3D Printed 6-Axis Collaborative Arm Robot Using Force Limiting Feature for Service Robot

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Abstract. Collaborative arm robot is a robot that can work alongside humans. By using force limiting (FL) feature, where the force of the arm robot is limited and controlled, the robot can sense collision and stop its movement when it occurs. The idea is to apply the mentioned concept for service purposes. In this research a 6-axis arm robot with collision detection is developed. The design of the arm robot adopted the design of Universal Robot’s UR3 with each joint capable of 360° rotation. The design approach is chosen for its flexibility to work in tight space with a maximum reach of half meter, as it is intended to work closely with human. This initial version robot is not intended to carry heavy load or move at high precision. With a maximum load of one Kg, this arm robot targets numerous applications that help human to do complex repetitive tasks, extend the reach of human operators, and help humans on many daily chores that usually does not involve heavy loads. The whole frame, which also serve as the cover of the robot, was made by 3D printing with multiple materials that fit to the strength and temperature requirement at each part of the robot. In order to detect collision, the arm robot employed smart servos at each joint with the ability to detect overcurrent and overvoltage, which allow the implementation of force limiting (FL) feature that will stop the robot in case of collision. The resulting arm robot managed to lift 1 kg load and able stop its movement in the event of collision. Future research to improve the movement precision of the arm robot by adaptive methods is promising.

Keyword: Arm robot; Collaborative; Service Robot; 3D Printing; Force Limiting.

1. Introduction

The concept of collaborative robot is basically where humans and robot can cooperate and work together to finish certain tasks [1]. This concept is very useful because there are some things that a robot cannot do better than humans, and by combining the perceptual sense of humans with the pin point accuracy, speed, and durability of a robot, certain tasks will be done more efficiently and will have better results [2].

Collaborative arm robot enabled humans to interact physically with an arm robot in one working space. There are four types of collaborative robot operation that meets the standards of ISO 10218 [3]. This project propose to apply force limiting (FL) operation type, where force limitation will applied to the arm robot, as a result, there will not be any extra force if the movement of the arm robot are...
blocked or if there is collision with any object or human. However, there are shortcomings of using force limiting feature. By using this force limiting method, each joint needs to use a low speed motor so the motor can stop after collision and not harm the environment [4].

According to some unstructured interviews with two representatives of arm robot companies in Indonesia, it is found that collaborative arm robots have not been used widely in manufacturing industry in Indonesia. It is mainly because of the slower cycle time of collaborative arm robot in general, which does not meet the standards of most manufacturing industries that require fast cycle time.

However, there are a lot of possible applications for collaborative arm robots, one of them is service robots [5]. There are some examples of collaborative arm robot applications as service robot, for example: in the field of catering, the arm robot can help the chef to prepare the food ingredients while the chef cooks. In addition, in cleaning services area such as helping human to sweep, and social service such as helping people with special needs by feeding or taking stuffs. Applying collaborative arm robot in service area can also attract people around stores, such as in a restaurant, a show where the chef and robot cooks together will attract customers to see the attraction and eat.

This research aimed to develop a 6-axis collaborative arm robot with force limiting feature, and a frame that is built entirely by 3D printing to reduce weight and complexity. The resulting arm robot can be used in industries where service robot can be beneficial.

2. Mechanical Design and Stress Analysis
Mechanical drawing for arm robot is designed based on six axis service arm robot specification that suitable in Indonesia. Six axis service arm robot specification is shown in Table 1.

| Table 1. 6 axis robot arm specification |
|----------------------------------------|
| Payload:                               | 1 kg |
| Working area:                          | 1 m  |
| Degrees of freedom:                    | 6 rotating joints |

Payload is a weight of load that arm robot can lift with maximum speed. With a one-kilogram payload, arm robot will be able to sustain to lift many things. In cookery section, one kilogram can lift spatula, kitchen knife, and food material. In cleaning section, one kilogram can lift cleaning equipment like mops, brushes, sponges, and windows cleaning equipment. In rehabilitation section, one kilogram can lift spoon and fork to feed people with special needs. Working area is area arm robot can be reached. According interview with arm robot companies, common arm robot working area suitable for industries in Indonesia is around one meter. Degrees of freedom is classified based on total number of joint. With 6 rotating joints, arm robot can travel through X-Y-Z axes and turn around each axis.

UR3 robot arm from the company Universal Robot in Figure 1 becomes the reference for the robot arm model in this research. This model was chosen because each joint can rotate +/- 360 degrees. It is possible because at the connection from one link to the next one, there is a horizontal offset that makes the two parallel links never touch each other when the joint between them rotate. For example, between the second and third links, there is a horizontal distance of d4 which enable the third link to rotate around joint 3 freely without hitting the previous link. This structure is used in all the joints between links in the arm robot. This approach improves the flexibility of the arm robot to move in limited space compared to conventional design where two consecutive links are inline vertically, because the end effector can be placed close to the center of the robot at various height.
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Figure 2. Developed Collaborative Arm Robot

Figure 3. Developed Collaborative Arm Robot Stress Analysis

Figure 1. UR3 Universal Robot Design and Dimension [6]

Figure 2 is the detailed design and dimension of the robot in this research. The size of each joint is designed according to the dimensions of the selected servo motor. The target diameter of the working area is one meter, hence the length of the second to fifth joints are calculated to achieve a target reach of 500mm while maintaining the proportion in the reference design.

