Structural organization of robotic building and mounting complexes

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Abstract –

The object of the research is construction robot manipulators for mounting works. The results of mathematical identification of mounting manipulators on the basis of a tower crane model are presented. The design of movement trajectories of a manipulator or technological equipment is performed taking into account the limitations both on the trajectory itself and on the movements of the manipulator links. The trajectory of movement is represented as a sequence of typical elementary sections. Recommendations on creation of databases for manipulators operating according to a cyclic program for their use at the stage of trajectories design are given.

Keywords –

Robot; Building and Mounting Works; Mathematical Modell; Path Planning

1 Introduction

Construction and installation work belongs to the main and labor-intensive activities on the construction site. They account for about 23 % of the total labor costs for the construction of the above-ground part of the building. They are divided into two groups: installation cycle operations and auxiliary operations. The most labor-intensive are the assembly cycle operations, the share of which exceeds 65% of the total installation labor costs. Important and often repetitive are the basic operations of the installation cycle, including picking up the panel, lifting it and transporting it to the installation site, positioning and seating it in place, aligning the planned position of the panel and securing it. These operations completely determine the cycle time and account for 50 % of all installation labor. In addition, they are characterized by difficult and hazardous working conditions. At present, these tasks can be solved on the basis of using crane manipulators, positioning robots and special mounting equipment.

Recent years have seen an increasing use of robotic manipulators in the construction industry. Their kinematic diagrams differ in a great variety, which is associated with different areas of their application and functional tasks [1,2]. The number, type, and mutual arrangement of the degrees of mobility of construction robots are determined by the features of the technological operation performed, the required service area, and the needed orientation ability.

Kinematic schemes of construction manipulators are developed on the basis of formulated functional, design and operational requirements. The functional requirements are primarily those determining the shape, size and location of the working area, the possible technological forces on the working elements, the necessary speed and acceleration ranges of the working elements. In addition, in the case of the mounting robot, the specific shape, size and weight of the structure to be assembled must also be taken into account. When developing the kinematic schemes, the design requirements must include the shape and dimensions of the workspace in which the robot is to operate, the permissible compression ratio and the permissible static and dynamic errors. The operational requirements should include the reliability and compactness of the handling system in the working and transport position. The choice of the structure of the kinematic scheme of the robot, the determination of the number of degrees of mobility, the optimum length of the links and their limiting displacements is one of the most important tasks in the design of specialized construction robots. The solution of this problem must be based on optimization methods that ensure the minimization of the robot's work envelope for a given operating envelope [3].

2 Mathematical identification of construction robot manipulators for mounting work

To present an approach for mathematical identification of a robotic assembly complex as an object of research, consider a crane (Fig. 1a) consisting of a stationary tower 1 on which a horizontal rotary boom 2 with a trolley 3 moving along it is located. The crane is equipped with a rope, which holds the load on an hinged suspension.

A special feature of the crane mathematical model is the need to consider the elastic deformations in its structure arising from the action of wind and dynamic loads. Since the installation process is carried out at low speeds, the amplitude of the cable oscillations is negligible and the wave processes in the cable can be neglected. During the construction of the crane model, its mechanical part with the load is considered as a manipulation structure [4,5]. At this stage, the elastic displacements and vibrations of the rope are replaced by holonomous couplings. Further, to the Lagrange equations describing the dynamics of the holonomy system, the terms taking into account the action of elastic and dissipative forces are added.

