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Kinematic Analysis of Delta Parallel Robot: Simulation Study

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Abstract—This work is focused on the kinematic analyses and simulation of the Delta parallel robot. This robot is proposed in this study, which solves the forward kinematics by vector method. The half-angle formula is used to derive the inverse kinematics. The workspace of the Delta robot is presented dependent on the solution of forward kinematics. This parallel robot model was built in Solidworks and then imported into MATLAB/Simscape to do the simulation. The simulation represents the position and velocity of the moving plate, study the angular position and velocity of each joint.

Keywords: *Delta Robot, Parallel Robot, kinematic simulation, and SimScape*

1. Introduction

Nowadays, robotics plays an essential role in industrial automation, depending on the kinematic structure. The industrial robots are classified into serial and parallel. Parallel robots are composed of several kinematic chains that connect the end-effector to the base frame as multiple closed-loop chains. It allows for load sharing on each kinematic chain, allowing sharing load with each other kinematic chain. Several advantages for this kinematics chain can be expressed as an increase in the accuracy, rigidity, and the velocity of the end effector compared with serial mechanisms.

Furthermore, a lighter structure may be achieved when all the actuators are fixed to the manipulator base such that the kinematic chains do not carry the weight of the actuators. It increases the payload capacity relative to the total robot mass compared to serial robots. Parallel robots have recently drawn many interests in a growing range of applications (medical, machine tools, pick & place, and manipulation). Delta robots are a kind of parallel robots, which are widely used in industries. Traditional delta robots have three translational DOFs. They are used in various fields, which DOFs can no longer meet the more complex working conditions [1].

Delta parallel robot consists of three active links; each link has connected directly to the actuator. The joints between these links are universal joints with two DOFs. The mechanisms are connected to the moving plate can be described with respect to the base frame. The workspace is created based on the lengths of links and relative motion called workspace [2]. The parallel robot shows better stiffness with resonance and load carrying capacity distributed into the motors than serial robots. Research is conducted to use delta robot properties such as the parallel kinematic machine to increase the surgeon's accuracy and dexterity. At the same time, reduce the noise from shanking to perform a high biopsy of brain tissue or placed electrodes for Parkinson's disease treatments [3][4][5].

The Delta robot, which can perform three translational motions are presented by Clavel [6], and it has already become a commercial success because of high speed performance. Pierrot et al. [7] Analyzed the inverse and direct kinematics, inverse statics, and inverse dynamics of the Delta parallel manipulator with few trigonometric and arithmetic operations. Considering the swing range of spherical joints and desired workspace, Liu et al.[8] presented a method to design the robot. To improve the accuracy, Ni [9] investigated the kinematics, error modeling, sensitivity, and tolerance allocation of the parallel manipulator. A new method is presented to solve the Delta mechanism's inverse kinematic using cylindrical coordinates instead of Cartesian coordinates [10]. Based on the Jacobian and geometric error models, Ghazi et al. [11] evaluated Delta parallel manipulator's kinematic accuracy. Using algebraic tools, Jha et al. [12] studied the singularities, the joint space, and the workspace of a family of delta-like mechanisms. According to the elliptical trajectory with a modified sine motion profile, Huang et al. [13] studied the motion planning to smoothen the torque. Using the elastic dynamics and finite element method, Kuo [14] derived the mathematical model and analyzed the Delta robot's natural frequency. The results showed that flexible link compensation was the importance of precise robot motion. Considering joint friction and jerk constraints, Liu et al. [15] has studied the trajectory planning to improve tracking accuracy. In addition to the problems of trajectory planning and design, some scholars have studied how to improve the speed of Delta robot from the perspective of control [16]. Few works of literature describe why the Delta robot can only perform translational motion and the critical role of its 4S mechanism's geometric condition.

