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# DESIGN AND DEVELOPMENT OF A DELTA ROBOT FOR PICK AND PLACE APPLICATION USING GEOMETRIC ANALYSIS METHOD

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**Abstract**— This paper discusses the development work to design and build a three-axes Delta robot for pick and place applications. A 3D model of the Delta robot was designed using SolidWorks. The kinematics algorithm of the robot was formulated using geometric analysis method. The 3D model of the robot was subsequently imported into CoppeliaSim robotic simulation software to test the feasibility of the design and its kinematics algorithm. The prototype of the Delta robot was then built after a successful simulation test. To control the robot, a software of robotic manipulation and control was written in C# language using Microsoft.Net framework. Experiments were carried out to test the performance of the prototype. As a result, the Delta robot was able to perform its motion at a repeatability of 1.49 mm with positioning accuracy of 98.1%. In conclusion, the prototype of the Delta robot has shown high repeatability and accuracy in its motion.

## I. Introduction

Pick and place operation using industrial robots is currently an essential element in modern manufacturing centres as they replace human labour in executing highly repetitive tasks [1]. With their high speed and precise positioning capability, industrial robots can greatly improve the efficiency and productivity of a manufacturing system [2]. There are many useful applications of pick and place robots in manufacturing sector for example parts arranging, product screening, product packing, layout changing, and etc. [3]. However, robots still generally have a functional disadvantage compared to human workers which is the ability to adapt to changes as the control method used are usually pre-programmed [4].

Industrial robotic manipulators can be categorized into two groups according to their mechanism, namely serial and parallel manipulators. Delta robot is one of the parallel manipulators and it is commonly used in pick and place applications due to its agility and precision. Delta robot has high rigidity, compact size, high control bandwidth, low error accumulation, high dexterity which are suitable for positioning control system [5].

Several challenges require thorough consideration when designing a Delta robot and its motion control system. First, the design and dimensions of its mechanical joints and linkages. Second, a kinematic algorithm that is feasible with reference to its mechanical design. Third, its ability to achieve an operational performance that is precise and high repeatability in positioning.

Fourth, its trajectory profile that is smooth and collision free.

The aim of this paper is to design and build a Delta robot with high positioning ability for pick and place application. To achieve the aim, the following objectives were formulated. First, to formulate forward and inverse kinematics control algorithm for the Delta robot. Second, to test the feasibility of the mechanical design and the formulated kinematics algorithm of the Delta robot in a robotic software. Third, to construct a prototype and evaluate the performance of the Delta robot.

## II. Literature Review

The structure of Delta robot consists of an end-effector i.e. a travelling platform that is linked to the base platform by three arms where each arm consists of a bicep (actuating arm) and two forearm (passive arm) links as illustrated in Figure 1. Each forearm pairs form a parallelogram that are connected with four ball joints. Thus, the end-effector is able to stay parallel to the fixed base platform which located at the top. The end-effector of the Delta robot is controlled by three motor joints that are positioned 120° apart at the fixed base where the actuators are controlled by a controller that calculates the required motor angles using inverse kinematics algorithm [6, 7].

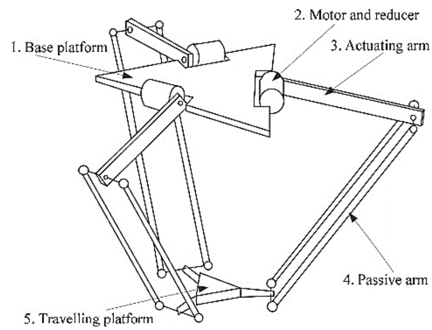

Figure 1: Configuration of a Delta robot [7]

This paper reviewed several previous works on mechanical design and kinematics algorithm of Delta robot as well as architecture of Delta robot with vision system which published in recent years [8-14]. Robotic vision system was included in the literature review because eventually a vision system would be integrated into the Delta robot control system for pick and place application. Nevertheless, the focus of this paper is on design and development of a Delta robot where the discussion of Delta robot with vision system would be separated in another paper.

In the review, the standards of design and fabrication, requirement of hardware and software, kinematics algorithm, robotic vision and visual servo control systems were analysed and adopted. The selected methods are presented in the next section, Research Methodology.

## III. Research Methodology

### A. Delta Robot Kinematics Algorithm

The kinematics algorithm of the Delta robot was formulated using geometric analysis method with reference to the work by Williams [15], where the kinematic chain of the robot structure is illustrated in Figure 2. With the vector relationship, the angles of the joints can be obtained from the coordinate information of the end-effector.

