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Robotization of mounting and finishing operations in building

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SUMMARY
Construction is of great interest in the application of practical and theoretical results in the field of robotics. The economic efficiency potential of using robots is defined by construction quantities, a high level of manual work, and hard and unfavorable working conditions. Mounting and finishing operations are the main focus for the practical use of robots. This paper describes technological characteristics of such operations, suggests kinematic structures for mounting and finishing operations, and provides kinematic model designs as examples. Taking into consideration the management details of mounting and finishing operations, this paper also makes recommendations on movement planning and on the formation of the laws of drive control. In the conclusion, recommendations on applying the results and using computer technologies in the development of control programs are presented.

KEYWORDS: Robots; Robotics; Construction; Building; Kinematics; Control.

1. INTRODUCTION

Mechanization and automation of construction operations through conventional methods are not always sufficient to provide the desired outcomes. The introduction of robots advances construction technology. An analysis of the major types of construction work shows that mounting and finishing operations are of the greatest practical interest in the application of robots. Technological and economic analyses of these types of work point to technological operations most suited to robotization. Construction mounting operations include mounting of components and structures and welding during mounting.[1–3] Among finishing operations, priority is given to the preparation of the surface and its priming and painting. As for repair work, the robotization of the washing and painting of outer building walls and of the application of moisture-proof coating is of interest.

An analysis of developments in the field of construction robotics indicates that the desired outcome can only be achieved through the use of special-purpose robots and by fully considering technological, design, and operational features of construction operations. The robotization of mounting operations is connected with the provision of the preset of orientation and installation of components and structures. In addition, the components to be mounted have large overall sizes and weights and are distinguished by the relationship of overall sizes with the manner of fixation in the design position. The development of mounting robots and robotized mounting technology are dependent on the successful resolution of issues involved in designing kinematic structures and in mathematical and algorithmic provisions. Finishing operations are characterized by great volumes and large surfaces requiring painting. However, the application of primes and paints doesn't require high accuracy in tool positioning, and the paths of tool travel are mainly rectilinear. Robotization of finishing operations is impossible without developing compact and mobile designs of special-purpose robots permitting the movement of the equipment between rooms. The load capacity of these robots is principally defined by the weight of the tooling.

In view of the described features of robotizing mounting and finishing operations let us consider the principles of kinematic structure design as we address the problems of planning movement and end-effector controls in mounting and painting robots.

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2. KINEMATIC STRUCTURE OF ROBOTS

An analysis of mounting technology given the stated requirements shows that the successful design of robotization tasks is dependent on the development of original kinematic structures and by a proper structural synthesis. Different mounting operations require robots designed with attention on load capacity, service range, and operational tasks. Three main kinematic structure types for mounting robots are recommended, depending on the task to be performed:

- construction-mounted robots equipped with a telescopic arm placed on a tool carrier;
- tower crane-manipulators traveling on a rail track;
- mobile orienting robots.

For construction-mounted robots (i.e. the first type), a structural design with six degrees of freedom is suggested and presented in Figure.1a. Structural analysis of this design shows that it provides handling, installation and orientation of components at a height up to 10–15 meters with minimal power costs and time requirements. A basic type of such a robot may involve a mobile crane with a telescopic arm and an additional turning boom with an installed orienting mobile and gripping automatic traverse. The main application of these robots is in the mounting of houses, administration buildings, industrial installations, and various pavilions. The structure of the translational degrees of freedom provides component handling to the mounting

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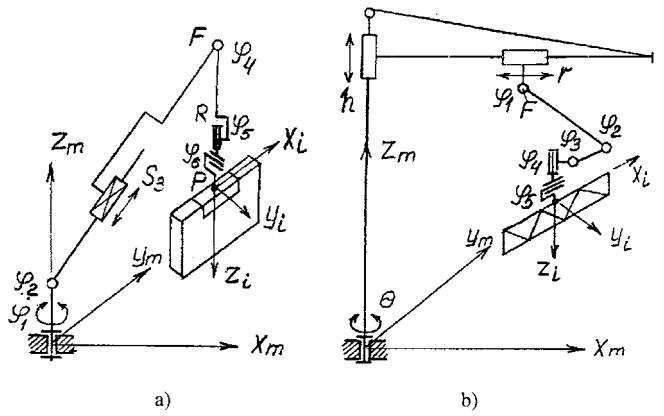


Fig. 1. Construction-mounting robots.

location and assumes a limitation on the movement trajectory. Vertical design is concerned with the position of boom four, while the orientation around the vertical axis Z_i and the avoidance of pitch relative to the axis X_i is determined by the degrees of freedom of the orienting module.