In the present investigation, a delta parallel manipulator is described. The forward and inverse kinematic of this mechanism are analyzed. The working area where the robot can move, which also called workspace, is optimizing in this paper. The trajectory and jacobian are discussed with simulation results using MATLAB/Simulink. The paper is organized as follows; the full robot description is presented in section 2. Moreover, a full mathematical model for the kinematic model, including the forward and inverse, are described in section 3. Furthermore, the whole workspace and the results' analysis are presented in sections 4 and 5, respectively. Finally, section 6 presents the conclusions of the work.

2. Robot Description

The CAD model of the delta parallel robot is shown in Fig. 1. The delta robot structure includes three identical in-paralleled limbs, where the angles between any two adjacent branches are equal to each other. Each branch can be driven through an actuator mounted on the fixed platform of the fixed frame. This structure consists of Actuators, which are fixed into motor support, connecting to drive arm, and follow arm with parallelograms. Therefore, collect each of them into a moving plate.

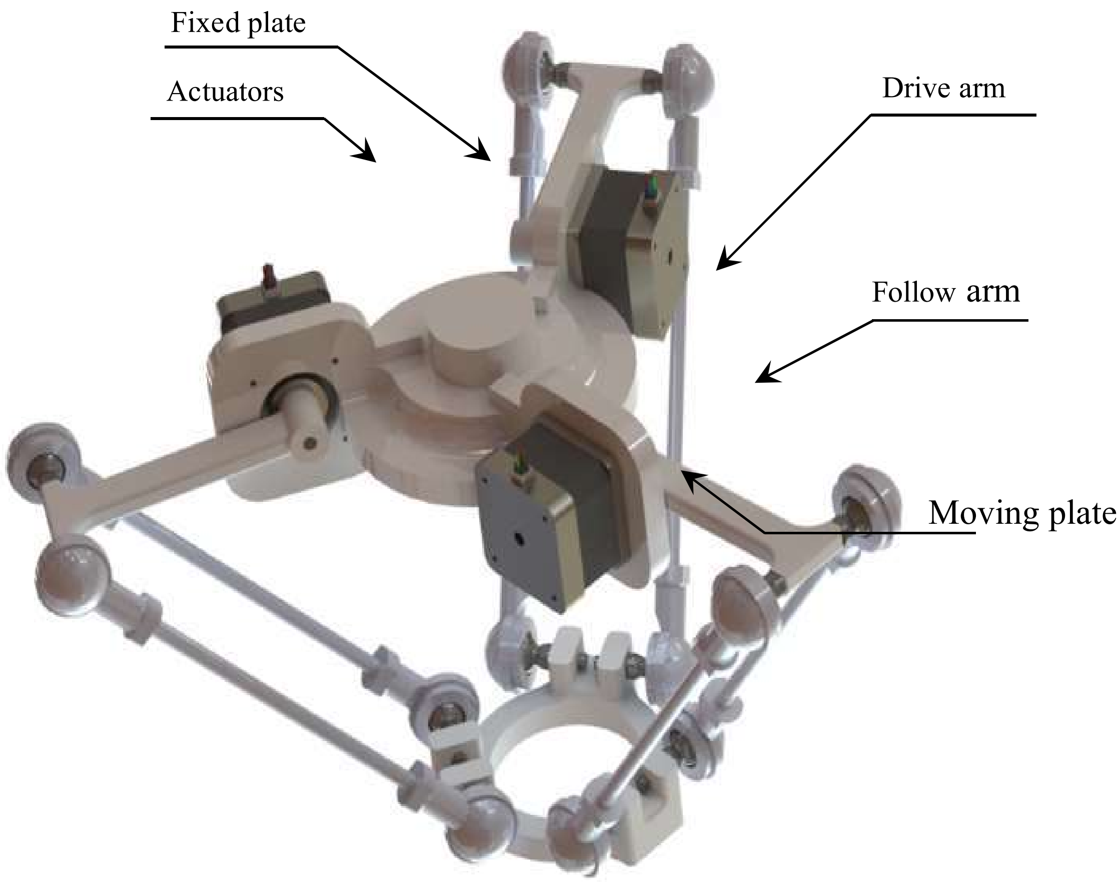


Fig. 1: Structure of Delta parallel robotic.

