Design of a Delta Robot for Pick and Place Application in Delivery Hubs to Sort Packages*

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***Abstract*— There are several applications that require robots to move with high speed and accuracy. One such application is the sorting mechanism in delivery hubs of courier delivery companies. Time is crucial while sorting mails from different locations. Delta robots can be used as a vital component of the sorting mechanisms as we want to increase the number of packages sorted per hour while also maintaining high positional accuracy of the robot. Thus, a control system is also needed for such an application. The paper deals with the design of a delta robot for the proposed application and subsequently the design of the controller for such an application. A model for the robot is created using Simulink and computed torque control method is used to design a controller for the delta robot.**

I. Introduction

Courier delivery companies such as DHL and FedEx offer one-day shipping across the country. To facilitate this claim, they use multiple aircrafts. Every evening, aircrafts from across the country pick up the packages from their regions and fly to a central hub. All these aircrafts bring packages from across the nation heading towards everywhere across the nation to the delivery hub. In the next three hours, the delivery hubs sort the packages according to their destination and all the aircrafts are loaded with the cargo destined for their home airports. Within 3 hours, hundreds of thousands of packages are sorted. The sorting facility is the most critical cog in this system. Courier companies typically invest billions of dollars in developing entire terminals devoted to being sorting facilities[2]. Any improvement in the sorting mechanism or in the speed of sorting would mean that companies can save millions of dollars. They would also be able to sort packages quicker, thereby allowing more time for delays.

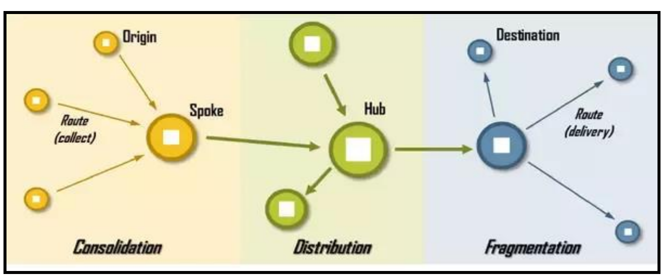

Figure 1: Companies collect packages from several regions and transport them to the hub. Packages are sorted in the hub and then sent back to the respective spokes. Also known as the hub and spoke model.

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The sorting mechanisms used in these sorting facilities are as follows. All the packages from the airlines are loaded on to a central conveyor belt. As the belt moves forward, there are several chutes on each side on the conveyor belt. Each chute represents a final destination. The packages move along on the conveyor belt and if they reach the chute representing their final location, a mechanism diverts the package into that chute.

Different companies use different types of mechanisms to divert these packages. Some companies use arms that block the forward motion of the package to diver it while others divide the conveyor belt into small horizontal strips with each having a package placed on it. There are rollers under the belts and as the package reaches its respective chute, the rollers push the object into the chute. However, in the first technique, all packages must have at least a minimum clearance between each other while in the second method, each section of the belt must be actuated.

The use of delta robots will help overcome both of these limitations. Unlike the arms, which require a minimum amount of clearance between packages, delta robots work in the vertical plane and thus do not require any such clearance. The packages can be placed extremely close to each other on the conveyor belt and can still be rapidly picked up by delta robots. Also, unlike the segmented conveyor belt mechanism, the delta robots do not need an actuator on each segment of the belt. Thus, the company can reduce the size of its facility as lesser space is required if packages are placed closer to each other and also reduce its turn around time as packages are sorted faster.

In this paper, the authors discuss the design of a delta robot whose main application is to pick and place parcels.

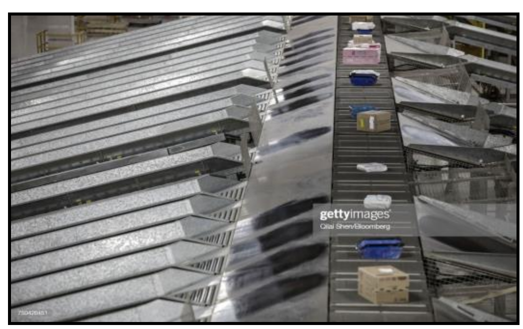

Figure 2: Sorting facility at one of the hubs. Packages can be seen traveling down a conveyor belt. Chutes can be seen on the side. Each chute represents a separate destination

II. Delta Robots

The Delta robot is a parallel robot, i.e. it consists of multiple kinematic chains connecting the base with the end-effector. The robot can also be seen as a spatial generalization of a four-bar linkage. The key concept of the delta robot is the use of parallelograms which restrict the movement of the end platform to pure translation, i.e. only movement in X, Y and Z direction with no rotation.

