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АКАДЕМИЯСЫ» РҚБ

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

# ХАБАРЛАРЫ

# ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
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# MOBILE 3D PRINTER WITH MECHANICAL PROCESSING FOR MANUFACTURING MINING EQUIPMENT PARTS

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**Abstract.** Modern industrial sectors, including mining, geological exploration, and mechanical engineering, play a key role in the economic development of the Republic of Kazakhstan. Their efficient operation depends on the quality of manufacturing and restoration of technological equipment components. However, the production and repair of such components require significant costs, and their restoration in remote areas is complicated by the lack of specialized machinery, leading to additional expenses and downtime.

To address these challenges, this study proposes the concept of a mobile 3D printer with an integrated mechanical processing system. The primary focus is on developing a manipulator that ensures precise positioning of the welding nozzle and spindle, which perform key functions in the printing process and subsequent mechanical processing. The manipulator must operate within a workspace range of X ±250 mm, Y ±250 mm, Z ±200 mm. Its selection is justified based on criteria such as structural rigidity and positioning speed. Direct and inverse kinematics problems were solved to determine the working area and dimensions of the manipulator. Homogeneous Denavit–Hartenberg transformation matrices were constructed, and Jacobian matrices were obtained to establish the relationship between input and output velocities and accelerations.

The proposed concept has significant potential for the rapid production and restoration of technological equipment components in remote areas. Implementing this technology will reduce production costs, minimize equipment downtime, and enhance the technological independence of industrial enterprises.

**Keywords:** geological exploration equipment, metal 3D printer, WAAM, manipulator, inverse kinematics, direct kinematics, workspace.

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## ТАУ-КЕН ЖАБДЫҚТАРЫНЫҢ БӨЛШЕКТЕРІН ЖАСАУҒА АРНАЛҒАН МЕХАНИКАЛЫҚ ӨҢДЕУІ БАР МОБИЛЬДІ 3D-ПРИНТЕР

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**Аннотация**. Қазіргі заманғы өнеркәсіп салалары, соның ішінде тау-кен өндіру, геологиялық барлау және машина жасау, Қазақстан Республикасының экономикалық дамуында маңызды рөл атқарады. Олардың тиімді жұмыс істеуі технологиялық жабдықтың бөлшектерін сапалы өндіру мен қалпына келтіруге байланысты. Алайда, мұндай бөлшектерді өндіру және жөндеу айтарлықтай шығындарды талап етеді, ал оларды шалғай аудандарда қалпына келтіру арнайы станоктардың болмауынан қиынға соғады, бұл қосымша шығындар мен жабдықтың тоқтап қалуына әкеледі.

Осы мәселелерді шешу үшін бұл жұмыста механикалық өңдеу жүйесі біріктірілген мобильді 3D-принтердің тұжырымдамасы ұсынылады. Негізгі назар дәнекерлеу саптамасы мен шпиндельді дәл орналастыруды қамтамасыз ететін манипуляторды әзірлеуге бағытталған. Олар басып шығару және кейінгі механикалық өңдеу процестерінде негізгі функцияларды орындайды. Манипулятордың жұмыс кеңістігі X ±250 мм, Y ±250 мм, Z ±200 мм шегінде болуы тиіс. Оның таңдалуы құрылымдық қаттылық және орналасу жылдамдығы сияқты критерийлерге негізделген. Жұмыста манипулятордың жұмыс аймағы мен өлшемдерін анықтау үшін тура және кері кинематика есептері шешілді. Денавит–Хартенбергтің біртекті түрлендіру матрицалары құрылып, кіріс және шығыс жылдамдықтары мен үдеулерінің өзара байланысын анықтайтын Якоби матрицалары алынды.

Ұсынылған тұжырымдама шалғай аудандарда технологиялық жабдық бөлшектерін жедел өндіру және қалпына келтіру үшін үлкен әлеуетке ие. Бұл технологияны енгізу өндіріс шығындарын азайтуға, жабдықтың бос тұрып қалуын барынша азайтуға және өнеркәсіптік кәсіпорындардың технологиялық тәуелсіздігін арттыруға мүмкіндік береді.

**Түйін сөздер:** геологиялық барлау жабдықтары, металл 3D принтері, WAAM, манипулятор, кері кинематика, тура кинематика, жұмыс аймағы.

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## МОБИЛЬНЫЙ 3D ПРИНТЕР С МЕХАНИЧЕСКОЙ ОБРАБОТКОЙ ДЛЯ ИЗГОТОВЛЕНИЯ ДЕТАЛЕЙ ГОРНОДОБЫВАЮЩИХ ОБОРУДОВАНИЙ

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**Аннотация.** Современные промышленные отрасли, включая горнодобывающую, геологоразведочную и машиностроительную, играют ключевую роль в экономическом развитии Республики Казахстан. Их эффективное функционирование зависит от качества изготовления и восстановления деталей технологического оборудования. Однако производство и ремонт таких деталей требуют значительных затрат, а их восстановление в удаленных районах осложняется отсутствием специализированных станков, что приводит к дополнительным расходам и простоям.

