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EXPLORING INCLINED DELTA ROBOTS FOR ENHANCED 3D PRINTING

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Abstract- Parallel manipulator robots find extensive use across various applications due to their significant benefits, including high speeds and accelerations, robust stiffness, and commendable dynamic performance. In the realm of additive manufacturing, there is a growing exploration of such kinematic structures to devise innovative strategies for curved and multi-directional fabrication. In this specific context, the study presents the kinematic modeling, dimensional synthesis, and accuracy potential of an inclined configuration of a delta robot designed for utilization in 3D printers. Firstly, it introduces the kinematic modeling of inclined configuration. Secondly, it synthesizes the optimal dimensions using a geometrical approach. Thirdly, it proposes a method for accuracy analysis within the reachable workspace. Numerical results showcase the potential of this architecture for low-cost 3D printer development. The kinematic modeling and accuracy analysis prove valuable for designing and comparing delta robot-based 3D printers

Keywords: Forward Kinematic, Inverse Kinematic, Delta Robot, Accuracy Analysis.

1. INTRODUCTION

For the last thirty years, delta robots have stood out as the most commercially successful models among parallel architectures. The initial model was conceived by Reymond Clevel [1, 2, 3]. The fundamental three degrees of freedom in the linear delta robot stem from the connection of two platforms through three parallelograms, with one of the platforms usually designated as mobile. Each parallelogram is formed by links attached to the two platforms with spherical joints. The primary benefit of this mechanism lies in its ability to swiftly manipulate lightweight objects. This is achieved by placing heavy drives on a stationary platform, while all the mobile components of the mechanism are constructed from lightweight, frequently composite materials. These types of architectures demonstrate excellent performance in terms of high speed, low inertia, good stiffness, and accuracy [4-8].

The delta robot architecture has found successful applications in various manufacturing processes such as Selecting and positioning tasks, assembly, painting, and numerically controlled machine (CNC) [9]. In the field of additive manufacturing, the adoption of delta kinematics has become widespread due to its numerous advantages over traditional sequential kinematics. The delta 3D printer offers a notable advantage in terms of cost-effectiveness due to its streamlined component count. This advantage serves as motivation for researchers to conduct a comprehensive comparison between the delta 3D printer and other 3D printers, focusing on factors such as accuracy, speed, and surface quality, as outlined in [10]. The Delta robot proves to be highly suitable for the Fused Deposition Modelling (FDM) process in manufacturing. Additionally, as highlighted by Song, et al. [12], the utilization of a parallel kinematic FDM machine enables multidirectional manufacturing. This approach holds the potential to produce printed parts with enhanced surface finish, increased structural strength, and improved accuracy.

This research looks into a new setup for a delta robot, where the linear guide axes are inclined to make a pyramid shape. Initially made for pick-and-place tasks, this design is both small and fast. The study results highlight the potential of the pyramidal setup for improving affordable 3D printing technology. The paper's structure is delineated as outlined below: In section 2, the kinematic modeling of the inclined delta robot is presented. In Section 3, a geometric method is presented for synthesizing the primary parameter dimensions required for a specified workspace. The subsequent section, Section 4, conducts an accuracy analysis within the workspace. Section 5 provides numerical results, and the study is ultimately concluded in Section 6.

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2. KINEMATIC MODELING FOR THE INCLINED CONFIGURATION OF DELTA ROBOT

As depicted in Figures 1-3, the proposed Delta robot consists of a stationary base and a movable platform linked by three identical parallelograms. Each parallelogram is connected on one side to the mobile platform and on the other side to the movable slide. The three slides possess translational degrees of freedom relative to symmetrically inclined slides fixed to the stationary platform. Spherical connections link each side of the parallelogram to its corresponding counterpart. The actuating sub-system is situated on the fixed base, while the end-effector is located on the moving platform.

The reference points for the stationary and mobile platforms are designated as O and O', respectively. The origin of the spatial reference (O, xyz), linked to the mobile platform, is situated at its center. The z-axis is vertically oriented, normal to the base, and the y-axis is positioned along the A_3O direction. The reference point of the connection between the parallelogram and the base is denoted by B_i, and the reference point of the connection between the parallelogram and the movable slide is denoted by P_i, where i varies from 1 to 3.

