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INVESTIGATION OF THE ACCURACY OF THE MANIPULATOR OF THE ROBOTIC COMPLEX CONSTRUCTED ON THE BASIS OF CYCLOIDAL TRANSMISSION

The object of research is modern robotic systems used in hotspots. In their arsenal, such mobile works are equipped with manipulators with high-precision hinges, which provide accurate positioning of the gripper (object of manipulation). Considering ground-based robotic complexes with a wheel or caterpillar base, the implementation of the process of manipulation on a stationary basis, a number of problem areas were identified that affect the accuracy of positioning.

In the course of research and analysis of modern robotic complexes, their circuit and design of components and mechanisms that provide the necessary qualities and parameters. The problem of developing high-precision hinges is central to the creation of efficient ground-based robotic systems.

The methodology of kinematic research of rotary hinges of the manipulator for the ground robotic complex is stated. The analysis of influence of deformations of material of impellers of not involute transfer on accuracy of positioning of a final subject is carried out. A kinetostatic analysis of the manipulator circuit was performed and the maximum moments acting in the hinged units on the drive unit were determined, which allowed to make a quantitative assessment using the Solidworks software package.

The mathematical model of construction of transfer and definition of accuracy of a rotary knot for a ground robotic complex, with use of cycloidal transfer without intermediate rolling bodies is investigated and developed. Mathematical modeling and taking into account the features of mechanical processes occurring in the manipulator, allows to increase the technical level of robotic complexes.

Ways of improvement are defined for maintenance of a progressive design of the manipulator that not only will satisfy necessary technical characteristics, but also will allow to simplify manufacturing technology.

Modern technologies and materials (stereolithography, carbon fiber, superhard materials) make it possible to implement advanced designs of spatial drive systems. Therefore, work in this direction is relevant, as robotic mechanical complexes for special purposes are widely used when performing work in emergencies.

Keywords: *manipulators with high-precision hinges, rotary unit, stress-strain state of cycloidal transmission, high-precision hinge.*

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1. Introduction

Modern ground-based robotic complexes are characterized by high technical characteristics. Existing manipulators that use an electric drive are controlled by an intelligent control system [1], they have a fairly high load capacity, accuracy and reliability. With remote control, objects are usually moved with a fixed chassis at low speeds. In most cases, this eliminates the need to provide high dynamic performance of the manipulator.

Designs and control systems of modern robotic systems are changing rapidly and are improving. The most advanced direction of development is the use of artificial vision systems. This allows, in conjunction with the use of artificial neural networks of deep learning [2] to fully automate the process of moving on rough terrain, even with a rather complex (anthropomorphic) configuration of the robot [3]. Artificial intelligence is also widely used to manipulate objects. Advanced artificial neural networks, which are the basis of the robot control system, allow not only to move completely autonomously on a complex surface, avoiding obstacles, or taking them into account when moving in automatic mode. They also allow to manipulate objects (capture, rotate, move) in a fully automatic mode [4, 5]. The operator does not need to manually specify the work, how to get around or overcome an obstacle, the robot does it autonomously. Also, the operator does not need to manually control the parameters of the manipulator. If it is necessary to capture the object, the capture force, its precise and rough movements in linear or angular coordinates are carried out autonomously. The operator indicates only the object that is recognized by the neural network and the action to be performed.

However, in order to be able to manipulate objects, the robot must be equipped not only with an advanced control system. It must use a progressive design of the manipulator, which provides the necessary characteristics that allow to perform appropriate operations.

Therefore, research in this area is relevant, as special-purpose robotic systems are widely used in emergency work. It is increasingly important and necessary to ensure the accuracy of positioning of manipulators.

2. The object of research and its technological audit

The object of research is a manipulator of a robotic complex.

The mechanical system of manipulators is driven by electric motors controlled by an intelligent control system.

Additional use of feedback allows to increase the level of accuracy of the manipulator. However, without taking into account the peculiarities of the work and constructive implementation of the mechanical system, the accuracy of the system will be underestimated.

Taking into account all the features of the mechanical system is carried out using a mathematical model, which is embedded in the control system of the manipulator. Only in this case, the control system provides full disclosure of the potential of electric motors equipped with feedback sensors, to ensure the maximum level of accuracy of the manipulator.

That is why, when studying the mechanical characteristics of the manipulator it is necessary to conduct a comprehensive study of the system, including links and rotary units, taking into account the peculiarities of their design and the principle of operation. The main parameter that characterizes the accuracy of positioning is repeatability. This parameter makes it possible to predict the linear or angular range of the coordinate in which the moving coordinate system of the output link will fall when repeatedly moved to a given coordinate.

With a typical lever configuration of the manipulator, the accuracy and repeatability will depend on the part of the workspace in which the manipulation operations are performed. Accordingly, the accuracy should be considered in relation to the working space of the manipulator and its configuration (kinematic scheme). When assessing the accuracy of positioning should take into account all the factors that affect the position of the output link of the manipulator. Namely, the presence of backlashes and gaps, inaccuracies in the manufacture of parts of the mechanical system, as well as deformation of the parts of the manipulator and components of the mechanical transmission.

This paper does not cover the workflows in the direct capture of the object of manipulation by cam or other capture and retention of the object. However, the accuracy of technological operations will be determined by the position of the object of manipulation. Accordingly, this issue is a direction of further research.

