ІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ, СИСТЕМНИЙ АНАЛІЗ ТА КЕРУВАННЯ

UDC 681.51/.54

DOI: 10.29202/nvngu/2018-1/11

G. G. Diachenko,
orcid.org/0000-0001-9105-1951,
O. O. Aziukovskyi, Cand. Sc. (Tech.), Assoc. Prof.,
orcid.org/0000-0003-1901-4333

National Mining University, Dnipro, Ukraine, email: diachenko.g@nmu.one

CONTROL LAWS OF ELECTRIC DRIVES AS A RESULT OF AN IN-DEPTH KINEMATIC ANALYSIS OF THE DELTA ROBOT

Г. Г. Дяченко,
orcid.org/0000-0001-9105-1951,
О. О. Азюковський, канд. техн. наук, доц.,
orcid.org/0000-0003-1901-4333

Державний вищий навчальний заклад „Національний гірничий університет”, м. Дніпро, Україна, email: diachenko.g@nmu.one

ЗАКОНИ КЕРУВАННЯ ЕЛЕКТРОПРИВОДАМИ ЯК РЕЗУЛЬТАТ ПОГЛИБЛЕНОГО КІНЕМАТИЧНОГО АНАЛІЗУ ДЕЛЬТА-РОБОТА

Purpose. To provide a simple and clear approach to kinematic analysis and motion computations useful to those who may wish to program and employ nice delta robots.

Methodology. A circle and sphere intersection model is used to describe positioning of the elements, which allows obtaining the analytical solution for the forward and inverse kinematics problem. For the verification of the proposed solution, the results were processed configuring the mechanical model of the kinematic system using SimMechanics Blocks in MATLAB/Simulink environment, which allows simulating various geometric configurations and reactions to mechanical stress and develop effective control strategies.

Findings. A mathematical expression describing the movement of the end-effector of the delta robot taking into account the mutual positioning of the elements of the kinematic system is obtained. A synthesis algorithm that is convenient for scaling and replication in automatic mode of operation is proposed.

Originality. For the first time, the solution was obtained that takes into account the mutual positioning of the elements and the parameters of the linear dimensions of the mechanism with the involvement of IT technologies and real equipment. The distinctive feature of the proposed solution is the adaptation to the control system of the electromechanical system.

Practical value. A parallel robot consisting of three arms connected to universal joints at the base is most effective when it is necessary to perform a quick displacement along a complex or simple trajectory while simultaneously changing the coordinates x, y and z. This fact makes the task actual to develop an algorithm for obtaining mathematical expressions for the simultaneous control of the electric motors of the delta robot. The obtained mathematical expressions for the inverse and forward kinematics problem are the first step in developing a control system that ensures the coordination and consistency of required displacements of all executive bodies in accordance with a specified program, which is understood as the set of requirements to ensure the implementation of the technological process.

Keywords: *delta-robot, inverse kinematics, forward kinematics, electromechanical system*

Introduction. Recently, parallel manipulators have received increasing amount of research focused on their design and development due to their high speed, precision and stiffness. Nowadays Clavel’s 3-RRR Delta robot is one of the most widely used designs in industrial applications like packaging, medical and pharmaceutical industry, and surgery. The requirements on machinery continuously increase resulting in higher demands for performance, energy efficiency and complexity of the installed plants. The tasks of control, diagnosis and measurements are important for correct behavior. Thus, the accuracy of the considered model is crucial for future behavior prediction as well as quality improvement.

Analysis of the recent publications. The fundamental issue both in kinematic and dynamic model of any mechanism is mobility. Concerning the delta robots, it is by far the main parameter. One depends on the relationship between the design parameters such as the number of links and joins, the constraints. Before proceeding to any analysis or design, the number of degrees of freedom is always determined. The paper [1] suggests a new matrix method, that always gives the correct results compared to conventional approaches like Grubler and Kutzbach formulas, but it is more complex and requires high computational efforts. As a proof, the method was applied to the mechanisms like the four-bar planar linkage, augmented 4-bar linkage, university of Maryland manipulator, Cartesian parallel manipulator and delta robot and orthoglide robot scheme. The results obtained using different methods for these mechanisms were compared and effectiveness of the suggested matrix approach was shown. The number of degrees of freedom for delta robot to be considered in this paper is calculated to be 3.

