Position Error Estimation and Compensation of 3-DOF Delta Robot under the effect of link tolerances

**Abstract**

Spatial parallel mechanism is one of the prominent areas of research in robotics. Delta robots are widely used in the area of biomedical and surgical and other mechanisms aimed to enhance the movement of manipulators for various tasks in the industries. This article presents the investigation of position error in a 3-DOF delta robot under the effect of link tolerance. First the generalized mathematical formulation is demonstrated and then the comparative estimation is presented. The forward and inverse kinematics of the manipulator is derived using loop-closure solution. The position error is estimated by using the proposed approach. Different combinations of tolerances are considered and an effort is made to compensate for the maximum position error occurred by varying the input angles. The proposed approach is helpful in analyzing spatial parallel configurations further it is providing a computational method for simulating complex manipulations.

*Keywords: Link-tolerance, Maximum position error, Loop closure equation, Forward and Inverse kinematics*

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| **Nomenclature** |  |
|  | Projection of point |
|  | Projection of point |
|  | Projection of point |
|  | X coordinate of |
|  | Y coordinate of |
|  | Z coordinate of |
|  | X coordinate of |
|  | Y coordinate of |
|  | Z coordinate of |
|  | X coordinate of |
|  | Y coordinate of |
|  | Z coordinate of |
|  | X coordinates of tool attachment point |
|  | Y coordinates of tool attachment point |
|  | Z coordinates of tool attachment point |
|  | X coordinates of tool attachment point under tolerance |
|  | Y coordinates of tool attachment point under tolerance |
|  | Z coordinates of tool attachment point under tolerance |
|  | Joint angle 1 |
|  | Joint angle 2 |
|  | Joint angle 3 |
|  | Upper link length |
|  | Lower link length |
|  | Distance between centroid of moving platform and link attachment point |
|  | Distance between centroid of fixed platform and motor attachment point |
|  | Centroid of moving platform |
|  | Binary joint point between upper and lower link |
|  | Motor attachment point |
|  | Origin at centroid of fixed platform |

**1. Introduction**

Over the last two decades, theoretical and practical research in the field of parallel manipulators has accelerated dramatically. The fundamental reasons are that these processes are stronger, quicker, and more precise. Parallel industrial robots have a number of advantages over serial robots, including a compact structure, high rigidity, high repeated positioning accuracy, strong load-bearing capacity, and so on (Brinker, 2017; Xue sheng et al.,2002). As a result, it is used in high-speed and high-precision tasks [1].However, parallel robots can have their own issues, earlier research concentrated on parallel mechanisms with six degrees of freedom (DOF), which have the advantages of high stiffness, low inertia, and great payload capacity. They do, however, have the issue of a relatively limited usable workspace and design challenges. To overcome these issues, there has lately been a rising trend toward parallel manipulators with three translational degrees of freedom, which are better suited for high speed and high stiffness manipulation. Furthermore, the availability of closed-form systems allows for precise design and efficient control. One well-known example is the Delta robot, which was developed by Clavel [2]. It is ideal for pick and place tasks with light items. Delta robots of various sizes have been adopted into a wide range of industrial applications, including the food, pharmaceutical, and electronics industries [3-6].

The work of Bai et al. is concerned with the kinematic calibration of the Delta robot using distance measurements. The study proposes a linearized compensator for real-time error compensation. The testing findings suggest that the approach can increase the robot's positioning accuracy [7]. Peng suggested a way of managing the good that provides an effective method for enhancing robot placement accuracy. Vischer and Clavel devised an error calibration technique and used the vector method to create the Delta robot's parametric model. The robot's kinematics are calibrated using implicit calibration and semi-parametric calibration [8]. Among the available literature, much of the study is concentrated on component dimension mistakes, with few studies focusing on clearance errors.

End-effector position accuracy is a key metric for assessing parallel robot performance. However, it has not yet been completely resolved [9–16]. Parallel robots are becoming faster and lighter and the parameters influencing end effector position accuracy are becoming more complicated. Scholars are now conducting extensive study in the subject of parallel robot position accuracy and compensating methods [17–20]. Chen [21] developed an error model for a four-axis Delta robot and investigated the sensitivity of the mechanism error source that affects end effector position precision. The references [22-28] investigated the influence of joint clearance on the position error of the parallel mechanism. Chen et al. [29] methodically explained the uncertainty that joint clearance had on the positional inaccuracy of a parallel robot.

In this paper a method is derived to reduce the maximum positional error obtained due to the manufacturing tolerances in the binary links of a spatial 3-DOF delta robot. Compensation of error was performed using inverse kinematics approach.