3. The aim and objectives of research

The aim of research is a comprehensive analysis of the element base of the manipulator, namely the links and rotary units, to determine the degree of influence of the parameters of the element base, which determine the accuracy of positioning in relation to the working space of the manipulator.

To achieve this aim it is necessary to perform the following objectives:

1. Analyze the circuit solution of the manipulator of the robotic complex. Investigate the working space of the manipulator using Monte Carlo methods based on the developed mathematical model.
2. Investigate the kinematics of the rotary assembly, including the bearing assembly and cycloidal transmission, to determine and formalize the influence of its parameters on the accuracy of the manipulator.
3. Investigate the stress-strain state of the elements of mechanical transmission, to establish the relationship between the forces, deformations and accuracy of the manipulator.
4. Determine the effect of current loads on the deformation of the links of the manipulator, justify the optimal value of deformation of the links.
5. Determine the integral influence of all factors that determine the accuracy of the manipulator and develop a calculation model suitable for use in the control system.

4. Research of existing solutions to the problem

In addition to load capacity, one of the most important characteristics of the manipulator is the positioning accuracy. In the absence of the ability to ensure high accuracy, the intelligent control system will not be able to perform the tasks assigned to it to ensure the manipulation of objects.

Considering ground-based robotic complexes [6], it should be noted that the accuracy of positioning depends on the kinematic scheme and design of the components and parts of the manipulator. Under the action of the load there will be a deformation of the manipulator links [7], which will affect the accuracy of operations. However, the main factor influencing the accuracy is the design and technical implementation of the rotary units.

As a rule, manipulators of modern robotic complexes [8] are equipped with rotary units. The rotary unit is a complex system that includes a bearing, an electric motor and a gearbox. The need to use a gearbox is due to the desire to provide maximum specific power. Typically, electric motors generate maximum power at high speeds, respectively, it is more appropriate to use a high-speed motor in conjunction with a gearbox, which provides a high gear ratio [9]. This allows to significantly reduce the weight and dimensions of the rotary unit.

High positioning accuracy and, if necessary, high dynamic characteristics are ensured by an intelligent control system that directly controls the motors. Motors that provide high performance in terms of accuracy, reliability and speed, namely servomotors or stepper motors equipped with accurate feedback sensors, must be used. However, the motors of the manipulator, which work as part of the rotary units, also contain a mechanical transmission, gearbox and bearings.

Among the mechanical transmissions of various types with high specific power (the ratio between transmission power and mass) are planetary and cycloidal transmissions [10], which are widely used in robotic systems. In this case, the output link of the transmission directly drives the link of the manipulator.

Planetary transmissions, due to their characteristic coaxial configuration and good power transmission, have found their place in the robotics industry [11]. A particularly compact configuration of the planetary gearbox was first invented in 1912 [12] and was used in RE series gearboxes by ZF Friedrichshafen AG (ZF) aimed at industrial robotic systems [13].

REFLEX Genesis Robotics has attracted a lot of attention in robotics due to the appearance of their direct drive engine, LiveDrive. To expand the range of its applications, a compatible gearbox called Reflex [14] was introduced, which is designed for light robots, capable of providing gear ratios up to 1:400 [15]. An interesting aspect of this design is the conical shape of the planetary gears, which is associated with the possibility of providing backlash.

Because the design of the manipulator is a complex multi-link structure, the elements of which are interconnected by rotary hinges, which are high-precision gear motors and bearing assemblies. Therefore, it will not be enough to consider only the error of the mechanical transmission of the gearbox.

5. Methods of research

A typical solution of the manipulator of the robotic complex is made according to the *Z*-shaped scheme, which provides a significant working space and compactness in the folded state. The manipulator (Fig. 1) consists of four rigid links, and the initial link *OA* rotates around the vertical axis *Z*, and link 4 rotates around its own axis. In the node *O* is a direct connection of the manipulator and the chassis, which is a robotic complex with a 4-link manipulator, the plane of which rotates with the link *OA*. The manipulator has 5 degrees of freedom, which is enough to perform most operations, the 5th degree of freedom (not shown) provides rotation of the *CD* link around its axis.

