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DYNAMIC CHARACTERISTICS OF A MOBILE ROBOT MANIPULATOR BUILT ON THE BASIS OF A MECHANISM WITH PARALLEL KINEMATIC COUPLINGS

Розроблена математична модель динамічних характеристик мобільного робота з паралельними кінематичними зв'язками на основі використання теорії нечітких множин. Для динамічної системи платформи введено чотири парціальні динамічні підсистеми. Три з них описують поступальні переміщення платформи у трьох напрямках, а підсистема сферичного руху описує поворотний рух платформи відносно полюса. Динамічні підсистеми штанг змінної довжини враховують розподіленість параметрів штанг по довжині. Проведено математичне моделювання динамічних процесів мобільного робота з паралельної кінематики при одиничних і пакетних імпульсних динамічних збуреннях штанг.

Ключові слова: динамічні характеристики мобільного робота, математичне моделювання

Разработана математическая модель динамических характеристик мобильного робота с параллельными кинематическими связями на основе использования теории нечетких множеств. Для динамической системы платформы введены четыре парциальные динамические подсистемы. Три из них описывают поступательные перемещения платформы в трех направлениях, а подсистема сферического движения описывает поворотное движение платформы относительно полюса. Динамические подсистемы штанг переменной длины учитывают распределенность параметров штанг по длине. Проведено математическое моделирование динамических процессов в роботах параллельной кинематики при единичных и пакетных импульсных динамических возмущениях штанг.

Ключевые слова: динамические характеристики мобильного робота, математическое моделирование

The mathematical model of dynamical characteristics of a mobile robot with parallel kinematic bonds is developed on the basis of the use of the theory of fuzzy sets. For the dynamic system platform, four partial dynamic subsystems are introduced. Three of them describe the translational movement of the platform in three directions, and the subsystem of the spherical motion describes the rotary motion of the platform relative to the pole. Dynamic subsystems of a variable-length rod take into account the distribution of the parameters of the rod in length. The mathematical modeling of dynamic processes in mobile works of parallel kinematics at single and packet pulse dynamic shock disturbances is carried out.

Keywords: dynamical characteristics of a mobile robot, mathematical modeling

Currently robotic equipment is widely developed on the basis of mechanisms with parallel structures. Mobile work of this type has low material capacity and wide functionality. Therefore, work in the field of research of multi-coordinate mobile robots with parallel kinematic structures is relevant.

The problem in general form is to increase the quality of accuracy of multi-coordinate mobile robots.

The problem is related to the important scientific and practical tasks of creating highly efficient robotic complexes of special purpose.

Famous studies and publications [1-3] provide information on the development and use of multi-coordinate mobile robots. It is noted that improvement of qualitative indexes of manipulators can be achieved by applying mechanisms with parallel kinematic bonds [4-6].

As a result of the analysis of literary sources, the design of mobile robots with parallel kinematics requires thorough theoretical and experimental studies [7, 8].

This scientific problem is devoted to a significant number of publications [9-11]. In the main, the authors investigate the laws of kinematics of mobile robots with parallel structures [12, 14].

Mobile work with parallel kinematics works in hard dynamic modes. Therefore, it is especially important to study their dynamic characteristics. Dynamic characteristics of mobile robots are considered in a number of papers [15-18]. In the main they are presented general questions on modeling the movement of the executive body of the mechanism. There are no mathematical models for determining the dynamic properties of mobile robots of this type in the literature.

Unsettled parts of the common problem include the development of a refined mathematical model of a multi-coordinate mobile robot that takes into account the distribution of parameters in a dynamic system and the presence of factors that take into account the unclearly defined hard sleep and dissipative parameters of the dynamic mobile robot system.

The purpose of the research outlined in this article is to develop a mathematical model of structural type intended to study the dynamic properties of multi-coordinate mobile robots, which takes into account the unclear parameters of the dynamic mobile robot system and the mathematical modeling of the parameters of the accuracy of the mobile robot.

The objectives of the research are to construct a structural mathematical model, to develop methods for taking into account the distribution of the parameters of a dynamic system under unclear conditions of mobile robot operation and the implementation of multi-coordinate mobile robot modeling in typical operating modes.

Presentation of the main research material

Multi-coordinate mobile robot with parallel kinematics is a complex spatial dynamic system in which there are complex oscillations (Fig. 1).