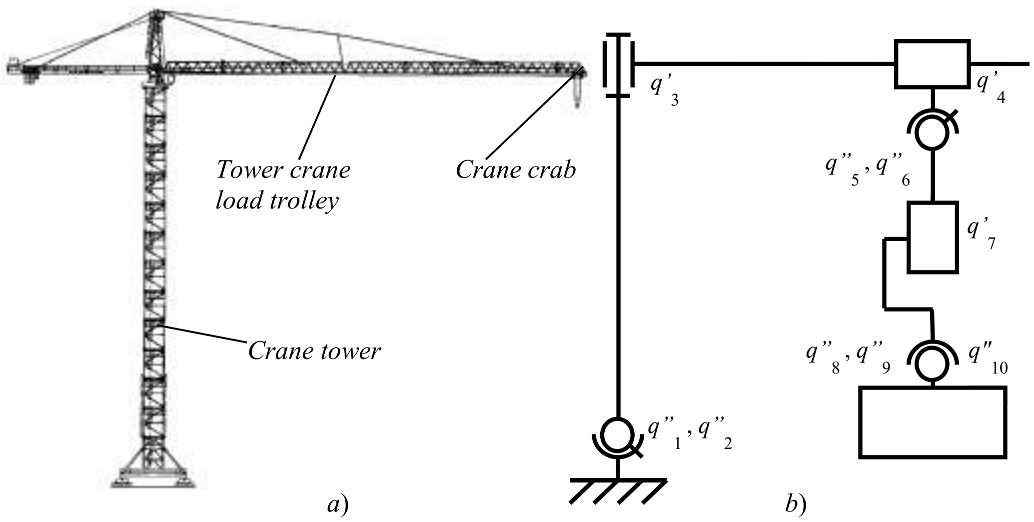

Fig. 1. Tower crane (a) and its kinematic diagram (b) used to build the mathematical model.

It is better to build the crane dynamic model based on Lagrange equations. In this case, the dynamics of the crane without taking into account the forces generated in the elastic elements is described by the following equation: $\mathbf{M} = D(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{b}(\mathbf{q},\dot{\mathbf{q}}) - \sum_{k=1}^{l} G^{\mathrm{T}}\left(\mathbf{q},\Delta\mathbf{x}^{(k)}\right)\mathbf{F}_s^{(k)} - \mathbf{M}_w$, from which

$$\ddot{\mathbf{q}} = D^{-1}(\mathbf{q})\left(\mathbf{M} - \mathbf{b}(\mathbf{q},\dot{\mathbf{q}}) + \sum_{k=1}^{l} G^{\mathrm{T}}\left(\Delta\mathbf{x}^{(k)},\mathbf{q}\right)\mathbf{F}_s^{(k)} + \mathbf{M}_w\right), \quad (1)$$

where $\mathbf{M}$ is the vector of generalized forces arising in the joints of the manipulator; $\mathbf{D}(\mathbf{q})$ – dynamics matrix; $\mathbf{b}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{h}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{c}(\mathbf{q})$, $\mathbf{h}(\mathbf{q},\dot{\mathbf{q}})$ – vector of Coriolis and centrifugal forces; $\mathbf{c}(\mathbf{q})$ – vector of gravitational forces; $\mathbf{F}_s^{(k)}$ – vector of forces arising in the k-th grip, measured in the absolute coordinate system; $\Delta\mathbf{x}^{(k)}$ – a vector of displacement of the point of application of the k-th external force, measured in the crane's crosshead coordinate system; l – number of attachment points of the positioning robot's gripping devices; $\mathbf{M}_w$ – a vector of generalized forces, caused by external influences on the crane mechanism apart from the influence of the positioning robot [6,7].

The elements of the dynamics matrix D and the vectors h and c are calculated from the expressions:

$$D_{ik} = \sum_{j=\max(i,k)}^{n} Tr\left(U_{jk} J_j U_{ji}^{\mathrm{T}}\right), \; i,k = \overline{1,n},$$

$$h_i = \sum_{k=1}^{n}\sum_{m=1}^{n} h_{ikm}\dot{q}_k\dot{q}_m, \; h_{ikm} = \sum_{j=\max(i,k,m)}^{n} Tr\left(U_{jkm} J_j U_{ji}^{\mathrm{T}}\right), \quad (2)$$

$$c_i = \sum_{j=1}^{n}\left(-m_j \mathbf{g} U_{ij}\mathbf{r}^{(j)}\right), \; i = \overline{1,n},$$

where J_j – is the matrix of moments of inertia of the j-th link; $\mathbf{g}$ is the vector of free fall acceleration; m_j is the mass of the j-th link; $\mathbf{r}^{(j)}$ is the position vector of the centre of mass of the j-th link in its coordinate system.