3. Forward Kinematic Model

The kinematics description aims to identify the mechanism construction depending on the robot's parameters regarding fixed coordinates and vice versa. This section presents the kinematics model of the Delta parallel robot, including both forward and inverse kinematics. Figure 2 represents the geometric parameters of this robot, which can be defined as the radius of the fixed plate as $\boldsymbol{\mathcal{R}} = \boldsymbol{O_0 A_i}$, the radius of the moving plate as $\boldsymbol{r} = \boldsymbol{O_0 C_i}$ the length of the drive Link is $\boldsymbol{\ell_1} = \boldsymbol{A_i B_i}$ And the length of the following link as $\boldsymbol{\ell_2} = \boldsymbol{B_i C_i}$.where $i = 1,2,3$

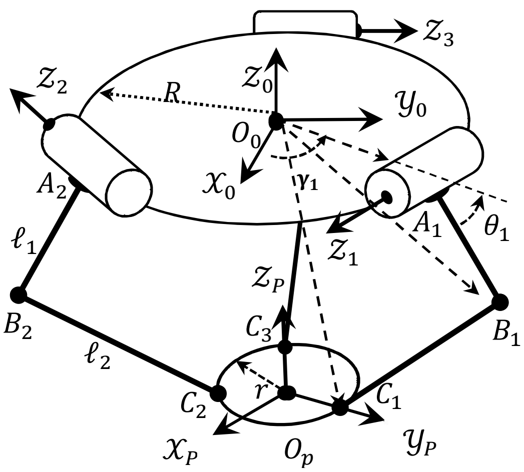


Fig. 2: kinematic diagram of Delta parallel robotic.

The configuration of the end-effector with respect to the fixed frame as a function of the geometric parameters can be defined as forward kinematics. In this section, the delta parallel manipulator forward kinematics is represented using the vector method, which achieves the configuration of the end-effector (x, y, z) with respect to active joint θ_i.

$$\overline{\boldsymbol{O_0 \mathcal{A}_i}} = [\mathcal{R}\cos\gamma_i \quad \mathcal{R}\sin\gamma_i \quad 0]^{\boldsymbol{T}} \tag{1}$$

Where $\gamma_i = n\pi/4$, $n = 1,2,3$ Similarly, point C_i relative to frame $\{\boldsymbol{P}\}$ is

$$\overline{\boldsymbol{O_P \mathcal{C}_i}} = [r\cos\gamma_i \quad r\sin\gamma_i \quad 0]^{\boldsymbol{T}} \tag{2}$$

Describing Point $\boldsymbol{B_i}$ with respect to Frame$\{\boldsymbol{0}\}$, we obtain,

$$\overline{\boldsymbol{O_0 \mathcal{B}_i}} = \begin{bmatrix} (\mathcal{R} + \ell_1 \cos\theta_i)\cos\gamma_i \\ (\mathcal{R} + \ell_1 \cos\theta_i)\sin\gamma_i \\ -\ell_1 \sin\theta_i \end{bmatrix} \tag{3}$$

Considering the origin of frame $\{P\}$ relative to Frame $\{0\}$ is $\boldsymbol{E} = [\mathcal{X}_P, \mathcal{Y}_P, \mathcal{Z}_P]^T$, $\boldsymbol{C_i}$ can also be expressed with respect to Frame $\{0\}$ as

$$\overline{\boldsymbol{O_0 \mathcal{C}_i}} = \begin{bmatrix} x_P + r\cos\gamma_i \\ y_P + r\sin\gamma_i \\ z_P \end{bmatrix} \tag{4}$$

Considering the geometry of the parallel robot, we have the following constrain

$$\boldsymbol{\ell_2} = |\boldsymbol{O_0\mathcal{B}_i} - \boldsymbol{O_0\mathcal{C}_i}| \quad (5)$$