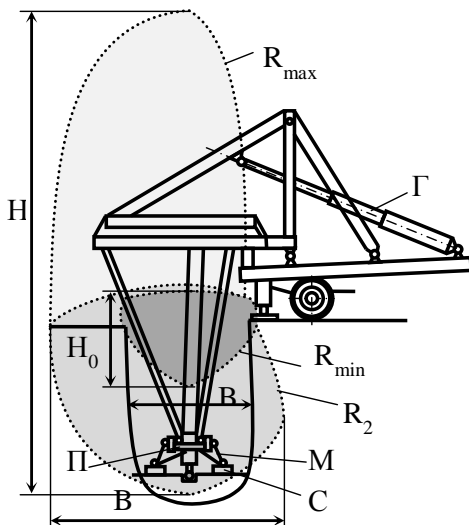


Fig.1 Constructive scheme of multi-coordinate mobile robot of parallel kinematics

The robot has a frame P that changes its position with the help of a hydraulic drive T. On the frame, six rods of variable length S are installed which are pivotally connected to the mobile platform II. On the platform there is a manipulator (catch) of the robot M that interacts with the object of manipulation WITH.

The robot provides the exact movement of the platform within the R_{min} working space. With an increase in the initial length of the bar, the working space increases, extending beyond the boundary of the region R_2 . When the frame R is rotated by the hydraulic drive G, the working space of the robot expands to the region R_{max} .

The mobile robot is implemented as a prototype [19]. To test the performance of the robot developed a special equipment. The frame work with variable-length barbs and a mobile platform is installed on a special support, which has racks 1 and 2 with beams 3 and 4 (fig. 2).

The support has a traverse 5, on which the turning frame of the frame 6 is fixed. The peculiarity of the design of a mobile robot is the presence of malo-rigid rod systems, which connect the platform of a mobile robot with a fixture mounted on it.

The mobile robot platform has six coordinates. It carries forward movements in the directions x, y, z and the transverse angular displacements ψ , θ , φ around the visage coordinates.

Movement of the executive body provides six drives that change the length of the rod 5.

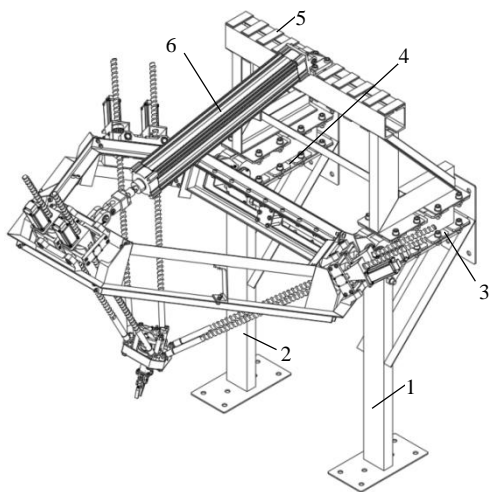


Fig. 2. Installation of a mobile frame of a mobile robot on a special support

The feature of a multi-coordinate mobile robot is the complex spatial movement of individual nodes and parts of the mobile robot.

To determine the basic properties of a dynamic mobile robot system and to construct mathematical models of individual dynamic subsystems, an analysis of the system was performed to determine the characteristics of the movement of individual nodes.

The design scheme of the dynamic system of mobile robot, which unites the platform and the executive body as one solid body, is developed, and the rod of variable length presents in the form of equivalent deformed rods with distributed mass. The equivalent dynamic model of elastic system of robot in the form of a set of elastic bars is offered (Fig. 3).

External force factors in the form of force act on the executive body of the mobile robot.

The working body of the mobile robot has the form of a platform that is located on the supports of the rod. In supports there are supporting reactions that are internal forces of the dynamic system. The executive body of the mobile robot (cheat) has a mass of much less mass of the platform. Therefore, we can assume that the specific inertial loads on the grip and the platform are close and consider the platform and grip of one solid. The rods of the variable length of the mobile robot have a certain stiffness and significant dissipative properties that need to be taken into account when developing a mathematical model of the dynamic processes of mobile robots with parallel kinematics.

