A dynamic algorithm for stabilization of the working body of a mobile robot weeding for the future of agriculture

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Abstract. The article considers the development of a control algorithm for the actuating links of a manipulator with a parallel-serial structure. The authors suggest a two-stage procedure for resolving the problem of controlling the robot operating body motion into a set neighborhood of the final state for a set time. The first stage covers the process of solving the problem of defining the manipulator generalized coordinates at the set coordinates of the operating body. Then the problem of determining the laws of the formation of reference influences for the actuators is solved, which ensures the movement of the working body in the vicinity of a given point. The technique for the synthesis of dynamic algorithms for stabilizing the effector relative to a given position and implementing the program paths is based on generating the control signals of actuators by solving the inverse dynamic problem using a control signal generation algorithm provided that deviations from the current program path values are the solutions of a second-order differential equation. The laws of change in control voltages are obtained. The results of numerical modeling are presented, confirming the efficiency of the proposed algorithm on the example of a specific manipulator.

1. Introduction

When cultivating vegetables and cucurbits, one of the time-consuming and energy-consuming tillage operations is weeding [1, 2], commonly carried out by cultivation. The effectiveness of mechanical weed control largely depends on the weeding quality. Manual weeding is still practiced for raising vegetables and cucurbits in open ground. This is also explained by the fact that in case of the mechanical destruction of weeds the operating bodies of the cultivator (“arms”) process only the aisles. To solve the problem of complete weeding, both in row spacings and in rows, a weeding robot was developed (Figure 1) for the target weeding.

The weeding robot consists of a frame 1, steered wheels 2, a control and navigation system with instrumentation 3, a power supply system 4 and a computer vision sensor 7 [3].

The motion mechanism of the operating body of the weeding robot (Figure 2) is a flat mechanism of a parallel-serial structure with three degrees of freedom [4]. To move the operating body 8 in the horizontal plane, three linear actuators 5 are used, and the linear actuator 6 is used to move the operating body in a vertical plane. The operating body is rotated by means of the electric motor 9.
The robot operates as follows. With the help of the control and navigation system, the weeding robot enters the plant beds. In automatic mode, using a computer vision system, the coordinates of the location of weeds in a row are determined. The cutting tool of the implement moves to the weed. When the implement cutter is above the weed, the linear drive moves the implement vertically downward, which cuts the weed and loosens the soil next to it.

The sensor system consists of two main components: one is rigidly attached to actuators, and the second, which performs most of the functions of global navigation and spatial orientation, as well as computer vision, is connected to the top-level control unit.

The feedback on the running drives implements odometric navigation, and the feedback of the actuators provides accurate positioning of the manipulator. The global navigation system includes a GPS receiver, the data from which are combined with the readings of odometric sensors on wheels.

1.1 Problem statement

For the implementation of the described technology, it is necessary to develop algorithms for the formation of a system to control the motion of the weeding robot operating body. The control system must set the motion of the operating body to a given point in the operating area with a required accuracy. The motion of the manipulator in the horizontal plane is considered. The generalized manipulator coordinates are the lengths of the actuating links \( q_i = l_i(t) \), \( q_2 = l_2(t) \), \( q_3 = l_3(t) \). The motion of the operating body from a known initial position with coordinates \( (x_{0\text{out}}, y_{0\text{out}}) \) to a predetermined final position \( (x_{\text{fin}}, y_{\text{fin}}) \) is provided by changing the lengths \( l_i(t), (i = 1 + 3) \) of the manipulator actuating links. The problem is solved in two stages. First, the positioning problem is solved: for the given final coordinates \( (x_{\text{fin}}, y_{\text{fin}}) \) of the attachment point of the vertical actuator (Figure 2), it is required to obtain the generalized coordinates of the manipulator \( l^{\text{in}}, (i = 1 + 3) \). Since the number of the Cartesian coordinates of the actuator attachment point is two, and the number of generalized coordinates of the manipulator is three, the maneuverability of the manipulator is one \([5]\). That is, the final position of the actuator with the operating body corresponds to an infinite number of manipulator configurations. Thus, the solution of this problem is of an optimization nature.