The design process of the parallel robot consists of the following stages: kinematics analysis, dynamic optimization and path tracking control. This paper deals with kinematics. Kinematic analysis is one of the first steps in the design of most industrial robots. Kinematic analysis allows the designer to obtain information on the position of each component within the mechanical system. This information is an inevitable part for subsequent dynamic analysis along with control paths.

There are many methods devoted to this problem such as an analytical solution using geometric method [2], where a problem is simplified to defining intersection point of two circles and then transforming the coordinated systems to get the final solution. In paper [3] the main part is devoted to proper determination of kinematic parameters leading to a desired workspace, but the kinematics analysis is also briefly given using similar approach requiring solution of multiple coupled nonlinear algebraic equations. There are also iterative methods based on neural network algorithms as described in paper [4]. This work proposes a methodology using the ability of adaptive neuro-fuzzy inference system to solve an inverse kinematics problem. The network applies known combination of least squares as well as back-propagation gradient descent search algorithm for training the neurons the input-output map of the inverse kinematics. This solution is quite complex, but still acceptable as an alternate approach to solving the inverse kinematics problem. An approach based on probability theory with special focus on the Levenberg-Marquardt algorithm is presented in [5]. The parameter estimation of the dynamic system is based on Functional Mock-up Interface and the underlying optimization problem the Ceres Solver is utilized. The results seem promising. There are also different numerical algorithms like real coded genetic algorithms, polynomial methods and so on. Recently, research on haptic devices for application in rehabilitation and virtual reality has become popular; for example, paper [6] where an interesting approach to kinematics of delta robot is presented very briefly. And the current paper addresses this point and investigates the kinematics problem in a numerical study using similar approach with the purpose of obtaining simple mathematical expressions that are suitable for implementation with conventional control systems. The efficient dynamic position control of the actuators could be performed in each direction using methodologies described in paper [7].

Unsolved aspects of the problem. It is necessary to take into account the fact that the obtained equations describing the motion of the elements of the kinematic system of the delta robot are to be implemented based on low-performance digital devices. A distinctive feature of the proposed solution is the dependence between the numerical values characterizing the instantaneous position of the kinematic system and their graphical interpretation, providing also the possibility of solving the inverse kinematics problem when the equations of the kinematic system of the delta robot are obtained from predefined coordinates in space.

Objective of the article. It is required to develop a simple and clear method for kinematic analysis for both forward and inverse kinematics problems using geometric constructions describing accurately the mutual positioning of the robot chains for efficient control in order to enhance the dynamic behavior.

Presentation of the main research and explanation of scientific results. Now let us proceed with the examination of the inverse and direct kinematics with the help of geometric constructions. These are pretty easy to understand following this paper. In order to build a parallel delta robot, two main problems have to be solved. The first problem is determining the corresponding angles of each of three arms, in case the desired position of the end effector is known to set each motor in proper position. Such a process is called an inverse kinematics. And the second problem, knowing the angles, the end effector position has to be determined for example, to make some corrections of its current position. It is called forward kinematics. Theoretical part of parallel delta robot kinematics comes further.

Inverse kinematics. The kinematic model of a parallel delta robot in three-dimensional Cartesian coordinate system with origin at point $T_0(0, 0, 0)$ and axis lines X, Y and Z, oriented by arrows, is shown in Fig. 1.

Top and bottom planes of the robot are presented as equilateral deltas. Top plane is stationary. Control motors are mounted on it at points T_1, T_2 and T_3. Bottom plane is movable. Point B_0 is the position of the end effector. All physical dimensions in Fig. 1 are determined by design of the robot.

Let us consider a part of the robot model containing arm T_1H_1 and projections of H_1B_1 along X and Z axes of the coordinate system in Fig. 2. The target angle α_1 is

