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DEVELOPMENT OF A METAL 3D PRINTER USING A 3-UPU PARALLEL MANIPULATOR

This paper explores the potential application of a 3-UPU manipulator as a design for a metal 3D printer. To determine the working area of the 3-UPU manipulator, its inverse kinematics were investigated. Using the Denavit-Hartenberg method, the required lengths of the manipulator's prismatic pairs were analytically calculated based on the coordinate system transformation matrices. The obtained results were verified by numerical methods in MATLAB program and the correctness of analytical solutions was confirmed. The study showed that the working area of the 3-UPU manipulator is 800x800x600 mm, which is large enough for metal 3D printers. This work area gives you the ability to print from small parts to large parts as well as body parts. The precise positioning and dexterity of the 3-point manipulator ensures sufficient precision in part production. This working area makes it possible to print from small parts to large parts as well as body parts. The positioning accuracy and dexterity of the 3UPU manipulator provides sufficient accuracy in part production. This accuracy of part fabrication reduces the post-processing time of parts by machining, resulting in less material consumption for chips and wear of cutting tools.

This research work can provide a scientific basis to enable the 3-UPU arm to be used in metal 3D printers. Future research following this work is planned to explore issues such as improving the dynamic model of the manipulator and increasing its efficiency by optimizing control algorithms.

Keywords: 3-UPU manipulator, additive manufacturing, working area, metal 3D printer, inverse kinematic.

Introduction

In recent decades, additive manufacturing has revolutionized production and engineering processes by enabling the fabrication of complex geometries with minimal time and cost requirements [1–3]. Despite its numerous advantages, traditional 3D

printers are limited by their constrained workspace and accuracy, making them less suitable for tasks that demand higher precision and larger build volumes [4–6].

Parallel manipulators, particularly the 3UPU configuration, have emerged as promising solutions to address these challenges by offering superior accuracy and an extended workspace [7–8]. Investigating the kinematic and dynamic properties of 3UPU manipulators is essential for their effective integration into practical manufacturing applications [9–11]. Accurate modeling of the manipulator's workspace and adapting it for 3D printing have become significant areas of interest in current research [12].

Additionally, the application of metal-based additive manufacturing, which demands high precision and stability, further underscores the necessity of employing advanced robotic systems like the 3UPU manipulator [13–14]. This paper explores the use of the 3UPU manipulator to drive a 3D printer's print head along a predefined trajectory. The inverse kinematics of the manipulator is calculated to evaluate its workspace and adaptability to additive manufacturing tasks. These findings aim to contribute to the advancement of 3D printing technology, particularly in the context of high-precision and large-scale applications [15].

Materials and methods

Inverse kinematics of a 3-UPU parallel manipulator

A parallel manipulator (PM) 3-UPU (where U stands for universal and P for prismatic kinematic pairs) consists of a triangular fixed base $A_1A_2A_3$ (Fig. 1), a moving platform, and three closed kinematic chains (legs) of the UPU type, which connect the moving platform to the fixed base. The absolute coordinate system $O_0X_0Y_0Z_0$ is attached to the center of the three universal joints $A_1A_2A_3$, located on the fixed base, while the local coordinate system PUVW is fixed at the center of the universal joints connecting the legs to the moving platform and moves along with it.

As stated in [16], this parallel manipulator (PM) has three translational degrees of freedom, meaning that the moving platform of the manipulator will move parallel to the base along the three axes of the absolute coordinate system $O_0X_0Y_0Z_0$.

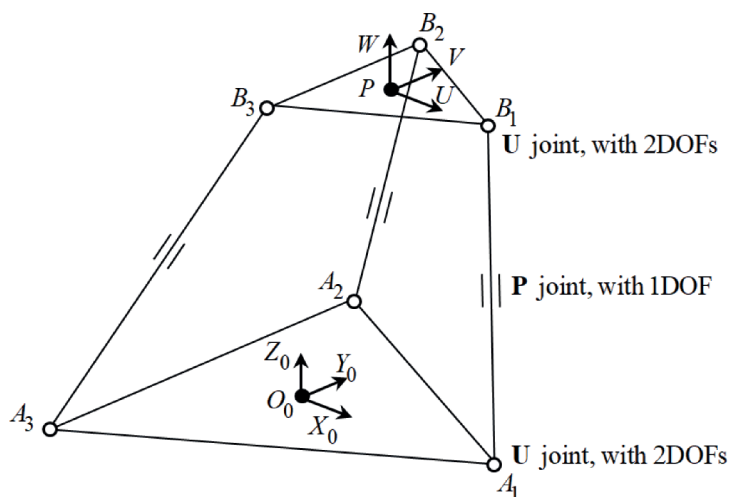


Figure 1 – Kinematic diagram of the 3-UPU PM

To solve the inverse kinematics problem of the PM, the position of the moving platform in space is given, after which the positions of the active prismatic kinematic pairs S_i ($i=1,2,3$) are computed. The closure equations of the vector loops for this manipulator are defined as follows

$$\mathbf{O}_0 \mathbf{P} + \mathbf{P} \mathbf{h}_i = \mathbf{O}_0 \mathbf{A}_{1,i} + \mathbf{B}_{1,i}. \quad (1)$$