To get the different between $(\boldsymbol{\mathcal{V}_i})$and $(\boldsymbol{O_0\mathcal{C}_i})$ we do the following

$$\boldsymbol{O_0\mathcal{B}_i} - \boldsymbol{O_0\mathcal{C}_i} = \begin{bmatrix} (\mathcal{R} - r + \ell_1 \cos\theta_i)\cos\gamma_i - x_P \\ (\mathcal{R} - r + \ell_1 \cos\theta_i)\sin\gamma_i - y_P \\ \ell_1 \sin\theta_i - z_P \end{bmatrix} \quad (6)$$

By using the main equation (7) to get the coordinate of moving plate with respect to base frame

$$x_p^2 + y_p^2 + z_p^2 + a_i x_p + b_i y_p + c_i z_p + d_i = 0 \quad (7)$$

Where;

$$\begin{aligned} a_i &= 2(\mathcal{R} - r + \ell_1 \cos\theta_i)\cos\gamma_i \\ b_i &= 2(\mathcal{R} - r + \ell_1 \cos\theta_i)\sin\gamma_i \\ c_i &= 2\ell_1 \, sin\,\theta_i \\ d_i &= \ell_1^2 - \ell_2^2 + (\mathcal{R} - r)^2 + 2(\mathcal{R} - r)\ell_1 \cos\theta_i \end{aligned} \quad (8)$$

Leads to three linear equations as,

$$\begin{aligned} x_p^2 + y_p^2 + z_p^2 + a_1 x_p + b_1 y_p + c_1 z_p + d_1 &= 0 \\ x_p^2 + y_p^2 + z_p^2 + a_2 x_p + b_2 y_p + c_2 z_p + d_2 &= 0 \\ x_p^2 + y_p^2 + z_p^2 + a_3 x_p + b_3 y_p + c_3 z_p + d_3 &= 0 \end{aligned} \quad (9)$$

After solver equation (9) to obtain $\boldsymbol{x_p}$,and $\boldsymbol{y_p}$ find,

$$x_p = m_1 z_p + n_1 \qquad y_p = m_2 z_p + n_2 \quad (10)$$

Where:

$$m_1 = \frac{c_2 b_1 - c_3 b_1 + c_3 b_2 - c_1 b_2 + c_1 b_3 - c_2 b_3}{b_2 a_1 - b_2 a_2 - b_3 a_1 + b_3 a_2 - b_1 a_2 + b_1 a_3 + b_2 a_2 - b_2 a_3}$$

$$n_1 = \frac{d_2 b_1 - d_2 b_2 + d_3 b_2 - d_1 b_2 + d_2 b_2 - d_2 b_3}{b_2 a_1 - b_2 a_2 - b_3 a_1 + b_3 a_2 - b_1 a_2 + b_1 a_3 + b_2 a_2 - b_2 a_3}$$

$$m_2 = \frac{c_1 a_2 - c_1 a_3 + c_2 a_3 - c_2 a_1 + c_3 a_1 - c_3 a_2}{b_2 a_1 - b_2 a_2 - b_3 a_1 + b_3 a_2 - b_1 a_2 + b_1 a_3 + b_2 a_2 - b_2 a_3}$$

$$n_2 = \frac{d_1 a_2 - d_1 a_3 + d_2 a_3 - d_2 a_1 + d_3 a_1 - d_3 a_2}{b_2 a_1 - b_2 a_2 - b_3 a_1 + b_3 a_2 - b_1 a_2 + b_1 a_3 + b_2 a_2 - b_2 a_3}$$

4. Inverse kinematics

The inverse kinematics (IK) refers to the use of the kinematics equations of a robot to determine the joint parameters that provide a desired position of the end-effector. Ik is a function of end-effector position in terms of joint parameters. Inverse kinematics is used to solve the joint angles $\boldsymbol{\theta_i}$ at given configuration target of the end-effecter (***x, y***, *z*). This mechanism has only three translational degrees of freedom. In this section, represents the inverse kinematics of the parallel manipulator using half angle formula. To get the joint angles from Eq. (7), which transformed as: $\theta_i (i = 1,2,3)$

$$\mathcal{A}_i \cos(\theta_i) + \mathcal{B}_i \sin(\theta_i) + \mathcal{C}_i = 0 \tag{11}$$