Для решение вышеуказанных проблем в данной работе предлагается концепция мобильного 3D-принтера с интегрированной системой механической обработки. Основное внимание уделено разработке манипулятора, обеспечивающего точное позиционирование сварочного сопла и шпинделя, выполняющих ключевые функции в процессе печати и последующей механической обработки. Манипулятор должен обеспечивать перемещение в рабочем пространстве с диапазонами X ±250 мм, Y ±250 мм, Z ±200 мм. Его выбор обоснован такими критериями, как жёсткость конструкции и скорость позиционирования. Решены задачи прямой и обратной кинематики для определения рабочей зоны и размеров манипулятора. Построены однородные матрицы преобразования Денавита–Хартенберга, а также получены матрицы Якоби, устанавливающие связь между входными и выходными скоростями и ускорениями.

Предложенная концепция обладает значительным потенциалом для оперативного производства и восстановления деталей технологического оборудования в удалённых районах. Внедрение данной технологии позволит снизить производственные издержки, минимизировать время простоя оборудования и повысить технологическую независимость промышленных предприятий.

**Ключевые слова:** геологоразведочное оборудование, металлический 3D-принтер, WAAM, манипулятор, обратная кинематика, прямая кинематика, рабочее пространство.

**Introduction.** The mining and geological exploration industries face challenges related to equipment reliability and maintenance due to harsh operating conditions.

Special difficulties arise in the manufacturing and repair of complex-shaped parts, such as drill bits, rods, and pump components. Additionally, mining shearers frequently fail, especially milling drums and cutting tools, which experience intense wear (Florea, et al., 2022). The cutter sleeves of continuous miners suffer from cracks, wear, and plastic deformation, often due to unsuitable materials and manufacturing processes (Lindsay, et al., 2023). Large components, such as gear wheels in bucket-wheel excavators, can break prematurely, requiring costly replacements or complex repairs (Arsić, et al., 2021). In remote geological exploration, mining, and mechanical engineering sites, the lack of specialized equipment for restoration and repair necessitates transporting parts to factories or purchasing new ones, increasing costs and downtime. One alternative solution to this problem is mobile manufacturing. However, traditional metalworking machines are often too bulky and heavy for mobile use in field conditions. In recent decades, there has been rapid development in three-dimensional printing technology, which has become an integral part of modern manufacturing and scientific research. This evolution has led to the creation of numerous innovative methods and devices aimed at expanding the capabilities of 3D printing. One of the most promising technologies is metal additive manufacturing, which enables the production of medium and large metallic components for various industries, including mining, geological exploration, and mechanical engineering (Shah, et al., 2023).

Metal 3D printer is a metalworking technology that is an alternative to traditional processes such as casting and subtractive machining. This technology is widely used in engineering due to its many advantages such as rapid prototyping, product weight reduction, and geometric freedom (Capasso, et al., 2024). There are 2 types of metal printing based on additive technology: powder 3D printing (Renderos, et al., 2016) and Wire Arc Additive Manufacturing (hereafter referred to as WAAM) based 3D printing (Çam, et al., 2022). Due to the fact that metal wire manufacturing technology is relatively simpler than metal powder manufacturing, products manufactured using WAAM technology are cheaper (Knezović, et al., 2019) and can reduce production time by 40-60% depending on the size of parts compared to traditional manufacturing methods (Ribeiro, et al., 1998). However, this technology has disadvantages, in particular, compared to metal powder printing systems, it is less accurate, difficult to create complex geometries and requires more time for post-printing machining (Srivastava, et al., 2023), as well as its stationarity.

In industrial 3D printers (Glashier, et al., 2023; Ferreira, 2024), the WAAM technology does not include post-mechanical processing, requiring additional machines or extra functionalities for existing 3D printers. Another drawback of industrial 3D printers is their stationary nature, which results in additional time and cost for transporting parts.

To address the aforementioned issues, this paper proposes a new concept of a multifunctional mobile metal 3D printer for industrial applications, equipped with a post-printing mechanical processing system. The key component of the printer is a manipulator, which determines its efficiency, as well as its ability to print complex parts and perform post-processing of fitting surfaces. As part of the study, an analysis of the manipulator's mobility was conducted, including direct and inverse kinematics problems, velocity and acceleration analysis, and the determination of the working area based on inverse kinematics. Additionally, the dimensions of the delta robot's links, featuring three translational degrees of freedom, were selected, and a 3D model was designed.

**Materials and methods.** o ensures mobility and mechanical processing; a new concept has been proposed (Fig. 1). Conceptually, the manipulator (3), as the main working unit of the metal 3D printer based on WAAM technology, provides three primary translational degrees of freedom, while the worktable (1) has two rotational degrees of freedom. Therefore, the total number of degrees of freedom for the entire printer is five (3+2) (Fig. 1). This degree of freedom allows for the creation of numerous complex-shaped products without the need for support structures. At the same time, it enhances the product's resistance to mechanical loads, enabling the use of advanced printing strategies. In metal 3D printing, quality is influenced not only by the melting process but also by the selection of the appropriate 3D printing strategy, which is one of the key factors (Xin, et al., 2021).