At the second stage, it is necessary to determine the laws of change in the control signals \( u_i(t), (i = 1 + 3) \) of DC drive motors when moving the attachment point of the working body from the
initial to the vicinity of the designated point. Acceleration of change of generalized coordinates is taken as controlled parameters $\ddot{l}_i(t)$, $(i = 1 \div 3)$.

2. Materials and methods

2.1. Manipulator positioning

The design of the manipulator stipulates for the holonomic constraints between the coordinates of the point $O_i(x_i, y_i)$, the lengths of the actuating links and the manipulator geometric parameters

$$l_2 = \sqrt{(y_i - l_i)^2 + (AC + x_i)^2}, \quad l_3 = \sqrt{(y_i - l_i)^2 + (BC - x_i)^2}$$

(1)

The configuration of the manipulator is determined from the minimum condition of the quadratic function - the criterion of generalized energy [6]

$$\Phi = \sum_{i=1}^{3} c_i \cdot (l_{ik} - l_{i0})^2$$

with inequality constraints

$$l_{i\min} \leq l_{i}^{op} \leq l_{i\max},$$

(2)

where $c_1, c_2, c_3$ are weighting factors, the values of which are proportional to the loads on the actuating links; $l_{i\min}, l_{i\max}$ are the minimum and maximum permissible values of the lengths of the manipulator actuating links (Figure 2); $l_{i}^{op}$ is an optimal length.

The Lagrange objective function has the form [7]

$$\Phi^* = \sum_{i=1}^{3} c_i (l_{ik} - l_{i0})^2 + \lambda_{2i-1} (\varphi_{2i-1}^2 + l_{i} - l_{2i-1,\max}) + \lambda_{2i} (\varphi_{2i}^2 + l_{i\min} - l_{i}),$$

(3)

where $\varphi_i$ - are auxiliary functions; $\lambda_i$ - are Lagrange multipliers.

The necessary conditions for the extremum of function (3) are written in the form

$$\frac{\partial \Phi^*}{\partial l_i} = c_i \frac{\partial (l_{ik} - l_{i0})^2}{\partial l_i} + c_2 \frac{\partial (l_{2i} - l_{i0})^2}{\partial l_i} + c_3 \frac{\partial (l_{3i} - l_{i0})^2}{\partial l_i} + \lambda_{2i} - \lambda_{2i-1} = 0,$$

(4)

$$\begin{align*}
\lambda_{2i-1} &= 0, \text{ if } l_{i}^{op} < l_{i\max}, \lambda_{2i} = 0, \text{ if } l_{i}^{op} < l_{i\min}, \\
\lambda_{2i} &> 0, \text{ if } l_{i}^{op} = l_{i\max}, \lambda_{2i-1} > 0, \text{ if } l_{i}^{op} = l_{i\min}
\end{align*}$$

(5)

Since the Lagrange function (3) is convex, and the multipliers $\lambda_{2i-1} \geq 0, \lambda_{2i} \geq 0$, the necessary conditions (4), (5) are sufficient.

2.2. Stabilization of the manipulator given position

Since the manipulator has great rigidity, the Cartesian coordinates of the actuator attachment points with the operating body are determined through the lengths of the actuating links with a high accuracy [8]

$$x_4 = \frac{l_2^2 - l_4^2}{4AC}, \quad y_4 = l_1 + \sqrt{l_2^2 - \left(\frac{l_3^2 - l_2^2}{4AC}\right)^2 + \frac{l_2^2 - l_4^2}{2}} - AC^2$$

(6)
Below is a method for synthesizing a control system algorithm for the laws of change in the lengths of executive links.