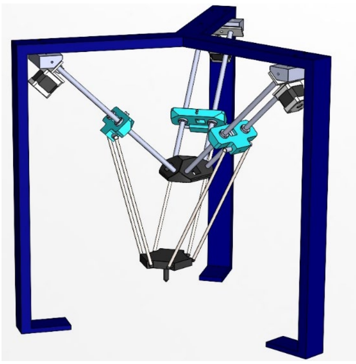


Figure 1. The Inclined Delta Robot Modeled using SolidWorks

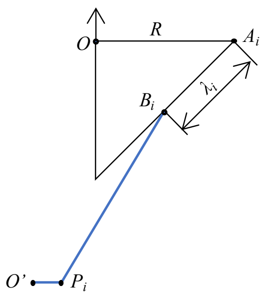


Figure 2. Kinematic description of the i-th kinematic chain

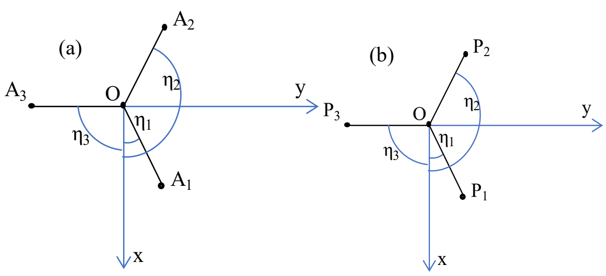


Figure 3. a) Aerial perspective of the base, b) the movable platform

Figure 3 depicts an aerial perspective of the base (a) and the mobile platform (b). Consider the provided parameters R and r, where: $OA_i = R$, and $O'P_i = r$. The length of the parallelogram link is represented as L. Then, $\eta_i = (4i-3)\pi/6$ designates the angle between x and the line OA_i. The φ designates the angle between the axes of the linear guides and the line OA_i.

2.1. Inverse Position Kinematic (IPK)

The objective of inverse kinematics is to determine the slide displacement that corresponds to a specified position of the movable platform reference point, denoted as O'. The geometric closure of the polygon $OA_iB_iP_iO'O$ in i-th kinematic chain is expressed as:

$$\overrightarrow{OA_i} + \overrightarrow{A_iB_i} + \overrightarrow{B_iP_i} + \overrightarrow{P_iO'} + \overrightarrow{O'O} = \vec{0} \tag{1}$$

In the fixed reference (O, xyz), the coordinates of point O' can be expressed as: $\overrightarrow{OO'} = (x, y, z)^T$, where, $\overrightarrow{A_iB_i} = (-\lambda_i \cos\varphi \cos\eta_i, -\lambda_i \cos\varphi \sin\eta_i, -\lambda_i \sin\varphi)^T$ denote actuated joints variables. The vectors $\overrightarrow{OA_i}$ and $\overrightarrow{P_iO'}$ can be respectively expressed in coordinate system 0-xyz as: $\overrightarrow{OA_i} = (R\cos\eta_i, R\sin\eta_i, O)^T$, $\overrightarrow{P_iO'} = (-r\cos\eta_i, r\sin\eta_i, 0)^T$.

The initiation of solving the Inverse Position Kinematics (IPK) begins with the formulation of the constraint equation: $\left(\overrightarrow{B_iP_i}\right)^2 = L^2$.

Then the vector Equation (1) is converted into three scalar equations, yielding:

$$\begin{aligned} L^2 &= \left[x-(R-r)\cos\eta_i + \lambda_i \cos(\varphi)\cos(\eta_i)\right]^2 + \\ &+\left[y-(R-r)\cos\eta_i + \lambda_i \cos(\varphi)\sin(\eta_i)\right]^2 + [z+\left[\lambda_i \sin(\varphi)\right]]^2 \end{aligned} \tag{2}$$

where, $\eta_i = \dfrac{4i-3}{6}\pi$, and i= 1, 2, 3.

Three scalar equations can then be written as follows:

$$\lambda_1^2 + B_1\lambda_1 + C_1 = 0 \tag{3}$$

$$\lambda_2^2 + B_2\lambda_2 + C_2 = 0 \tag{4}$$

$$\lambda_3^2 + B_3\lambda_3 + C_3 = 0 \tag{5}$$

where, $B_1 = -\sqrt{2}(R-r) + \dfrac{\sqrt{6}}{2}x + \dfrac{\sqrt{2}}{2}y + \sqrt{2}z$