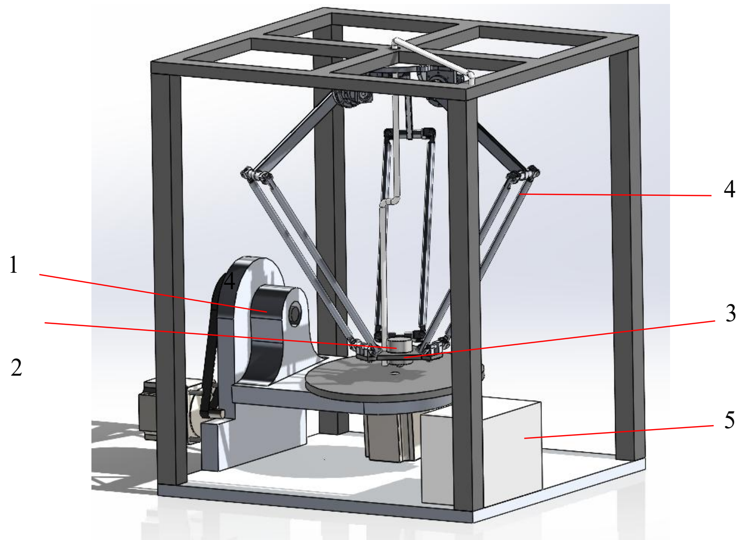


Figure 1 - Metal 3D printer concept

According to the proposed concept, the workflow sequence is as follows: the part is printed on the 3D printer on the worktable (1), with a flat metal base plate and a removable platform secured underneath the printed part. The printing head (2) is mounted on the movable platform (3) of the manipulator (4). Metal wire will be used as the material for 3D printing, and a standard welding machine (5), adapted for 3D printing, will be used to melt this wire. The 3D printing process is carried out on five axes, eliminating poor interlayer bonding, which is common in traditional 3D printing. After completing the 3D printing process, the printing head is automatically replaced with a spindle, enabling mechanical processing such as turning, milling, drilling, and grinding with the appropriate cutting tools. The finished product is then cut from the platform using a mechanized saw and directed for installation on machinery or equipment.

For the multifunctional mobile metal 3D printer to operate efficiently, the manipulator, used as the main working unit, must meet several key requirements. First, it must ensure high precision. Second, it must be sufficiently rigid to withstand heavy loads during mechanical processing. At the same time, it should be lightweight and compact for easy transportation.

In metal 3D printing using the WAAM technology, serial manipulators are commonly used as the primary motion system. For example, one of the leading companies in WAAM technology, the Dutch company MX3D and WAAM3D, as well as the study by Horgar et al. (2018), utilized an articulated manipulator. Meanwhile, Parc3D and the study by M. Dinovitzer et al. (2019) employed a gantry-type manipulator. Although serial manipulators provide a large working area and high maneuverability, studies by Neugebauer et al. (2019) and Uchiyama et al. (2019) indicate that their load capacity is limited due to their cantilevered design. Therefore, these serial manipulators do not align with our concept. Additionally, studies by Baigunchekov et al. (2020), Merlet et al. (2000), and Mustafa et al. (2024) highlight that, compared to serial manipulators with open kinematic chains, parallel manipulators with closed kinematic loops offer higher load capacity, greater structural rigidity, improved positioning accuracy, reduced moving mass, and better dynamic performance.

Therefore, a delta robot which has a parallel structure is considered as the main working body of a multifunctional mobile metal 3D printer. The positioning accuracy of the delta robot is about 0.1 mm (Bentaleb, et al., 2011). In the next section, the forward and inverse kinematics problems of the delta robot are solved, its working area is calculated, and the structural dimensions, velocities and accelerations of the center of the mobile platform are determined.

Delta robot Clavel is a parallel manipulator (PM) consisting of three identical parallel kinematic chains 4 $A_j, C_j, D_j\ (j=1,2,3)$, which connect the moving platform 5 and the fixed base 1 (Fig. 2). Each kinematic chain includes active revolute kinematic pairs 3 $A_j$ attached to the fixed base 1, which are driven by electric motors 2. The moving platform was connected by parallelograms, with their centers forming universal kinematic pairs $C_j$ and $D_j$.

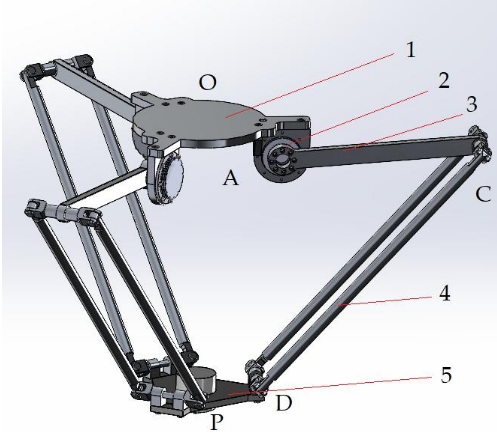


Figure 2 - 3D model of the Delta robot

Each leg of this PM has 5 DOFs, therefore, the DOF of the moving platform can be determined as follows

$$F_c = \sum_{i=1}^{n} F_i - 6(n-1) = (5+5+5) - 6(3-1) = 3, \quad (1)$$

where $F_i$ is the number of DOF of the kinematic chains (legs) of the PM, and n is the number of legs of the PM.