During mounting work, the crane is heavily influenced by wind loads. In order to mathematically describe the distributed force caused, it is necessary to break down the crane structure into elements that have a sail and then replace the distributed forces acting on the elements with equivalent concentrated forces:

$$\mathbf{F}_w^{(k)} = \left(\vartheta_x^{(k)}(\mathbf{q})w_x \quad \vartheta_y^{(k)}(\mathbf{q})w_y \quad \vartheta_z^{(k)}(\mathbf{q})w_z\right)^{\mathrm{T}}, \; k = \overline{1, n_w}, \tag{3}$$

where $\vartheta_x^{(k)}(\mathbf{q})$, $\vartheta_y^{(k)}(\mathbf{q})$, $\vartheta_z^{(k)}(\mathbf{q})$ is the wind load factor of the k-th element in the direction of the axes of the absolute coordinate system; w_x, w_y, w_z are the projections of wind speed [m/c].

If the force $\mathbf{F}_w^{(k,i)}$ has an application point with coordinates $\mathbf{r}_w^{(k,i)}$, measured in the coordinate system of the i-th link to which the k-th mass is rigidly connected, then the transition to generalized crane forces is of the follows form:

$$\mathbf{M}_w = \sum_i \sum_{k=1}^{l_{wi}} G_i^{\mathrm{T}}\left(\mathbf{r}^{(k,i)}, \mathbf{q}\right)\mathbf{F}_w^{(k,i)} = \widehat{G}^{\mathrm{T}}\left(\widehat{\mathbf{r}}, \mathbf{q}\right)\widehat{\mathbf{F}}_w, \; i = 2,3,4,7,10,$$

where где l_{wi} is the number of bodies with sail associated with the i-th link.

By separating the generalized crane coordinates into controllable coordinates $\mathbf{q}'$ and those introduced to simulate elastic deformation $\mathbf{q}''$, this equation is transformed to the form:

$$\mathbf{M}' = D'(\mathbf{q})\ddot{\mathbf{q}}' + \breve{D}(\mathbf{q})\ddot{\mathbf{q}}'' + \mathbf{b}'(\mathbf{q}, \dot{\mathbf{q}}) - \sum_{k=1}^{3} G'^{\mathrm{T}}\left(\mathbf{dx}^{(k)}, \mathbf{q}\right)\mathbf{F}_s^{(k)} - \mathbf{M}'_w,$$

$$\mathbf{M}'' = \breve{D}^{\mathrm{T}}(\mathbf{q})\ddot{\mathbf{q}}' + D''(\mathbf{q})\ddot{\mathbf{q}}'' + \mathbf{b}''(\mathbf{q}, \dot{\mathbf{q}}) - \sum_{k=1}^{3} G''^{\mathrm{T}}\left(\mathbf{dx}^{(k)}, \mathbf{q}\right)\mathbf{F}_s^{(k)} - \mathbf{M}''_w$$

The generalized forces $\mathbf{M}'$ are generated by the crane drives and the generalized forces which simulate the elastic displacements of the crane are determined by the stiffness and dissipation of the crane components:

$$\mathbf{M}'' = -\alpha\mathbf{q}'' - \beta\dot{\mathbf{q}}'', \tag{4}$$

where α, β – diagonal stiffness and dissipation matrices.

On the basis of the obtained equations it is possible to construct a structural diagram of the model of the crane with the plate to be mounted (Fig. 2). The resulting model of the elastic deforming mechanism of the crane in matrix form is convenient for constructing a model of the mounting complex and control algorithms [8].