$$B_2 = -\sqrt{2}(R-r) - \frac{\sqrt{6}}{2}x + \frac{\sqrt{2}}{2}y + \sqrt{2}z$$

$$B_3 = -\sqrt{2}(R-r) - \sqrt{2}y + \sqrt{2}z$$

$$C_1 = x^2 + y^2 + z^2 - L^2 + (R-r)^2 - \sqrt{3}x(R-r) - y(R-r)$$

$$C_2 = x^2 + y^2 + z^2 - L^2 + (R-r)^2 + \sqrt{3}x(R-r) - y(R-r)$$

$$C_3 = x^2 + y^2 + z^2 - L^2 + (R-r)^2 + 2y(R-r)$$

Solving the three quadratic Equations (3-5) yields the following result:

$$\lambda_1 = \frac{-B_1 - \sqrt{\Delta_1}}{2}; \lambda_2 = \frac{-B_2 - \sqrt{\Delta_2}}{2}; \lambda_3 = \frac{-B_3 - \sqrt{\Delta_3}}{2}$$

where, $\Delta_i = B_i^2 - 4C_i$.

It is important to highlight that the problem yields two solutions for each lambda. However, given the configuration of the robot, only one solution is taken into consideration.

2.2. Forward Position Kinematic (FPK)

The objective of Forward Position Kinematics (FPK) is to establish the Cartesian coordinates of O' in relation to the displacement of the actuated joints, denoted by λ_i. The forward kinematic solution initiates with vector Equation (2), which are projected to produce three scalar equations. Subtracting the second equation from the first and the third from the first results in two algebraic equations that establish relationships among the coordinates x, y, and z:

$$a_1 x + b_1 y + c_1 z + d_1 = 0 \tag{6}$$

$$a_2 x + b_2 y + c_2 z + d_2 = 0 \tag{7}$$

where, $a_1 = \frac{\sqrt{6}}{2}(\lambda_1 + \lambda_2) - 2\sqrt{3}(R - r)$,

$a_2 = \frac{\sqrt{6}}{2}\lambda_1 - \sqrt{3}(R - r)$ $b_1 = \frac{\sqrt{2}}{2}(\lambda_1 - \lambda_2)$,

$b_2 = \frac{\sqrt{2}}{2}\lambda_1 + \sqrt{2}\lambda_3 - 3(R - r)$ $c_1 = \sqrt{2}(\lambda_1 - \lambda_2)$,

$c_2 = \sqrt{2}(\lambda_1 - \lambda_3)$, $d_1 = \lambda_1^2 - \lambda_2^2 - \sqrt{2}(R - r)(\lambda_1 - \lambda_2)$,

$d_2 = \lambda_1^2 - \lambda_3^2 - \sqrt{2}(R - r)(\lambda_1 - \lambda_3)$.

From the two algebraic Equations (6) and (7), The coordinates x and y can be formulated exclusively in terms of z only Then:

$$x = Az + B \tag{8}$$

$$y = Ez + F \tag{9}$$

where, $A = \frac{-\left(c_1 - c_2 \frac{b_1}{b_2}\right)}{\left(a_1 - a_2 \frac{b_1}{b_2}\right)}$, $B = \frac{-\left(d_1 - d_2 \frac{b_1}{b_2}\right)}{\left(a_1 - a_2 \frac{b_1}{b_2}\right)}$,

$E = \frac{-\left(c_1 - c_2 \frac{a_1}{a_2}\right)}{\left(b_1 - b_2 \frac{a_1}{a_2}\right)}$, $F = \frac{-\left(d_1 - d_2 \frac{a_1}{a_2}\right)}{\left(b_1 - b_2 \frac{a_1}{a_2}\right)}$.

The substitution of the expressions of x and y in one of Equations (2), leads to a quadratic equation:

$$\alpha z^2 + \beta z + \gamma = 0 \tag{10}$$

where, $\alpha = A^2 + E^2 + 1$,

$\beta = 2AB + 2EF + Aa_2 + E\left(\frac{\sqrt{2}}{2}\lambda_1 - (R - r)\right) + \sqrt{2}\lambda_1$,

$\gamma = B^2 + F^2 + Ba_2 + F\left(\frac{\sqrt{2}}{2}\lambda_1 - (R - r)\right) +$

$+ (R - r)^2 - L^2 + \lambda_1^2 - \sqrt{2}\lambda_1 (R - r)$

The solution is as follows:

$$z = \frac{-\beta - \sqrt{\Delta}}{2\alpha} \tag{11}$$

where, $\Delta = \beta^2 - 4\alpha\gamma$.