Section 2 introduces the Case study, the objective behind the work and the methods used.

Section 3 indicates the methodology used inorder to solve the case as in section 2 in the form of a flowchart.

**2. Case Study**

The forward kinematics under ideal condition produces the desired workspace of the spatial delta robot. A delta robot with = 205 mm, = 50 mm, = 400 mm, = 1000 mm, is used in the experimentation.

Programming is used to create the 3-DOF manipulator model, and the range of joint variables is specified by the manipulator's structure. The range of angles of the motors taken were from -40 to 80 degrees.

The available angle range is divided into 30 equal pieces. Each range has 30 + 1 = 31 possible values. The three variables can provide a total of 31\*31\*31 = 29,791 distinct postures. These positions and postures are then translated into a set of discrete points in three-dimensional space using the forward kinematic formula of the Delta moving platform's position using MATLAB programming.

Further analysis is done to study its behavior under the influence of link-tolerance. The maximum positional error is studied from a range of 10-100 microns and the error is further compensated using the inverse kinematic approach.

**3. Methodology**

This section explains the approach used inorder to tackle the problem description as stated in the section 2.

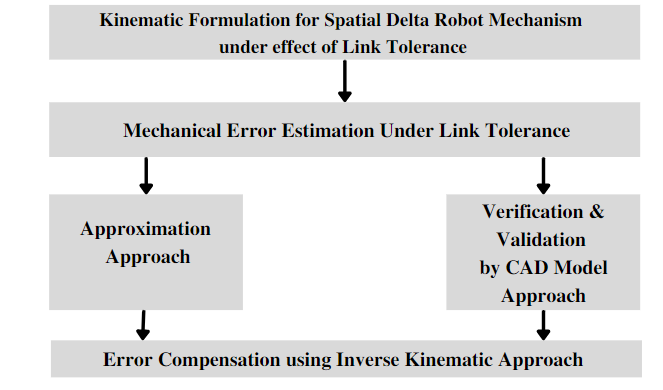
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Fig (1) Flowchart

**2. Forward Kinematics Under the Influence of Tolerance**

In this section the forward kinematics of a 3 dof parallel delta robot is studied under the influence of link-tolerance. Figure (1) shows the kinematic sketch of a spatial parallel delta manipulator made up of a moving platform, a fixed base and six binary links. Figure (2) describes the 3D CAD model of the parallel delta robot. The verification of position of end effector for a given orientation was done by comparing the values with that of Workspace Analysis of Delta Robot Based on Forward Kinematics Solution [30].

The forward kinematics of Delta robot is to obtain the three-dimensional position coordinate E0[x y z] of the terminal mobile platform by knowing the angles , of three active arms. Under the influence of tolerance equations of forward kinematics are as follows: -

(1) (2) (3) (4) (5) (6) (7) (8) (9) (10) (11) (12) (13) (14) (15) 🡪 (16) 🡪 (17) 🡪 (18) (19) (20)

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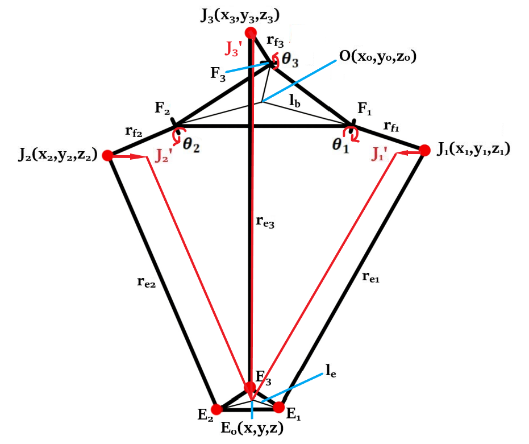
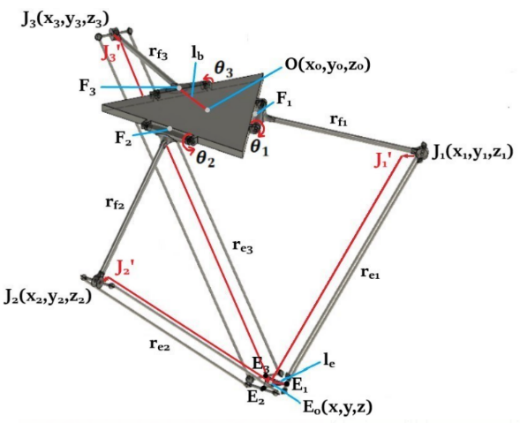
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Fig. 2. (a) Kinematic Sketch of a Delta Robot; (b) 3D CAD Model of a Delta Robot