### B. Simulation in CoppeliaSim

A 3D model of the 3-axes Delta robot was constructed in Solidworks. The model was then imported into a robotic simulation software, CoppeliaSim to verify the feasibility of the robot's kinematics algorithm before heading to build the prototype. Figure 3 shows the screenshot of CoppeliaSim software running the motion simulation of the developed Delta robot model. A GUI (graphic user interface) was written in CoppeliaSim to allow input of different targeted end-effector positions for positioning testing purpose. The kinematics calculator would calculate the respective joint angles for each robot axis required to move the end-effector to the targeted position. The results showed that the 3D model of the robot was functioning well in the simulation and the kinematics algorithm was tested to be able to move the end-effector of the robot to every desired position within the working envelope.

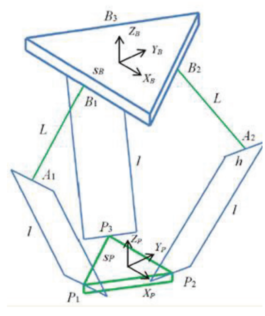


Figure 2: Kinematic chain of Delta robot with its base frame and end-effector frame [15]

### C. Simulation in CoppeliaSim

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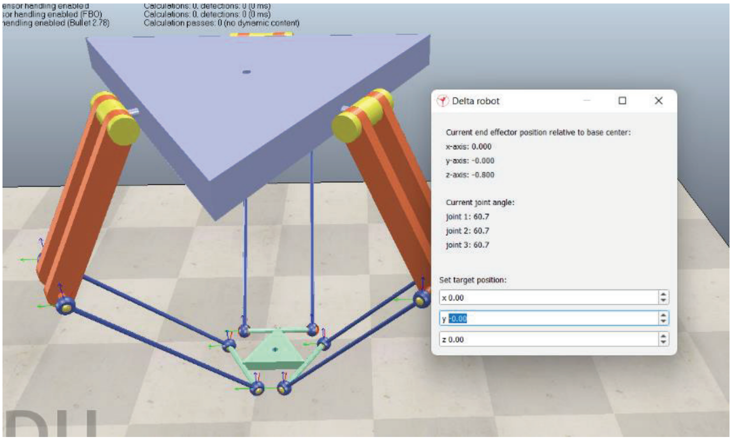


Figure 3: 3D model of Delta robot in CoppeliaSim simulation software

### D. Prototype of Delta Robot

After successful 3D model testing in simulation software, a prototype of the Delta robot with a conveyor was constructed as shown in Figure 4.

The base platform of the Delta robot was a laser cut acrylic plate. The actuating arm (bicep), travelling platform, stepper motor holder and gripper were 3D printed while 3 mm diameter fibre rods were used as the passive arms (forearms). A total of twelve ball rod-ends were used as ball joints between the actuating arm and forearm of the robot; as well as between the forearm and the travelling platform. Three units of wooden bar which vertically erected acting as the stand for the robot for the base platform of the robot to mount on.

Three units of NEMA 17HS4401 stepper motor were used as the actuator at each axis of the Delta robot. The stepper motor has a step size of 1.8 degree and 200 steps per revolution. On another hand, a unit of 28BYJ-48 stepper motor was used as the driver to move the conveyor belt. A SG90 servo motor was used as the actuator for the gripper.

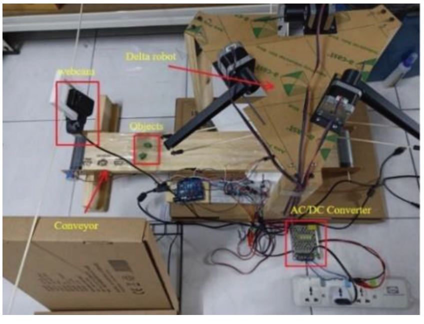

Figure 4: Prototype of the 3-axes Delta robot with a webcam and a conveyor belt

An AC to DC converter (AC220V / 110V to DC12V, 3A) was used as the power source for the stepper motors. Each NEMA 17HS4401 stepper motor was paired with an A4988 stepper motor driver for motion control. An Arduino UNO was used as the controller to control the robot actuators while connecting to a personal computer via serial communication. A 720P USB webcam was used as the visual input for the pick and place application to capture the position of the incoming objects sent by the conveyor. The schematic diagram of the electronics components and actuators is shown in Figure 5.