It is worth noting that only one solution is considered due to the robot's configuration in Figure 1.

3. SYNTHESIS OF OPTIMAL DIMENSIONS

The synthesis of optimal dimensions for delta robot is a complex task and should be consider many items such as workspace, singularity, accuracy, and so on. Numerous studies detail techniques for synthesizing robot dimensions to optimize workspace volume, as seen in works such as [13] and [14]. In this study, we adopt a geometric approach wherein the initial knowledge of the workspace volume guides the determination of dimensions. The dimensions are subsequently defined to enable the mobile platform's reference point to reach all points within the specified workspace.

In accordance with symmetry considerations, the intended workspace is defined as a cylinder with a radius represented by r_0 and a height denoted by H_0. The requirement is for this cylinder to be inscribed within the entire workspace. However, some dimensions need to be set up in advance. These parameters are affected by operating or design restrictions. These constraints can be explained as follows:

- The minimal value of the parameter R_l, defined in Figure 4a, can be determined according to the wide of the parallelogram links.
- The angle ψ, which represents the deviation from the vertical axis to the axis of the links, must not exceed the angle φ to avoid interference with linear guides.
- In order to avoid interference between the ball joints, the minimum radius (r_{min}) of the mobile platform is limited by the width of the parallelograms formed by the links.

As depicted in Figure 4a, the mobile platform is assumed to be at the plane $z=H_0$, and the reference point O' is assumed to extend to the workspace's furthest point. At this pose, there are:

$$R - r = r_0 \tag{12}$$

$$L_{\max} = 2R - 2r \tag{13}$$

$$H_{\max} = H_0 + L_{\max} \tag{14}$$

As depicted in Figure 4b, the mobile platform is assumed to be at the plane $z=0$, and the reference point O' is assumed to extend to the workspace's furthest point. At this pose, there are:

$$L_{\min} \sin(\psi) = R - 2r + R_l \tag{15}$$

For the proposed studies, the fixed parameters are as follows: R_l=40 mm, r=40 mm, φ=45 degrees. The value of R is directly deduced from Equation (12). Subsequently, the value of $L_{\max}$ is directly deduced from Equation (13), $H_{\max}$ from Equation (14), and finally, the value of $L_{\min}$ is computed using Equation (15). Table 1 summarizes the synthesized optimal dimensions of the inclined delta robot.

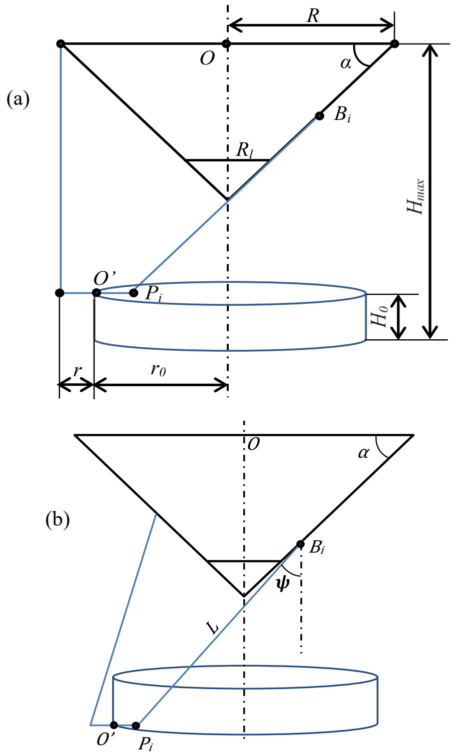


Figure 4. The extreme position of the mobile platform's center in relation to the inscribed cylinder: a) $z=H_0$, b) $z=0$

Table 1. optimal dimensions of delta robot

Parameters Design	Value
H_0	125 mm
r_0	150 mm
ψ_{max}	45 degrees
r	40 mm
R_l	40 mm
R	190 mm
L_{max}	280 mm
L_{min}	212.13 mm
H_{max}	405 mm

4. ACCURACY ANALYSIS ALONG REACHABLE WORKSPACE

In the context of 3D printers, achieving precise positioning is a paramount design requirement [15]. Position errors in a parallel robot stem from various factors, including manufacturing discrepancies, compliance issues, and active joint errors, among others. According to Merlet [16], active-joint errors, or input errors, stand out as the most substantial source of inaccuracies in a parallel robot that has been appropriately designed, manufactured, and calibrated.