The requirements for control accuracy are set only to the end point, without imposing restrictions on the path of the characteristic point, which may change during the motion of the operating body due to external disturbances. In this case, the solution of the problem is reduced to determining the laws of formation of the setting actions $u_i(t)$ for the executive drives, ensuring the motion of the operating body in the neighborhood of a given point on the plane to which the lengths of the actuating links $l_i(t) = l_{i\text{op}}$, $i = 1 - 3$ correspond. Assume that on the motion path the deviations from the final state of the actuating links $\Delta l_i(t) = l_{i\text{op}} - l_i(t)$ change in accordance with the solution of the differential equation

$$\Delta \ddot{l}_i(t) + a_{i1}\Delta \dot{l}_i(t) + a_{i2}\Delta l_i(t) = 0,$$

(7)

where $a_{i1}, a_{i2}$ are constant positive numbers.

The following differential equations correspond to the laws of the formation of the setting actions $l_k(t)$ of the actuators determined by equations (7)

$$\ddot{l}_i(t) + a_{i1}\dot{l}_i(t) + a_{i2}l_i(t) = a_{i2}l_{i\text{op}},$$

(8)

under the initial conditions describing the manipulator state at $t_0 = 0$

$$l_i(0) = l_{i0}, \quad \dot{l}_i(0) = \dot{l}_{i0}.$$  

(9)

A general solution for the equation (8) is a total of a general solution for the homogeneous equation and a partial solution of a heterogeneous equation; it has the form

$$l_i(t) = C_{i1}e^{p_{i1}t} + C_{i2}e^{p_{i2}t} + l_{i\text{op}},$$

(10)

where the roots $p_{i1}, p_{i2}$ are the roots of the corresponding characteristic homogeneous equation.

The integration constants are obtained from (8), taking into account (9)

$$C_{i1} = \frac{\Delta l_i(0)p_{i2} + \dot{l}_{i0}}{(p_{i1} - p_{i2})}, \quad C_{i2} = -\frac{\Delta l_i(0)p_{i1} + \dot{l}_{i0}}{(p_{i1} - p_{i2})}, \quad \Delta l_i(0) = l_{i\text{op}} - l_i(0),$$

(11)

The coefficients of equations (8) are determined using the roots of the characteristic equation

$$a_{i1} = -(p_{i1} + p_{i2}), \quad a_{i2} = p_{i1}p_{i2}.$$

To satisfy the requirement $l_i(t) \rightarrow l_{i\text{op}}$ for $t \rightarrow \infty$, the difference of the characteristic equation roots is negative.

The law of changing the lengths of the actuating links (10) is programmed. To construct a feedback control law, it is necessary to calculate the required acceleration from the current values of the generalized coordinates

$$\ddot{l}_i(t) = a_{i2}l_{i\text{op}} - a_{i1}\dot{l}_i(t) - a_{i2}l_i(t),$$

(12)

Thus, in the expressions (11), it is necessary to consider the current values of the generalized coordinates as initial.
3. Results and discussion

3.1. Complete model of manipulator dynamics

The generalized coordinates of the manipulator are the lengths of the executive links \( q_1 = l_1, \ q_2 = l_2, \ q_3 = l_3 \), and the angles of rotation of the executive links relative to the movable coordinate axes \( \alpha_1 = \alpha_2, \ \alpha_3 = \alpha_4, \ \alpha_5 = \alpha_6 \). The three coordinates are independent. The coordinates \( q_1 = l_1, \ q_2 = l_2, \ q_3 = l_3 \) are superimposed with holonomic connections.

\[
\begin{align*}
F_1 &= l_1 \cdot \cos \alpha_2 - l_2 \cdot \cos \alpha_3 - AB = 0 \\
F_2 &= l_2 \cdot \sin \alpha_2 - l_3 \cdot \sin \alpha_3 = 0
\end{align*}
\] (13) (14)

We assume that the mechanism of movement of the working body consists of seven masses: the mass of the rod of the first executive link together with the mass of the slider \( m_1 \); two bodies of actuators weighing \( m_{21}, m_{31} \); two rods weighing \( m_{22}, m_{32} \); the mass of the articulated slider \( m_4 \) together with the working body and the mass of the slider \( m_5 \).

Since the weeding robot is a multi-mass mechanism, the dynamics of its movements is described by a system of nonlinear differential equations, which are formed using the Lagrange equations with indeterminate multipliers with additional holonomic connections [9].