It is known that these three degrees of freedom are translational, and the positioning accuracy of such a robot is approximately one micron.

*Inverse kinematics.* The closure equations describing the vector loops of the legs in the PM have been derived

$$\mathbf{r}_{D_i} = \mathbf{r}_{\mathrm{OP}} + \mathbf{h}_i, \ (i = 1, 2, 3). \quad (2)$$

The absolute coordinate system $O_0X_0Y_0Z_0$ is placed at the center of the three points of location of the active revolute kinematic pairs $A_j \ (j = 1, 2, 3)$.

To determine the components of the vector $\mathbf{r}_{D_i}$ through the tripod legs, homogeneous transformation matrices based on the Denavit-Hartenberg parameters were obtained. Based on these matrices, the coordinates of the points $D_i$, where the passive universal joints connecting the tripod legs to the moving platform are located, were determined

$$\left.\begin{aligned} X_{D_i} &= c\theta_i \cdot (r_a + L_2 \cdot c\varphi_{1i}) + s\theta_i \cdot L_1 \cdot s\varphi_{3i} + L_1 \cdot c\theta_i \cdot c\varphi_{3i} \cdot c\varphi_{12i} \\ Y_{D_i} &= s\theta_i \cdot (r_a + L_2 \cdot c\varphi_{1i}) - c\theta_i \cdot L_1 \cdot s\varphi_{3i} + L_1 \cdot s\theta_i \cdot c\varphi_{3i} \cdot c\varphi_{12i} \\ Z_{D_i} &= L_2 \cdot s\varphi_{1i} + L_1 \cdot c\varphi_{3i} \cdot s\varphi_{12i} \end{aligned}\right\}, \quad (3)$$

where $\varphi_{1,i}, \varphi_{2,i}, \varphi_{3,i} \ (i = 1, 2, 3)$ are variable parameters defining the angles of the universal joints $A_j$, $r_a, r_b$ are distances from the centers to the vertices of the base and the moving platform of triangular shape, respectively, $L_1$, $L_2$ are distances between the joints $AC$ and $CD$ (Fig. 2),

$\theta_i$ are constant parameters, equal to 0, 120, and 240 degrees, respectively.

When solving the inverse kinematics problem, we set the position of the moving platform and determine the joint angles, $\varphi_{1,i}$, $\varphi_{2,i}$, $\varphi_{3,i}$ $(i=1,2,3)$, which define the configuration of each leg. The coordinates of the passive universal joints $D_i$ were determined based on the given position of the moving platform

$$\begin{bmatrix} X_{D_i} \\ Y_{D_i} \\ Z_{D_i} \\ 1 \end{bmatrix} = \left[\begin{array}{c:c:c:c} 1 & 0 & 0 & X_P \\ \hdashline 0 & 1 & 0 & Y_P \\ \hdashline 0 & 0 & 1 & Z_P \\ \hdashline 0 & 0 & 0 & 0 \end{array}\right] \left[\begin{array}{c} r_b \cdot c\psi_i \\ \hdashline r_b \cdot s\psi_i \\ \hdashline 0 \\ \hdashline 1 \end{array}\right], i=1,2,3, \tag{4}$$

where $\left[r_b \cdot c\psi_i \;\vdots\; r_b \cdot s\psi_i \;\vdots\; 0 \;\vdots\; 1\right]^T$ are coordinates of the universal joints $D_i$ relative to the local coordinate system $PX_PY_PZ_P$, which is attached to the center of the moving platform. Since the directions of the absolute $O_0X_0Y_0Z_0$ and local $PX_PY_PZ_P$ coordinate systems initially coincide, the angles $\psi_i$ are also equal to 0, 120, and 240 degrees, respectively.

From the matrix equation (4), taking into account system (3), the coordinates of the center of the moving platform relative to the absolute coordinate system $O_0X_0Y_0Z_0$ were obtained.

$$\left.\begin{aligned} X_P &= c\theta_i \cdot (r + L_2 \cdot c\varphi_{1i}) + L_1 \cdot s\theta_i \cdot s\varphi_{3i} + L_1 \cdot c\theta_i \cdot c\varphi_{12i} \cdot c\varphi_{3i} \\ Y_P &= s\theta_i \cdot (r + L_2 \cdot c\varphi_{1i}) - L_1 \cdot c\theta_i \cdot s\varphi_{3i} + L_1 \cdot c\varphi_{12i} \cdot c\varphi_{3i} \cdot s\theta_i \\ Z_P &= L_2 \cdot s\varphi_{1i} + L_1 \cdot s\varphi_{12i} \cdot c\varphi_{3i} \end{aligned}\right\}, \tag{5}$$

where $r = r_a - r_b, \varphi_{12i} = \varphi_{1i} + \varphi_{2i}$.