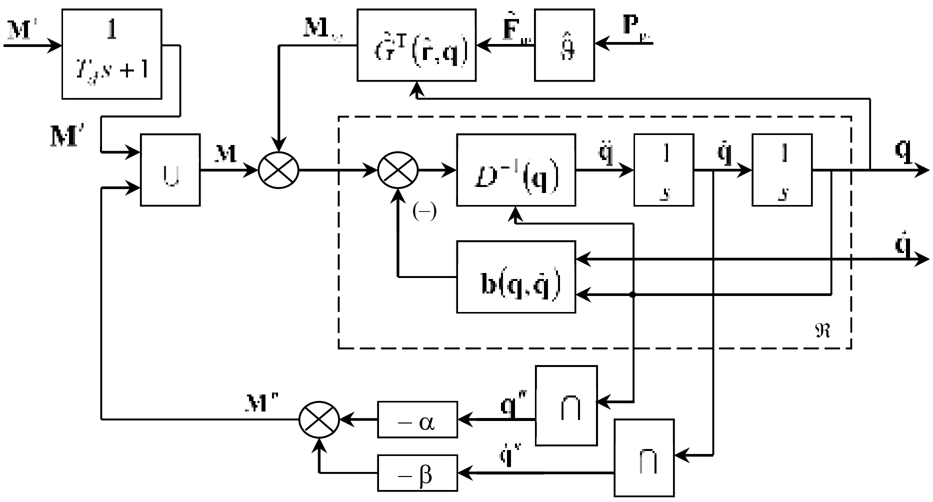

Fig. 2. Crane model structure diagram.

3 Path planning for construction mounting robots

The robot's construction and mounting operations require motion planning of the robot arm in space and time. Movement planning is performed based on constructed movement trajectories, node point tables and movement speeds. The planning task is to develop a mathematical description of the desired movements of the complex mechanisms. In most cases the motion trajectories of mounting robots are complicated spatial trajectories consisting of rectilinear sections, contiguous arcs of circles or smoothed curvilinear sections. When designing the motions of a robot handling system, the requirements for the character of the motion are also taken into account, ensuring the desired smoothness and continuity of the trajectory, the continuity of the velocities and accelerations. Thus, any complicated movement trajectory is represented as a sequence of typical elementary sections, for which typical motion planning algorithms are included as part of the robot software. In this connection, motion planning of any construction robot is reduced to the planning of typical elementary movements of the executive mechanism. The design of movement trajectories of a manipulator or technological equipment is performed taking into account the limitations both on the trajectory itself and on the movements of the manipulator links. When planning a trajectory in a non-dimensional environment, the possible nature of its change is taken into account [9].

The robotization of mounting operations by means of specialized cranes with software and adaptive control involves the transportation of components to the mounting area, its orientation and installation into the designed position. When constructing the trajectory of the part moving into the installation zone, changes in the position of mechanisms during the work, changes in the environment in the installation zone are taken into account. In order to avoid emergency situations, when designing the trajectory of the parts, it is necessary to take into account the shape, overall dimensions and inertial properties of the structure, the dimensions of the installation area, and wind loads. Analysis of mounting technology shows that it is more appropriate to use transport trajectories that consist of two or three rectangular sections (Fig. 3), including vertical lifting of the part to a given height, its horizontal movement in a straight line to the positioning point and vertical lowering of the part during mounting. For high and long objects, the transport of parts can be done with an inclined trajectory formed after the vertical lift of the part from the cassette. In this way, the motion trajectory of an mounting robot can be divided into 4 segments, each of which corresponds to a certain type of operation: vertical lifting of the building item to be mounted $(P_0 \to P_1)$; linear movement to the designated area $(P_1 \to P_2)$; horizontal movement to the installation site $(P_2 \to P_3)$; orientation and positioning of the item to the designed position $(P_3 \to P_4)$.