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} = \lambda_i \frac{df_1}{dq_i} + \lambda_2 \frac{df_2}{dq_i}, \quad i = 1 \div 5
\] (15)

The total kinetic energy \( T \) of the manipulator has the form

\[
T = T_1 + T_2 + T_3 + T_4 + T_5
\]

where \( T_1 \) - kinetic energy of the 1st link; \( T_2 \) - total kinetic energy of the 2nd link; \( T_3 \) - total kinetic energy of the 3rd link; \( T_4 \) - kinetic energy of the 4th link; \( T_5 \) - kinetic energy of the 5th link.

The first link of the mechanism performs a rectilinear forward movement. The bodies of the second and third actuators perform complex movements: portable translational and relative rotational around a fixed axis. The rods of these actuators also perform complex movements: portable translational and relative plane-parallel movement. The movement of the articulated slider with a mass of \( m_4 \) consists of the sum of translational movements, and the slider with a mass of \( m_5 \) performs a translational movement.

Using expressions for kinetic energy and equations of holonomic constraints (13, 14), from (15) we obtain five differential equations describing the dynamics of the robot weeding mechanism.

\[
\begin{align*}
F_1 &= M \tilde{l}_1 + (m_{22} + m_4 + m_3) \tilde{l}_2 \cdot \sin \alpha_2 + m_{32} \tilde{l}_3 \cdot \sin \alpha_3 + \tilde{\alpha}_2 \left[ (m_{22} + m_4 + m_3) l_2 + 0.5 (m_{21} - m_{22}) l_{2\text{min}} \right] \cos \alpha_2 + \\
&\quad + \tilde{\alpha}_3 \left[ m_{32} l_2 + 0.5 (m_{31} - m_{32}) l_{3\text{min}} \right] \cos \alpha_3 + (m_{22} + m_4 + m_3) \cdot (2 \tilde{l}_2 \cdot \cos \alpha_2 \cdot \alpha_2 - l_2 \cdot \sin \alpha_2 \cdot \tilde{\alpha}_2) + \\
&\quad + m_3 \left( 2 \tilde{l}_2 \cdot \cos \alpha_1 \cdot \alpha_1 - l_3 \cdot \sin \alpha_1 \cdot \tilde{\alpha}_3 \right) - \\
&\quad - 0.5 (m_{21} - m_{22}) l_{2\text{min}} \sin \alpha_2 \cdot \tilde{\alpha}_2^2 - 0.5 (m_{31} - m_{32}) l_{3\text{min}} \sin \alpha_1 \cdot \tilde{\alpha}_3^2,
\end{align*}
\] (16)

\[
M = (m_1 + m_{21} + m_{22} + m_{31} + m_{32} + m_4 + m_5),
\]