Where:

$$\mathcal{A}_i = 2\ell_1 x_P \cos\gamma_i + 2\ell_1 y_P \sin\gamma_i + 2(\mathcal{R} - r)\ell_1$$

$$\mathcal{B}_i = 2\ell_1 z_P$$

$$\mathcal{C}_i = \ell_1^2 - \ell_2^2 + (\mathcal{R} - r)^2 + 2(\mathcal{R} - r)\cos\gamma_i\, x_P + 2(\mathcal{R} - r)\sin\gamma_i\, y_P + x_P^2 + y_P^2 + z_P^2$$

From which we can find that

$$\theta_i = 2 * \tan^{-1}\left(\frac{-\mathcal{B}_i \pm \sqrt{\mathcal{B}_i^{\,2} - \mathcal{C}_i + \mathcal{A}_i}}{(\mathcal{C}_i - \mathcal{A}_i)}\right) \tag{12}$$

5. Jacobian kinematics

The Delta parallel robot's Jacobian matrix is defined as the relationship between the moving plate velocity and the actuated joint vector Differentiate equations (7) relative to the time to achieve the velocity and differentiated Equations (11) relative to the time to achieve the angular velocity, where

$\theta_i (i = 1,2,3)$

Similarly for eqn (11)

$$\boldsymbol{\mathcal{J}\dot{\theta}} = \boldsymbol{G\,\mathcal{V}} \tag{13}$$

Hence, by computing the velocity form of equation (13), which obtain:

$$\mathcal{V} = \frac{Adj.(G)}{\mathrm{Det.}(G)}\begin{bmatrix}\mathcal{J}_{11} & 0 & 0\\ 0 & \mathcal{J}_{22} & 0\\ 0 & 0 & \mathcal{J}_{33}\end{bmatrix}\begin{bmatrix}\dot{\theta}_1\\ \dot{\theta}_2\\ \dot{\theta}_3\end{bmatrix} \tag{14}$$

Where:

$$\mathcal{J}_{ii} = \ell_1 z_p \cos\theta_i + \ell_1(\mathcal{X}\cos\gamma_i + \mathcal{Y}\sin\gamma_i - \ell_3)\sin\theta_i$$

$$G_{i1} = x_P - \ell_3\cos\gamma_i - \ell_1\cos\theta_i\cos\gamma_i$$

$$G_{i2} = y_P - \ell_3\sin\gamma_i - \ell_1\cos\theta_i\sin\gamma_i$$

$$G_{i3} = z_p + \ell_1\sin\theta_i$$

6. Workspace

The workspace of the Delta parallel robot represents which acts as graphical representation solutions for the forward kinematics. The workspace's objective is to identify the volume's scope, dependent on actuator range and constraint. The workspace has been calculated based on a Nested- For loop code, that iterates the value of different input joint angle and calculate the final position of the end-effector. The final data is a matrix form the correlates the all the expected joint angles to the final position of the end-effector. The complete volume of the workspace is presented in Fig 3.