Fig.2 shows the vectors that are included in equation (1) for one leg of the PM, with the others being defined in a similar manner.

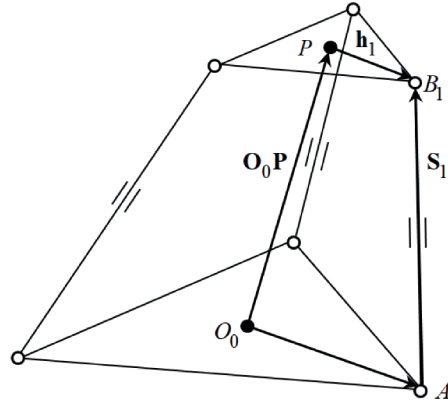


Figure 2 – Closure equations of the vector loops for the 3-UPU PM

In solving the inverse kinematics problem, the left-hand side of equation (1) is given, while the right-hand side is determined by constructing homogeneous transformation matrices of Denavit-Hartenberg [17], which include all the constant and variable parameters of the PM. Both sides of the vector equation (1) define the coordinates of the centers of the universal joints attached to the moving platform.

The left-hand side of the vector equations (1) is defined through the relationship between the absolute $O_0X_0Y_0Z_0$ and local $PUVW$ coordinate systems as follows

$$\begin{bmatrix} X_{B_i} \\ Y_{B_i} \\ Z_{B_i} \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & X_P \\ 0 & 1 & 0 & Y_P \\ 0 & 0 & 1 & Z_P \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} U_{B_i} \\ V_{B_i} \\ W_{B_i} \\ 1 \end{bmatrix}, i = 1, 2, 3, \quad (2)$$

where $U_{B_i}, V_{B_i}, W_{B_i}$ – the coordinates of the points B_i in the local coordinate system $PUVW$.

Are determined as follows

$$\begin{bmatrix} U_{B_i} \\ V_{B_i} \\ W_{B_i} \\ 1 \end{bmatrix} = \begin{bmatrix} r_b \cdot \cos(\zeta_i) \\ r_b \cdot \sin(\zeta_i) \\ 0 \\ 1 \end{bmatrix}, \zeta_i = 0^\circ, 120^\circ, 240^\circ. \quad (3)$$

To determine the right-hand side of the vector equation (1), we construct the following homogeneous transformation matrices from the absolute coordinate system $O_0X_0Y_0Z_0$ to the local coordinate system $O_{4,i}X_{4,i}Y_{4,i}Z_{4,i}$:

1) $O_0X_0Y_0Z_0 \rightarrow O_1X_1Y_1Z_1$

$$\mathbf{T}_{01,i} = \begin{bmatrix} \cos \theta_i & 0 & \sin \theta_i & r_A \cos \theta_i \\ \sin \theta_i & 0 & -\cos \theta_i & r_A \sin \theta_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, i = 1, 2, 3, \theta_i = 0^\circ, 120^\circ, 240^\circ. \quad (4)$$

2) $O_1X_1Y_1Z_1 \rightarrow O_2X_2Y_2Z_2$

$$\mathbf{T}_{02,i} = \mathbf{T}_{01,i} \mathbf{T}_{12,i}, \quad (5)$$

where

$$\mathbf{T}_{12,i} = \begin{bmatrix} \cos \varphi_{1,i} & -\sin \varphi_{1,i} & 0 & 0 \\ \sin \varphi_{1,i} & \cos \varphi_{1,i} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, i = 1, 2, 3. \quad (6)$$

3) $O_2X_2Y_2Z_2 \rightarrow O_3X_3Y_3Z_3$

$$\mathbf{T}_{03,i} = \mathbf{T}_{02,i} \mathbf{T}_{23,i}, \quad (7)$$

where

$$\mathbf{T}_{23,i} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (8)$$

3) $O_3X_3Y_3Z_3 \rightarrow O_4X_4Y_4Z_4$

$$\mathbf{T}_{04,i} = \mathbf{T}_{03,i} \mathbf{T}_{34,i}, \quad (9)$$

where

$$\mathbf{T}_{34,i} = \begin{bmatrix} \cos \varphi_{2,i} & -\sin \varphi_{2,i} & 0 & S_1 \cos \varphi_{2,i} \\ \sin \varphi_{2,i} & \cos \varphi_{2,i} & 0 & S_1 \sin \varphi_{2,i} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, i = 1, 2, 3. \quad (10)$$