The parameters associated with the positional performance of a robot include accuracy, repeatability, and resolution [17]. These factors depend on various components used in the construction of the robot, such as links, motors, encoders, the controller, and the quality of manufacturing. Resolution is characterized as the smallest step move that the end effector can generate. Repeatability measures the robot's capability to consistently return to the same position and orientation. Accuracy is defined as the robot's proficiency in precisely reaching a specified position in 3-D space. These principles are visually depicted in Figure 5.

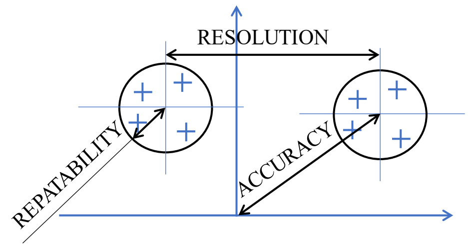


Figure 5. Accuracy vs resolution and repeatability

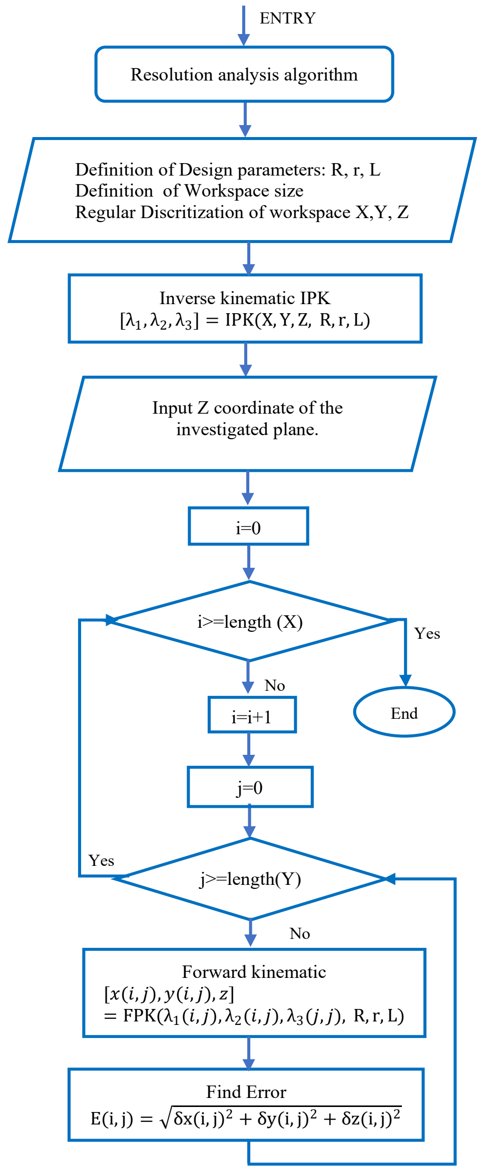


Figure 6. Algorithm of theoretical positioning error along reachable workspace

To investigate the viability of the inclined delta robot for additive manufacturing applications, an accuracy analysis has been conducted. This study specifically addresses positioning errors, focusing on the limitations imposed by the stepper motor's restricted resolution. A practical definition of the positioning error can be expressed as [18]:

$$E = \sqrt{\delta x^2 + \delta y^2 + \delta z^2} \tag{16}$$

where, δx, δy,δz represents the smallest displacements that the mobile platform can perform for smallest movement of the motor step. Hens, δx, δy,δz can be defined as:

$$\delta x = \frac{\partial x}{\partial \lambda_1} d\lambda_1 + \frac{\partial x}{\partial \lambda_2} d\lambda_2 + \frac{\partial x}{\partial \lambda_2} d\lambda_2 \tag{17}$$

$$\delta y = \frac{\partial y}{\partial \lambda_1} d\lambda_1 + \frac{\partial y}{\partial \lambda_2} d\lambda_2 + \frac{\partial y}{\partial \lambda_3} d\lambda_3 \tag{18}$$

$$\delta z = \frac{\partial z}{\partial \lambda_1} d\lambda_1 + \frac{\partial z}{\partial \lambda_2} d\lambda_2 + \frac{\partial z}{\partial \lambda_3} d\lambda_3 \tag{19}$$

where, $\partial x / \partial \lambda_i$ represent the partial derivative of x with respect to λ_i . $d\lambda_i$ represent the smallest displacement obtained by the actuator. Analytical resolution of the problem is very fastidious. In this work, the partial derivatives are performed using the symbolic tool of Python programming language. the derived expression of partial derivative is then used to determinate the accuracy numerically using the following algorithm Figure 6.