**3. Compensation Using Inverse Kinematic Approach**

The inverse kinematic approach is used inorder to compensate the maximum positional error obtained for each tolerance value, i.e. from 10-100 microns. Table 1 shows that the necessary error compensation required inorder to obtain the desired position and nullify the effect of link tolerance on the delta robot. Below are the equations for inverse kinematics: -

Equation of circle with radius F1J1 and corresponding point J1 on circumference and center as F1 -> -> (1) Equation of circle with radius JIE1’ and corresponding point J1 on circumference and center as E1’ > -> (2) From (1), -> (3) Substituting (3) in (2), we get -> (4) where Substituting (4) in (3), we get where Upon solving for discriminant, we get -> (5) Substituting (5) in (4), we get zj1 Then,

For finding theta2, use

For finding theta3, use

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| --- | --- | --- | --- | --- |
| Input Angles | Desired Position | Input Angles (Under Tolerance) | Position (Under Tolerance) | Error Compensation |
| 𝜃1  𝜃2  𝜃3 | x y z |  |  |  |
| 80 80 80  80 80 80  80 80 80  80 80 80  80 80 80  80 80 80  80 80 80  80 80 80  80 80 80  80 80 80 | 0 0 -1368.40  0 0 -1368.40  0 0 -1368.40  0 0 -1368.40  0 0 -1368.40  0 0 -1368.40  0 0 -1368.40  0 0 -1368.40  0 0 -1368.40  0 0 -1368.40 | 80.00 80.00 79.92  79.98 80.01 80.01 80.02 79.97 80.02  80.02 80.02 79.97 79.96 80.03 80.03 79.95 80.04 80.04 80.04 79.95 80.04 80.05 80.05 79.94 79.93 80.06 80.06 80.07 79.92 80.07 | -0.05 -0.09 -1368.41  0.22 0 -1368.42  -0.17 0.29 -1368.42  -0.22 -0.39 -1368.43  0.57 0 -1368.43  0.68 0 -1368.44  -0.39 0.69 -1368.45  -0.45 -0.79 -1368.45  1.02 0 -1368.46  -0.57 0.98 -1368.47 | 0.00 0.00 0.00  -0.01 0.01 0.01  0.02 -0.02 0.02  0.02 0.02 -0.02  -0.03 0.03 0.03  -0.04 0.04 0.04  0.04 0.04 0.04  0.05 0.05 -0.05  -0.06 0.06 0.06  0.07 -0.07 0.07 |

Table 1 Compensation Table

**4. Results & Discussion**

The fig (3) depicts the ideal condition workspace of a spatial parallel delta robot wen 30 intervals were taken within the given range of actuator angles of -40 to 80 degrees.

The fig (4) & fig (5) respectively depict the XZ and YZ Plane of the workspace.

Because there is a risk of collision among the robot's three follower rods during motion, but the collision of the Delta robot happens in the singular configuration, the singular configuration is restrained to avoid the rod collision.

Fig (6) depicts the plot showing the comparison of the workspace under the influence of tolerance versus that of the desired position, indicating that there is a deviation from that of the desired workspace.

Fig (7) portrays the 3D Plot of Tolerance vs Position vs Maximum Positional Error, according to the plot we deduce the conclusion that the maximum positional error increases with the increase in tolerance value. The maximum error was obtained at 100 Micron link tolerance and Minimum at 10 Micron Tolerance.

Fig (8) represents the 2D plot of maximum positional error vs Tolerance indicating for three ranges i.e. 10 Micron,50 Microns and 100 Microns. The graph indicates the increasing positional error with increase in tolerance.

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| --- | --- |
| Fig (3) Workspace Plot of 31 Cube Combinations | Fig (4) XZ Plane Plot of 31 Cube Combinations |
| Fig (4) YZ Plane Plot of 31 Cube Combinations (29791) | Fig (6) Desired and Deviated Condition Plot |
| Fig (6) Desired and Deviated Condition Plot | Fig (8) Maximum Positional Error vs Tolerance Plot |

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**5. Conclusions**

This study assesses the positional accuracy of robotic manipulators while taking into consideration the randomness of link lengths and joint angles. The positional error obtained can be linked to term “Kinematic Reliability”. The kinematics reliability is defined as the likelihood that the actual location of the end-effector falls within a sphere with a radius equal to a specified tolerance threshold, centered at the desired position. The limit-state function is nonlinear in order to engage the end-effector's dependent x-, y-, and z-coordinates with regard to the random link lengths and joint angles. Because of the problem's complexity, typical dependability approaches are inapplicable.

The study shows us the increasing maximum positional error with increase in tolerance value.

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