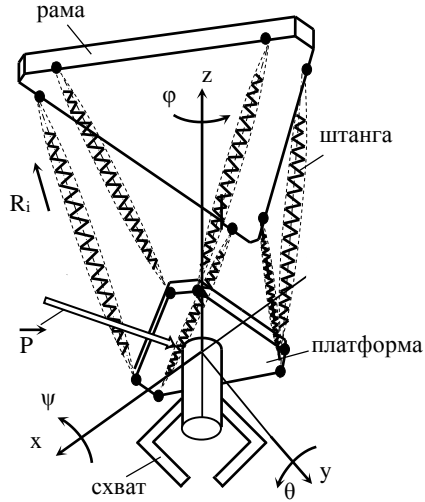


Fig. 3. Equivalent dynamical model of mobile robot of parallel kinematics, which takes into account the distribution of parameters of the rod

Mobile work with parallel kinematics has a complex spatial structure of the dynamic system. Accordingly, in the dynamical system of mobile robot there are various partial dynamic systems.

Partial dynamic systems correspond to the spatial movements of individual mobile robot nodes. The main dynamic nodes are a rod and a platform. The platform moves in space under the action of supporting reactions in the supports of the rod. These power factors are reduced to the main vector and the main moment:

$$\vec{R}_p = \sum_{i=1}^n \vec{R}_i, \quad \vec{M}_p = \sum_{i=1}^n \vec{R}_i \vec{b}_i,$$

where \vec{R}_i – vector of the dynamic reaction of the i -th rod; \vec{b}_i – radius-vector of force action \vec{R}_i relative to the pole; $n=6$ – Number of rods on which the platform is installed. The platform has six degrees of freedom. Therefore, for the description of its dynamics, three partial systems of translatory movement of the platform pole and one partial system of spherical motion of the platform relative to the pole are used (Fig. 4).

According to the proposed dynamic model of the platform a structural mathematical model is developed.

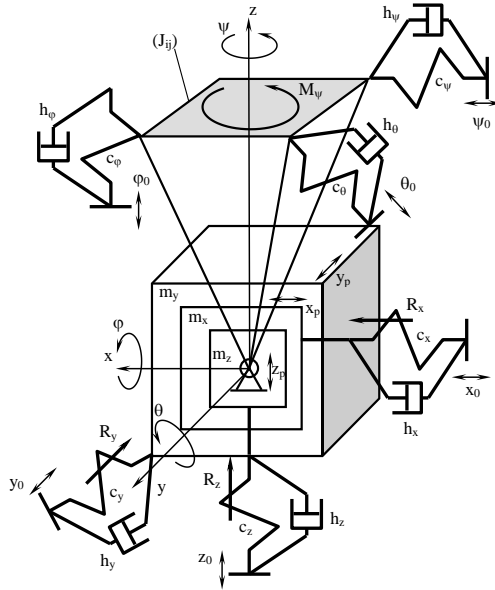


Fig. 4. Partial dynamic systems of translational and spherical motion of the platform

The block diagram of a mathematical model of a dynamic platform of the platform includes a block 1 for the simulation of three components of the partial system of translational platform movement (Fig. 5).

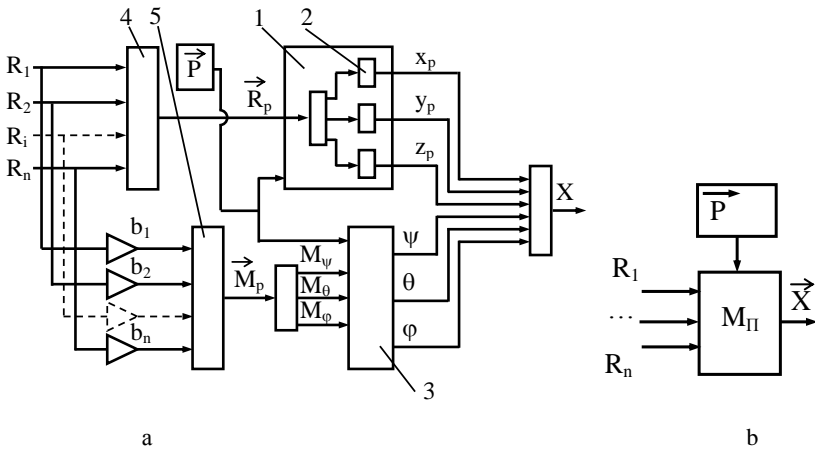


Fig. 5. Structural flowchart of the mathematical model of the dynamic system of spatial displacement of the platform (a) and representation of the model in the form of a block (b)

The components x_p , y_p , z_p the translational movement of the platform is modeled by separate blocks 2, each of which determines the displacement of the center of the masses of the platforms in the corresponding direction. Block 3 simulates the partial system of spherical motion of the platform relative to the pole. Blocks 4 and 5 form respectively the main vector and the main moment that acts from the side of the rod to the platform.