When performing mounting operations at heights up to 10–25 meters, tower crane-manipulators have been found advantageous (Figure 1b).

The tower with the arm installed on the movable truck has three degrees of freedom: the turn angle q, the arm hoisting height h, and the truck movement along the arm r. The manipulator with two turning links and the orienting module with three degrees of freedom are installed on the trucks. Mounting operations over a small area require that the orienting module is installed on a horizontal traverse with flexible and rigid connections to the arm and tower. One of the applications of such cranes-manipulators is in the mounting of prefabricated multistorey residential buildings. Robots designed by the authors demonstrate the potential of program control over the whole process, assuming the use of an automatic system of control over the displacement and orientation of the units to be mounted.

In the mounting of high-rise buildings one of the promising trends is the development of robotized mounting systems consisting of tower cranes with program control and a mounting robot (Figure 2). The crane transports the unit to the mounting area and to its previous installation and

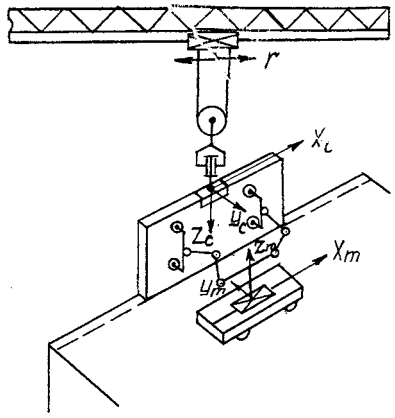


Fig. 2. Robotized mounting systems.

holds the unit during the process of orientation. The mounting robot provides the position correction and the precision orientation of the component while mounting.

The structural analysis shows that it is expedient to use a two-arm manipulation installed on a self-propelled platform and with a translation degree of freedom S_1 in its base. The platform is supplied with retracting controlled supports. The position control over the component being mounted is performed by the laser orientation devices that provide continuous control and automate the process of mounting.

When performing robotic mounting operations, special attention should be paid to the choice of coordinate system used for designing kinematic models and for generating control algorithms. In all variants of robotization, the coordinate system of the object $X_0Y_0Z_0$ is considered the basic coordinate system. It is relative to the position and orientation of the components to be mounted and the trajectory of their displacement.

The main challenge in the creation of finishing tools is the development of optimal kinematic structures. Moreover, it is necessary to establish the criteria for the evaluation and fulfillment of parametric synthesis of the manipulating system. An analysis of residential and administrative buildings has shown that finishing operations require special-purpose robots with a kinematic structure that provides displacement and orientation of the end-effector over flat surfaces of different dimensions. These robots must be provided with devices for outer control and for measurement of the process parameters. When developing finishing robots it is necessary to calculate optimal parameters of the kinematic configuration that perfectly satisfy the criteria of compactness and effective use of the working area. In the given case it is advantageous to use computer modeling to ensure visual representation of different variants and to evaluate geometry and functional possibilities of each structure. The analysis of technological features of finishing shows that for priming, as well as for priming and painting coatings, a manipulator with five degrees of freedom, of which three are movable and two are orienting is required. An analysis of the technology of performing finishing operations, developments in the field of their robotization, and the stated requirements for finishing operations allow the definition of some basic kinematic structures for painting robots. For painting and printing walls in residential buildings it is preferable to use the kinematic diagram shown in Figure 3a. Its characteristic

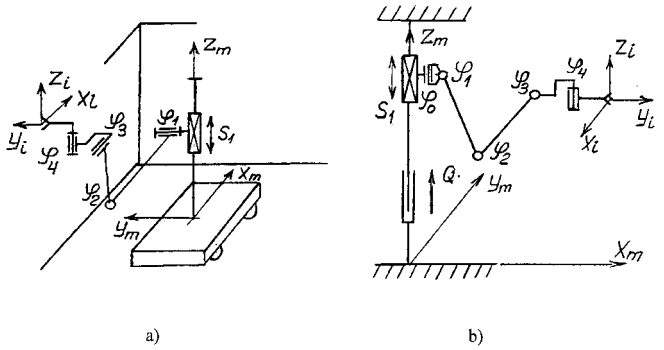


Fig. 3. Robots for finishing operations in residential construction.

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feature is the compactness of the manipulating system in working and transport positions.