From the matrix $\mathbf{T}_{34,i}$, the coordinates of the universal joints are determined as follows

$$\begin{bmatrix} X_{B_i} \\ Y_{B_i} \\ Z_{B_i} \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \mathbf{T}_{34,i}. \quad (11)$$

From equation (11), taking into account equations (2), the coordinates of the center of the moving platform can be determined as follows

$$\begin{cases} X_P = r \cdot \cos\theta_i + S_i \cdot \sin\theta_i \cdot \sin\varphi_{2i} - S_i \cdot \cos\theta_i \cdot \cos\varphi_{2i} \cdot \sin\varphi_{1i}, \\ Y_P = r \cdot \sin\theta_i - S_i \cdot \cos\theta_i \cdot \sin\varphi_{2i} - S_i \cdot \sin\theta_i \cdot \cos\varphi_{2i} \cdot \sin\varphi_{1i}, \\ Z_P = S_i \cdot \cos\varphi_{1i} \cdot \cos\varphi_{2i}, \end{cases} \quad (12)$$

where $r = r_A - r_B$, r_A, r_B the distances from the centers to the vertices of the base and the movable platform, which have a triangular shape, S_i the input parameters of the stroke of the linear actuators, $\varphi_{1i}, \varphi_{2i}$ the angles of the passive universal joints attached to the base, which determine the orientation of the three legs of the PM.

Numerical examples of solving the inverse kinematics problem

The following constant parameters are given: $r_a = 400$, $r_b = 200$, $X_P = 100$, $Y_P = 100$, $Z_P = 500$, $\theta_1 = 0^\circ$, $\theta_2 = 120^\circ$, $\theta_3 = 240^\circ$. A program was developed that automatically selects the solutions to the equations (16), (17), and (18) for the correct determination of the positions of the PM.

Results and discussion

By adding the first and second equations of the system (12), after multiplying them by $\cos\theta_i$ and $\sin\theta_i$, respectively, we obtain

$$X_P \cdot \sin\theta_i - Y_P \cdot \cos\theta_i = S_i \cdot \sin\varphi_{2i}. \quad (13)$$

The system of equations (12) is rewritten in the following form

$$\begin{cases} X_P - r \cdot \cos\theta_i - S_i \cdot \sin\theta_i \cdot \sin\varphi_{2i} = -S_i \cdot \cos\theta_i \cdot \cos\varphi_{2i} \cdot \sin\varphi_{1i}, \\ Y_P - r \cdot \sin\theta_i + S_i \cdot \cos\theta_i \cdot \sin\varphi_{2i} = -S_i \cdot \sin\theta_i \cdot \cos\varphi_{2i} \cdot \sin\varphi_{1i}, \\ Z_P = S_i \cdot \cos\varphi_{1i} \cdot \cos\varphi_{2i}. \end{cases} \quad (14)$$

From the sum of the squares of the three equations of the system (14), taking into account the equations (13), we obtain

$$\begin{aligned} S_i^2 \cdot (2 \cdot \sin^2\varphi_{2i} - 1) - 2 \cdot (X_P \cdot \sin\theta_i - Y_P \cdot \cos\theta_i)^2 + \\ r^2 + X_P^2 + Y_P^2 + Z_P^2 - 2 \cdot r \cdot (X_P \cdot \sin\theta_i - Y_P \cdot \cos\theta_i) = 0 \end{aligned} \quad (15)$$

From the equations (13), we determine $\sin\varphi_{2i}$, and substituting this into the equations (15), we obtain a single equation with one unknown S_i . After some straightforward transformations, we obtain the following solutions

$$S_i = \pm \sqrt{r^2 + X_P^2 + Y_P^2 + Z_P^2 - 2 \cdot r \cdot (X_P \cdot \cos\theta_i - Y_P \cdot \sin\theta_i)}. \quad (16)$$

In this problem, the movable platform is positioned in the positive direction of the Z_0 -axis, so only positive values of S_i will be used for the calculations.