The output of the mathematical model of the dynamic system of the platform is a six-dimensional vector position of the platform.

The inputs of the dynamic system of the platform are the vectors of the supporting forces of the rod $R_1..R_n$ and the loading vector.

As blocks 1.2, known mathematical models are used [19]. Known mathematical models are tested at calculations in order to confirm their adequacy.

General characteristics of the dynamical accuracy of the mechanism determine the dynamic properties of the rod. The bars correspond to separate partial systems that determine the specific, dynamic processes that accompany their displacement. The essential output parameters for the dynamical systems of the barb is the movement of joints. Therefore, for each rod allocated partial dynamic systems describing the longitudinal displacement of the rod, taking into account the distribution of their parameters (Fig. 6).

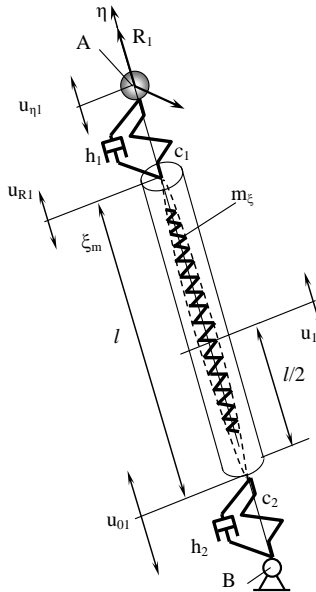


Fig. 6 Dynamic model of longitudinal displacement of a rod, taking into account the distribution of its parameters

Let's assume that the bar of length l represents a quasi-homogeneous rod with a mass distributed in length.

We will assume that the ends of the rod carry out harmonious movements by law:

$$u_{R1} = u_{aR} \sin(\omega_1 t), \quad u_{01} = u_{a0} \sin(\omega_2 t + \psi_0), \quad (1)$$

where u_{aR} , u_{a0} - the amplitudes of harmonic displacements; ω_1 , ω_2 - circular frequencies of harmonic displacements of boundary bar cross sections; ψ_0 - the phase difference of the harmonic displacements of the ends of the bar.

Let's assume that the ends of the bar are firmly fixed in the supports. Accordingly, the parts and forms of oscillation are determined in the form [8]:

$$p_i = \frac{i\pi a}{l}, \quad a = \sqrt{\frac{E}{\rho}}, \quad X_i = \sqrt{\frac{2}{l}} \sin\left(\frac{P_i x}{a}\right), \quad i = 1, 2, \dots, \infty, \quad (2)$$

where l – rod length; i – shape number of oscillations; E – An equivalent modulus of elasticity of the rod; ρ - Seamless weight of the rod; a - equivalent sound speed in a rod. An equivalent modulus of elasticity is found by experimentally measuring the stiffness of the rod. The loading of the rod by the longitudinal force F_k was carried out and the relative displacement of the ends of the rod was measured. Rigidity was the ratio of the increase in force to the increase in displacement by the formula:

$$C_k = \frac{\Delta F_k}{\Delta l_k}. \quad (3)$$

Measurements are made at variable loads under different values of force and, accordingly, displacement. It is established that the value of stiffness essentially depends on the amplitude of loads (deformations). At low amplitudes of alternating loads, the stiffness of the rod decreases. This is due to the selection of backlashes and gaps in the kinematic chain. Increasing the load amplitude leads to increased stiffness. Results of rigidity measurements subject to statistical processing. The histograms of the relative frequency of rigidity measurements of this value are constructed. For this purpose, the measured values of rigidity are broken down into discharges and a calculation of the number of measurements that fall into each discharge is made. The number of values of measurements that fall into the category with the maximum number of values of measurements is taken as the norm. Relative number of measurements in each level N is established relative to it.

The measurements of rigidity at different amplitudes are grouped into separate histograms N_m and N_a (Fig. 7).