The material used for the collaborative arm robots is PLA and ABS and using the 3D printing process to make the parts of the collaborative arm robots, the use of 3D printing is due to some parts of the robot arm that are complicated in shape. PLA material is used in parts that are not in contact with the servo, because the PLA is less resistant to heat. ABS is used on parts that come into direct contact with the servo, because this material is more resistant to heat [7].

Stress analysis is done to evaluate the mechanical properties of materials and strain of plastic properties [8]. Stress analysis (Figure 3) is carried out using Inventor program that can provide the results of stress analysis of objects that are made and give the force according to the desired place.

3. Mechanical Design and Stress Analysis
Kinematic analysis is a study about geometry and movement of the arm robot according to the systems reference coordinates as a function, regardless of its force and moment that causes the movement [9].
Transformation matrix (T) from the systems reference coordinate from link - (i) until link - (i-1) can also be called as link transformation matrix, where the general equation is as follows:

\[
i^{-1}T = \begin{bmatrix}
    \cos \theta_i & -\sin \theta_i & 0 & a_{i-1} \\
    \sin \theta_i \cos(a_{i-1}) & \cos \theta_i \cos(a_{i-1}) & -\sin(a_{i-1}) & 0 \\
    \sin \theta_i \sin(a_{i-1}) & \cos \theta_i \sin(a_{i-1}) & \cos(a_{i-1}) & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]  

(1)

For n total link, link transformation matrix (T) can be written as:

\[
0^nT = 0^1T0^2T \ldots 0^{-1}T
\]  

(2)

Denavit-Hartenberg parameter or as usually known as DH-Parameter is a way to describe the arm robot kinematically by using 4 parameters for each link, where 2 parameters describes the link itself, and the other 2 is used to describe the connection between its link and the other link [10]. The design of the arm robot is similar to Universal Robot’s UR3 and so because of that the DH-Parameter that are used also comes from UR3 robot. Each Link’s transformation matrix (T) are obtained by inserting the parameters from the D-H table into the link transformation matrix general equation.

| Table 2. Denavit-Hartenberg Parameter |
|--------------------------------------|
| i | \(a_{i-1}\) | \(a_{i-1}\) | \(d_i\) | \(\theta_i\) |
|---|---|---|---|---|
| 1 | 0 | 0 | \(d_1\) | \(\theta_1\) |
| 2 | \(a_1 = 90^\circ\) | 0 | 0 | \(\theta_2\) |
| 3 | 0 | \(a_2\) | 0 | \(\theta_3\) |
| 4 | 0 | \(a_3\) | \(d_4\) | \(\theta_4\) |
| 5 | \(a_4 = 90^\circ\) | 0 | \(d_5\) | \(\theta_5\) |
| 6 | \(a_5 = -90^\circ\) | 0 | \(d_6\) | \(\theta_6\) |

Dynamic analysis of arm robot deals with the mathematical formulations of the equations of robot arm motion[9]. The dynamic equation of motion is a set of mathematical equations describing the dynamic behavior of the manipulator. The equation then can be used for computer simulation of the movement, making the control of the arm robot, and can be used to analyze the design and structure of the arm robot. As in this case, dynamic analysis is used to determine the required power of the servo.

The actual dynamic model of the arm robot can be obtained from known physical laws such as the laws of Newtonian mechanics and Lagrangian mechanics, this leads to various development of the dynamic equations of motion. The method that are commonly used to get the dynamic equation of motion are the conventional Lagrange-Euler or Newton-Euler approach. There are various of method that can be used to find the dynamic equation of motion that are obtained from the two conventional method such as, Uicker’s Lagrange-Euler equations, Bejezy, Hollerbach’s Recrusive-Lagrange equation, Luh’s Newton-Euler equation, dan Lee’s generalized d’Alembert equation.

In this project, the dynamic analysis equation are obtained using the Lagrange-Euler method, because in this project there are no need for speed in computation and Lagrange-Euler method are known for its systematic and simple approach, where the down side of this method is its computation speed. The general equation of Lagrange-Euler dynamics are as follows:

\[
\frac{d}{dt} \left( \frac{\partial L}{\partial q_i'} \right) - \frac{\partial L}{\partial q_i} = \tau_i \quad i = 1, 2, \ldots, n
\]  

(3)

Where

\[
L = \text{Lagrangian function} \quad K = \text{kinetic energy} \quad P = \text{potential energy} \quad P = \text{total potential energy}
\]

\[
q_i = \text{generalized coordinates}
\]
\[ q_i = \text{first time derivative of the generalized coordinate}, \quad q_i \]
\[ \tau_i = \text{generalized force applied to the system at joint } i \text{ to drive link } i \]

The dynamic and kinematic analysis are calculated using Matlab software. The calculation is done using a program that are made for the robot Jaco2 6 DOF [12] which have a slight difference in dimension and shape, but it has the same number of axis. After tweaking the parameters that are needed to match the design and checking the theory behind it, the max torque can be calculated, and the results are shown in Table 3.