The recommended length of the links is 1–1.2 meters, which allows the painting of walls and ceilings up to 3–4 meters in height. Manipulator travel along the walls is enabled by the controlled truck. The distinctive feature of this structure is the displacement of the axes of the movable degrees of freedom (φ_1, φ_2) perpendicular to the surface being painted. Travel S_1 is positional and provides manipulator setting at the required height depending on the height of the room being painted.

Finishing operations of large areas with great heights should be performed with help of semi-stationary robots mounted on a telescopic rod with five degrees of freedom (Figure 3b). The analysis of this kinematic structure shows that, with an optimal choice of link length, walls and ceilings, 30–50 m^2 in area, can be painted from one unit.

Robotization of the processes of cleaning and painting outer surfaces should be performed on the basis of kinematic structures presented in Figure 4. The first structure is designed for small and medium height buildings and the second is for high buildings and constructions. The basis of the first manipulating design (Figure 4a) is a self-propelled platform with a rotating plate and a two-link arm. Motions φ_1, φ_2 and φ_3 provide travel of the robotic tool to the given paint on the painted surface and its travel along the given trajectory.

Degrees of freedom φ_2 and φ_5 enable the necessary orientation of the tool relative to the surface. Operation of the translational degree of freedom (S_1) between them provides satisfactory painting of wide stripes and obstacle avoidance while travelling along the path. Robotization of the processes of cleaning facades and painting outer walls of high buildings can be realized through an application of the suspended two-axis truck (Figure. 4b). The third degree of freedom ensures necessary rotational movements of the tool, stipulated by the technological process. Truck movement along the vertical is performed by program-controlled winches equipped with position transducers.

Movement planning of the mounting and finishing robots under consideration is based on kinematic models. For convenience in planning movements one should distinguish transport, adjusting, and orienting movements. In connection with these we define degrees of freedom providing their fulfillment. Kinematic models include equations determining the positions and speeds of the system elements and specifying the mentioned movements. Control of mounting and finishing robots can be performed either in the coordinate system of the manipulator $X_mY_mZ_m$ or in the coordinate system of the building $X_bY_bZ_b$. It is recommended to plan transport movements in the system $X_mY_mZ_m$ and to perform adjusting, orienting, and technological operations in the coordinate system $X_bY_bZ_b$.

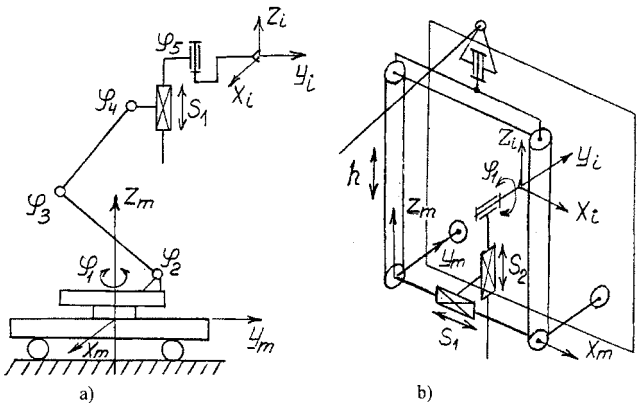


Fig. 4. Robots for cleaning and painting building exteriors.

The characteristic features of designing kinematic models can be considered through the example of the kinematic structures shown in Figure.1a. The position of the coordinate systems while developing the kinematic model must ensure conventional representation of mechanism locations and simplify the process of coordinate transformation. For the manipulator under consideration, the basic coordinate system $X_mY_mZ_m$ is connected with the rotation axis, and the axis X_m is directed along the self-propelled truck. For the rotational degrees of freedom, the axes of which are perpendicular to the links (second, fourth, and sixth pairs), it is convenient to combine the X axes with the rotation axes and to direct the Z axes along the link. For the translational degree of freedom, as well as the rotational degree of freedom with the location of the axis along the line, it is necessary to direct the Z axes along the axes of movement and to combine the X axes with the X axes of the previous degrees of freedom. It is convenient to direct axis Z_i of the grasp coordinate system along the last link and axis X_i along the traverse of the gripping device. In finishing robots it is recommended to direct axis Y_i along the last link and to locate axis Z_i in the plane of the mechanism. In this case the position and orientation of point F, which is used to set the transport paths of the movement, are described by the matrix:

$$T_F = T_1T_2T_3 = \begin{bmatrix} C\varphi_1 & -S\varphi_1C\varphi_2 & S\varphi_1S\varphi_2 & S_3S\varphi_1S\varphi_2 \\ S\varphi_1 & C\varphi_1C\varphi_2 & -C\varphi_1S\varphi_2 & -S_3C\varphi_1S\varphi_2 \\ 0 & S\varphi_2 & C\varphi_2 & l_1+S_3C\varphi_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