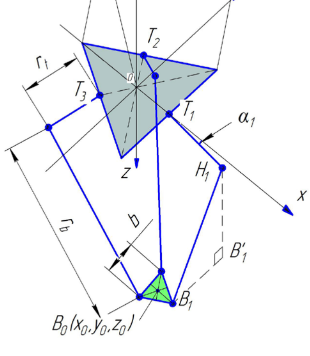

Fig. 1. Kinematic model of the parallel delta robot

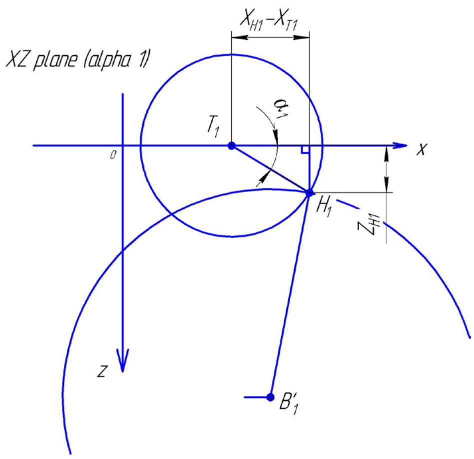

Fig. 2. XZ plane

defined as the arctangent of the ratio of the arm T_1H_1 projections on the axes X and Z. Let us see how these projections can be defined. The robot is designed in such a way that T_1H_1 can only rotate in XZ plane forming a circle with the center at point T_1 and radius r_t. As opposed to T_1, H_1 and B_1 are universal joints, which means that H_1B_1 can rotate freely round point B_1 forming sphere with radius r_b. Intersection of this sphere and XZ plane is a circle with the center at point B_1'. So, in order to define the projections, it is necessary to compose a system of equations consisting of two equations of circles with centers at points T_1, B_1' and radiuses r_t, H_1B_1' respectively.

The general view of the system is as follows

$$\begin{cases} \left(X_{H_1} - X_{T_1}\right)^2 + \left(Z_{H_1} - Z_{T_1}\right)^2 = \left|T_1H_1\right|^2 \\ \left(X_{H_1} - X_{B_1'}\right)^2 + \left(Z_{H_1} - Z_{B_1'}\right)^2 = \left|H_1B_1'\right|^2 \end{cases}, \tag{1}$$

where X_{H_1}, X_{T_1} and $X_{B_1'}$ are projections of points H_1, T_1 and B_1', respectively, on X axis. Z_{H_1}, Z_{T_1} and $Z_{B_1'}$ are projections of points H_1, T_1 and B_1', respectively, on Z axis.

For this purpose, the lacking unknowns are to be found. The length of line segment connecting the center of the bottom delta B_0 to its vertex B1: $\left|B_0B_1\right| = b\tan 30°$. Then, point B_1 has the next coordinates $B_1(x_0 + b\tan 30°)$. So, coordinates of point B_1' are $B_1'(x_0 + b\tan 30°,\ 0,\ z_0)$. Coordinates of point T_1 : $T_1(t/2\tan 30°,\ 0,\ 0)$. Now the length of B_1B_1' can be defined as $\left|B_1B_1'\right| = y_0$. Finally, knowing the length of the arm B_1H_1 and length of line segment B_1B_1', the length of H_1B_1' can be found as

$$\left|H_1B_1'\right| = \sqrt{\left|B_1H_1\right|^2 - \left|B_1B_1'\right|^2} = \sqrt{r_b^2 - y_0^2}.$$

The data obtained above is sufficient to compose the desired system of equations. Substituting the data into (1), we obtain

$$\begin{cases} \left(X_{H_1} - (t/2)\tan 30°\right)^2 + \left(Z_{H_1}\right)^2 = r_t^2 \\ \left(X_{H_1} - x_0 - b\tan 30°\right)^2 + \left(Z_{H_1} - z_0\right)^2 = r_b^2 - y_0^2 \end{cases}. \tag{2}$$

The next step is to designate the left-hand side and the right-hand side arguments of the system of equations (2) as $r_t^2 = r_1^2$, $r_b^2 - y_0^2 = r_2^2$, $x_1 = (t/2)\tan 30°$, $x_2 = x_0 + b\tan 30°$ and open all brackets. Then the system of equations looks like

$$\begin{cases} X_{H_1}^2 - 2X_{H_1}x_1 + x_1^2 + Z_{H_1}^2 = r_1^2 \\ X_{H_1}^2 - 2X_{H_1}x_2 + x_2^2 + Z_{H_1}^2 - 2Z_{H_1}z_0 + z_0^2 = r_2^2 \end{cases}. \tag{3}$$

Subtract from the first equation of the system (3) the second equation, make some math manipulations and then rewrite the system as

$$\begin{cases} X_{H_1}\left(2x_2 - 2x_1\right) + 2Z_{H1}z_0 = r_1^2 - r_2^2 + x_2^2 + z_0^2 \\ X_{H_1}^2 - 2X_{H_1}x_1 + x_1^2 + Z_{H_1}^2 = r_1^2 \end{cases}. \tag{4}$$