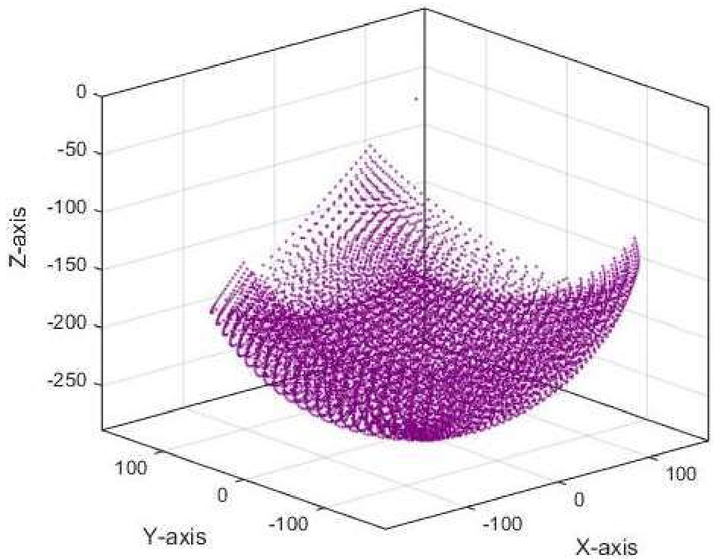
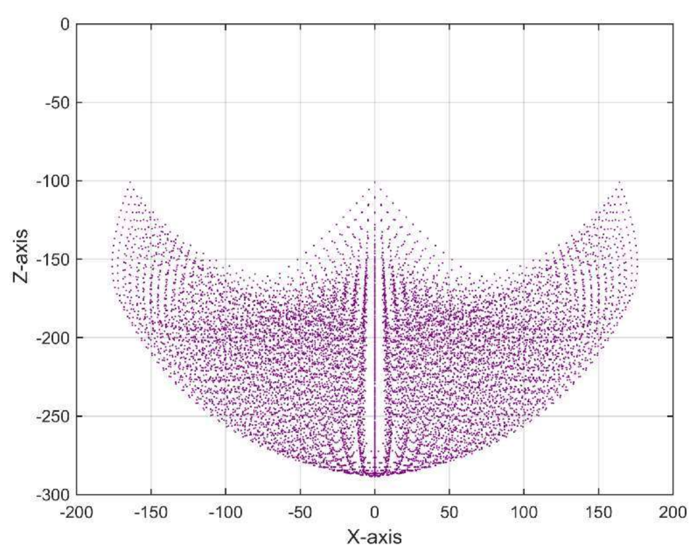
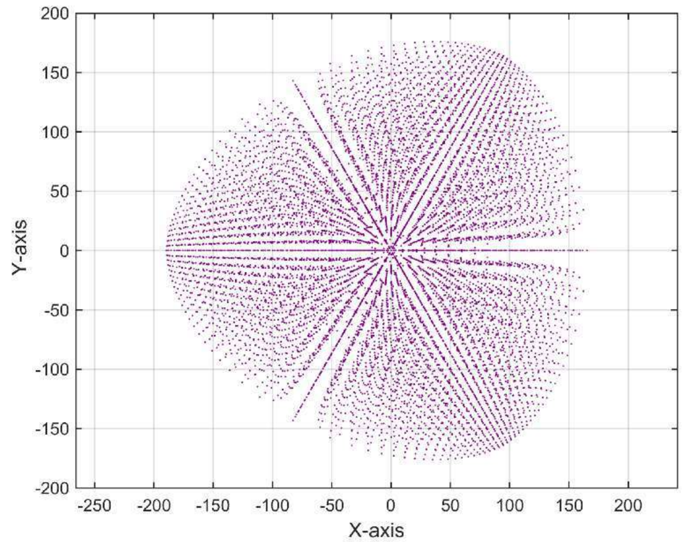


Fig. 3: Delta parallel manipulator workspace volume.

The workspace projection is presented in the X-Z plane, and the Y-Z plane is shown in Fig. 4a and 4b, respectively. The workspace boundary is smooth, and the effective workspace is immense and without holes in the space



(a)