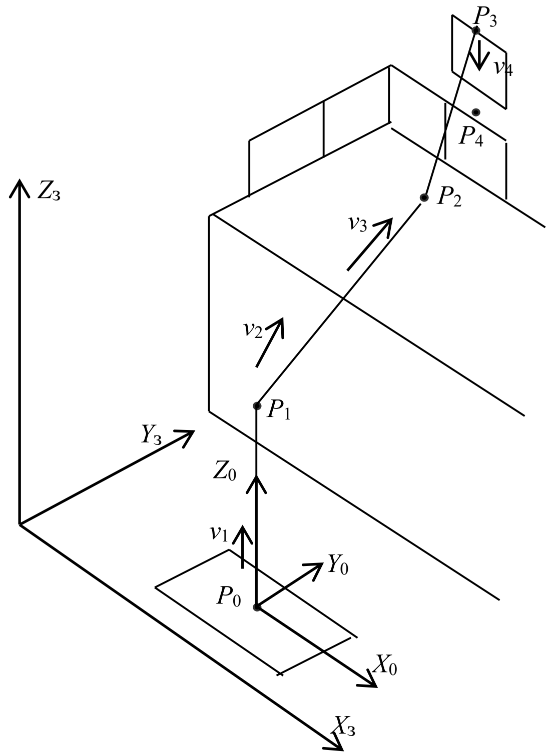

Fig. 3. Trajectories for transporting the building structure into the mounting area.

The constituent sections of a trajectory are normally straight. When constructing a trajectory, between the 1st and 2nd section and the 2nd and 3rd sections there are contiguous sections to ensure a smooth transition from one section of the trajectory to the other and non-stop movement until the point P_4, where, in accordance with installation technology requirements, the movement speed should be set to zero. The trajectory points P_0, P_1, P_2, P_3, P_4 are defined in the building coordinate system. To describe them, it is convenient to use the matrix S_T, each column of which contains the coordinates of points P_i and Euler angles describing the orientation of the grip in each point:

$$S_T = \begin{bmatrix} x_i \\ y_i \\ z_i \\ \theta_i \\ \varphi_i \\ \psi_i \end{bmatrix} = \begin{bmatrix} x_0 & x_1 & x_2 & x_3 & x_4 \\ y_0 & y_1 & y_2 & y_3 & y_4 \\ z_0 & z_1 & z_2 & z_3 & z_4 \\ \theta_0 & \theta_1 & \theta_2 & \theta_3 & \theta_4 \\ \varphi_0 & \varphi_1 & \varphi_2 & \varphi_3 & \varphi_4 \\ \psi_0 & \psi_1 & \psi_2 & \psi_3 & \psi_4 \end{bmatrix}. \quad (5)$$

The values of the elements of this matrix are determined analytically. The accuracy of the position values is ± (0.5-1) mm and the accuracy of the orienting angles is no more than 2 arcmin.

For each section of the trajectory, process speeds are specified. The lifting operation is performed at medium speeds v_1, the transportation on the 2nd and 3rd sections can be performed at maximum speeds v_2, v_3, which are limited by the weight of the load and its dimensions. On the last section, where mounting operations, which require increased positioning accuracy, are performed, the speed v_4 of the construction element to be mounted is selected to be reduced. A velocity matrix is produced when constructing the trajectory V_T:

$$V_{\mathrm{T}} = \begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{z}_i \\ \dot{\theta}_i \\ \dot{\varphi}_i \\ \dot{\psi}_i \end{bmatrix} = \begin{bmatrix} 0 & \dot{x}_1 & \cdot & \cdot & \cdot & 0 \\ 0 & \dot{y}_1 & \cdot & \cdot & \cdot & 0 \\ \dot{z}_0 & \dot{z}_1 & \cdot & \cdot & \cdot & \dot{z}_m \\ 0 & \dot{\theta}_1 & \cdot & \cdot & \cdot & 0 \\ 0 & \dot{\varphi}_1 & \cdot & \cdot & \cdot & 0 \\ 0 & \dot{\psi}_1 & \cdot & \cdot & \cdot & 0 \end{bmatrix}. \quad (6)$$

The first and last columns of the matrix are made based on the technological requirements of lifting and lowering the structure to be mounted. Before the structure is moved to the installation area, it must be lifted off the fixture or platform in an upright, torsion-free manner. The structure is also placed in its intended position without changing its orientation angles, by means of a vertical landing.