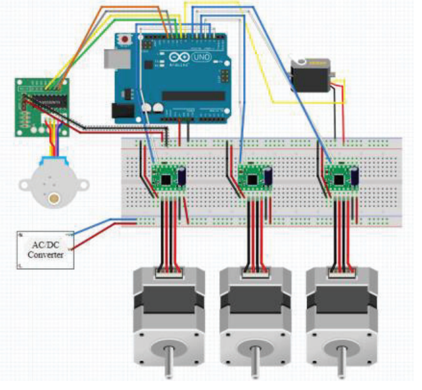

Figure 5: Schematic diagram of the electronic components and actuators

## E. Motion Control

As the robot mechanical linkages are interconnected to each other for a Delta robot, all the stepper motor would need to start and stop simultaneously to generate a smooth trajectory movement i.e. a simultaneous control is required for all the motors. Otherwise the contradictions of the motor angles will put a strain to the robot arm linkages causing jerky movements hence leading to positioning errors at the end-effector. To achieve simultaneous motion, a preset *total_reach_time* was required and then the *time_interval* variable (the time duration of each step of the motor) was calculated based on the *total_reach_time*. Figure 6 shows the pseudocode of the motion control algorithm for the stepper motors.

```
set total_reach_time = 500000 microseconds
calculate step of each motor from angle (step = angle/360 * 200)
time_interval = total_reach_time/Step

get current motor time (cmt = micros())
set step to false
if stepcount < step then
    if cmt - pmt > time_interval then
        set step to true
        increase stepcount by 1
        pmt = cmt
    end
end
```

Figure 6: Pseudocode of the motion control of the stepper motors

## F. GUI using .Net Framework

A desktop application with graphical user interface (GUI) was needed between Arduino and human for robot control and monitoring purpose. The GUI was developed in Microsoft .Net Framework using C#. Figure 7 shows a screenshot of the written GUI in C# Winform. Features included in the GUI were

- Manual control of robot gripper position with textbox and 2D visual tracker
- Displays of: current angle for each motor, current gripper position, target angle for each motor, target gripper position, angle to move, and gripper position to move
- Display of the status of serial connection to the Arduino microcontroller
- Gripper control (grip / release)
- Camera view window
- Position data of the detected object (centroid x and y, and size of the detected object).

Figure 7: GUI layout of the Delta robot pick and place system

### G. Serial Communication between PC and Arduino

When the GUI receives new target position to move, it would execute the kinematics algorithm that was written in C#. The outputs of the algorithm i.e. the angle to move for each motor would be sent to Arduino via serial communication along with gripper control command. Upon receiving the control data, the Arduino would execute the motion control to simultaneously move each motor hence the end-effector (i.e. the gripper) to the target position.

## IV. Results and Discussion

Positioning repeatability and accuracy were the metrics used to measure the performance of a robot. Two experiments were setup to test the Delta robot's ability to repeatedly place its end-effector (i.e. gripper) at a targeted position; and its ability to place its end-effector to different intended positions accurately.

For Experiment 1, Repeatability Test: the targeted position of gripper was set at X0 Y0 Z250 (in unit of mm) with displacement of 250 mm from the centre of the base platform. The targeted rotation angle of every stepper motor to move each of the bicep arms of the Delta robot is 36° in order to move the end-effector to the targeted position.

During data collection, the end-effector would be programmed to move to a fixed position then moving to the targeted position. When it stopped at the targeted position, the rotation angle of each stepper motor was then measured and recorded. The position of the gripper in Cartesian space was then calculated using forward kinematics equations by feeding in the values of the measured stepper motor rotation angles. The displacement of gripper from the centre of the base platform was subsequently calculated using the Cartesian space position data *x, y & z* of the gripper. The displacement error was calculated by comparing the real end-effector displacement with the targeted position of the gripper. There were total 20 repeated movements (from the fixed position to the targeted position) carried out in Experiment 1 and the result is tabulated in Table 1. On the other hand, Figure 8 shows the displacement of the 20 repeated movements.

