Modelling and Simulation of a 3DOF End Effector for Material Handling with a Delta Robot

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Abstract. In order to improve workspace and material handling system of the delta robot, this paper describes a design of an End-effector with 3 degrees of freedom (3DOF) which makes the End-effector more flexible and having sufficient range of working space. This End-effector will be mounted on a delta parallel robot to perform the desired task in handling materials accordingly. The robot is able to pick and place a given material to the right place and positioning as it is desired by the user. The methodology used to design this robot was based on 3 major components which are: Sliding rails which deals with translational motion along horizontal axis, this motion carries the whole system from side to side and is going to play a role of increasing workspace in either assembling line or picking and placing system. Delta robot is in charge of manipulating its end effector in 3 dimensions along (x, y, z - axis) according to the object tracking localization as a human’s arm manipulate the hand. The end effector’s purpose is to perform rotational motion then pick the object and place as the system requires, this performance has advantage of handling materials and positioning respectively. It showed that the proposed system is safe and is feasible for application. The proposed material handling system can minimize the disadvantages of utilizing a delta robot by attachment of the presented end-effector to the delta robot.

1. Introduction
Industrial robots are classified into two categories which are serial robots and parallel Delta robots looking at the geometry, Serial robots comprise a sequence of arms with a fixed base, whereas delta robots comprise a multibody system with a moving platform[1][2]. The delta robot has seen a lot of development since its invention. Research based on delta robot technology has shown a great potential to researchers because of its high speed, precision, stiffness [3]; as a result, it needs to be employed in a large range of applications including 3D printing, packaging, assembly operation, and mainly for picking and placing materials [4]. Delta robots have been modified in various ways to satisfy industrial needs. It was within the early ’80s when Raymond Clavel came up with the brilliant idea of using parallelograms to create a parallel robot with three -translational and one rotational degree of freedom [5]. Clavel was presented with the Golden Robot Award, sponsored by ABB Flexible Automation, for his innovative work on the Delta parallel robot. Ali Kermanian described extensive details on the characteristics and architectures of the parallel mechanisms [6]. The Parallel Delta Robot is very demanded by many industries/factories to satisfy the customers' needs. Furthermore, it plays a significant role in our industries/factories by its excellent performance, especially within the area of picking and placing. This is often due to its repetitive positioning accuracy, strong bearing capacity,
high stiffness, compact structure, and fast pick and place operation [7]. However, this helps industries to tackle the essential needs of their customers. Because the population of the globe keeps on increasing at an exponential rate, the demand for products and services also increases. The end effector is one of the most important parts of the Delta robot [8], which is designed to interact with the environment. These robots have proven to dramatically increase productivity, especially in the field of electronic product assembly, medical and pharmaceutical industries [9]. Most end-effector are usually, or quasi constrain to only promote pick and place items during a vertical direction[10]; therefore, the aim of this Project is to design a delta parallel robot’s end effector which can imitate the human hand assigned in picking and placing operation. The design objectives of this robot involve high reliability and stability, accurate recognition, localization of objects, high efficient pick and place manipulation, ease maintenance and cost effectiveness. Hence, the computer vision technique is executed to recognize and select objects based on size or color and accurately localize picking point and placing (dropping) point based on using visual recognition system which has a camera combined with corresponding algorithms [11]. The end effector has 3 DOF which permit the robot to have enough flexibility to rotate in any direction and is going to handle materials smoothly. Therefore this end effector it operates as a serial robot manipulator and has three joints that may move independently. The end effector consists of components that rotate in three axes. The axes of the nearby links are always perpendicular to each other, they're referred as yaw axis, pitch axis, and roll axis, respectively. The delta robot is selected as the motion mechanism to carry out the trajectory tracking path for picking and placing operation. Also translation motion is needed for more workspace by mounting the entire system to the designed flames which having sliding rails permit the robot to move in horizontal motion (forward and backward motion).

2. Proposed System

Proposed system is basically classified into two types, which are serial robot and parallel robot. As the major components of the proposed material handling system are the rail, delta robot and the end-effector which is considered as serial robot manipulator and has three joints which can move independently. The proposed system is shown in Figure. 1.