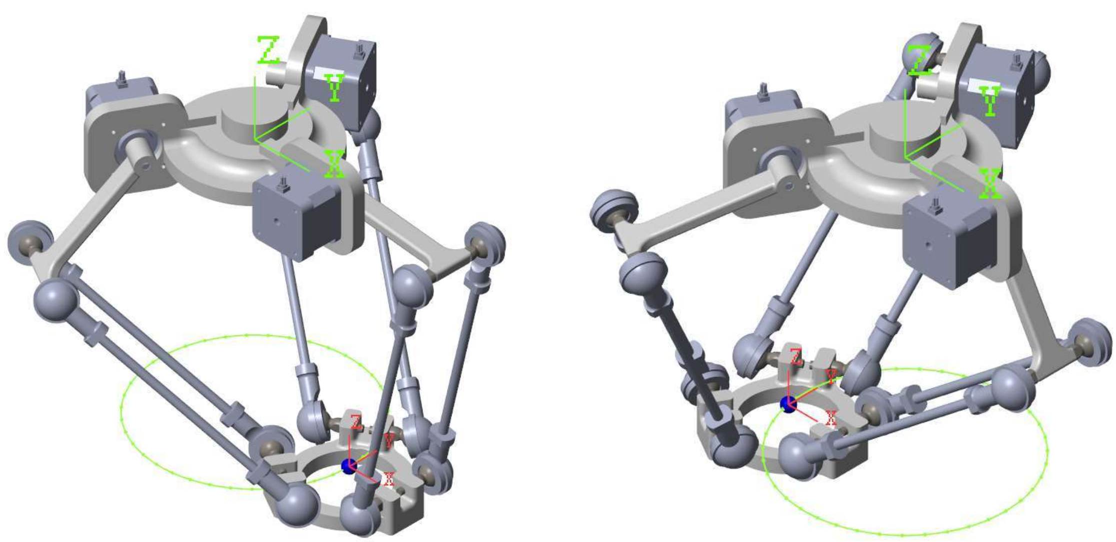


(b)

Fig. 4: (a) Projection of ZX plane of workspace (b) Projection of XY plane of workspace.

7. Simulation Analysis

In this section, a three-dimensional path is considered to verify the kinematic equations. The delta robot model is built in SolidWorks and imported into MATLAB's SimScape to verify the performance, representing the duration time of trajectory simulation shown in Fig. 5a and 5b, respectively.



(a) (b)

Fig. 5 a and b: The simulation model of delta parallel built MATLAB/Simulink

The specification of the physical parameter of this Delta parallel robot presented as R =70 mm, ℓ_1=95 mm, ℓ_2 = mm, r = 40 mm. Figure 6 shows the circular trajectory path of the moving plate for the delta robot, the relation between the desired and actual path trajectory is presented.

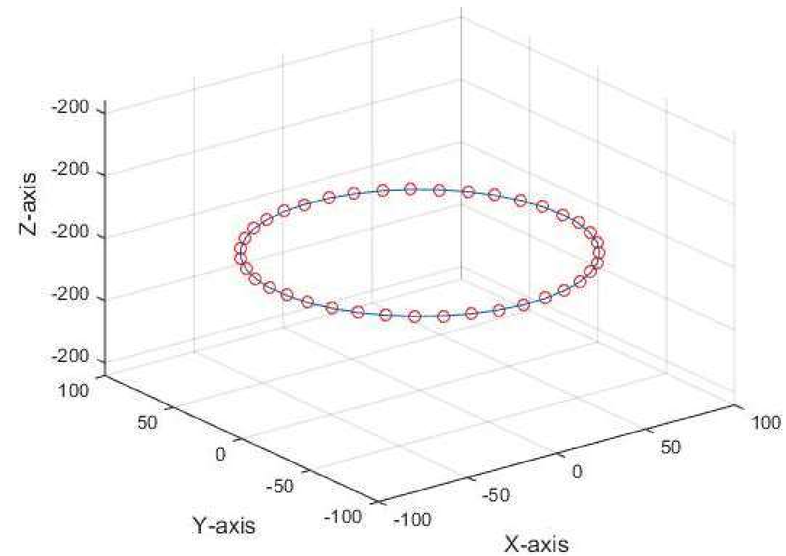
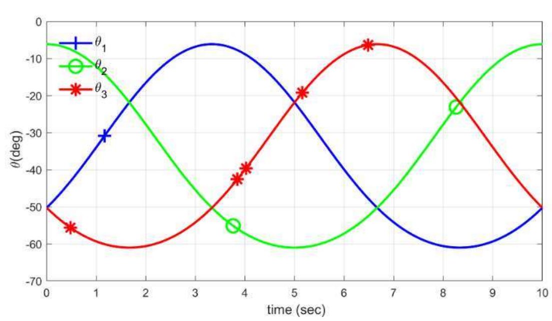
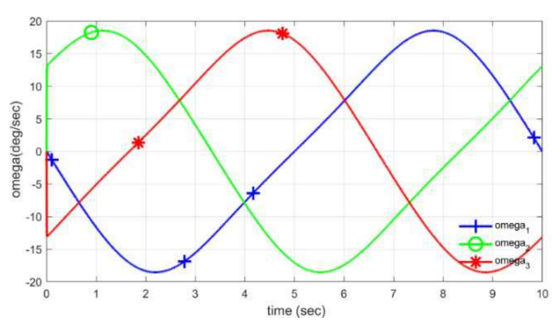