Table 1: Repeatability Test

| n | Measured angles (deg) | | | Position (mm) | | | Displacement (mm) | Displacement Error (%) |
|---|---|---|---|---|---|---|---|---|
| | a1 | a2 | a3 | x | y | z | | |
| 1 | 37.5 | 36.0 | 36.0 | -3.7 | 0 | -252 | 252 | 0.8 |
| 2 | 38.5 | 36.0 | 37.0 | -5.0 | 2.1 | -255 | 255 | 2.0 |
| 3 | 38.0 | 36.0 | 36.0 | -4.9 | 0 | -253 | 253 | 1.2 |
| 4 | 39.0 | 36.0 | 36.3 | -7.1 | 0.64 | -254 | 254 | 1.6 |
| 5 | 39.0 | 36.2 | 36.0 | -7.2 | -0.43 | -254 | 254 | 1.6 |
| 6 | 39.1 | 36.1 | 36.0 | -7.6 | -0.21 | -254 | 254 | 1.6 |
| 7 | 39.0 | 36.2 | 36.2 | -7.0 | 0 | -255 | 255 | 2.0 |
| 8 | 39.2 | 36.4 | 36.1 | -7.4 | -0.64 | -255 | 255 | 2.0 |
| 9 | 39.1 | 36.3 | 36.0 | -7.36 | -0.64 | -255 | 255 | 2.0 |
| 10 | 38.8 | 36.7 | 36.5 | -5.5 | -0.43 | -255 | 255 | 2.0 |
| 11 | 39.5 | 36.5 | 36.3 | -7.77 | -0.43 | -256 | 256 | 2.4 |
| 12 | 39.5 | 36.2 | 37.0 | -7.28 | 1.71 | -256 | 256 | 2.4 |
| 13 | 39.5 | 36.5 | 37.0 | -6.91 | 1.07 | -257 | 257 | 2.8 |
| 14 | 39.5 | 36.5 | 36.0 | -8.14 | -1.07 | -255 | 255 | 2.0 |
| 15 | 39.5 | 36.2 | 36.2 | -8.26 | 0.00 | -255 | 255 | 2.0 |
| 16 | 40.0 | 36.5 | 37.0 | -8.20 | 1.07 | -257 | 257 | 2.8 |
| 17 | 40.1 | 36.2 | 36.0 | -10.04 | -0.43 | -256 | 256 | 2.4 |
| 18 | 40.2 | 36.5 | 36.4 | -9.45 | -0.21 | -257 | 257 | 2.8 |
| 19 | 40.2 | 36.4 | 36.4 | -9.57 | 0.00 | -257 | 257 | 2.8 |
| 20 | 40.5 | 36.2 | 37.2 | -9.61 | 2.15 | -258 | 258 | 3.2 |
| Mean | 39.3 | 36.3 | 36.4 | 7.40 | 0.21 | -255 | 255 | |
| Standard Deviation | 0.746 | 0.209 | 0.423 | 1.67 | 0.93 | 1.49 | 1.49 | |

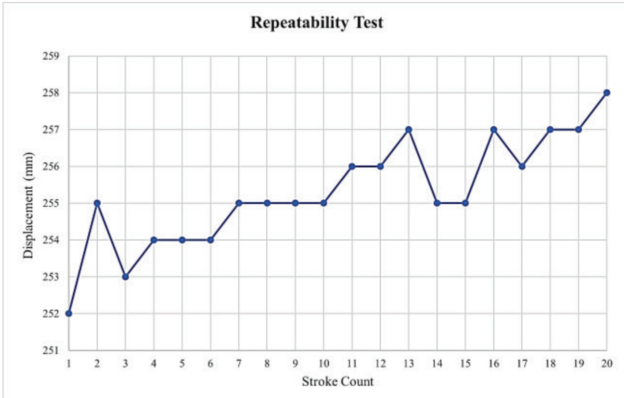


Figure 8: Repeatability Test of 20 repeated movements

For Experiment 2: Accuracy Test: there were six intended positions of the end-effector (i.e. the gripper) randomly set. Table 2 shows the position values of these intended positions. The gripper was programmed to move to these positions and it would be paused at each of these positions and the rotation angle of each motor would be measured. The actual positions (experimental values) of the gripper would be calculated with the measured motor angles. The positioning error was then calculated at every position to measure the accuracy of the Delta robot to move the gripper to the intended positions. There were total six movements carried out in Experiment 2 and the result is tabulated in Table 2. Meanwhile, Figure 9 shows the experiment values and intended values of the gripper's displacement. It shows high accuracy of the robot's positioning performance in six stroke counts.

Ideally, a system with high repeatability shall have low standard deviation. Table 1 shows that the built Delta robot was able to produce good repeatability with standard deviation of 1.49 mm in displacement and average displacement error of 2.12% in the repeatability test. It was observed that the error was propagated from 0.8% to 3.2%. The error accumulated was due to the robot repeatedly moving between a fixed position and the targeted position. This prototype can be further improved by integrating a rotary encoder to each motor to give position feedback to the controller about the rotation angle of each motor for precise positioning.