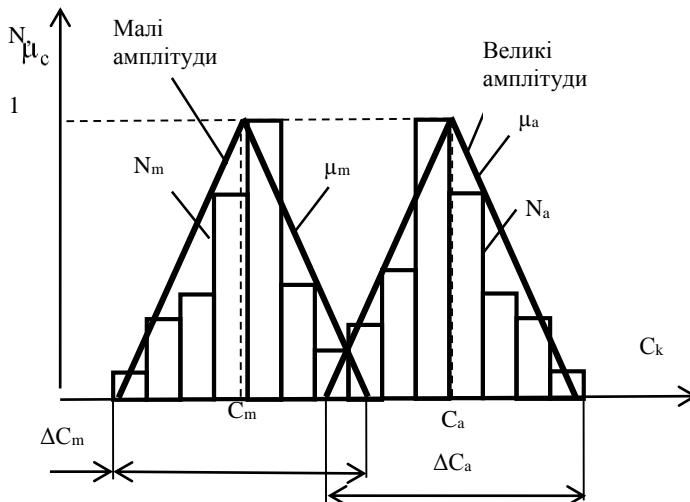


Fig. 7. Experimentally determined values of the equivalent stiffness of the rod, presented in the form of histograms and corresponding functions of the membership of fuzzy sets describing the equivalent stiffness of the rod

As a result of experimental measurements, it was established that histograms are close to triangular graphs with maxima corresponding to the mean values of stiffness C_m and C_a and width ΔC_m and ΔC_a .

Triangular functions μ_m and μ_a have been introduced to describe the histograms, which are interpreted as characteristic features of fuzzy (blurred) sets [20], which describe the characteristics of rod stiffness. For small amplitudes of oscillations, stiffness is determined by the function μ_m , and for large amplitudes, by the function μ_a .

On the basis of measured rigidity values the current values of the equivalent elastic modulus are determined. Dependence is used for this purpose:

$$E = C_k \frac{l}{s_e}, \quad (4)$$

where l - rod length; s_e - equivalent to the cross-sectional area of the rod; C_k - the value of the current stiffness of the rod, which is determined taking into account the value of the amplitude of the oscillation of the rod in accordance with the value of the characteristic function μ_m і μ_a .

Assume the characteristic movement of a rod in its middle part at $x = \frac{l}{2}$.

Characteristic displacement of the rod as a system with distributed parameters is determined by the next [19]:

$$u_1 = \left[\frac{1}{2} + \frac{2l^2}{\pi^3 a^2} \sum_{i=1}^{\infty} \frac{\sin\left(\frac{i\pi}{2}\right)}{i^3} \cdot \frac{\omega_1^2}{\left(1 - \frac{\omega_1^2}{p_i^2}\right)} \right] u_{aR} \sin(\omega_1 t) + \left[\frac{1}{2} - \frac{2l^2}{\pi^3 a^2} \sum_{i=1}^{\infty} \frac{(-1)^i \sin\left(\frac{i\pi}{2}\right)}{i^3} \cdot \frac{\omega_2^2}{\left(1 - \frac{\omega_2^2}{p_i^2}\right)} \right] u_{a0} \sin(\omega_2 t + \psi_0), \quad (5)$$

where the parameters of formula (5) are determined by the dependences (1) - (4).

Formula (5) defines polarharmonic displacements of a characteristic mid-section of a rod at sinusoidal displacements of its ends. Expressions in square brackets represent the amplitude-frequency characteristics of the dynamical rod system with two sinusoidal inputs in the form of moving its ends. These frequency characteristics are frequency functions in the form of infinite series:

$$W_1(\omega) = \frac{1}{2} + \sum_{i=1}^{\infty} K_{1i} \frac{\omega^2}{(-T_i^2 \omega^2 + 1)}, \quad W_2(\omega) = \frac{1}{2} - \sum_{i=1}^{\infty} K_{2i} \frac{\omega^2}{(-T_i^2 \omega^2 + 1)}. \quad (6)$$

where:

$$K_{1i} = \frac{2l^2}{\pi^3 a^2} \frac{\sin\left(\frac{i\pi}{2}\right)}{i^3}, \quad K_{2i} = \frac{2l^2(-1)}{\pi^3 a^2} \frac{\sin\left(\frac{i\pi}{2}\right)}{i^3}, \quad T_i = \frac{1}{p_i}. \quad (7)$$

The coefficients defined by formula (7) are fuzzy sets defined according to the dependences (2), (4).

Frequency characteristics (6) include only the square of the frequency. Therefore, they correspond to the transmission functions of the form:

$$W_1(s) = \frac{1}{2} + \sum_{i=1}^{\infty} \frac{K_{1i}s^2}{T_i^2s^2 + 1}, \quad W_2(s) = \frac{1}{2} - \sum_{i=1}^{\infty} \frac{K_{2i}s^2}{T_i^2s^2 + 1}, \quad (8)$$

where s is Laplace's operator.