5. NUMERICAL RESULTS

This section presents a numerical validation of inverse and forward kinematic formulas, determines the reachable workspace and evaluates the accuracy along the accessible workspace.

5.1. Numerical Verification of Inverse and Forward Kinematic Formulas

In the field of robotics, conducting simulations through CAD software and Simulink, as mentioned in [19], is highly intriguing as it validates equations of motion, singularity, workspace, and more. In this study, numerous trajectory simulations were executed for varying dimensions of robot parameters, employing a CAD model, motion tool, and MATLAB-based Inverse Kinematics program. In this section, numerical simulation is proposed to validate the inverse and forward kinematic formulas. The desired trajectory is modeled as a helix with radii equal to 80 mm and step of 25 mm.

The displacements of actuators are calculated using the inverse kinematic formulas (IPK), and the result is shown in Figure 8. Subsequently, the forward kinematic formulas are employed to generate the trajectory of the moving platform. The generated trajectory is expected to align with the desired one. As shown in Figure 10, the obtained trajectory is exactly the same as the simulated one. Which makes it possible to confirm the accuracy of the FPK and IPK formulas.

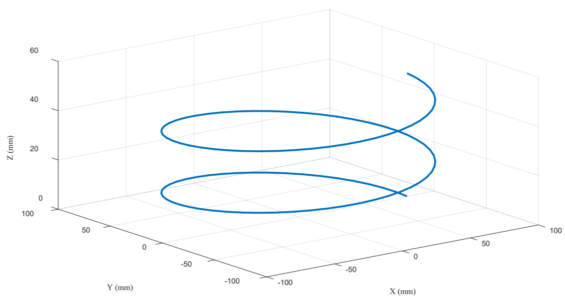


Figure 7. Graphical representations of a helix trajectory

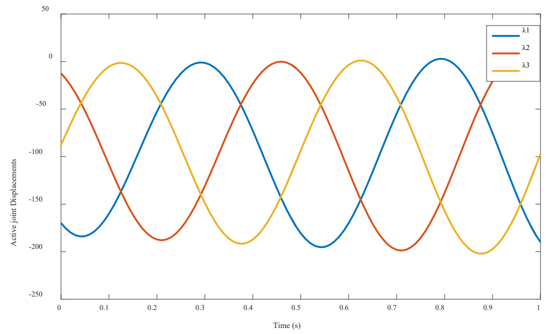


Figure 8. Calculated displacement of the active joint denoted as λ_i

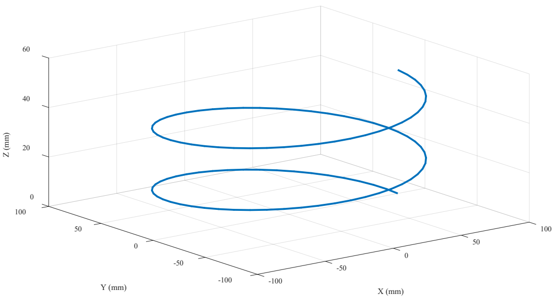


Figure 9. Calculated trajectories using FPK equations

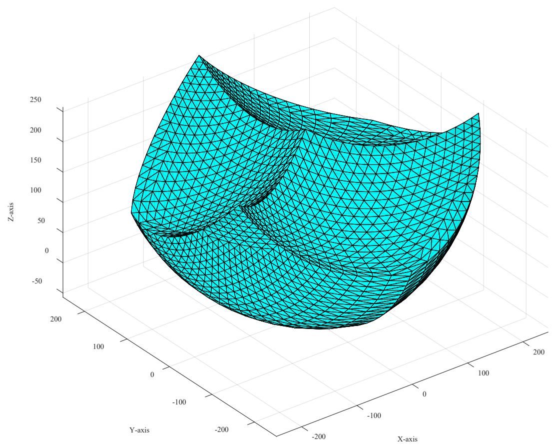


Figure 10. Reachable workspace boundaries

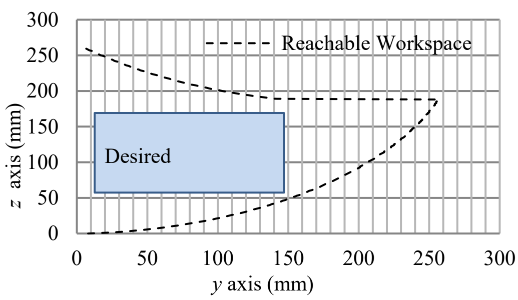


Figure 11. The desired workspace is situated within the confines of the workspace boundary