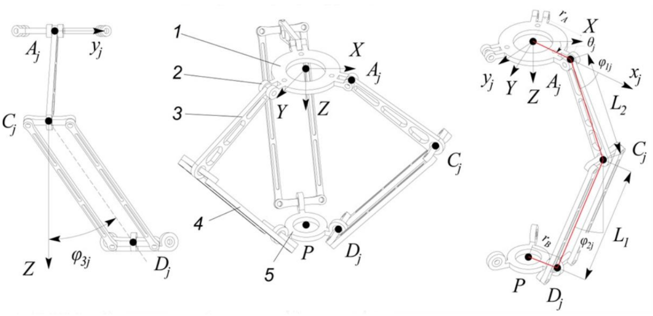


Figure 3 - Constant and variable parameters

From the sum of the squares of the three equations in system (6), we obtain

$$(X_P - X_i)^2 + (Y_P - Y_i)^2 + (Z_P - Z_i)^2 - L_1^2 = 0, \tag{6}$$

where $X_i = c\theta_i \cdot (r + L_2 \cdot c\varphi_{1i}), Y_i = s\theta_i \cdot (r + L_2 \cdot c\varphi_{1i}), Z_i = L_2 \cdot s\varphi_{1i}, i = 1,2,3.$

Expanding the brackets in equation (6), we rewrite it in the following form

$$l_i \cdot c\varphi_{1i} + m_i \cdot s\varphi_{1i} - n_i = 0, \quad (7)$$

where $l_i = 2 \cdot r \cdot L_2 - 2 \cdot L_2 \cdot X_P \cdot c\theta_i - 2 \cdot L_2 \cdot Y_P \cdot s\theta_i$, $m_i = -2 \cdot L_2 \cdot Z_P$,

, $n_i = -(r^2 - L_1^2 + X_P^2 + Y_P^2 + Z_P^2 - 2 \cdot X_P \cdot r \cdot c\theta_i - 2 \cdot Y_P \cdot r \cdot s\theta_i + L_2^2).$

From equations (7), we obtain two solutions for the angle $\varphi_{1i}$ of the active rotary drives $A_j$ for the two assemblies of each tripod leg

$$\varphi_{1i} = \alpha_i \pm c^{-1}(n_i / k_i), \quad (8)$$

where $k_i = \sqrt{l_i^2 + m_i^2}, \alpha_i = t^{-1}(m_i / l_i).$

From the addition of the first two equations of system (5), after multiplying the first equation by $c\theta_i$ and the second by $s\theta_i$, we obtain $a_i = L_1 \cdot c\varphi_{3i} \cdot c\varphi_{12i}$. The third equation of system (5) is transformed into the form $b_i = L_1 \cdot c\varphi_{3i} \cdot s\varphi_{12i}$. From the ratio of $b_i$ to $a_i$, we obtain the value of one of the angles of the passive universal joints $C_j$ attached to the active links

$$\varphi_{2i} = tg^{-1}(b / a) - \varphi_{1i}. \quad (9)$$

where $a_i = (X_P - (r + L_2 \cdot c\varphi_{1i}) \cdot c\theta_i) \cdot c\theta_i + (Y_P - (r + L_2 \cdot c\varphi_{1i}) \cdot s\theta_i) \cdot s\theta_i$,

$b_i = Z_P - L_2 \cdot s\varphi_{1i}.$

Adding the squares of $a_i$ and $b_i$, we obtain the second rotation angle of the passive universal joints

$$\varphi_{3i} = \pm c^{-1}\left(\frac{\sqrt{a_i^2 + b_i^2}}{L_1^2}\right). \quad (10)$$

The sign of the angles $\varphi_{3i}$ in equation (10) will change depending on the signs of $X_P$ and $Y_P$.

*Direct kinematics*. When solving the direct kinematics problem of the PM, the positions of the active revolute kinematic pairs $\varphi_{1i}$ are given, and the coordinates of the center of the moving platform $X_P$, $Y_P$, $Z_P$ are determined. Accordingly, the rotation angles of the passive revolute kinematic pairs $\varphi_{2i}, \varphi_{3i}$ are also determined, and the positions of all moving links of the tripod have been determined.

Equations (6) are rewritten in the following form

$$\left.\begin{array}{l}(X_P - X_1)^2 + (Y_P - Y_1)^2 + (Z_P - Z_1)^2 - L_1^2 = 0 \\ (Y_P - X_2)^2 + (Y_P - Y_2)^2 + (Z_P - Z_2)^2 - L_1^2 = 0 \\ (Z_P - X_3)^2 + (Y_P - Y_3)^2 + (Z_P - Z_3)^2 - L_1^2 = 0\end{array}\right\}. \tag{11}$$

Expanding the brackets, we subtract the second equation of system (11) from the first one, and similarly, we subtract the third equation from the first one. These equations are then rewritten in matrix form

$$A \cdot \begin{bmatrix} X_P \\ Y_P \end{bmatrix} = B, \tag{12}$$

where $A = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}, B = \begin{bmatrix} 2 \cdot Z_P \cdot Z_1 - 2 \cdot Z_P \cdot Z_2 - m_{13} \\ 2 \cdot Z_P \cdot Z_2 - 2 \cdot Z_P \cdot Z_3 + m_{23} \end{bmatrix},$

$$m_{11} = -2 \cdot X_1 + 2 \cdot X_2, \quad m_{12} = -2 \cdot Y_1 + 2 \cdot Y_2,$$

$$m_{13} = X_1^2 + Y_1^2 + Z_1^2 - X_2^2 - Y_2^2 - Z_2^2, \quad m_{21} = -2 \cdot X_2 + 2 \cdot X_3,$$

$$m_{22} = -2 \cdot Y_2 + 2 \cdot Y_3, \; m_{23} = X_2^2 - X_3^2 + Y_2^2 - Y_3^2 - Z_3^2 + Z_2^2.$$