Make the following designations in the first equation of (4), $a_1 = 2x_2 - 2x_1$ $q = r_1^2 - r_2^2 + x_2^2 + z_0^2$ and $b_1 = 2z_0$. Afterwards, resolve this expression relatively Z_{H_1}

$$Z_{H_1} = \frac{q - a_1X_{H_1}}{b_1}. \tag{5}$$

Substitute (5) into the second equation of the system (4) in order to get an expression resolved relatively X_{H_1}

$$X_{H_1}^2\left(1 + \frac{a_1^2}{b_1^2}\right) + X_{H_1}\left(-2x_1 - 2\frac{qa_1}{b_1^2}\right) + \left(x_1^2 + \frac{q^2}{b_1^2} - r_1^2\right) = 0.$$

We have got a quadratic equation, let us reduce it to a common view. For the sake of simplicity, designate the equation coefficients as follows $a = 1 + a_1^2/b_1^2$, $b = -2\left(x_1 + qa_1/b_1^2\right)$, $c = x_1^2 + q^2/b_1^2 - r_1^2$. The final view of quadratic equation

$$aX_{H_1}^2 + bX_{H_1} + c = 0,$$

where X_{H_1} represents an unknown, and a, b and c are the coefficients of the equation. To find roots of this equation, firstly, the discriminant of the quadratic equation that is often represented using as upper case D must be found

$$D = b^2 - 4ac.$$

A quadratic equation with real coefficients can have either one or two distinct real roots, or two distinct complex roots. In this case the discriminant determines the number and nature of the roots. There are three cases:

If $D < 0$, the equation possesses no solutions for our problem, which means that the desired position of end effector is beyond the region of admissible displacements (i.e. workspace).

Otherwise if $D = 0$, then there is exactly one real root. It can be found as $X_{H_1} = -b/2a$.

Otherwise $D \geq 0$, then the equation possesses two roots, which can be calculated as $-b+\sqrt{D}/2a$ and $-b-\sqrt{D}/2a$. The choice for our problem is the root with the most positive value.

The next step is to substitute the calculated value of X_{H_1} into (5). Thereby X_{H_1} and Z_{H_1} are both defined. This fact allows calculating the target angle

$$\alpha_1 = \arctan\left(\frac{Z_{H_1}}{X_{H_1} - X_{T_1}}\right).$$

Such algebraic simplicity comes from a good choice of the reference frame. To pursue even further this advantage and find the two remaining angles we use the symmetry of deltas and just simply rotate the coordinate system by dint of the next rotation matrix

$$R = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix},$$

which rotates points in the XY-Cartesian plane counterclockwise through an angle θ ($\theta = 120°$ to get α_2 and $\theta = 240°$ to get α_3) round Z-axis of the Cartesian coordinate system. To perform a rotation using the given matrix, the position of the point must be represented by a column vector, containing its coordinates x_0 and y_0. The rotated vector is obtained by using the matrix multiplication

$$\begin{bmatrix} x_0' \\ y_0' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \end{bmatrix}.$$

Thus, the coordinates x_0' and y_0' of the end-effector position B_0 after rotation

$$x_0' = x_0\cos\theta + y_0\sin\theta;$$

$$y_0' = -x_0\sin\theta + y_0\cos\theta.$$

Substituting these coordinates into the system of equations (2) instead of x_0 and y_0, the remaining angles α_2 and α_3 can be calculated easily using the same technique.

Forward kinematics. Now let us examine the forward kinematics via geometric constructions. The solution of this problem is based on similar, but not quite identical geometry. As mentioned earlier H_1, H_2, H_3, B_1, B_2, B_3 are the so-called universal joints. It means that arms H_1B_1, H_2B_2 and H_3B_3 can rotate freely around points B_1, B_2 and B_3, respectively, forming spheres with radiuses r_b. Thereby, the most obvious and simple way to determine the position of the end effector knowing angles α_1, α_2 and α_3 beforehand is to compose a system of equations for these three spheres, one of the solutions of which will be the point B_0 containing the coordinates of the end effector. Firstly, as angles α_1, α_2 and α_3 are known, the coordinates of universal joints H_1, H_2 and H_3 have to be determined

$$H_1\left(OT_1 + r_t\cos\alpha_1, 0, r_t\sin\alpha_1\right);$$

$$H_2\begin{pmatrix} -\left[OT_2 + r_t\cos\alpha_2\right]\sin 30° \\ \left[OT_2 + r_t\cos\alpha_2\right]\cos 30°, r_t\sin\alpha_2 \end{pmatrix};$$

$$H_3\begin{pmatrix} -\left[OT_3 + r_t\cos\alpha_3\right]\sin 30° \\ -\left[OT_3 + r_t\cos\alpha_3\right]\cos 30°, r_t\sin\alpha_3 \end{pmatrix}.$$

In order to obtain point B_0 from as a root of the system of equations for the spheres, its centers must be shifted as shown in Figs. 3 and 4.