For the positioning accuracy test, Table 2 shows the average position error recorded was 1.89%. The result implies that the positioning of the built Delta robot is accurate in reaching every intended position with an accuracy of 98.1%.

Table 2: Gripper Displacement Accuracy Test

| Experimental Values | | | | | | Intended Values | | | | | | Gripper Displacement Percent Error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Motor Angles (deg) | | Gripper Coordinate (mm) | | Gripper Displacement (mm) | | Motor Angles (deg) | | Gripper Coordinate (mm) | | Gripper Displacement (mm) | | |
| 1 | 19.8 | x | 1.7 | 185 | | 1 | 19.0 | x | 0 | 179 | | 3.35 |
| 2 | 22.0 | y | -3.9 | | | 2 | 19.0 | y | 0 | | | |
| 3 | 19.5 | z | -185 | | | 3 | 19.0 | z | -179 | | | |
| 1 | 10.0 | x | 25 | 182 | | 1 | 8.0 | x | 30 | 181 | | 0.552 |
| 2 | 25.5 | y | -3.4 | | | 2 | 25.0 | y | 0 | | | |
| 3 | 23.4 | z | -180 | | | 3 | 25.0 | z | -179 | | | |
| 1 | 10.5 | x | 26 | 185 | | 1 | 9.0 | x | 30 | 184 | | 0.543 |
| 2 | 18.7 | y | 21 | | | 2 | 16.0 | y | 30 | | | |
| 3 | 32.0 | z | -182 | | | 3 | 35.0 | z | -179 | | | |
| 1 | 32.0 | x | -31 | 186 | | 1 | 31.0 | x | -30 | 183 | | 1.64 |
| 2 | 7.5 | y | 22 | | | 2 | 4.0 | y | 30 | | | |
| 3 | 22.4 | z | -182 | | | 3 | 25.0 | z | -179 | | | |
| 1 | 32.4 | x | -32 | 180 | | 1 | 31.0 | x | -30 | 183 | | 1.64 |
| 2 | 25.6 | y | -32 | | | 2 | 25.0 | y | -30 | | | |
| 3 | 3.8 | z | -180 | | | 3 | 4.0 | z | -179 | | | |
| 1 | 36.5 | x | -9.4 | 241 | | 1 | 36.0 | x | 0 | 250 | | 3.60 |
| 2 | 35.0 | y | -10 | | | 2 | 36.0 | y | 0 | | | |
| 3 | 30 | z | -241 | | | 3 | 36.0 | z | -250 | | | |

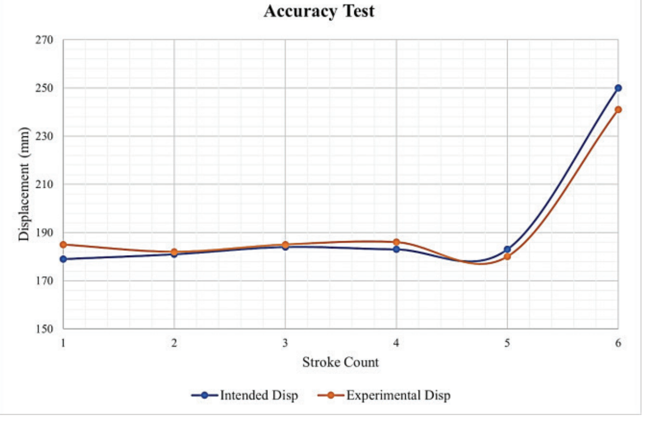


Figure 9: Accuracy test results

## V. Conclusion

In summary, a 3D mechanical design of a Delta robot was precisely modelled in Solidworks. With reference to the mechanical dimensions, the forward and inverse kinematics control algorithm for Delta robot has been studied and written in a robotic software, CoppeliaSim. The feasibility of the design and its control algorithms were tested in CoppeliaSim and the result was successful. Subsequently, a prototype of the Delta robot was built and performance of the robot was evaluated with repeatability test and accuracy test. The results showed that the prototype yields good repeatability in its motions with standard deviation of 1.49 mm in displacement; and it yields accuracy of 98.1% in its motion accuracy. The result indicates that the mechanical design and kinematics algorithms used to control the Delta robot are workable, accurate and precise. For future development, a close-loop system with a rotary encoder as feedback can be considered to increase the performance of the prototype. It must be noted that this Delta robot prototype was integrated with a vision system and a conveyor for real time object pick and place application. The discussion of robotic vision with pick and place would be carried out in a separate paper.

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