The analytical description of the trajectory sections is as follows:

– 1st section:

$x = x_0 = \text{const},\ y = y_0 = \text{const},\ z_0 \le z \le z_1 \rightarrow$
$P_0 \le P(x, y, z) \le P_1;$

– 2nd and 3rd section:

$$\frac{x - x_1}{x_2 - x_1} = \frac{y - y_1}{y_2 - y_1} = \frac{z - z_1}{z_2 - z_1} \rightarrow$$
$P_1 \le P(x, y, z) \le P_3;$

– 4th section: $x = x_3 = \text{const},\ y = y_3 = \text{const} \rightarrow$
$P_3 \le P(x, y, z) \le P_4.$

For the convenience of the planning algorithms, the transformation matrices T_i for each of the node points of the trajectory are written on the basis of the matrix S_T, describing the node points of the trajectory. In doing so, the coordinate system of the building is converted to the crane coordinate system. These transformations can be performed based on the following transformations. The position vector $T_0^{(i)}$ of the matrix can be derived from the first three elements of the i-th column of the matrix S_T as:

$$P_0^{(i)} = \begin{bmatrix} x_0^{(i)} \\ y_0^{(i)} \\ z_0^{(i)} \end{bmatrix} = \begin{bmatrix} x_i^{(3)} & + & x_0^{(3)} & \rightarrow & \text{var} \\ y_i^{(3)} & + & y_0^{(3)} & \rightarrow & \text{const} \\ z_i^{(3)} & + & z_0^{(3)} & \rightarrow & \text{const} \end{bmatrix}, \quad (7)$$

where $x_0^{(3)}, y_0^{(3)}, z_0^{(3)}$ - the position of the system $X_0Y_0Z_0$ starting in the building coordinate system $X_3Y_3Z_3$.

The matrix of directional cosines $A_0^{(i)}$ characterizing the orientation of the working body in the manipulator coordinate system $X_0Y_0Z_0$ is compiled on the basis of the Euler angles $\theta_0^{(i)}, \varphi_0^{(i)}, \psi_0^{(i)}$, which correspond to the angles $\theta_3^{(i)}, \varphi_3^{(i)}, \psi_3^{(i)}$ since the building $X_3Y_3Z_3$ and manipulator coordinate systems $X_0Y_0Z_0$ are orthogonal and coaxial. The parameters $\theta_3^{(i)}, \varphi_3^{(i)}, \psi_3^{(i)}$ are the elements of matrix S_T for the i-th point of trajectory (last three elements of i-th column). Using position vectors $P_0^{(i)}$ and matrices of directional cosines $A_0^{(i)}$ the transformation matrices are compiled:

$$T_0^{(i)} = \begin{vmatrix} \multicolumn{3}{c}{A_0^{(i)}} & P_0^{(i)} \\ 0 & 0 & 0 & 1 \end{vmatrix}. \quad (8)$$

After these transformations, each node point of the trajectory is obtained represented in the robot coordinate system $X_0Y_0Z_0$ by the obtained matrices $T_0^{(i)}$. The transition of the gripper with the building element $T_0^{(i-1)}$ to $T_0^{(i)}$ be mounted from to is planned as a rectilinear movement between the points P_{i-1} and P_i, if this is not hindered by objects in the environment.

This is where the process of constructing mounting robot trajectories ends in principle. Transition smoothing sections are described during the planning phase of the manipulator movement. The return of the gripper for the next part follows the same trajectory. However, travel speeds can be set differently, using a matrix V_T.