The base of the robot is mounted above the workspace. The actuators are mounted on this base. The actuators in our robot are servo motors and their axis lies parallel to the base of the robot. The actuators are connected to three arms which extend outside and the servo motors can rotate them. These arms which are connected to the servo motors are known as the ‘bicep’ arms of the delta robot. Each of these biceps is then connected to another arm. These new links are known as ‘fore-arms’. The forearms are then connected to an end effector link which has the same geometrical shape as the base. The forearms are connected to the biceps with a universal joint. Thus, they can rotate about 2 axes. Also, each forearm consists of a pair of parallel links. This causes the end-effector to always be parallel to the base of the robot.

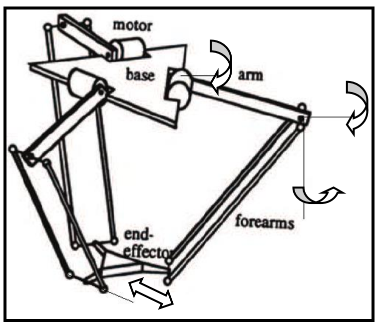

Figure 3: Representation of Delta Robot. As can be seen, the forearms rotate about two axes, while the arm (also known as biceps, rotates about one axis.[4]

The actuators, which are typically the heavier parts of any system, are connected to the base of the system. The biceps and the forearms only act as force transmitters. Thus, they can be made of extremely lightweight materials. This means that the inertia of the moving parts of the system is extremely low. Thus, the system can move with extremely high accelerations and work at high speeds. This quality is extremely useful in applications where speed is an important factor. However, the weight carrying capacity is of delta robots is limited. One must have large motors to build delta robots capable of carrying high loads.

III. WORKSPACE

The workspace of a delta robot is one of the most important criteria to consider while designing a delta robot. It is extremely hard to create a workspace for a delta robot given the length of its links. Having data about the envelope of the volume of a workspace can also be extremely useful. A possible method to calculate the workspace of the system would be to use forward kinematics. For a given set of base size, bicep and forearm length and the end effector shape, we can find the workspace as follows. The inputs to the system are the joint values of the three servo motors. Since we know the parameters and dimensions of all the other components of the system, we can calculate the position of the Centre of Mass of the end effector of the system for a given set of joint values.

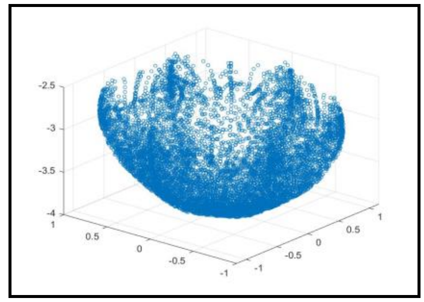

Figure 4: Workspace of a particular configuration of delta robots plotted using the Simulink model. It is similar to a hemisphere.

If we feed the system with all possible joint values, then we can use forward kinematics to get the possible end effector states for all the values. That allows us to build the workspace using all these values. However, the number of possible states is a cubic function of the number of joint states of each joint[3]. Another method that could be utilized would be to create a model of the system. Now, for a given set of parameters, if we applied a force to the end effector in different directions about all three axes, and plotted the motion of the end effector, we would be able to create a workspace of all the possible states of the end-effector. This allows us to create an envelope of all the points the end effector can reach.

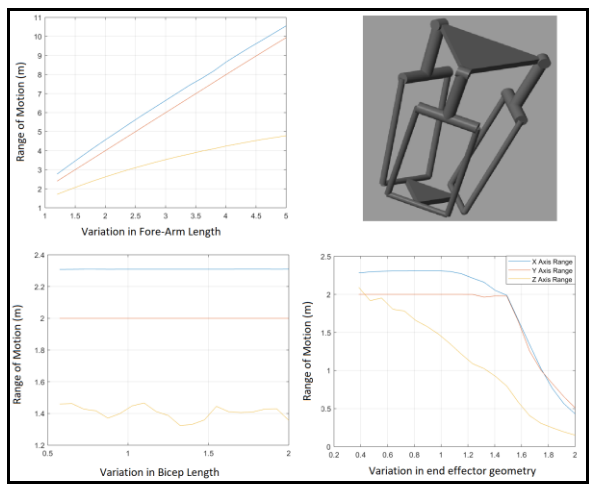

Figure 5: Graph of the variation of range of workspace as bicep, fore-arm, and end-effector vary in geometry

The authors created a model of the system as this allows for faster calculation. While in most systems, forward kinetic would be faster, in delta robots one has to solve quadratic equations to find the solution of the center of mass. This makes calculating Forward kinematics extremely difficult and we choose to directly apply forces to the end-effector and measure its positions. However, this was only possible because the authors created a model of the system on Simulink (Simscape) which allowed us to integrate the kinematic and also dynamic systems into the model.