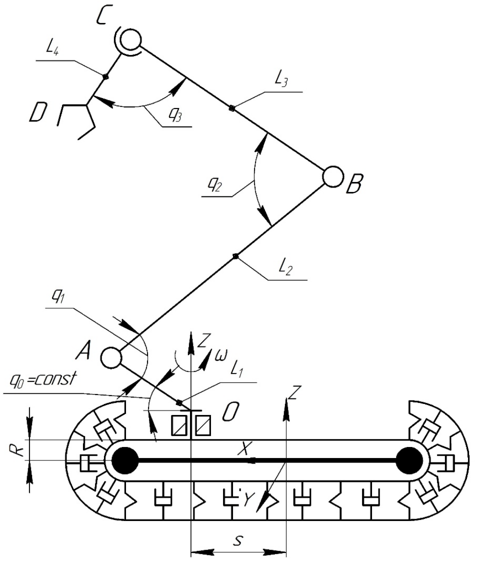

Fig. 1. Kinematic scheme of the manipulator of the ground robotic complex

The mathematical model [16], which describes the kinematics of the manipulator, can be represented by a system of 12 equations. The manipulator of the robotic complex (Fig. 1) consists of links connected by rotary nodes (*O*, *A*, *B*, *C*, *D*) [17]. The working processes of the rotary units primarily affect the accuracy of the mechanical system as a whole. Accuracy is also affected by the deformation of the links *OA*, *AB*, *BC* and *CD* having lengths L_1, L_2, L_3, L_4. Subject to the introduction of corrections that take into account the deformation of the links, it is possible to assume that the integral factor determining the accuracy of the mechanism as a whole are the generalized coordinates of the mechanism. Namely, the angles: ω, q_1, q_2, q_3, which determine the spatial position of the links relative to each other. Direct exit to the position of the output link of the manipulator is carried out by rotating the links relative to each other at appropriate angles. However, the presence of a complex mechanical system that forms a rotary unit leads to differences between the signal supplied by the control system and the actual angle of rotation of the link.

For convenience, the mathematical dependencies describing the kinematics of the manipulator are reduced to a coordinate system associated with the chassis of the robotic complex.

The equations that determine the *i*-th position of the node *D* (corresponds to the position of the moving coordinate system) as a result will look like:

$$Xd_i = \cos(\omega_i)\cdot\begin{pmatrix} L_1\cdot\cos q_0 - L_2\cdot\cos(q_0 - q_{1i}) + \\ +L_3\cdot\cos(q_0 - q_{1i} + q_{2i}) - \\ -L_4\cdot\cos(q_0 - q_{1i} + q_{2i} + q_{3i}) \end{pmatrix} + s,$$

$$Yd_i = \sin(\omega_i)\cdot\begin{pmatrix} L_1\cdot\cos(q_0) - L_2\cdot\cos(q_0 - q_{1i}) + \\ +L_3\cdot\cos(q_0 - q_{1i} + q_{2i}) - \\ -L_4\cdot\cos(q_0 - q_{1i} + q_{2i} + q_{3i}) \end{pmatrix},$$

$$Zd_i = \begin{pmatrix} L_1\cdot\cos(q_0) - L_2\cdot\cos(q_0 - q_{1i}) + \\ +L_3\cdot\cos(q_0 - q_{1i} + q_{2i}) - \\ -L_4\cdot\cos(q_0 - q_{1i} + q_{2i} + q_{3i}) \end{pmatrix} + R, \qquad (1)$$

where R – height of attachment of the node O from the center of gravity of the frame with a caterpillar drive; s – displacement of the fastening of the node O from the center of gravity of the frame with a caterpillar drive.

Determination of the working space of the manipulator of the mobile robotic complex is carried out by dependence (1) using the Monte Carlo method. The essence of the method is to find a large number of random points corresponding to the position of the movable coordinate system (gripping device) [18].

The Monte Carlo method is a numerical method used to solve mathematical problems in the theory of random selection. In solving this problem, the nodes of the manipulator operate within their operating ranges:

$$qj_i^{\min} \le qj_i \le qj_i^{\max}),\ j \in (0,1\ldots 4).$$

Analyzing the characteristics of the working space, it is possible to draw conclusions about the effectiveness of the structural implementation of mechanisms and geometric parameters of the manipulator. If the origin for the manipulator is the reference point *O*, then the set of points that can reach the grip will be the working space of the manipulator.

The Monte Carlo method requires the generation of a large number of random vectors *q* (sets of values of the generalized coordinates of the manipulator). Solving a direct kinematic problem, the position of the moving coordinate system (associated with the capture) is determined.

The components of each vector are generated randomly using the Mathcad mathematical package.

In this case, the generated values are random variables from a given range that have a normal distribution law. Visualization of the results of modeling the working space of the manipulator is presented in Fig. 2, 3.