According to Fig. 4 coordinates of shifted centers of the spheres are

$$H_1'\left(OT_1 + r_t\cos\alpha_1 - b\tan 30°, 0, r_t\sin\alpha_1\right);$$

$$H_2'\begin{pmatrix} -\left[OT_2 + r_t\cos\alpha_2 - b\tan 30°\right]\sin 30° \\ \left[OT_2 + r_t\cos\alpha_2 - b\tan 30°\right]\cos 30°, r_t\sin\alpha_2 \end{pmatrix};$$

$$H_3'\begin{pmatrix} -\left[OT_3 + r_t\cos\alpha_3 - b\tan 30°\right]\sin 30° \\ \left[OT_3 + r_t\cos\alpha_3 - b\tan 30°\right]\cos 30°, r_t\sin\alpha_3 \end{pmatrix}.$$

For the sake of simplicity, we designate the coordinates of these points as $H_1'(x_1, y_1, z_1)$, $H_2'(x_2, y_2, z_2)$, $H_3'(x_3, y_3, z_3)$. Then the general view of the system of equation for the spheres appears like

$$\begin{cases} (x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2 = r_b^2 \\ (x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2 = r_b^2 \\ (x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2 = r_b^2 \end{cases}. \quad (6)$$

Mathematical manipulations with this system come further with the purpose of obtaining simple expressions for roots calculation that could be used in programming and simulation without any issues. Firstly, let us open all brackets in each equation of the system (6) and group up similar variables

$$x^2 + y^2 + z^2 - 2xx_1 - 2zz_1 = r_b^2 - x_1^2 - z_1^2; \quad (7)$$

$$x^2 + y^2 + z^2 - 2xx_2 - 2yy_2 - 2zz_2 = r_b^2 - x_2^2 - y_2^2 - z_2^2; \quad (8)$$

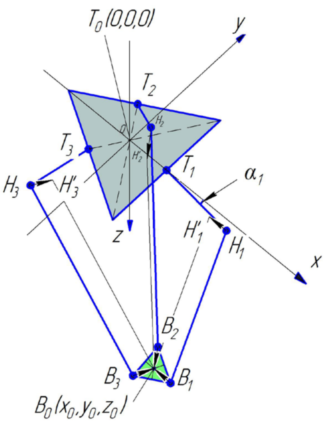

Fig. 3. Direction of spheres centers shift

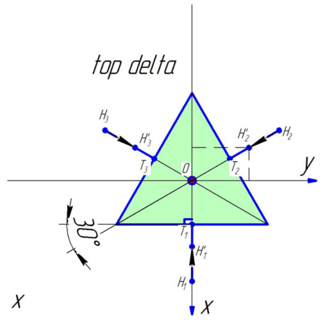

Fig. 4. View of top delta in XY plane

$$x^2+y^2+z^2-2xx_3-2yy_3-2zz_3=r_b^2-x_3^2-y_3^2-z_3^2. \quad (9)$$

Subtract (7–8)

$$2x\left(x_2-x_1\right)+2yy_2+2z\left(z_2-z_1\right)=$$
$$=-x_1^2-z_1^2+x_2^2+y_2^2+z_2^2.$$

Subtract (7–9)

$$2x\left(x_3-x_1\right)+2yy_3+2z\left(z_3-z_1\right)=$$
$$=-x_1^2-z_1^2+x_3^2+y_3^2+z_3^2.$$

Subtract (8–9)

$$2x\left(x_3-x_2\right)+2y\left(y_3-y_2\right)+2z\left(z_3-z_2\right)=$$
$$=-x_2^2-y_2^2-z_2^2+x_3^2+y_3^2+z_3^2.$$