From (12), we determine $X_p$ and $X_p$

$$X_P = k_{11} \cdot Z_P + k_{12}, Y_P = t_{11} \cdot Z_P + t_{12}, \tag{13}$$

where $k_{11} = \frac{2}{q}\left(m_{12}(Z_3 - Z_2) + m_{22}(Z_1 - Z_2)\right),$

$$k_{12} = \frac{1}{q}\left(m_{12} \cdot m_{23} - m_{13} \cdot m_{22}\right), \quad t_{11} = \frac{2}{q}\left(m_{11}(Z_2 - Z_3) + m_{21}(Z_2 - Z_1)\right),$$

$$t_{12} = \frac{1}{q}\left(m_{13} \cdot m_{21} - m_{11} \cdot m_{23}\right), q = m_{11} \cdot m_{22}$$

From the third equation of system (11), taking into account equation (13), we obtain

$$Z_P = 2 \cdot k_{11} \cdot X_3 - 2 \cdot k_{11} \cdot k_{12} - 2 \cdot t_{11} \cdot t_{12} + 2 \cdot t_{11} \cdot Y_3 + 2 \cdot Z_3 \pm \sqrt{\frac{D}{2 \cdot (k_{11}^2 + t_{11}^2 + 1)}}, \tag{14}$$

where $D = (2 \cdot k_{11} \cdot k_{12} - 2 \cdot k_{11} \cdot X_3 + 2 \cdot t_{11} \cdot t_{12} - 2 \cdot t_{11} \cdot y3 - 2 \cdot Z_3)^2 -$

$$-4 \cdot (k_{11}^2 + 1 + t_{11}^2) \cdot (k_{12}^2 - 2 \cdot k_{12} \cdot x3 + t_{12}^2 - 2 \cdot t_{12} \cdot Y_3 + X_3^2 + Y_3^2 + Z_3^2 - L_1^2).$$

From (13), taking into account (14), we obtain the values of $X_p$ and $Y_p$.

*Velocity and acceleration analysis.* To determine the relationship between the velocities of the active kinematic pairs and the moving platform, we take the time derivative of equations (7)

$$\dot{l}_i \cdot c\varphi_{1i} + (m_i \cdot c\varphi_{1i} - l_i \cdot s\varphi_{1i}) \cdot \omega_i + \dot{m}_i \cdot s\varphi_{1i} - \dot{n}_i = 0, i = 1,2,3, \quad (15)$$

where $\dot{l}_i = -2 \cdot L_2 \cdot c\theta_i \cdot V_x - 2 \cdot L_2 \cdot s\theta_i \cdot V_y$, $\dot{m}_i = -2 \cdot L_2 \cdot V_z$,

$\dot{n}_i = (2 \cdot r \cdot c\theta_i - 2 \cdot X_P) \cdot V_x + + (2 \cdot r \cdot s\theta_i - 2 \cdot Y_P) \cdot V_y - 2 \cdot Z_P \cdot V_z, i = 1,2,3.$

Equations (15) are rewritten in the following matrix form

$$\begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{pmatrix} \cdot \begin{pmatrix} Vx \\ Vy \\ Vz \end{pmatrix} = \begin{pmatrix} d_1 & 0 & 0 \\ 0 & d_2 & 0 \\ 0 & 0 & d_3 \end{pmatrix} \cdot \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix} \quad (16)$$

where $c_{i1} = 2 \cdot X_P - 2 \cdot r \cdot c\theta_i - 2 \cdot L_2 \cdot c\varphi_{1i} \cdot c\theta_i$,

$c_{i2} = 2 \cdot Y_P - 2 \cdot r \cdot s\theta_i - 2 \cdot L_2 \cdot c\varphi_{1i} \cdot s\theta_i$, $c_{i3} = 2 \cdot Z_P - 2 \cdot L_2 \cdot s\varphi_{1i}$,

$d_i = 2 \cdot L_2 \cdot Z_P \cdot c\varphi_{1i} + 2 \cdot L_2 \cdot r \cdot s\varphi_{1i} - 2 \cdot L_2 \cdot X_P \cdot c\theta_i \cdot s\varphi_{1i} - 2 \cdot L_2 \cdot Y_P \cdot s\varphi_{1i} \cdot s\theta_i$,

$i = 1,2,3.$

From equations (16), the velocity of the moving platform can be determined for given angular velocities of the active revolute kinematic pairs. To determine the accelerations of the center of the moving platform for given angular accelerations of the active links, we take the time derivative of equations (15) and express them in matrix form

$$\begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix} \cdot \begin{pmatrix} W_x \\ W_y \\ W_z \end{pmatrix} = \begin{pmatrix} f_1 & 0 & 0 \\ 0 & f_2 & 0 \\ 0 & 0 & f_3 \end{pmatrix} \cdot \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{pmatrix}, \quad (17)$$

where $k_{i1} = 2 \cdot X_P - 2 \cdot r \cdot c\theta_i - 2 \cdot L_2 \cdot c\varphi_{1i} \cdot c\theta_i$,