Solving the equations (13) for the variables φ_{2i} , we obtain the following two solutions

$$\varphi_{2i(1)} = \arcsin\left(\frac{X_P \cdot \sin\theta_i - Y_P \cdot \cos\theta_i}{S_i}\right), \quad \varphi_{2i(2)} = \pi - \arcsin\left(\frac{X_P \cdot \sin\theta_i - Y_P \cdot \cos\theta_i}{S_i}\right). \quad (17)$$

Solving the third equation of the system (14) for the variable φ_{1i} , we obtain the following solutions

$$\varphi_{1i(1)} = +\arccos\left(\frac{Z_P}{S_i \cdot \cos\varphi_{2i}}\right), \quad \varphi_{1i(2)} = -\arccos\left(\frac{Z_P}{S_i \cdot \cos\varphi_{2i}}\right). \quad (18)$$

In solving the inverse kinematics problem of the parallel robot, the position is specified, i.e., the coordinates of the center of the moving platform X_P, Y_P, Z_P , while the coordinates of the passive universal joints $X_{d,i}, Y_{d,i}, Z_{d,i}$ attached to the movable platform are determined by the equations (2). Based on the equations (16), (17), and (18), the variable parameters $\varphi_{1i}, \varphi_{2i}, S_i$ are determined, as well as the positions of all the moving links. This is how the workspace of a metal 3D printer is defined.

Numerical examples of solving the inverse kinematics problem

The results of numerical methods of problem solving show the reliability of the data obtained analytically. Fig. 3 shows the assembled manipulator based on the solution of the inverse kinematics problem.

Based on the inverse kinematics problem, the workspace of the PM was determined. The values of X_P, Y_P were varied from -400 to 400 with a step of 50, and Z_P was varied from 0 to 600 with a step of 50. Additionally, constraints were set on the minimum and maximum values of the input parameters S_i ($100 \leq S_i \leq 500$)

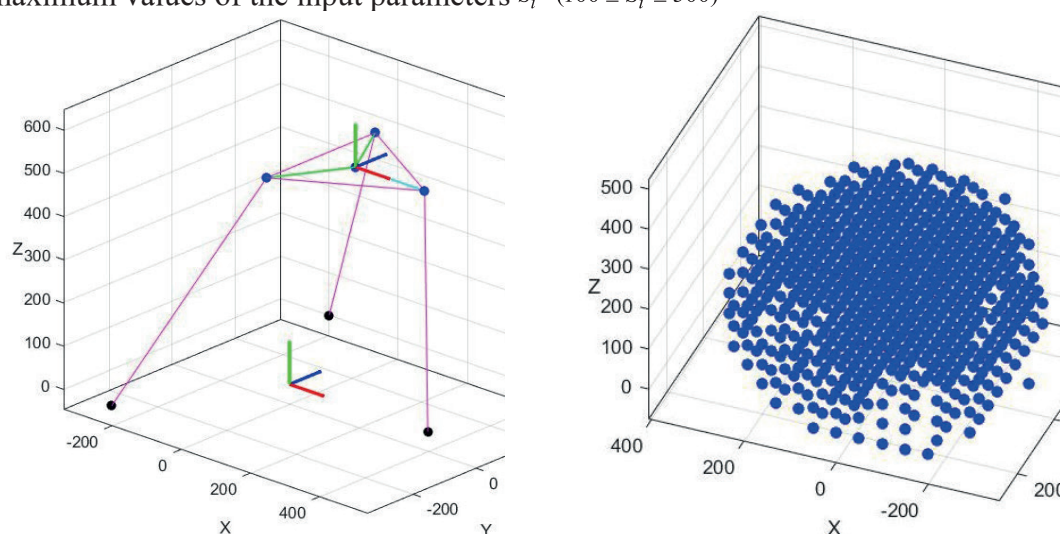


Figure 3 – Solution of the inverse kinematics problem and the workspace

Thus the working area of the 3D printer was defined as 800x800x600 mm. Which is large enough for 3D printers printing metal materials. And also found the geometric parameters of the 3upu manipulator, which is the design of the metal 3D printer.

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Conclusions

This study investigated the feasibility of using the 3-UPU manipulator as a design of a metal 3D printer. Specifically, the potential of the 3-UPU manipulator's movable platform, which has three degrees of freedom, to guide the print head along a preprogrammed digital trajectory for metal additive manufacturing was explored.

Since one of the most critical characteristics of a 3D printer is its workspace, this study focused on determining the workspace of the 3-UPU manipulator.

To achieve this, the inverse kinematics problem of the manipulator was solved. The manipulator's motion characteristics were analyzed using an analytical approach based on vector loop equations. The Denavit-Hartenberg method was employed to calculate the required lengths of the manipulator's prismatic joints (P) through transformation matrices between coordinate systems. This approach enabled precise determination of the manipulator's geometric parameters.