![Figure. 1. Detailed structure of material handling delta robot.](image)

This robot would be able to move from a given point to the destination required, this is a proposed design system of rails mounted to the stationary Frame of the robot which allows the delta robot to maneuver from one point to another. This advantage allows better performance of the robot and reduces the number of robots used in production, manufacturing and assembly, which is cost effective. The slide rails are used to move the robot from one end to the other along the horizontal axis (X-axis). In this paper, modeling and simulation of the end effector is mainly discussed.
2.1. Designing the End Effector
The end effector consists of components that rotate in three axes. The axes of the nearby links are always perpendicular to each other. They are named as yaw link 1, pitch link 2 and roll link 3 respectively, the arrangement of the links and the system are shown in Figure 2.

Figure. 2 Complete assembly design of end-effector.

Consistent with link 1, link 2, and link 3 that are rotated 180°, 90°, and 90°, respectively during the motion, the rotational direction of the axes is often considered off from the end effector. The payload utilized in the simulation is a cubic shape with a side length of 250 mm, having a mass of 100 g. All the three links can rotate 360°. But to avoid the repetition of the same point in the workspace, the ranges of the links are limited as shown in Table 1.

Table 1. Selected ranges for joint movements

| Link | Range       |
|------|-------------|
| Link 1 | -180° to 180° |
| Link 2 | -90° to 90°   |
| Link 3 | -90° to 90°   |

According to the initial position of the link 3, the workspace of the end effector can have two possibilities. In one case workspace of end point 1 and end point 2 coincides. In the second case those two points have two different workspaces. To have the mentioned two possibilities, the line joining the two end points should be perpendicular and parallel respectively to the axis of the link 2. Under the simulation of the system, the second case is considered. Figure 3 shows the initial position of the end effector when the workspace of the system is analyze and its axis of link 2 is parallel to the line joining the two end points. The workspace of the end effector is taken by using Simmechanics in Matlab. The software is used to track the path of the end points while letting the system to move with all the possible joint angles. Those 3 links can rotate one after the other or can rotate at the same time, for better motion yaw, pitch and roll should rotate one after the other to avoid unwanted vibration which can affect accuracy as well as smooth motion which is the main purpose of this end-effector.

Figure.3 Positions of end effector (a) Initial position, (b) Final position

3. Kinematic analysis
Kinematic analyze of the system is performed using the mathematical equations. The moving linkages and the critical parameters are identified and the body fixed coordinate frame for each and every component is defined as shown in Figure. 4
Frame i$^\prime$ – Fixed frame (Blue color) Frame a$^\prime$ – Link 1 fixed frame (Green color) Frame b$^\prime$ – Link 2 fixed frame (Pink color) Frame c$^\prime$ – Link 3 fixed frame (Yellow color). Let’s assume the frame a$^\prime$ is rotated angle $\theta_1$ relative to frame i$^\prime$, frame b$^\prime$ is rotated angle $\theta_2$ relative to frame a$^\prime$ and frame c$^\prime$ is rotated angle $\theta_3$ relative to frame b$^\prime$.

Let the position vector of the end point relative to Frame $\hat{t}$ is $d$.

$$d = -l_1 \hat{t}_3 + l_2 \hat{a}_2 - l_3 \hat{b}_3 + l_4 \hat{c}_2$$

By substituting equations 1, 2, and 3 this can be written in Frame $\hat{t}$.

$$d = \begin{bmatrix} -l_2 \sin \theta_1 - l_3 \cos \theta_1 \sin \theta_2 - l_4 (\cos \theta_1 \cos \theta_2 \sin \theta_3 + \sin \theta_1 \cos \theta_3) \\ l_2 \cos \theta_1 - l_3 \sin \theta_1 \sin \theta_2 - l_4 (\sin \theta_1 \cos \theta_2 \sin \theta_3 + \cos \theta_1 \cos \theta_3) \\ -l_1 - l_3 \cos \theta_2 + l_4 \sin \theta_2 \sin \theta_3 \end{bmatrix} \begin{bmatrix} \hat{t}_1 \\ \hat{t}_2 \\ \hat{t}_3 \end{bmatrix}$$
Here,

$$0 \leq \theta_1 \leq 2\pi, \quad -\frac{\pi}{2} \leq \theta_2 \leq \frac{\pi}{2}, \quad -\frac{\pi}{2} \leq \theta_3 \leq \frac{\pi}{2}$$