$k_{i2} = 2 \cdot Y_P - 2 \cdot r \cdot s\theta_i - 2 \cdot L_2 \cdot c\varphi_{1i} \cdot s\theta_i$,

$\dot{b}_i = 2 \cdot L_2 \cdot (V_z \cdot c\varphi_{1i} - Z_P \cdot s\varphi_{1i} \cdot \omega_1) + 2 \cdot L_2 \cdot r \cdot c\varphi_{1i} \cdot \omega_i -$

$- 2 \cdot L_2 \cdot c\theta_i \cdot (V_x \cdot s\varphi_{1i} + X_P \cdot c\varphi_{1i} \cdot \omega_i) - 2 \cdot L_2 \cdot s\theta_i \cdot (V_y \cdot s\varphi_{1i} + Y_P \cdot c\varphi_{1i} \cdot \omega_i)$,

$\dot{a}_{i1} = 2 \cdot V_x + 2 \cdot L_2 \cdot c\theta_i \cdot s\varphi_{1i} \cdot \omega_i$,

$\dot{a}_{i2} = 2 \cdot V_y + 2 \cdot L_2 \cdot s\theta_i \cdot s\varphi_{1i} \cdot \omega_i$, $\dot{a}_{i3} = 2 \cdot V_z - 2 \cdot L_2 \cdot c\varphi_{1i} \cdot \omega_i, i = 1,2,3.$

From equations (17), the acceleration of the moving platform can be determined for given angular accelerations of the active revolute kinematic pairs.

**Results.** Numerical results for the inverse kinematics problem. The following constant parameters were given: $r_a = 180\,mm, \quad r_b = 100\,mm, \quad r = r_a - r_b,$ $L_1 = 700\,mm, \quad L_2 = 400\,mm, \quad \theta_1 = 0^0, \theta_2 = 120^0, \theta_3 = 240^0.$

Additionally, the coordinates of the center of the moving platform: $X_P = 300\,mm,\ Y_P = 300\,mm,\ Z_P = 750\,mm.$ Figure 5 shows the position of the PM for specific numerical values. A program was developed that automatically adjusts the equation solutions based on the signs of the coordinates of the center of the moving platform and determines the position of the PM.

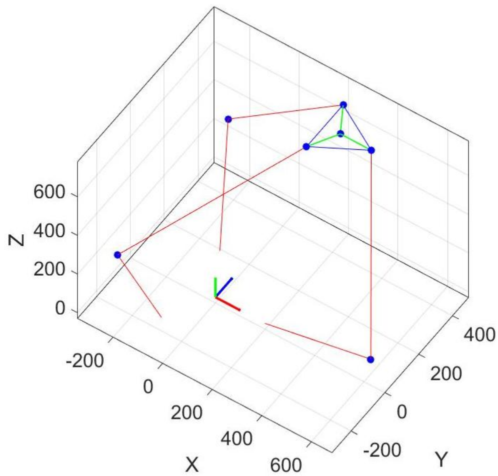


Figure 4 Solution of the inverse kinematics problem

The coordinates of the center of the moving platform were set within a parallelepiped, where the values of $X_p$, $Y_p$ vary from -300 mm to +300 mm in 50 mm increments, and $Z_p$ varies from 400 mm to 750 mm in 50 mm increments. The workspace of the PM (Fig. 6) was obtained based on the inverse kinematics problem. From Figure 5, it can be seen that the center of the moving platform can reach all internal points of the given parallelepiped, meaning that the dimensions of the PM were selected to achieve a specific workspace.

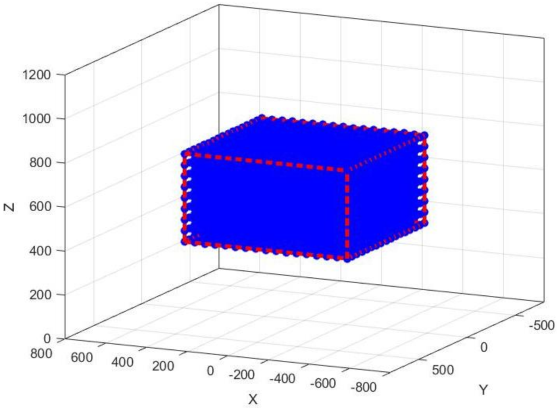


Figure 5 Workspace based on the inverse kinematics problem

*Numerical examples for the direct kinematics problem.*

We set the following constant parameters:

$$r_a = 180\, mm,\ r_b = 100\, mm,\ r = r_a - r_b,$$

$$L_1 = 700\, mm,\ L_2 = 400\, mm,\ \theta_1 = 0^0,\ \theta_2 = 120^0,\ \theta_3 = 240^0.$$

The rotation angles of the active revolute kinematic pairs are set based on the obtained values from the inverse kinematics problem

$$\varphi_{11} = 0.3496, \varphi_{12} = 0.6922, \varphi_{13} = 1.3209.$$ f123.