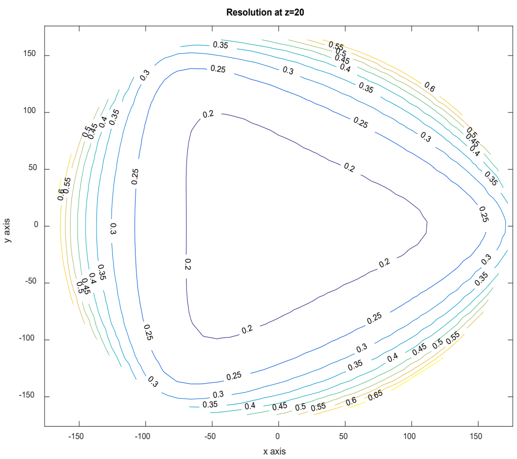
5.2. Reachable Workspace

The reachable workspace represents the area covered by the delta robot when some of the parameter is varied such as active joint or link length [20]. The method considered in this work is based on forward kinematic.

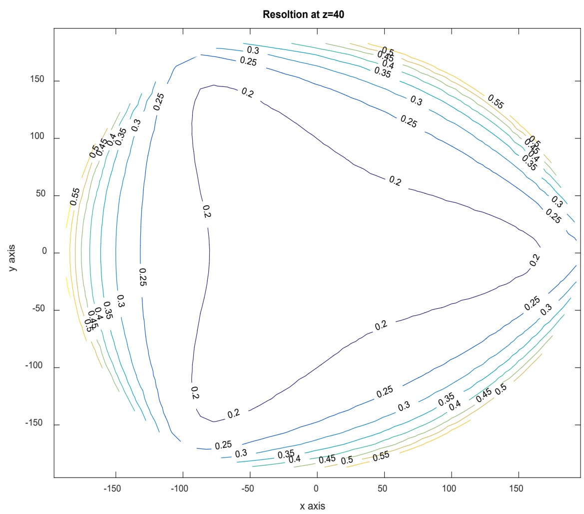
Figure 10 shows the theoretical reachable pose of the reference point of the mobile platform O', when the actuated joint parameters λ_i varies from 0 to 212 mm with step equal to 5 mm. This study aims to validate the proposed prototype in term of inscribed cylindrical workspace. As can be shown in Figure 11, the desired cylinder is inscribed in the reachable workspace.

5.3. Accuracy Inside the Reachable Workspace

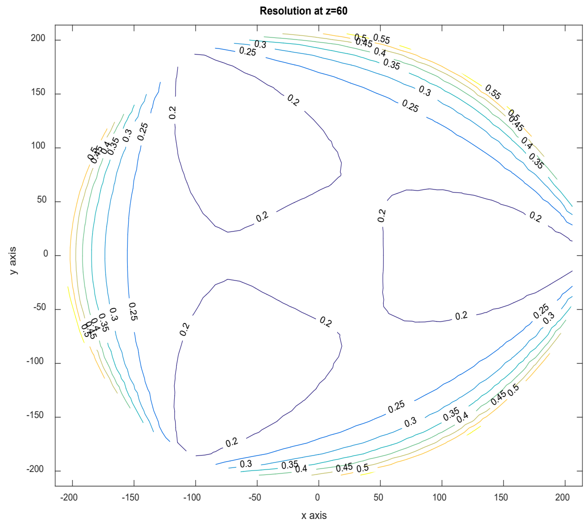
The assessment of accuracy entails examining the positioning error E, as defined in Section 4, while varying across a plane situated within the accessible workspace of the Delta robot. The examined planes are discretized with a specified density along the x and y axes. The local positioning error is then calculated at each point using the algorithm outlined in Section 4. The actuator step considered in this simulation is 1.8 degrees. As illustrated in Figure 12, the positioning error in the reachable workspace is about 0.2 mm, and arranged to align with the orientation of the three actuated slides around the axis (O, z). In the context of additive manufacturing, this outcome is satisfactory. In fact, enhancing the result is achievable by fine-tuning the resolution of the stepper motor within a range of 1/2 to 1/16.