Let us introduce the following designation

$$Q_i=x_i^2+y_i^2+z_i^2.$$

Taking into account the above manipulations and just introduced designation the set of equations looks like

$$x\left(x_2-x_1\right)+yy_2+z\left(z_2-z_1\right)=\left(Q_2-Q_1\right)/2; \quad (10)$$

$$x\left(x_3-x_1\right)+yy_3+z\left(z_3-z_1\right)=\left(Q_3-Q_1\right)/2; \quad (11)$$

$$x\left(x_3-x_2\right)+y\left(y_3-y_2\right)+z\left(z_3-z_2\right)=\left(Q_3-Q_2\right)/2. \quad (12)$$

Continue further mathematical manipulations with equations (10–12). Subtract (10–11)

$$x\left(\frac{x_2-x_1}{y_2}-\frac{x_3-x_1}{y_3}\right)+z\left(\frac{z_2-z_1}{y_2}-\frac{z_3-z_1}{y_3}\right)=$$
$$=\frac{Q_2-Q_1}{2y_2}-\frac{Q_3-Q_1}{2y_3}.$$

Represent this expression with respect to x as

$$x=a_1z+b_1, \quad (13)$$

where

$$a_1=\left(\frac{z_3-z_1}{y_3}-\frac{z_2-z_1}{y_2}\right)/d_1;$$

$$b_1=\left(\frac{Q_2-Q_1}{2y_2}-\frac{Q_3-Q_1}{2y_3}\right)/d_1;$$

$$d_1=\frac{x_2-x_1}{y_2}-\frac{x_3-x_1}{y_3}.$$

Now subtract (11–12)

$$y\left(\frac{y_3}{x_3-x_1}-\frac{y_3-y_2}{x_3-x_2}\right)+z\left(\frac{z_3-z_1}{x_3-x_1}-\frac{z_3-z_2}{x_3-x_2}\right)=$$
$$=\frac{Q_3-Q_1}{2\left(x_3-x_1\right)}-\frac{Q_3-Q_2}{2\left(x_3-x_2\right)}.$$

Represent this expression with respect to y as

$$y=a_2z+b_2, \quad (14)$$

where

$$a_2=\left(\frac{z_3-z_2}{x_3-x_2}-\frac{z_3-z_1}{x_3-x_1}\right)/d_2;$$

$$b_2=\left(\frac{Q_3-Q_1}{2\left(x_3-x_1\right)}-\frac{Q_3-Q_2}{2\left(x_3-x_2\right)}\right)/d_1;$$

$$d_2=\frac{y_3}{x_3-x_1}-\frac{y_3-y_2}{x_3-x_2}.$$

Finally, substitute (13) and (14) into (7). After opening all brackets and grouping similar variables the expression looks as follows

$$\left[a_1^2+a_2^2+1\right]z^2+2\left[a_1\left(b_1-x_1\right)+a_2b_2-z_1\right]z+$$
$$+\left[\left(b_1-x_1\right)^2+b_2^2+z_1^2-r_b^2\right]=0.$$

So, we get quadratic equation which can be represented in common view as

$$az^2+bz+c=0,$$

where z represents an unknown, and a, b and c are the coefficients of the equation. To find roots of this equation, firstly, the discriminant of the quadratic equation must be found just like it was done in the section describing inverse kinematics problem. If $D\geq 0$, then the equation possesses two roots, which can be calculated as $-b+\sqrt{D}/2a$ and $-b-\sqrt{D}/2a$. The choice for our problem is the root with the most positive value of z.

The next step is to substitute the calculated value into (13) and (14). Thereby the two remaining coordinates x and y are both defined and the problem of forward kinematics is solved.

Conclusions. The problem of inverse and direct kinematics with the help of geometric constructions is examined. The mathematical expressions describing the movement of the end-effector of the delta robot taking into account the mutual positioning of the elements of the kinematic system are obtained. It is claimed that the simplest analytical solution to the inverse and direct kinematics problems for high speed delta robots has been exposed for the first time herein. The proposed solution can be adapted to the control system of the electromechanical system. The future work will be devoted to the development of the algorithms for the simultaneous control of the electric motors of the delta robot to perform quick displacements along complex or simple trajectories.

References.

1. Kambiz Ghaemi Osgouie and Bahman Gard, 2017. Using the matrix method to compute the degrees of freedom of mechanisms. *Journal of Applied and Computational Mechanics* [e-journal], 3(3), pp. 158–170. DOI: 10.22055/jacm.2017.20542.1085.