\[
\begin{align*}
(m_{22} + m_4) \left( \tilde{l}_2 \cdot \sin \alpha_2 - m_{22} \cdot \tilde{\alpha}_2^2 \left( l_2 - \frac{l_{2\text{min}}}{2} \right) - m_4 \cdot l_2 \cdot \tilde{\alpha}_2^2 + m_5 \cdot \sin \alpha_2 \cdot (2l_2 \alpha_2 \cos \alpha_2 - \\
&\quad - l_2 \cdot \sin \alpha_2 \cdot \tilde{\alpha}_2^2 + \tilde{l}_2 \cdot \sin \alpha_2 + l_2 \cdot \cos \alpha_2 \cdot \tilde{\alpha}_2) \right) = F_2 + \lambda_1 \cdot \cos \alpha_2 + \lambda_2 \cdot \sin \alpha_2,
\end{align*}
\] (17)
\[ m_{32} \left( \dddot{l}_3 + \ddot{l}_3 \cdot \sin \alpha_3 - \dddot{\alpha}_3 \left( \ddot{l}_3 - \frac{l_{3\text{min}}}{2} \right) \right) = F_3 - \lambda_1 \cdot \cos \alpha_3 - \lambda_2 \cdot \sin \alpha_3, \quad (18) \]
\[ m_{22} \left( \dddot{l}_2 - \frac{l_{2\text{min}}}{2} \right) \left[ \dddot{\alpha}_2 \left( \ddot{l}_2 - \frac{l_{2\text{min}}}{2} \right) + \dddot{l}_2 \cdot \cos \alpha_2 + 2\ddot{l}_2 \cdot \dot{\alpha}_2 \right] + \dddot{\alpha}_2 \left( I_{z21} + I_{z22} \right) + m_4 \left( \dot{l}_2^2 \cdot \dddot{\alpha}_2 + 2\dot{l}_2 \cdot \dddot{\alpha}_2 + \ddot{l}_2 \cdot \dddot{\alpha}_2 \right) \]
\[ + 2 \cdot \dot{l}_2 \cdot \dddot{\alpha}_2 + \dddot{l}_2 \cdot \cos \alpha_2 \right] + m_{32} \left( \dddot{l}_2 - \frac{l_{2\text{min}}}{2} \right) \left[ \dddot{\alpha}_2 \left( \ddot{l}_2 - \frac{l_{2\text{min}}}{2} \right) + \dddot{l}_2 \cdot \cos \alpha_2 + 2\ddot{l}_2 \cdot \dot{\alpha}_2 \right] + \dddot{\alpha}_2 \left( I_{z31} + I_{z32} \right) + m_5 \cdot \dddot{l}_2 \cdot \cos \alpha_2 = \lambda_1 \cdot \dddot{l}_2 \cdot \sin \alpha_2 + \lambda_2 \cdot \dddot{l}_2 \cdot \cos \alpha_2, \quad (19) \]

Expressing the indefinite factors \( \lambda_1(q_1, \dot{q}_1, \ddot{q}_1) \) and \( \lambda_2(q_2, \dot{q}_2, \ddot{q}_2) \) from equations (19), (20)

\[ \lambda_1 = \dddot{l}_1 \cdot \cos \alpha_2 \cdot \cos \alpha_3 \left[ \dddot{l}_1 \cdot \sin \left( \alpha_1 - \alpha_2 \right) \right] + \dddot{\alpha}_2 \left( I_{z31} + I_{z32} \right) + \frac{1}{l_1} \dot{l}_1 \cdot \sin \left( \alpha_1 - \alpha_2 \right) \]
\[ + \frac{1}{l_1} \dddot{l}_1 \cdot \cos \alpha_2 \cdot \cos \alpha_3 \left( I_{z31} + I_{z32} - l_{1\text{min}} \cdot m_{22} + 0.25l_{3\text{min}}^2 \cos \alpha_2 + 0.25l_{3\text{min}}^2 \cos \alpha_3 \right) \]
\[ + \frac{1}{l_1} \dddot{l}_1 \cdot \cos \alpha_2 \cdot \cos \alpha_3 \left( I_{z31} + l_{2\text{min}} \cdot m_{32} + 0.25l_{3\text{min}}^2 \cos \alpha_2 + 0.25l_{3\text{min}}^2 \cos \alpha_3 \right) \]

where: \( \alpha_2, \alpha_3 \) - angles of rotation of actuators 2 and 3 relative to the mounting axis; \( l_{1\text{min}}, l_{2\text{min}} \) - minimum actuator lengths; \( l_2, l_3 \) - current actuator lengths; \( I_{z21}, I_{z31} \) - the main central moments of inertia of the masses of the 2 and 3 housing of the actuators; \( I_{z22}, I_{z32} \) - the main central moments of inertia of masses 2 and 3 of the actuator rods; \( F_1, F_2, F_3 \) - forces required to perform programmed movement; \( \lambda_1, \lambda_2 \) - Lagrange multipliers.

With the known laws of displacement of the working body of the manipulator \( l_i(t) \), from expressions (13, 14, 16-20), the driving forces \( F_i(t) \), \( i = 1 \ldots 3 \) are found, which ensure the execution of the programmed movement, as well as the values of dynamic loads in kinematic pairs.