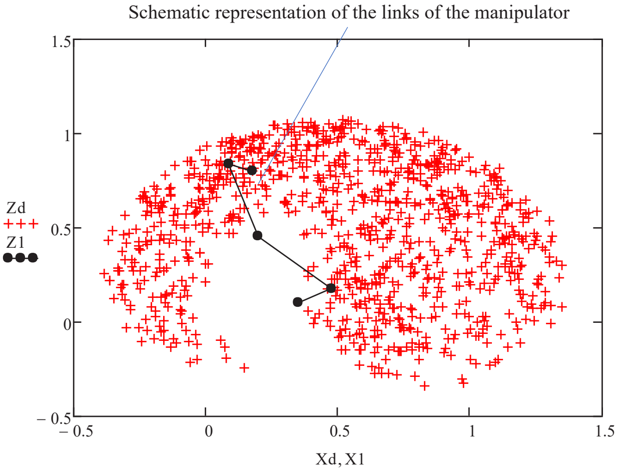

Fig. 2. Working idle in the projection on the XOZ plane

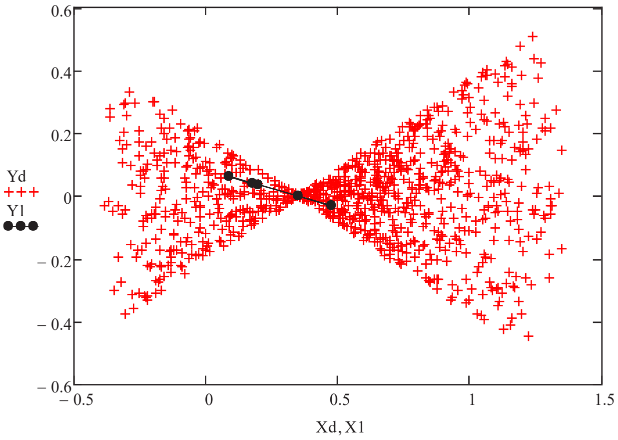

Fig. 3. Workspace in projection on the XOY axis

The advantages of the Monte Carlo method used include the simplicity of the structure of the calculation algorithm, workspace, versatility and clarity. The disadvantages of the Monte Carlo method include the dependence of the accuracy of solutions on the number of iterations that can be performed.

The working space of the manipulator is quite complex, and depending on the part of the space in which the manipulator works at a given time, the accuracy can vary significantly. That's why accuracy needs to be considered in relation to the workspace. However, in general, it is possible to identify a number of factors that affect the accuracy of the manipulator, namely:

– deformation of links (rods) of the manipulator;
– deformation of links (gears) of mechanical transmission;
– presence of backlashes and gaps in bearings;
– presence of backlash and gaps directly between the links (wheels) of the mechanical transmission;
– inaccuracies in the manufacture of mechanical transmission parts (wheels).

All these factors have a combined effect and determine the real accuracy of the manipulator mechanism. The influence of the above factors can be reduced to the corresponding error of the angular coordinates.

6. Research results

6.1. Determining the error of the bearing assembly. The primary influence of inaccuracies of bearing assemblies on the accuracy parameters of the mechanism as a whole is the stiffness of the rolling bearing, which is characterized by the amount of elastic deformation of the bearing under load. As a rule, the deformation of the bearing is small and can be neglected. However, when used in robotic complexes, bearing stiffness is a key operating parameter. Due to the peculiarities of the contact conditions of the rolling elements and tracks, roller bearings, for example, cylindrical or tapered, have a higher rigidity than ball bearings. The stiffness of the bearing can be increased by pre-tensioning [19].

There are 3 types of radial clearance: initial, landing, and working.

The initial radial clearance is the clearance in the bearing before it is mounted on the shaft and in the housing.

The bearing radial clearance is the clearance in the bearing after its installation on the workplace, i. e. after the reduction of the inner diameter of the outer ring and the increase of the outer diameter of the inner ring as a result of the landing tension.

The working gap is formed during operation of the mechanism at a constant temperature in the bearing assembly. The landing clearance is always smaller than the initial one due to the change in the diameters of the bearing rings during their installation with the landing tension, and the working clearance decreases or increases under the influence of temperature differences and increases under the applied load.

The smaller the gaps, the higher the accuracy of rotation of the bearing, the greater its durability, because in contact are several rolling elements. However, bearings with zero clearances are not available, because in tight positions of the housing and shaft due to heating of the bearing assembly can cause pinching (jamming) of the rolling elements and, ultimately, even the destruction of the mechanism.

Depending on the size, the selection of bearings [20] and direct data on its gaps (Fig. 4) and the required tension are selected individually according to the parameters of the manufacturer [21] or regulations [22].

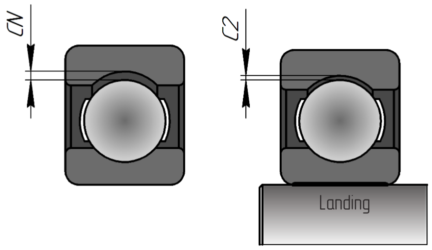

Fig. 4. General information about the gap in the bearing:
C2 – reduced radial clearance; *CN* – normal radial clearance

According to the tabular data of the clearances for roller bearings [23], for diameters from 0 to 100, defined for the first group of accuracy, the working clearances do not exceed 60 μm. Compared to other factors that affect the accuracy of these errors, they are quite small.

Kinematic errors of this type, in contrast to others, are directly added to other kinematic errors of the source link. Moreover, it is necessary to take into account the kinematic errors in each rotary unit of the manipulator.

Much more significant is the influence of kinematic inaccuracies, which are characteristic of the reducers of rotary units. The backlash of the gearbox is usually a small angle of rotation of the output shaft, which corresponds to the fixed position of the input shaft. The backlash of gearboxes is a random variable and it will be slightly different for gearboxes even from one batch. In modern designs of gearboxes it is possible to provide the amount of backlash at the level of not more than 0.3 to 0.5 angular minutes [24]. The backlash task is a complex task and is related to the concept of gearbox deadlock. The dead stroke of the gearbox is a complex value, because it also takes into account the deformation of the links. This value shows the angle of rotation of the output shaft when exposed to 3 % of the rated torque, with a rigidly fixed input shaft. According to the manufacturers' catalogs (Nabtesco), this value does not exceed one angular minute [25].

The presence of backlash can be directly taken into account when determining the accuracy of the manipulator of the robotic complex based on the available kinematic model. However, not only the presence of gaps in the gearbox reduces the accuracy of the entire system. The manipulator works under the action of significant static loads, which lead not only to deformation of the links. These loads also lead to deformation of the elements of mechanical transmissions, which negatively affects their accuracy.