2. Xuewen Yang, Zuren Feng, Chenyu Liu and Xiaodong Ren, 2014. A geometric method for kinematics of delta robot and its path tracking control. In: *Proc. of IEEE 14th Int. Conf. on Control, Automation and Systems (ICCAS)* [e-journal], pp. 509–514. DOI: 10.1109/ICCAS. 2014. 6988043.

3. Mahmoodi, M., Tabrizi, M.G., Alipour, K., 2015. A new approach for kinematics-based design of 3-RRR delta robotics with a specified workspace. *In Proc. of IEEE AI & Robotics (IRANOPEN)* [e-journal]. DOI: 10.1109/ RIOS.2015.7270746.

4. Tuong Phuoc Tho, Nguyen Truong Thinh, Nguyen Trong Tuan, Ma Ngoc Thanh Nhan, 2015. Solving inverse kinematics of deltarobot using Anfis. *In Proc. of IEEE 15th Int. Conf. on Control, Automation and Systems (ICCAS)* [e-journal], pp. 790–795, DOI: 10.1109/ICCAS. 2015. 7364728.

5. Kampfmann, R., Mösch, D., Menager, N., 2017. Parameter estimation based on FMI. *In Proc. of the 12th Int. Modelica Conf.* [e-journal], pp. 313–319. DOI: 10.3384/ ecp17132313.

6. Hirano, J., Tanaka, D., Watanabe, T., Nakamura, T., 2014. Development of delta robot driven by pneumatic artificial muscles. *In Proc. of IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics (AIM)* [e-journal], pp. 1400–1405. DOI: 10.1109/AIM.2014.6878278.

7. Aziukovskyi, O.O. and Bakutin, A.V., 2014. Design of optimal high-order speed controller, *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 1, pp. 71–76.

Мета. Розробити простий і чіткий підхід до кінематичного аналізу та обчислень руху, корисних для тих, хто бажає програмувати й використовувати дельта-роботи.

Методика. Для опису позиціонування елементів використовується модель перетину кола та сфери, що дозволяє отримати аналітичне рішення для задачі прямої й зворотної кінематики. Для перевірки запропонованого рішення результати були оброблені при налаштуванні механічної моделі кінематичної системи з використанням блоків бібліотеки SimMechanics у середовищі розробки MATLAB/Simulink, що дає змогу імітувати різні геометричні конфігурації й реакції на механічні впливи, а також розробляти ефективні стратегії керування.

Результати. Отримано математичний вираз, що описує рух робочого органа дельта-робота з урахуванням взаємного позиціонування елементів кінематичної системи. Запропоновано алгоритм синтезу, зручний для масштабування й тиражування в автоматичному режимі роботи.

Наукова новизна. Уперше було отримано рішення, що враховує взаємне розташування елементів і параметри лінійних розмірів механізму із залученням ІТ-технологій і реального обладнання. Відмінною рисою запропонованого рішення є адаптація до системи керування електромеханічною системою.

Практична значимість. Паралельний робот, що складається з трьох важелів, приєднаних за допомогою карданних шарнірів до основи, є найбільш ефективним, коли необхідно швидко здійснювати переміщення по складній або простій траєкторії, одночасно змінюючи координати *x*, *y* та *z*. Цей факт робить актуальним завдання розробки алгоритму отримання математичних виразів для одночасного управління електродвигунами дельта-робота. Отримані математичні вирази для задачі прямої й зворотної кінематики є першим кроком у створенні системи керування, що забезпечує координацію та узгодженість необхідних переміщень усіх виконавчих органів відповідно до певної програми, яка розуміється як сукупність вимог щодо забезпечення реалізації технологічного процесу.

Ключові слова: *дельта-робот, зворотна кінематика, пряма кінематика, електромеханічна система*

Цель. Разработать простой и четкий подход к задаче кинематического анализа и вычислений движения, полезный для тех, кто желает программировать и использовать дельта-роботы.

Методика. Для описания позиционирования элементов используется модель пересечения окружности и сферы, которая позволяет получить аналитическое решение для задачи прямой и обратной кинематики. Для проверки предложенного решения результаты были обработаны при настройке механической модели кинематической системы с использованием блоков библиотеки SimMechanics в среде разработки MATLAB/Simulink, которая дает возможность имитировать различные геометрические конфигурации и реакции на механические воздействия, а также разрабатывать эффективные стратегии управления.