The solution to this problem is associated with the integration of differential equations. However, due to the inertia of the mechanisms of the gearbox and the ball screw pair of actuators, the actual displacements may differ from the specified.

To form the control forces of the executive drives of the weeding robot, we use the acceleration control algorithm. The control circuits of the executive motors are synthesized in the process of constructing the control algorithm. The synthesis of the stabilization algorithm is formed according to the equations of the dynamics of the manipulator (16-20).
\[ \lambda_2 = \frac{l}{l} \left[ l \cos \alpha_2 \sin^2 \alpha_2 \left( 2l \left( m_1 + m_2 + m_{22} \right) + l_{2mm} \left( m_{11} - m_{22} \right) \right) + 0.5l \sin 2\alpha_2 \sin \alpha_2 \left( l_{2mm} \left( m_{11} - m_{12} \right) + 2l, m_{22} \right) \right] + \]
\[ \frac{l \cos \alpha_2 \cos (\alpha_2 - 2\alpha_2)}{l} + \]
\[ \frac{l \cos \alpha_2 \sin 2\alpha_2 + 2\alpha_2 l \sin \alpha_2}{l} + \]
\[ \frac{l \cos \alpha_2 \cos (\alpha_2 - 2\alpha_2)}{l} + \]
\[ \frac{2\alpha_2 l \sin \alpha_2}{l} \left[ l_{21} + l_{22} + l_2 \left( m_1 + m_2 + m_3 \cos^2 \alpha_2 \right) + 0.25l_{2mm} \left( m_{11} + m_{22} \right) - l_2 \left( m_{11} + m_{12} \right) \right] + \]
\[ \frac{l \cos \alpha_2 \cos (\alpha_2 - 2\alpha_2)}{l} + \]
\[ \frac{2\alpha_2 l \sin \alpha_2}{l} \left[ l_{21} + l_{22} + l_2 \left( m_1 + m_2 + m_3 \cos^2 \alpha_2 \right) - 0.5l_{2mm} \left( m_{11} + m_{12} \right) \right] + \]
\[ \frac{l \cos \alpha_2 \cos (\alpha_2 - 2\alpha_2)}{l} + \]
\[ \frac{4\alpha_2 l \sin \alpha_2}{l} \left[ l_2 \left( m_1 + m_2 + m_3 \cos^2 \alpha_2 \right) - 0.5l_{2mm} \left( m_{11} + m_{12} \right) \right] + 2l_3 \sin \alpha_2 \sin \alpha_2 \left( 2l_1 - l_{2mm} \right) - \alpha_2^2 l_3 \sin \alpha_2 \sin^2 \alpha_3 \]

and substituting in (18, 19), we find expressions for the efforts \( F_i \) depending on the kinematic variables of the manipulator \( q_i \) and their speeds \( \dot{q}_i \).

To calculate the control forces (21), it is necessary to calculate the current values of the angles of rotation of the actuators, their speed and acceleration

\[
\cos \alpha_2 = \frac{l^2 - l_1^2 + AB^2}{2l_1 AB}, \quad \cos \alpha_3 = \frac{l_2^2 - l_3^2 - AB^2}{2l_2 AB}, \quad \sin \alpha_2 \cdot \dot{\alpha}_2 = \left( \frac{\cos \alpha_2}{l_2} - \frac{1}{AB} \right) \dot{l}_2 + \frac{l_3}{l_2 AB},
\]

\[
\sin \alpha_2 \cdot \dot{\alpha}_2 = \left( \frac{\cos \alpha_2}{l_2} - \frac{1}{AB} \right) \dot{l}_3 + \frac{l_3}{l_2 AB},
\]

\[
\sin \alpha_3 \cdot \dot{\alpha}_3 = -\frac{l_2}{l_3 AB} + \left( \frac{\cos \alpha_3}{l_3} + \frac{1}{AB} \right) \dot{l}_3,
\]

\[
\sin \alpha_3 \cdot \dot{\alpha}_3 = -\frac{l_2}{l_3 AB} + \left( \frac{\cos \alpha_3}{l_3} + \frac{1}{AB} \right) \dot{l}_3 - \frac{l_3}{l_3 AB} - \frac{l_3^2}{l_3 AB} - \frac{l_3^2}{l_3^2 AB} - \frac{l_3^2}{l_3} \sin \alpha_3 - \cos \alpha_3 \dot{\alpha}_3^2.
\]

The required laws of change in the control efforts are found after the substitution of expressions (12) into the formulas for the control efforts \( F_i \).