To calculate the effect of loads perceived by the grip of the manipulator, consider the following calculation scheme (Fig. 5). Static study will further determine the loads that directly load the rotary units of the manipulator.

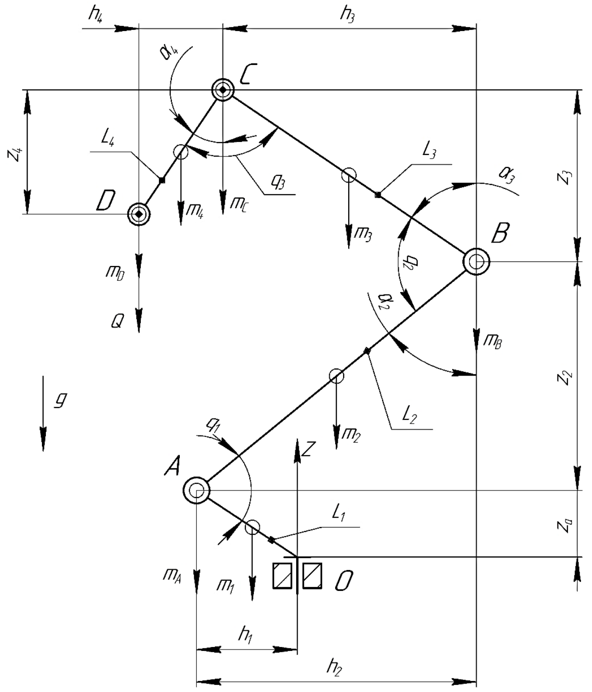

Fig. 5. The calculated scheme of the power load of the manipulator: A, B, C, D, O – rotary nodes; L_1, L_2, L_3, L_4 – link lengths; ω, q_1, q_2, q_3 – angles of rotation of the links in the nodes; h_1, h_2, h_3, h_4 – distance between the nodes along the X axis; z_1, z_2, z_3, z_4 – distance between the nodes along the Z axis; m_1, m_2, m_3, m_4 – mass of the link; m_A, m_B, m_C, m_D – mass of the node

According to the proposed calculation scheme, by typical dependence, let's determine the static moment in node A, which is one of the most loaded rotary nodes of the manipulator:

$$\begin{aligned}
Mxa_i &= (Q+m_D)\cdot(h_{4i}+h_{3i}+h_{2i})+\\
&+m_4\cdot\left(\frac{h_{4i}}{2}+h_{3i}+h_{2i}\right)+m_C\cdot(h_{3i}+h_{2i})+\\
&+m_3\cdot\left(\frac{h_{3i}}{2}+h_{2i}\right)+m_D\cdot(h_{2i}+h_{3i}+h_{4i})+\\
&+m_2\cdot\left(h_{2i}+h_{3i}+\frac{h_{4i}}{2}\right);\\
Mza_i &= (Q+m_D)\cdot(z_{2i}+z_{3i}-z_{4i})+m_4\cdot\left(z_{3i}+z_{2i}-\frac{z_{4i}}{2}\right)+\\
&+m_C\cdot(z_{3i}+z_{2i})+m_3\cdot\left(\frac{z_{3i}}{2}+z_{2i}\right)+m_D\cdot z_{2i}+m_2\cdot\frac{z_{2i}}{2}. \qquad (2)
\end{aligned}$$

Accordingly, the total static moment:

$$Ma_i=\sqrt{Mza_i^2+Mxa_i^2}. \qquad (3)$$

According to the found static moment, let's perform research in the module of the CAD/CAE SolidWorks software package of the stress-strain state of the transmission teeth, determine the deformations [26] and their further impact on the positioning accuracy.

Considering the loaded cycloidal transmission, which is engaged (contact) with all teeth, it is possible to conclude that in such a transmission, the transmitted torque is distributed to all points of contact.

Fig. 6, 7 show the calculated model of 2-speed transmission (shaft and bearing assemblies are not shown). Fig. 8 depicts a grid of finite elements.

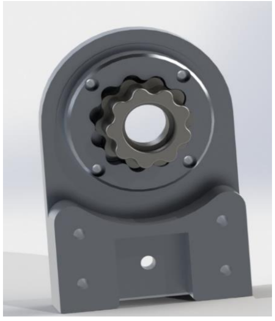

Fig. 6. Calculation model – one stage of transmission

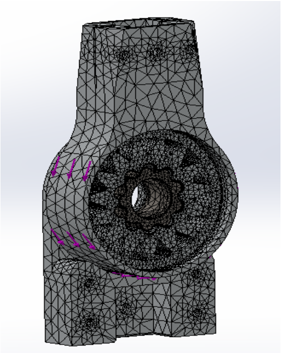

Fig. 7. Grid of finite elements with the applied static moment

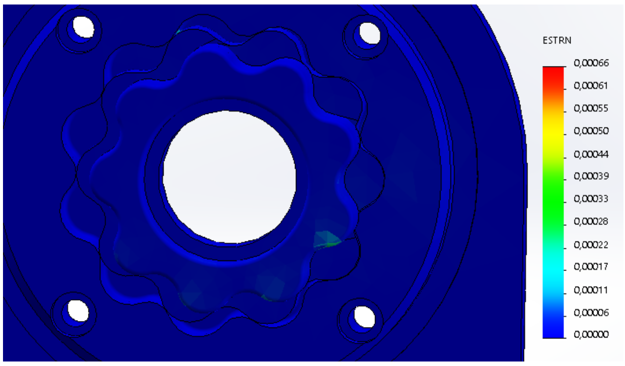

Fig. 8. Diagram of equivalent deformations of the cycloidal transmission of the rotary unit of the manipulator