### Table 3. Torque Calculation Results (Without Servo Weight)

| \( \tau_n \) | Torque (Nm) | Torque (Nm), at speed = 0 rpm |
|---|---|---|
| \( \tau_1 \) | 2.062 | 0 |
| \( \tau_2 \) | 13.435 | 13.810 |
| \( \tau_3 \) | 6.3672 | 5.810 |
| \( \tau_4 \) | 1.3447 | 1.110 |
| \( \tau_5 \) | 0.898 | 0.710 |
| \( \tau_6 \) | 0.008 | 0 |

The first results are used to decide the servo specifications in each joint. As the servos are decided, servos weight is included into the calculation with the results tabulated in Table 4.

### Table 4. Torque Calculation Results (With Servo Weight)

| \( \tau_n \) | Torque (Nm) | Torque (Nm), at speed = 0 rpm |
|---|---|---|
| \( \tau_1 \) | 2.577 | 0 |
| \( \tau_2 \) | 17.738 | 18.253 |
| \( \tau_3 \) | 7.915 | 7.253 |
| \( \tau_4 \) | 1.402 | 1.153 |
| \( \tau_5 \) | 0.924 | 0.730 |
| \( \tau_6 \) | 0.008 | 0 |

### 4. Electrical Design

In the drive section, the servo motor used is the Dynamixel smart servomotor. Dynamixel servo motor has the ability to detect present current and voltage at the dc motor. The current and voltage measurement feature are used to detect obstacles that block the robot’s movement. The communication standard used in Dynamixel servo are TTL and RS485 depending on the model of the servo motor. In addition to the servo motor there are also other devices used to provide communication and power supply interface. The USB to Serial Module (Downloader) is used to interface between the PC USB port and Controller in order to download the sequence of instructions into the controller. The controller stores and runs the sequence of instructions for the servo motors. Electric current is channeled from the power supply through the Controller to all servo motors. Figure 4 shows the block diagram of the electronic design.
5. Experiment Result
The frame of the 6-axis arm robot is produced with 3d printing with ABS and PLA materials. Figure 5 shows the arm robot after assembly and wiring of all the servos to the controller. All the joint 1, 2, 4, 5, and 6 can travel 360°, except joint 3 can travel 300° only.

For payload testing, 10 pieces of 100 grams load used. Figure 6 shows the experiment where the developed arm robot could lift 1 kg of load.

In order to control the servos, the Roboplus 1.0 is used to drive the 6 servos. To make a force limiting system, the internal sensor in the dynamixel smart servos is used, that are the present load (current) sensor and the present voltage sensor. In the first experiment, the robot arm was tested 10 times using a weight sensor (Present Load). The purpose of this experiment is to test whether the controller can stop the arm robot upon collision with a barrier or obstacle. The load sensor gives load data at the joint. However, the data from the experiment showed that the load data is too noisy, hence...
ineffective to detect collision and stop the arm robot. Figure 7 shows the profile of the load sensor data with an dashed line that shows the impact time.

![Figure 7. Present Load (current) vs Time](image)

At the second experiment, the robot arm is tested with collision for 10 times while collecting the data from the voltage sensor (Present Voltage). From the experiment data, it can be shown that the voltage values on all servo arm robots are more stable compared to the current data and can be used to stop the arm robot upon collision with obstacles. It can be shown in Figure 8, that the voltage value is small when the movement of the servo motor is slowed down by collision. Below is a graphic of voltage sensor data with an orange line that shows the impact time. By using the voltage data, a program is written in the Roboplus Task to stop the movement of the arm robot when the present voltage value is less than a pre-calibrated threshold.

![Figure 8. Present Voltage vs Time](image)

**Conclusions**
The proposed arm robot has been designed with a reference to UR5 manipulator to obtain similar movement flexibility. The kinematic and dynamic simulation has been carried out to estimate the
maximum torque required in all joints, in order to determine the servo motor at all joints. The arm robot has been developed with 3D-printed structure with ABS and PLA plastic materials and Dynamixel servo motor, along with the electrical system required to control the movement of the arm robot.

Based on the experiments, it is found that the arm robot managed to carry the intended one kg of load at the end of the manipulator. It is also found that the arm robot can be programmed to stop in the event of collision during movement. The best method to detect collision is to use the present voltage sensor, due to more stable value of the voltage at the servo motor compared to the erratic measurement from the current sensor at the servo motor.

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