These transmission functions represent an infinite number of parallel chains, each of which has two sequentially connected differentiation links and one conservative link [21]. The presence of a conservative link does not correspond to the physical nature of the problem, namely the presence of a process of energy dissipation in the dynamic system of the rod. Therefore, in transmitting functions, conservative links are replaced by oscillations [21] and accordingly obtained:

$$W_1(s) = \frac{1}{2} + \sum_{i=1}^{\infty} \frac{K_{1i}s^2}{T_i^2s^2 + 2\xi_i T_i s + 1}, \quad W_2(s) = \frac{1}{2} - \sum_{i=1}^{\infty} \frac{K_{2i}s^2}{T_i^2s^2 + 2\xi_i T_i s + 1}, \quad (9)$$

where ξ_{li} - a set of attenuation parameters that determine the dissipative characteristics of the rod.

As a result of experimental measurements of the proper oscillation of the rod, it is found that the damping parameters are insignificant and make up $\xi_i = 0.01..0.001$.

Taking into account the received transfer functions, the connection of the dynamic perturbations of the bar in the middle section and displacement of its ends is established:

$$u_{R1}(s) = [u_1(s) - W_2(s)u_{01}(s)] / W_1(s). \quad (10)$$

Accordingly, the reaction of the first rod:

$$R_1(s) = [u_{R1}(s) - \eta_1(s)](c_1 + h_1s), \quad (11)$$

where $\eta_1(s)$ - the movement of the platform in the direction of the axis of the rod, which is determined by the vector X coordinates; c_1 та b_1 - the stiffness and the resistance coefficient of the hinged fixing of the rod on the platform.

The movement of the platform in the direction of the axis of the bar is uniquely determined by the vector x coordinates of the platform in the form of linear dependence:

$$\eta_1(s) = \sum_{j=1}^6 \alpha_{1j} \cdot x_j. \quad (12)$$

The combination of relations (10) - (12) is carried out in a special block of the mathematical model (Fig. 8).

The inputs of the block are the coordinate vector of the platform X , the dynamic disturbance in the drive of the first bar u_1 and the dynamic perturbation (vibration) of the base u_{01} in the place of fixing the first rod.

To calculate the uncertain stiffness of the rod C_k is a special block of the model, which implements the dependence (4) in accordance with the experimental values (see Fig. 4), taking into account the amplitude of displacements of the upper joint hinge [23].

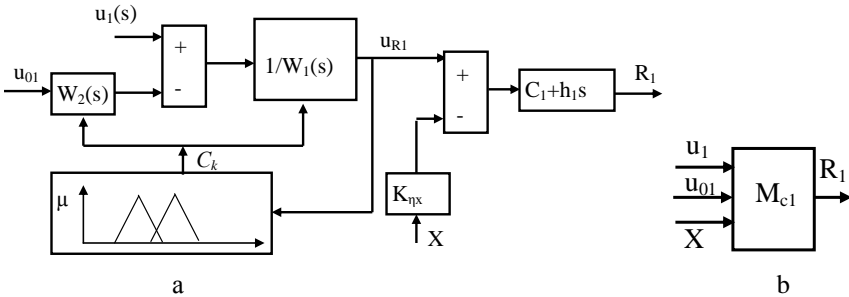


Fig. 8. Structural model is designed to calculate the reaction of the rod (a) and the presentation of this model in the form of block (b)

The mathematical model of the platform and the bar is combined into one general structural mathematical model (Fig. 9).

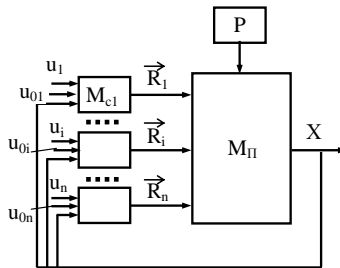


Fig. 9. Block diagram of a general mathematical model of a mechanism with parallel kinematics

The output of the mathematical model is the coordinate vector of the platform X , the inputs of the control signals of the drives of individual rods u_i and the vibration of the base u_{0i} .