The accuracy of the obtained results was verified based on the inverse kinematics problem.

*Numerical examples for velocity and acceleration analysis.*

We set the following constant parameters:

$$r_a = 180\, mm,\ r_b = 100\, mm;\ r = r_a - r_b,$$

$$L_1 = 700\, mm;\ L_2 = 440\, mm;\ \theta_1 = 0^0,\ \theta_2 = 120^0,\ \theta_1 = 240^0.$$

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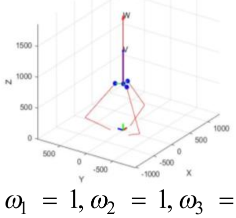
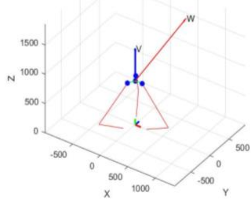
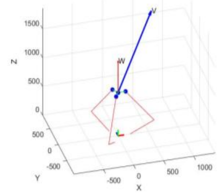
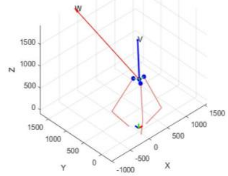
|  $\omega_1 = 1, \omega_2 = 1, \omega_3 = 1, \varepsilon_1 = 2, \varepsilon_2 = 2,$ $\varepsilon_3 = 2, X_P = 0, Y_P = 0, Z_P = 750.$ |  $\omega_1 = 1, \omega_2 = 1, \omega_3 = 1, \varepsilon_1 = 1, \varepsilon_2 = 2,$ $\varepsilon_3 = 3, X_P = 0, Y_P = 0, Z_P = 750.$ |




$\omega_1 = 1, \omega_2 = 2, \omega_3 = 3, \varepsilon_1 = 1, \varepsilon_2 = 1,$
$\varepsilon_3 = 1, X_P = 0, Y_P = 0, Z_P = 750.$




$\omega_1 = 1, \omega_2 = 1.5, \omega_3 = 2, \varepsilon_1 = 4, \varepsilon_2 = 1,$
$\varepsilon_2 = 3, X_P = 300, Y_P = 300, Z_P = 750.$

Figure 6 Velocity and acceleration analysis

Figure 6 shows the velocity and acceleration vectors of the center of the moving platform for given values of the center position, angular velocities, and accelerations of the input revolute active kinematic pairs.

**Discussion.** The numerical analysis of the inverse kinematics problem allowed us to determine the workspace of the PM and verify its kinematic feasibility for the given range of movements. The calculations revealed that the center of the moving platform can reach all points within the specified workspace, confirming the correctness of the chosen structural dimensions. This is supported by the results presented in Figure 6, which illustrates the manipulator's workspace.

To verify the obtained data, the direct kinematics problem was solved. During the analysis, the rotation angles of the active kinematic pairs were set based on the values obtained from the inverse kinematics solution. The calculations showed that the coordinates of the moving platform's center matched the previously computed values, confirming the accuracy of the developed model.

Additionally, an analysis of the velocities and accelerations of the moving platform's center was conducted. Figure 6 presents the velocity and acceleration vectors calculated for various platform positions and given angular parameters of the active kinematic pairs. The obtained results demonstrate that the developed kinematic model adequately describes the system's dynamic behavior and accounts for the manipulator's inertial characteristics.

Thus, numerical experiments confirmed the operability of the proposed kinematic model of the PM, the correctness of its geometric parameter selection, and the feasibility of efficiently controlling its movement within the specified workspace. Further research may focus on accounting for external force influences and calculating dynamic loads to improve positioning accuracy.

**Conclusion**.

The results of this study on the development of a multifunctional mobile 3D printer based on WAAM technology with an integrated mechanical processing system can be summarized as follows:

The proposed concept of a mobile 3D printer aims to address the challenge of manufacturing and repairing complex-shaped parts directly at geological exploration, mining, and mechanical engineering sites.

A kinematic analysis of the manipulator was conducted to ensure precise positioning of the printing head and subsequent mechanical processing. Based on an analysis of various kinematic structures, a delta robot with three translational degrees of freedom was selected as the printer's working unit.

Forward and inverse kinematics problems were solved, and the working area of the manipulator was determined using inverse kinematics: X ±250 mm, Y ±250 mm, Z ±200 mm. Homogeneous Denavit–Hartenberg transformation matrices were constructed, and Jacobian matrices were derived to establish the relationship between input and output velocities and accelerations. Additionally, the dimensions of the manipulator's links were defined.

The proposed design of the mobile 3D printer with post-processing surpasses subtractive methods by reducing repair time by 40–60%, lowering costs, and eliminating the need for part transportation, thereby increasing equipment reliability.

This study contributes to the further development of additive manufacturing in industrial applications, addressing additional challenges related to improving printing accuracy and automating post-processing.

*Author Contributions*

*YN, MS, AM conducted the research; AM, RK, ZhT analyzed the data; AM, ZhT wrote the paper; all authors had approved the final version.*

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