From Fig. 8 shows a diagram of the calculated equivalent deformations ESTRN – the algebraic sum of normal deformations and displacements along the coordinate axes, transmission. Deformations occur only at the points of contact of non-involute transmission. A characteristic feature of the gear is that the contact, and hence the load distribution occurs on more than 5 teeth. This feature has a positive effect on increasing the resource and the ability to transmit more torque at lower mass and dimensions.

From the scale of the diagram in Fig. 9 let's obtain the maximum equivalent deformations equal to 0.00066. The deformations found correspond to an angle of displacement of 2.26 minutes [27].

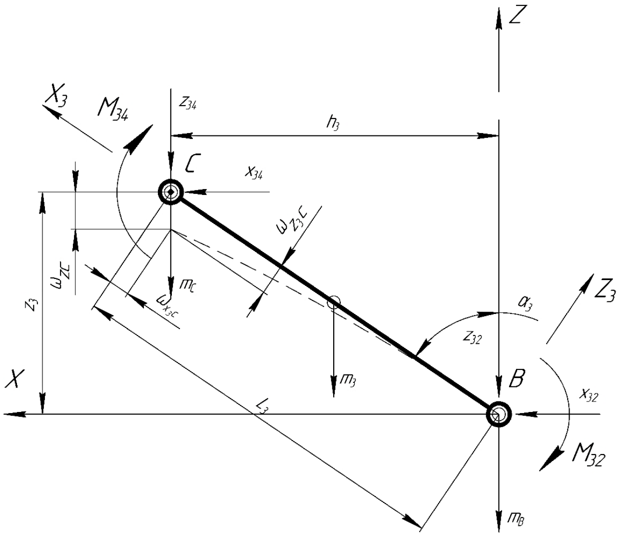

Fig. 9. Typical scheme of action of forces, on links, the manipulator: B, C – rotary knots; L_3 – link length; z_3 – projection of the link on the Z axis of the global coordinate system; h_3 – projection of the link on the X axis of the global coordinate system; α_3 – angle of rotation of the link relative to the Z axis of the global coordinate system; M_{34} – consolidated torque acting on node C; M_{32} – consolidated torque acting on node B; x_{34}, z_{34} – consolidated projections of forces acting on the node C; x_{32}, z_{32} – consolidated projections of forces acting on node B; m_3 – link mass of the link; m_B, m_C – mass of the node; ω_{zc} – movement of node C in global coordinates; ω_{x3c}, ω_{z3c} – movement of node C in local coordinates

The obtained data make it possible to directly assess the influence of loads and corresponding deformations of the mechanical transmission links on the integral accuracy of the manipulator.

6.2. Determination of deformations of links. The speed requirements for the robotic complex manipulator usually lead to considerable effort. Moreover, the analysis shows that when considering the kinetostatics of the actual design, the control moments are quite significant. The occurrence of such moments is due to the need for the manipulator drives in addition to the weight of the object of manipulation to overcome the weight of the links and drives, which are usually placed directly in the hinges of the manipulator.

An integral factor that will affect the accuracy of positioning will also be the cross section of the link of the manipulator, which provides the necessary rigidity of the system.

To assess the stiffness of the link it is necessary to determine its deflection ω_{C_i} and angle of rotation θ_{C_i} from the action of the payload, the weight of the links and rotary units. To ensure the necessary rigidity, which will directly affect the accuracy, the task is to fulfill the condition where the largest deflection of the link (angle of rotation) should not exceed the allowable value:

$$\theta_{D_i} \le [\theta_i]; \omega_{D_i} \le [\omega_i] \text{ mm.} \tag{4}$$

Consider the static equilibrium of the manipulator hinges (Fig. 10). Alternately composing for each of the links the differential equation of the deformed axis of the link or the differential equation of the elastic line [19]:

$$\pm \frac{d^2y}{dz^2} \le \frac{M_z}{EI_x}, \tag{5}$$

where M_z – bending moment in section; EI_x – stiffness of the cross section of the link (beam) when bending.

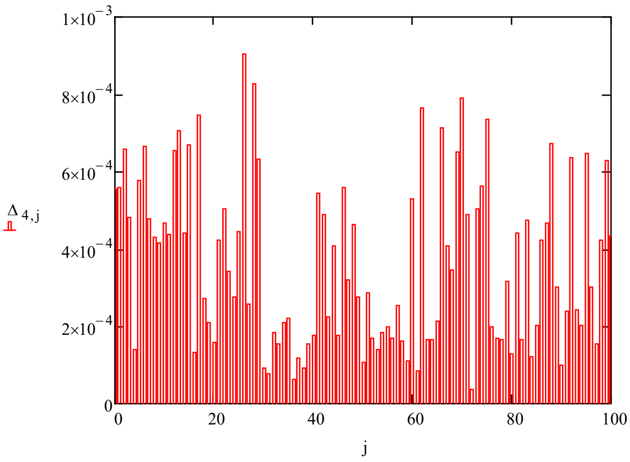

Fig. 10. Histogram of errors

The approximate differential equation of the elastic line of the beam allows to determine the deflections and angles of rotation in any section with satisfactory accuracy for practical purposes, for which let's use direct integration.