Robotic mounting is only effective if the installation of the next prefabricated component is cyclically repeated. To organize an mounting robot in a cyclic program, a database including a matrix S_T for each cycle or a law of variations in its parameters must be created at the design stage of the motion paths. In large-panel housing erection, parts are usually taken from one or more reference platforms that are rigidly connected to the building coordinate system (Fig. 4). The position of

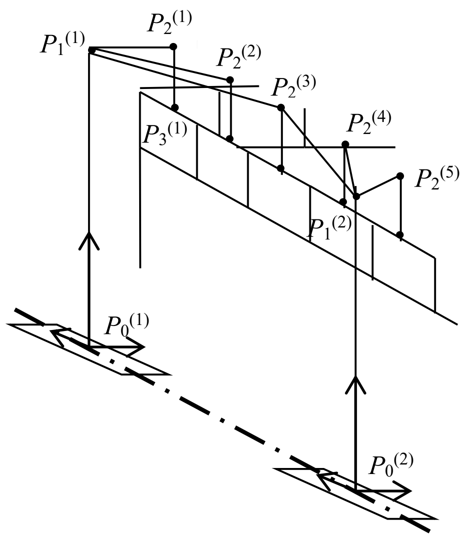

Fig. 4. Technological scheme for the erection of large panel buildings.

the points P_2 and P_3 the orientation of the gripper at these points is determined by the process flowchart of the building element installation sequence. The position of the first two points can be multiple, depending on the number of platforms (fixtures) from which the elements are taken. The movement between the points $P_0^{(k)}$ and $P_1^{(k)}$ is described by the matrix $S_{01}^{(k)}$, where k is the number of the element to be taken.

Before executing the next i-th cycle, the matrix $S_0^{(k)}$ corresponding to the location of the next element is selected and the element installation matrix is generated according to the mounting plan:

$$S_{24}^{(j)} = \begin{bmatrix} 0 & 0 & x_2^{(j)} & x_3^{(j)} & x_4^{(j)} \\ 0 & 0 & y_2^{(j)} & y_3^{(j)} & y_4^{(j)} \\ 0 & 0 & z_2^{(j)} & z_3^{(j)} & z_4^{(j)} \\ 0 & 0 & \theta_2^{(j)} & \theta_3^{(j)} & \theta_4^{(j)} \\ 0 & 0 & \varphi_2^{(j)} & \varphi_3^{(j)} & \varphi_4^{(j)} \\ 0 & 0 & \psi_2^{(j)} & \psi_3^{(j)} & \psi_4^{(j)} \end{bmatrix}. \quad (9)$$

By adding the generated matrices $S_{01}^{(k)}$ and $S_{24}^{(j)}$, the matrix $S_T^{(j)} = S_{01}^{(k)} + S_{24}^{(j)}$ describing the coordinates $P_l(k)$ of the trajectory of the next cycle is obtained. Finally, the trajectory lengths and their running times are evaluated. If there are no obstacles in the way of movement, the length of each trajectory segment is chosen to be equal to:

$$l_i = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2},$$

and the total length is determined by adding up the individual sections:

$$L_{mp} = \sum_{i=1}^{n} l_i, \quad (10)$$

where n is the number of sections, i – the section number. As for planning of technological process it is necessary to estimate time of performance of operations at each stage, at this stage a preliminary estimation of time of trajectory passage and installation of an element mounted in the given position is carried out:

$$t_c = \left(\sum_{i=1}^{n} \frac{l_i}{V_i}\right) + t_{or}, \quad (11)$$

where t_{or} is the element orientation time.

Conclusion

The system approach to the structural organization of robotic construction-assembly complexes was proposed and implemented during the research for the first time. For mathematical identification of construction robot arms and construction of their dynamic model, Lagrange equations were used. In order to take into account and mathematically describe the influence of wind loads on the performance of installation works, for the first time a model of an elastically deforming crane mechanism in matrix form has been proposed, which makes it possible to develop control algorithms and motion trajectories ensuring the required smoothness and continuity of the trajectory, constancy of speeds and accelerations. When planning a trajectory in a dimensionless environment, the possible nature of its change is taken into account. A further direction of research is the planning of movements of construction robots with speed optimization based on the use of two-level interpolation, which allows to reduce the velocity search area taking into account the constraints and significantly increase the speed of calculations. This will make it possible to create an effective system of robotic installation and assembly of building blocks and elements on the basis of a tower crane and a positioning robot.

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