Результаты. Получено математическое выражение, описывающее движение рабочего органа дельта-робота с учетом взаимного позиционирования элементов кинематической системы. Предложен алгоритм синтеза, удобный для масштабирования и тиражирования в автоматическом режиме работы.

Научная новизна. Впервые было получено решение, учитывающее взаимное расположение элементов и параметры линейных размеров механизма с привлечением ИТ-технологий и реального оборудования. Отличительной чертой предложенного ре-

шения является адаптация к системе управления электромеханической системой.

Практическая значимость. Параллельный робот, состоящий из трех рычагов, присоединенных с помощью карданных шарниров к основанию, является наиболее эффективным, когда необходимо быстро осуществлять перемещение по сложной или простой траектории, одновременно изменяя координаты *x*, *y* и *z*. Этот факт делает актуальной задачу разработки алгоритма получения математических выражений для одновременного управления электродвигателями дельта-робота. Полученные математические выражения для прямой и обратной задач кинематического анализа являются первым шагом в разработке системы управления, обеспечивающей координацию и согласованность требуемых перемещений всех исполнительных органов в соответствии с указанной программой, которая понимается как набор инструкций для обеспечения реализации технологического процесса.

Ключевые слова: *дельта-робот, обратная кинематика, прямая кинематика, электромеханическая система*

Рекомендовано до публікації докт. техн. наук С.І. Випанасенком. Дата надходження рукопису 22.12.16.

UDC 681.5.015: 622.693.4

DOI: 10.29202/nvngu/2018-1/12

I. M. Udovyk, Cand. Sc. (Tech.), Assoc. Prof.,
orcid.org/0000-0002-5190-841X,
A. I. Simonenko, Cand. Sc. (Tech.), Assoc. Prof.,
orcid.org/0000-0002-5584-3617,
O. A. Zhukova,
orcid.org/0000-0002-1619-9582,
S. D. Prykhodchenko,
orcid.org/0000-0002-6562-0601

National Mining University, Dnipro, Ukraine, e-mail: udovyk.i.m@nmu.one; symonenko.o.i@nmu.one; zhukova.o.a@nmu.one; prykhodchenko.s.d@nmu.one

ELECTROMECHANICS SYSTEM MODELLING OF HYDROTRANSPORT AT AN ENRICHMENT PLANT

І. М. Удовик, канд. техн. наук, доц.,
orcid.org/0000-0002-5190-841X,
О. І. Симоненко, канд. техн. наук, доц.,
orcid.org/0000-0002-5584-3617,
О. А. Жукова,
orcid.org/0000-0002-1619-9582,
С. Д. Приходченко,
orcid.org/0000-0002-6562-0601

Державний вищий навчальний заклад „Національний гірничій університет“, м. Дніпро, Україна, e-mail: udovyk.i.m@nmu.one; symonenko.o.i@nmu.one; zhukova.o.a@nmu.one; prykhodchenko.s.d@nmu.one

МОДЕЛЮВАННЯ ЕЛЕКТРОМЕХАНІЧНОЇ СИСТЕМИ ГІДРОТРАНСПОРТУ ЗБАГАЧУВАЛЬНОЇ ФАБРИКИ

Purpose. To construct and analyze electromechanical system model for hydrotransport used at factories, that will be able to take into account changes related to equipment wear, and also produce the accumulation of technical changes caused by the exploitation of the pipeline system.

Methodology. The dynamic model of the electromechanical system of hydrotransport is developed on the basis of data about physical parameters of hydrotransport systems, received empirically. It is based on the methods for identification of dynamic systems in the form of differential equations for elements of the inside-factory hydraulic transport technological object.

Findings. A model of the electromechanical system of hydrotransport is developed. Verifications of homogeneity by the Fisher's and Bartlett's criteria showed the homogeneity of the estimates of the variance of reproducibility. For the Fisher's criterion rating was 2.59; for the Bartlett's criterion verification showed that the coefficient is significant at the level less than 0.02, and this is indicating the reliability of the calculation of the correlation matrix.

Originality. For the first time a model for systems of the hydraulic transport, based on the Jeffcott's multi-mass rotor models, was applied. While modelling, wear of equipment in process is taken into account.

Practical value. Efficiency of usage of Jeffcott's multi-mass rotor models based model, has been proven. It allows describing the behavior of an object in specific technological regimes reliably and improves efficiency of the processes.

Keywords: *dynamic modeling, Jeffcott's rotor, multi-mass model, hydrotransport*