Accordingly, let's obtain the dependences for determining the deformations of the BC link, which will have the form:

– equation to determine the angle of rotation:

$$\theta_{c_i} = \frac{-\frac{Z_{23} \cdot h_{3i}^3}{2} + \frac{m_C \cdot h_{3i}^3}{2} + \frac{m_3 \cdot \frac{h_{3i}^3}{2}}{2} - M_{34} \cdot h_{4i}}{EI}; \tag{6}$$

– equation to determine the deflection:

$$\omega_{c_i} = -\theta_{c_i} \cdot l_3 - \frac{\frac{Q \cdot h_{3i}^2}{6} + \frac{m_C \cdot h_{3i}^2}{6} + \frac{m_3 \cdot \frac{h_{3i}^2}{2}}{6} - M_{34} \cdot h_{4i}^2}{EI} \text{ mm}, \quad (7)$$

where h_{3i} – horizontal distance (shoulder) of force; M_{34} – value that takes into account the payload; m_c – the weight of the rotary node C; m_3 – CB link weight; EI – the stiffness characteristics of the link, the modulus of elasticity and the moment of inertia of the section, respectively.

Determination of the angle of rotation and displacement for other nodes is carried out by similar dependencies.

From the analysis and analytical calculations let's obtain the desired values of angles of rotation and displacement in the nodes, which allows to include these angular errors, depending on the position of the output link of the manipulator. If to limit the value of the angle of inclination of the link and its deflection, based on the required accuracy, then based on condition (4) it is possible to determine the necessary parameters of the optimal cross section of the links at maximum load to ensure the required rigidity and accuracy.

From the calculated dependences let's obtain the optimal angle of rotation of the link, equal to $\left[\theta_{c_i}\right] \leq 0.5$ min, and deflection $\left[\omega_{c_i}\right] \leq l_k/2500$ mm, which on the one hand creates significantly lower errors than the angle of rotation of the link due to the backlash in the gearbox of the rotary unit. On the other hand, the presence of some elasticity of the link allows to reduce its weight and ensure optimal mass and dimensions of the links of the manipulator.

To determine the integral influence of all factors that determine the accuracy of the manipulator, each of its rotary nodes should be considered separately. As an integral parameter that takes into account all available errors (except for backlash in the bearings), it is possible to use the angular error of the movable link of the rotary unit.

This angular error takes into account the presence of backlash of the gearbox of the rotary unit, the deformation of the elements of the cycloidal transmission, presented as an equivalent value of the angular displacement. Also, subject to additional transformations, the angular error will include a suitably represented deformation of the link, expressed by the equivalent value of the angle of rotation. The angular error as an integral quantity shows the maximum possible value of the error. However, it should be noted that this error is random, and the impact of each of its components on the overall value is usually proportional to the external load. That is, with a greater external load will increase more significantly as the deformation of the links and the deformation of the gears of the mechanical transmission.

However, depending on the position of the manipulator, the load of the rotary nodes may differ significantly, and the errors of one rotary node may partially compensate for the error present in another rotary node. This leads to the need to take into account random factors when determining the accuracy of the manipulator, in relation to its working space.

This allows to determine both the minimum and average accuracy of the manipulator, both for a specific position in the workspace and for the entire workspace as a whole.

6.3. Determination of position error. To determine the error of the position of the grip of the manipulator, let's use random variables. The angular error will be a random variable with a normal distribution law. Its value will vary from zero to maximum. The maximum value of the angular error of the generalized angular coordinates, based on previously performed calculations is:

$$\Delta Oj = \Delta Aj = \Delta Bj = \Delta Cj = \Delta Dj \approx 3.27 \text{ min},$$

where deformation of the links (rods) of the manipulator = 0.00177 min; deformation of links (gears) of mechanical transfer = 2.26 min; presence of backlashes and gaps directly between links (wheels) of mechanical transfer = 0.5 min; inaccuracies in the manufacture of parts (wheels) of mechanical transmission = 0.5 min.

Accordingly, it is possible to determine the dependences of the errors of the coordinates of the grip on the angular error and the error due to the backlash in the bearings can be according to the dependences:

$$\Delta Xd_{i,j} = \cos(\omega_i + \Delta O_i) \times$$

$$\times \begin{pmatrix} L_1 \cdot \cos q_0 - L_2 \cdot \cos\left(q_0 - (q_{1i} + \Delta A_i)\right) + L_3 \times \\ \times \cos\left(q_0 - (q_{1i} + \Delta A_i) + (q_{2i} + \Delta B_i)\right) - L_4 \times \\ \times \cos\begin{pmatrix} q_0 - (q_{1i} + \Delta A_i) + (q_{2i} + \Delta B_i) + \\ + (q_{3i} + \Delta C_i) \end{pmatrix} \end{pmatrix} + s + \Delta o_i,$$