Once the model has been created, we apply a force to the end effector and record the trajectory it follows. We apply forces in all directions in the XY plane. Thus, we can create a mapping of the envelope of all the points of the end effector.

It is observed that the workspace is dependent on the bicep and forearm length, and then the dimension of the end-effector. Further, it is seen that the motion along Z-axis is most limited. We see that the Z-axis range is most affected by the change in the dimensions of the base. It reduces drastically as the base geometry increases. On the other hand, the range increase as the length of the forearm increases. The range does not vary much with a change in length of bicep.

IV. Forward And Inverse Kinematics

A. Forward Kinematics:

Forward Kinematics is the process of finding the position of the end-effector, if we know the position of the actuators. In an open chain, forward kinematics is a simple process. However, the closed loop case is more complicated. Here the actuators are only at the end of the chain. Multiple chains come together and connect to the end effector. The angles of the middle links in the chains can vary according to the angular positions of other actuators in the system. There can be a set of joint angles that can satisfy multiple positions of the end effector or there could be a set of values that has no solution for the end effector.

In a delta robot, if the actuators are given a set of joint values, then the angles and distance of the biceps are fixed. However, the angles of the forearm are not fixed[3]. The ends of all the three forearms lie on specific points that are related to the Center of Mass of the end-effector. Thus, the end of each forearm lies on a sphere with a radius of the length of forearm and is attached to a point which is at a specific distance from the Centre of Mass of the end-effector. Thus, we will have three equations of sphere and their relation to the Center of Mass of the system. For these reasons, solving Forward Kinematic is harder in closed chain robots.

Equations for the kinematic system by solving $A_i^B = B_i^B + L_i^B$[5]

A_i : *Knee Points*

B_i : *Distance of top joints from centre*

L_i : *Length of arm*

$$2L(y + a)cos\theta_1 + 2zLsin\theta_1 + x^2 + y^2 + z^2 + a^2 + L^2 + 2ya - l^2 = 0$$

$$-L\left(\sqrt{3(x+b)} + y + c\right)cos\theta_2 + 2zLsin\theta_2 + x^2 + y^2 + z^2 + b^2 + c^2 + L^2 + 2xb + 2yc - l^2 = 0$$

$$L\left(\sqrt{3(x-b)} - y - c\right)cos\theta_3 + 2zLsin\theta_3 + x^2 + y^2 + z^2 + b^2 + c^2 + L^2 - 2xb + 2yc - l^2 = 0$$

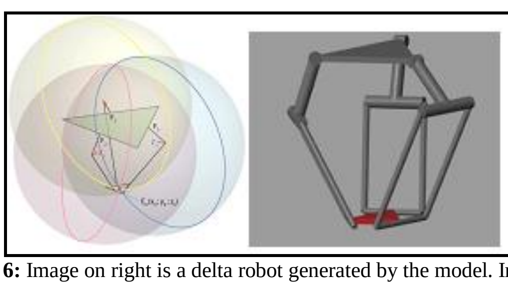

Figure 6: Image on right is a delta robot generated by the model. Image on left represents the forward kinematics process. The end-effector lies at the intersection of the three spheres which originate at the joints of fore-arms

B. Inverse Kinematics:

Inverse Kinematics is the method of finding the joint angles of the actuators when provided with the location of the Center of Mass of the end-effector. This method is easier in closed chain systems as they tend to have lesser number of links in each chain. In delta robots, each arm is connected to a point on the end effector. If we know the position of the Centre of Mass of the end-effector then the position of each of these points can be calculated. Once the end points of all three arms are available we can use inverse kinematics to find the angle of each actuator independently.

$$E_i cos\theta_i + F_i sin\theta_i + G_i = 0$$

Solving this equation, we can get solutions for $\theta = [\theta_1\ \theta_2\ \theta_3]$

V. Dynamics

Now, that we have discussed the Kinematics of the system, we must study the how the system behaves under the effect of forces. More importantly, we must discuss how to control the system. Since the system moves with high acceleration, controlling the motion of the system can be a challenge. Further, since the system is complex and has multiple forces acting on it, it is hard to compute the torque analytically. Thus, in such a scenario we use the computed torque method.

A. System Model:

As described above, a model of the system is already made. The system model consists of all the links of the delta robot and includes information about their dimension and weights. It also includes the relation between the different links. Thus, we can describe the motion and the axis of motion of each link in relation with the link it is connected to. The model also has a feature to simulate gravity conditions on the system. Once the basic model is prepared, we need to simulate the real-world conditions. Since an average package is considered to have a mass of 2 kg, we have to assume a load of 20 N acting on the end effector at all times in along the negative Z axis. This force is also added to the system.