(6)

Using the above mathematical model, the position of the top point of link 3 is often calculated for given angular displacements of the three axes. Let’s consider coordinate $[i_1, i_2, i_3]$ as the base of the end-effector and the delta robot is fixed to eliminate subsidence’s equations. Note that all links are rotational links. The first case of analyzing individual rotational joints:

(1) Link1 - $(\hat{a}_1, \hat{a}_2, \hat{a}_3)$ A rotational joint with $\theta_1$ as the angle of rotation

(2) Link2 – $(b_1^\wedge, b_2^\wedge, b_3^\wedge)$ B rotational joint with $\theta_2$ as the angle of rotation

(3) Link3 – $(\hat{c}_1, \hat{c}_2, \hat{c}_3)$ C rotational joint with $\theta_3$ as the angle of rotation (If $\theta_2 = 90°$ or 270°)

To analyze effectively the end-effector on 3 axis link 2 has no rotation at least 90° or 270° to line link3 in other words $\theta_2 \neq 0°$ or 180°.

3.1. Dynamic Analysis

Dynamic analysis is performed to identify the magnitudes and the directions of the forces and the torques applied on each and every component. Therefore the system is operated with some given inputs and the forces and torques are plotted against the time. The initial position and the final position of the end effector is shown in Figure 3. According to that link 1, link 2 and link 3 are rotated 180°, 90° and 45° respectively. The payload used in the simulation is cubic shape with side length 250mm, having a mass of 100g. During the simulation angular acceleration and deceleration of the joints are kept constant and they are equal to 20 rad $s^2$. The maximum angular velocity that a joint can achieve is taken as 30 rad $s^1$. When a joint reaches to the maximum possible angular velocity, it starts to move with constant angular velocity. The shape of the given motion to the joints is totally depend on the input angular displacements of the joints. The inputs given to the system during the simulation are presented as followed; the component can have an axial force, tangential force, and torque performing on each joint as shown in the figures below. The results taken from the dynamic analysis show the magnitudes and therefore the directions of the forces and torque against the time.

![Figure 6. Tangential forces of Joint](image)

![Figure 7. Axial forces of the three joints.](image)
4. Results

4.1. Workspace Analysis

The workspace of the two end points, plotted on the same graph is shown in Figure. 8. In this graph, blue color and red color points represents the workspace of the end point 1 and end point 2 respectively. The combination of the two workspace have a shape of a torus.

4.2 Experimental Analysis

To keep the system simple for implementation and maintaining the cost low: we have decided to substitute the previous prime mover, Dynamixel stepper motors, with RDS3120 servo-motors as our current actuator. The gimbal mechanism is equipped with three stepper motors; actuating the roll, yaw, and pitch motion. The system is composed of DC to DC buck converter, raspberry pi 3B+ (with camera module and a power backpack), pneumatic system (including solenoid valve, and DC pump), and breakup board relay. The End effector’s prototype set up is shown in the Figures below [8].
4.3 Implementation and Result.
The OpenCV in-built contour detection algorithm which identifies objects based on the color, shape, and size. Therefore, the objects can also be determined as it appears in Figure 11 shows respectively two objects with the same color but different sizes on the left figure and the other two objects in the middle figure are in different colors. The implemented algorithm calculates the size Area of the objects and identifies which object is bigger than the other then the robot will pick up according to the big in size and on the other hand, the algorithm is based on blue color for the target then the robot will select according to the color. In this case, the blue color was set as the detection target [11]. Human hand was used as simulating motion of the delta robot as a moving platform. Camera was used for simulating the target of the object which is the box in blue color and also the End effector picking the object targeted and move it accordingly as all details are shown in the right figure below.

5. Conclusion
The end effector model designed and proposed in this paper is suitable for mounting on a delta robot. The results of the workspace analysis show that the selected length and ranges are suitable for the end effector, and that the selected ranges successfully prevent the same points from overlapping at the two ends of the designed model. The required torques at each joint are analyzed in the dynamic simulation and the motors are selected accordingly. The results of the finite element analysis show that the parts of the end effector are within the load limits. This system has great operational flexibility in material handling. The analyzed, simulated, and tested design provides a wide range of operation that expands its application range.

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