$$\Delta Yd_{i,j} = \sin(\omega_i + \Delta 4_i) \times$$

$$\times \begin{pmatrix} L_1 \cdot \cos q_0 - L_2 \cdot \cos\left(q_0 - (q_{1i} + \Delta A_i)\right) + L_3 \times \\ \times \cos\left(q_0 - (qA_i + \Delta 1_i) + (q_{2i} + \Delta B_i)\right) - L_4 \times \\ \times \cos\left(q_0 - (q_{1i} + \Delta A_i) + (q_{2i} + \cdot B_i) + (q_{3i} + \Delta C_i)\right) \end{pmatrix} + \Delta o_i,$$

$$\Delta Zd_{i,j} = \begin{pmatrix} L_1 \cdot \cos(q_0) - L_2 \cdot \cos\left(q_0 - (q_{1i} + \Delta A_i)\right) + L_3 \times \\ \times \cos\left(q_0 - (q_{1i} + \Delta A_i) + (q_{2i} + \Delta B_i)\right) - L_4 \times \\ \times \cos\begin{pmatrix} q_0 - (q_{1i} + \Delta A_i) + (q_{2i} + \Delta B_i) + \\ + (q_{3i} + \Delta C_i) \end{pmatrix} \end{pmatrix} +$$

$$+ R + \Delta a_i + \Delta b_i + \Delta c_i, \quad (8)$$

where $\Delta a_i = \Delta b_i = \Delta c_i = \Delta o_i = -30 \ldots 30$ μm – range corresponding to bearing backlash.

The total error is calculated by the formula:

$$\Delta_{i,j} = \sqrt{\left(\Delta Xd_{i,j} - Xd_i\right)^2 + \left(\Delta Yd_{i,j} - Yd_i\right)^2 + \left(\Delta Zd_{i,j} - Zd_i\right)^2}. \quad (9)$$

According to the results of the calculation, a set of values of the total deviations for the hinge D for the entire working space of the i-th position was found. According to the histogram (Fig. 10) – the maximum and minimum values are equal to:

$$\Delta_{\max}^i = 0.91 \text{ mm}; \ \Delta_{\min}^i = 3.625 \cdot 10^{-2} \text{ mm}.$$

7. SWOT-analysis of research results

Strengths:

1. Development and application of the latest materials and technologies.

2. The latest approach in designing and finding optimal and effective solutions.

3. Development of competitive production and technologies.

Weaknesses:

1. Lack of own resources.
2. Depreciation of production assets and outdated technologies.
3. Low level of market infrastructure development.

Opportunities:

1. To carry out experimental check of efficiency of application of functionally-oriented element base in spatial systems of drives.
2. Develop recommendations for improving the element base and spatial drive systems.

Threats:

1. Imperfection and instability of the economy and domestic production.
2. Outdated production capacity and technology.
3. Insufficient provision of highly qualified personnel in the field of production.
4. The difficulty of obtaining the latest materials.

8. Conclusions

1. In the given work the modern technologies used in manipulators of ground robotic complexes were investigated, ways on their optimum application are defined. The kinematics of the manipulator is analyzed from the point of view of ensuring high positioning accuracy, in relation to the working space. The practical result of this approach is the ability to select areas in the workspace in which the manipulator has increased accuracy. The publication proposes to perform modeling of the workspace using the Monte Carlo method. The application of this method allowed to optimize the amount of calculations without significant loss of accuracy. This opens up opportunities for further use of the method to study the workspace of mechanisms of complex configuration, in particular the mechanisms of parallel structure.

2. The kinematics of the rotary unit, including the bearing unit and cycloidal transmission, is studied. A feature of the working process of rolling bearings is the presence of working gaps that avoid jamming and do not exceed 60 microns. It is established that the working gaps are one of the limiting factors that limit the accuracy of the manipulator.

3. Kinetostatic analysis of the manipulator was performed. Based on the obtained results, a study of the stress-strain state of the mechanical transmission was performed. The simulation was performed in the Solidworks software package and allowed to determine the corresponding angle of displacement of the links relative to each other by the deformations of the mechanical transmission elements. It is established that in the calculated operating modes its value does not exceed 2.26 angular minutes. The obtained results have a practical application and can be used in the development of the algorithm of the control system, which will allow, depending on the load, to predict the accuracy of the manipulator in real time.

4. As a result of the conducted researches it is established that rigidity of links of the manipulator influences accuracy, however is not a limiting factor. The paper proposes a method for determining the basic geometric dimensions of the links, based on pre-selected optimal values of deformation.

5. According to the developed mathematical model in the Mathcad software complex the integral value of deviation for any position of the manipulator was found. The accuracy of positioning of the output link, which corresponds to a random array of errors, which allows to set the range of change of the integral value of the deviation, is estimated. For the given initial conditions, the range of deviations from the theoretical position is obtained, which is limited from above by the value of 0.91 mm. The method of calculating the integral value of the deviation has a practical application, as it takes into account not only the design of the manipulator, but also the mode of its operation.

The application of the developed mathematical model, which takes into account the features of mechanical processes occurring in the manipulator, allows to increase the technical level of robotic systems and fully use the potential of intelligent control system to ensure maximum accuracy.

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