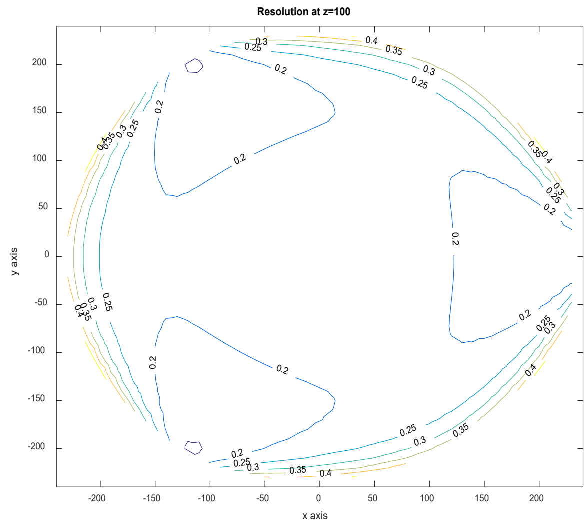
(a)



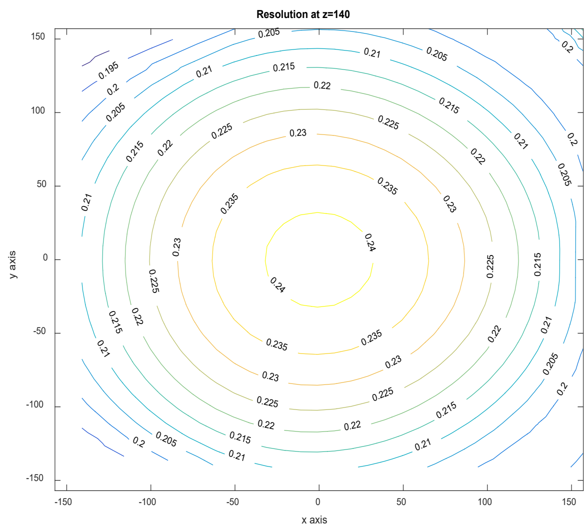
(b)



(c)



(d)



(e)

Figure 12. Local positioning error across planes (x,y): (a), (b), (c), (d), (e), z varies from 20 to 140 mm with step of 40 mm

6. CONCLUSIONS

In this article, an original study of inclined delta robot is presented. This study concerns kinematic modeling, synthesis of optimal dimensions and accuracy analysis inside the reachable workspace. The initial phase involves formulating the equations for both inverse and direct kinematics. These equations are derived analytically by ensuring geometric closure within the interconnected kinematic chains. Subsequently, the next stage entails identifying the ideal dimensions necessary for the designated workspace. This determination is made through a geometric methodology. Through proposed numerical simulations, validation of both the inverse and direct kinematic equations, as well as the optimal dimensions, is achieved. The final step involves a precision analysis aimed at determining the influence of limited actuator resolution on the end effector's position within the workspace.

The study shows that the inclined delta robot offers an interesting potential for additive manufacturing applications. It is compact, fast and accurate. Positioning error analysis suggests the feasibility of employing a standard stepper motor as an actuator. The prototype, once manufactured, showcases notable repeatability and acceptable precision, particularly given its cost-effectiveness. Future research will be devoted to refining effective accuracy through the application of calibration techniques centred around artificial neural networks. as exemplified in the referenced works [21] and [22].

NOMENCLATURES

1. Acronyms

CNC	Computerized Numeric Control
FDM	Fused Deposition Modelling
IPK	Inverse Position Kinematic
FPK	Forward Position Kinematic

2. Symbols / Parameters

R: The radii of the fixed platform
r: The radii of the moving platform
L: The length of the parallelogram link
λ_i : Coordinate of the actuated joint
η_i : The angle from the x-axis to the line OA_i (radian)
φ: The angle of inclination between the linear guides and the line OA_i. ($\pi / 4$)
x,y,z: The cartesian coordinate of the moving platform
Δ: The discriminant of a quadratic equation
$H_{\max}$: The height of the robot.
H_0 : The height of the desired cylindrical workspace
r_0 : The radii of the desired cylindrical workspace
Ψ : The angle between the vertical axis and the links axis
R_L : The limit horizontal distance from the point B_i
E: The positioning errors
δx , δy , δz : The smallest displacements that the mobile platform can perform (mm)

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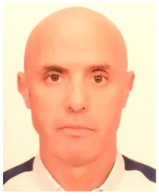
BIOGRAPHIES



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