B. PID controller:

It is extremely hard to study the dynamics of a complicated system. Thus, we have to resort to using a PID controller, and have to tune it specifically for our robot so that it is able to quickly reach the desired state and not overshoot it. A PID controller consists of three components, namely the proportional, integral and derivative components.

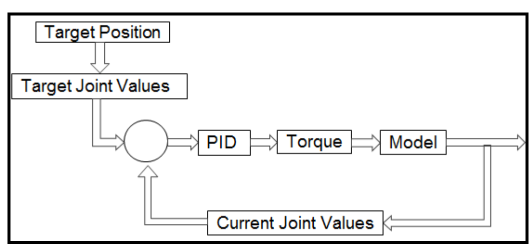

Figure 7: Control feedback loop for designing the controller

The proportional component of the PID measures the current error between the desired state and the actual state and multiplies it by a constant term to output the proportional component of the torque to the joint. The integrator is used to eliminate the steady state error which remains small and constant. The integral component measures the error value and stores a cumulative value of the error over time. It multiplies this by a constant to provide an output which represents the integral component of the PID. However, the problems with the proportional and integral system is that they tend to overshoot the ideal value and later hover around the ideal value. To avoid this problem, we add a differentiator to the system. The differentiator measures the rate of change of error and multiplies it with a constant. This has the effect of reducing the overshoot that occurs when there is a PD controller[2].

The next step involved in the process is the tuning of the controller. This is an extremely iterative process where we have to keep manipulating the PID constants till the system reacts in a way we want it to

We integrate a PID controller into the system to control the movement of the system. In a real-world scenario, the robot will be commanded to move to the end effector to a target set of cartesian co-ordinates from the current set of target Cartesian co-ordinates. The system is provided with target cartesian co-ordinates. The system uses Inverse Kinematics to compute the target joint states and compares it to the current state of joints. The PID controller takes feedback in the form of error and computes the torque to be provided by each actuator. At the next time step, the PID system takes feedback again from the model and computes the required torques.

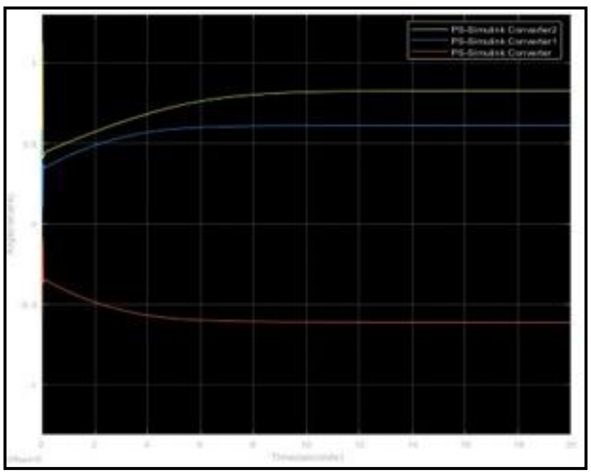

Figure 8: Motion Under action of PID controller. The X, Y, Z axis positions with time to reach final positions, without overshooting.

VI. Results

The authors have tried to study the characteristics of a delta robot and design a system which will be able to lift a load of 2 kg (small package) and move it at a distance 2 feet away from the initial point. We were able to draw the following conclusions from the project:

- Delta robots can move at high accelerations and velocities. This is primarily because the motors, which are the heaviest parts, are attached to the base and do not move.
- The advantage gained in velocity and movement of the robot is lost in the load carrying capacity of the robot. The torque required to move the robot also increases as the distance of the object from the center increases.
- The workspace of the robots is a key factor while designing a robot. The range of workspace is largely dependent upon the geometry of the plate of end-effector and the length of fore-arms.
- The system can be controlled using a PID controller. This allows us to move the end-effector to the target location without overshooting the target.

VII. Limitations And Future Work

The use of delta robots is limited to very specific applications in the industry, when compared to other robots. We look at a few of the limitations and suggest future work towards improving them.

- The PID controller of the robot requires that a huge torque input initially. Thus, a normal motor might not be able to meet this requirement. To accommodate for this, one must design the controller while taking the jerk into consideration.
- In the current system, we define only the initial and target position. However, another efficient method would be to divide the path into several waypoints. This would mean that we can control the trajectory of the robot with higher precision.
- Incorporating a gravity balancing system into the system might help it increase load carrying capacity.
- The end effector of the robot can move only linearly. Incorporating mechanisms to facilitate rotational movement would help increase the functionality of the robot.
- The solution developed by us has very little optimization. Further optimization should be carried out to improve the characteristics such as workspace and velocity.

Appendix

Simulink model of the entire system generated in MATLAB.

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APPENDIX

SIMULINK MODEL OF THE DELTA ROBOT: The model consists of all the links , joints and masses of the robot. We can calculate motion, position, force, velocity of all points in this system. The system also incorporates external forces and gravity.