The static characteristic of a DC drive motor with independent excitation has the form

\[
F_i = r u_i - s \dot{l}_i, (i = 1 - 3),
\]

where \( r, s \) – coefficients depending on the parameters of the engine and the mechanical transfer; \( u_i(t) \) – control voltage.

The dynamic algorithm for stabilization of the grip of the manipulator is based on the implementation of the expression ratios for the control voltages

\[
u_i = \frac{F_i(q_i, \dot{q}_i)}{r} + \frac{s}{r} \dot{l}_i, (i = 1 - 3).
\]

Figure 3 shows a block diagram of the stabilization algorithm.
3.2. Numerical example of the control algorithm implementation

At the initial moment of time, the working body of the manipulator was located at the point with the coordinates \( x_{40} = 60\,\text{mm}, y_{40} = 300\,\text{mm} \). Distance between the axes of the attachment points of the actuators \( AC = BC = 140\,\text{mm} \). These coordinates correspond to the lengths of the executive links \( l_{10} = 0\,\text{mm}, l_{20} = 360\,\text{mm}, l_{30} = 310\,\text{mm} \). By setting the coordinates of the end point \( x_4 = -120\,\text{mm}, y_4 = 420\,\text{mm} \), as a result of applying the positioning algorithm, we obtained

\[
l_{10}^{op} = l_0^0 = 93.5\,\text{mm}, l_{20}^{op} = l_2^0 = 327\,\text{mm}, l_{30}^{op} = l_3^0 = 417.4\,\text{mm}.
\]

In Figure 4 and Figure 5 show the results of calculations when moving the working body from a position determined by coordinates \( x_{40} = 60\,\text{mm}, y_{40} = 300\,\text{mm} \) to a point with coordinates \( x_4 = -120\,\text{mm}, y_4 = 420\,\text{mm} \) according to the laws (10): initial speed \( \dot{l_{10}} = 0 \);

\[
\dot{l}_i(t) = \dot{l}_i^0 + \frac{\Delta l_{10}}{p_{1i} - p_{2i}} \left( p_{2i}e^{p_{1i}t} - p_{1i}e^{p_{2i}t} \right), \quad \Delta l_i(t) = l_i^0 - l_{10}, \quad p_{1i} = -12, \quad p_{2i} = -20
\]

\[
\Delta l_{10} = -93.5\,\text{mm}, \quad \Delta l_{20} = -33\,\text{mm}, \quad \Delta l_{30} = 107.4\,\text{mm}.
\]

From the graphs (Figure 4, 5), it can be seen that within \( \tau = 0.5\,\text{s} \) the gripper device is stabilized in the specified position. Deviations from the specified position are not more than 0.1%, and the speeds and accelerations are almost zero. The trajectory of the point differs slightly from the straight line. If the generalized coordinates of the manipulator deviate from the program trajectory, it does not make...
sense to stabilize them on the original program trajectory, since at each current point a different program trajectory is constructed that satisfies the same final conditions [10].

4. Conclusion
The problem of positioning the manipulator and the problem of weak terminal control is solved. The program trajectory is corrected in such a way that at each moment of time it passes through the current position of the working body. Over time, the working body falls into the final area of the target point. The algorithm for generating control voltages is formed taking into account the kinematic parameters of the manipulator for all degrees of freedom. Mathematical modeling has shown that the proposed algorithm allows you to implement the movement of the gripper along the program trajectory with an error of no more than 1%. The algorithm also functions well in the presence of initial perturbations.

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