, Kushendarsyah Saptaji and Djati Wibowo, writing—original draft preparation, Wahyu Nur Budiarta, Raffy Frandito, Budi Hadisujoto and Janice Ong; writing—review and editing, Budi Hadisujoto and Janice Ong; visualization, Wahyu Nur Budiarta, Raffy Frandito, Budi Hadisujoto and Janice Ong; supervision, Budi Hadisujoto, Farid Triawan, Kushendarsyah Saptaji and Djati Wibowo; project administration, Budi Hadisujoto; funding acquisition, Wahyu Nur Budiarta and Raffy Frandito.

Conflicts of Interest
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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