Fig. 6: Circular trajectory bath of the delta robot.

Fig (7) a and b represent the relation between the actuators' angular position and velocity as a function of duration. The angular position and velocity of these actuators depend on the trajectory profile relative to all joints variation.



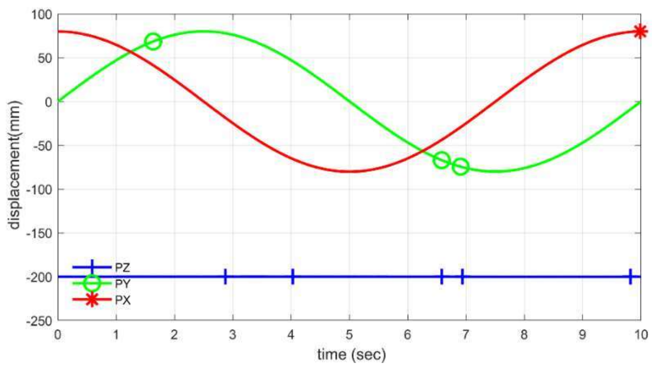
(a)



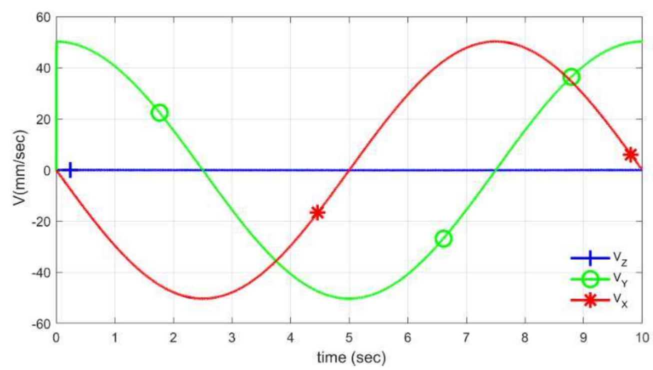
(b)

Fig. 7: Actuators position and velocity of the delta robot.

Figures 8a and 8b represent the relation between the absolute position and the moving plate's linear velocity as a duration time function. The total position of the moving plate depends on the trajectory profile relative to all joints variation.



(a)



(b)

Fig. 8 a and b: Moving plate position and velocity of delta robot.

8. Conclusions

This investigation work focused on the kinematic analyses of the Delta parallel robot. The forward kinematics are solved by the vector method. Also, the half-angle formula is used to derive the inverse kinematics. The workspace of the delta robot is presented dependent on the solution of forward kinematics. This parallel robot model was built in Solidworks and then imported into MATLAB/Simscape to simulate the results. The results represent the moving plate's position and velocity and study the joint's angular position and velocity. The working area where the robot can move, which also called workspace presented in this paper. The trajectory and jacobian are discussed with simulation results using MATLAB/Simulink Toolbox.

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