The mathematical modeling of the platform movement under the influence of impulse loads u_i in the drives of each separate rod is fulfilled. As a result of the calculations, it was found that when the pulse loads of the rod the platform carries a complex oscillatory motion. In the plane of the platform, this motion corresponds

to a spiral trajectory, which is localized in the elliptical region and fades with time (Fig. 10).

The parity of the elliptical parasites is 1,4 ... 1,7. The rails x_1 and y_1 correspond to the main axes of the rigidity of the elastic platform system. On the trajectory of movement of the platform there are loops similar areas 1, 2, 3. They correspond to the first basic frequency of oscillations of the bar with time fade.

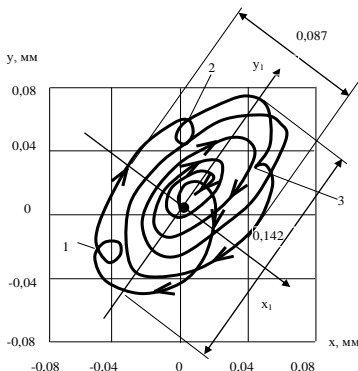


Fig. 10. Estimated trajectory of moving the center of the platform of a multi-coordinate mobile robot with impulse perturbation in the first rod

Sequential packet pulse disturbances in all mobile robot rods change the trajectory of moving the platform in the haw plane.

On the trajectory are traced to evil, corresponding to the presence of perturbations (Fig. 11).

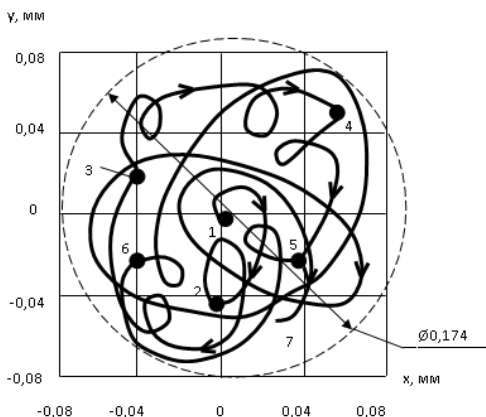


Fig.11. Trajectory of moving the pole of the platform with sequential pulse disturbances in all mobile robot rods

Evil occurs at points 1, .. 6, which correspond to the time of impulse (shock) loads in rods 1-6.

Consecutive pulsed loads complicate the movement of the platform. The trajectory is within the area close to the circle. On the trajectory, loop-like areas can be traced, similar to their own oscillations of individual rods. Subsequently (point 7 and further), the trajectory of the platform moves to a fading elliptic spiral, which ends at point 1.

Conclusions

1. It has been established that for mathematical modeling of the dynamics of spatial motion of a mobile robot platform, it is necessary to allocate four partial dynamic subsystems of the platform. Three of them determine the translational motion of the platform pole in three directions, and the fourth corresponds to the spherical motion relative to the pole. Six additional partial dynamic rotor systems take into account the distribution of the rod parameters at their longitudinal and transverse vibrations.

2. To describe the dynamical processes of a moving rod, it is expedient to use a mathematical model of an equivalent beam with a mass distributed in length. The elastic properties of the rod depend on the amplitude of the oscillations and represent a fuzzy set, which has two triangular functions of belonging, corresponding to small and large amplitudes of oscillations. At the same time, the stiffness of the rod at small amplitudes is $2 \cdot 3$ times lower than the stiffness at large amplitudes of oscillations.

3. The mathematical model of a mobile robot with parallel kinematics is structurally-blocked, with the blocks corresponding to the partial dynamic systems of the bar and platform, and the connections between the blocks, including feedback, lock the model, determining the spatial position of the platform, depending on the force factors that act on individual mobile robot nodes, in particular depending on impulse disturbances in drive changes in the length of the mobile robot rod.

4. As a result of mathematical modeling, it has been established that forced oscillations of the platform of a multi-coordinate mobile robot with unit pulse disturbances in one of the bars take place in a definite direction, which corresponds to the axis of the minimum stiffness of the elastic system of the mobile robot. At the same time, the velocity of oscillations in the direction of the axle of maximum stiffness is 0.6-0.7 times smaller than in the direction of the axle of minimum rigidity. In sequential packet pulse disturbances, in all rods of a mobile robot, the specified directions are leveled and the platform pole moves within a circular area with its successive decrease to zero.

5. As a direction of further research, it is recommended to clarify the structural mathematical model and its testing by comparing the results of modeling with experimental data.

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