The analytical results were verified using numerical methods in MATLAB. The numerical validation confirmed the accuracy of the analytical calculations. Based on the geometric parameters of the manipulator, its workspace was determined to be 800x800x600 mm. This workspace is significantly large for metal 3D printers and allows for the production of a wide range of parts.

The findings of this study demonstrate the suitability of the 3-UPU manipulator for use in 3D printing applications, particularly for metal additive manufacturing. Future research should focus on improving the dynamic model of the manipulator and optimizing its control algorithms to further enhance its performance and reliability in industrial applications.

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3-UPU ПАРАЛЛЕЛЬ МАНИПУЛЯТОРЫН МЕТАЛЛ 3D ПРИНТЕРІ РЕТІНДЕ ҚОЛДАНУДЫ ӘЗІРЛЕУ

Бұл мақалада 3D металл принтерінің конструкциясы ретінде 3UPU параллель манипуляторын қолдану мүмкіндігі қарастырылады. 3UPU манипуляторының жұмыс аймағын анықтау үшін оның кері кинематикасы зерттелді. Денавит-Хартенберг әдісін қолдана отырып, координаттар жүйесін түрлендіру матрицалары негізінде манипулятордың призмалық

жұптарының қажетті ұзындықтары аналитикалық түрде есептеледі. Алынған нәтижелер MATLAB бағдарламасында сандық әдістермен тексерілді және аналитикалық шешімдердің дұрыстығы расталды. Зерттеу көрсеткендей, 3UPU манипуляторының жұмыс аймағы 800x800x600 мм, бұл металл 3D принтерлер үшін айтарлықтай үлкен болып табылады. Мұндай жұмыс аймағы шағын бөлшектерден үлкен бөлшектерге, сондай-ақ корпус бөлшектеріне дейін басып шығаруға мүмкіндік береді. 3UPU манипуляторының позициялану дәлдігі мен ептілігі бөлшектерді жасаудың жеткілікті дәлдігін қамтамасыз етеді. Бұндай дәлдікпен бөлшектерді өндіру бөлшектерді 3D баспадан кейінгі өңдеу уақытын азайтады, бұл кесу құралдарының тозуы мен жаңқаға кететін материалдар шығынын азайтады.

Бұл зерттеу жұмысы 3-UPU манипуляторын металл 3D принтерлерде қолдануға мүмкіндік беретін ғылыми негізді қамтамасыз ете алады. Бұл жұмыстан кейінгі болашақ зерттеулерде манипулятордың динамикалық моделін жетілдіру және басқару алгоритмдерін оңтайландыру арқылы оның тиімділігін арттыру секілді мәселелер зерттеледі деп жоспарлануда.

Кілтті сөздер: 3UPU манипулятор, аддитивті өндіріс, жұмыс аймағы, металл 3D принтері, кері кинематика.

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РАЗРАБОТКА МЕТАЛЛИЧЕСКОГО 3D-ПРИНТЕРА С ИСПОЛЬЗОВАНИЕМ ПАРАЛЛЕЛЬНОГО МАНИПУЛЯТОРА 3-UPU

В данной статье рассматривается возможность применения манипулятора 3UPU в качестве конструкции для металлического 3D-принтера. Для определения рабочей зоны манипулятора 3UPU была исследована его обратная кинематика. С помощью метода Денавита-Хартенберга на основе матриц преобразования системы координат аналитически рассчитаны необходимые длины призматических пар манипулятора. Полученные результаты были проверены численными методами в программе MATLAB и подтверждена корректность аналитических решений. Исследование показало, что рабочая зона манипулятора 3UPU составляет 800x800x600 мм, что достаточно большой для металлических 3D-принтеров. Такая рабочая зона дает возможность печатать от маленьких деталей до больших деталей, а также корпусных деталей. Точность позиционирования и ловкость 3UPU манипулятора обеспечивает достаточную точность изготовления деталей. Такая точность изготовления деталей уменьшает время постобработки

деталей механической обработкой, что приводит уменьшению расход материалов на стружку и износ режущих инструментов.

Эта исследовательская работа может обеспечить научную основу, позволяющую использовать манипулятор 3-UPU в металлических 3D-принтерах. Планируется, что в будущих исследованиях после этой работы будут изучены такие вопросы, как совершенствование динамической модели манипулятора и повышение его эффективности за счет оптимизации алгоритмов управления.

Ключевые слова: 3UPU манипулятор, аддитивное производство, рабочая зона, металлический 3D-принтер, обратная кинематика.

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