The configuration of the kinematic model should comprise the description of position and location of the point R defining the initial position of the orienting module:

$$T_r = T_FT_4 = \begin{bmatrix} C\varphi_1 & -S\varphi_1C(\varphi_2+\varphi_4) & S\varphi_1S(\varphi_2+\varphi_4) & (S_3S\varphi_2+l_4S(\varphi_2+\varphi_4))S\varphi_1 \\ S\varphi_1 & C\varphi_1C(\varphi_2+\varphi_4) & -C\varphi_1S(\varphi_2+\varphi_4) & (S_3S\varphi_2+l_4S(\varphi_2+\varphi_4))C\varphi_1 \\ 0 & S(\varphi_2+\varphi_4) & C(\varphi_2+\varphi_4) & l_1S_3C\varphi_2+l_4C(\varphi_2+\varphi_4) \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

The change of the component position and orientation during the operation of the orienting degrees of freedom are described by the transformation matrix:

$$T_{or} = T_5 \cdot T_6 = \begin{bmatrix} -S\varphi_5 \cdot C\varphi_6 & -C\varphi_5 & S\varphi_5 \cdot S\varphi_6 & l_6 \cdot S\varphi_5 \cdot S\varphi_6 \\ C\varphi_5 \cdot C\varphi_6 & -S\varphi_5 & -S\varphi_6 \cdot C\varphi_5 & -l_6 \cdot C\varphi_5 \cdot S\varphi_6 \\ S\varphi_6 & 0 & C\varphi_6 & l_1+l_6 \cdot C\varphi_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Using these matrices one can define the position and orientation of the component being mounted with help of the transformation matrix: $T_P = T_F + T_{or}$. On the basis of this matrix one devises the system of equations to determine

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coordinates of point P in the coordinate system of the robot $X_mY_mZ_m$:

$$X_P = l_6 \cdot C\varphi_1 S\varphi_5 S\varphi_6 + l_6 \cdot S\varphi_1 C(\varphi_2+\varphi_4) C\varphi_5 S\varphi_6 + (l_5 + l_6 C\varphi_6) S\varphi_1 S(\varphi_2+\varphi_4) + (S_3 S\varphi_2 + l_4 S(\varphi_2+\varphi_4)) S\varphi_1;$$

$$Y_P = l_6 \cdot S\varphi_1 S\varphi_5 S\varphi_6 + l_6 \cdot C\varphi_1 C(\varphi_2+\varphi_4) C\varphi_5 S\varphi_6 + (l_5 + l_6 C\varphi_6) C\varphi_1 S(\varphi_2+\varphi_4) + (S_3 S\varphi_2 + l_4 S(\varphi_2+\varphi_4)) C\varphi_1;$$

$$Z_P = l_1 + S_3 C\varphi_2 + l_4 \cdot C(\varphi_2+\varphi_4) + (l_5 + l_6 C\varphi_6) C(\varphi_2+\varphi_4) + l_6 C\varphi_5 S\varphi_6 (\varphi_2+\varphi_4).$$

When controlling the robot's movement, data about the speed of the grip motions and the point defining the transport path of the movement are necessary. At the given speed of the manipulator link motioning the gripper linear velocity on the axis $X_mY_mZ_m$ is defined by the equations:

$$\nu_x^{(F)} = S_3' \cdot S\varphi_1 S\varphi_2 + S_3 C\varphi_1 S\varphi_2 \cdot \varphi_1' + S_3 S\varphi_1 C\varphi_2 \cdot \varphi_2';$$

$$\nu_y^{(F)} = -S_3' \cdot C\varphi_1 S\varphi_2 + S_3 S\varphi_1 S\varphi_2 \cdot \varphi_1' - S_3 C\varphi_1 C\varphi_2 \cdot \varphi_2';$$

$$\nu_z^{(F)} = S_3' \cdot C\varphi_2 + S_3 S\varphi_2 \cdot \varphi_1'.$$

The velocity of the arm upper point (point F) motion are described by the equations:

$$\nu_x^{(P)} = \sum_{i=1}^{4} \frac{\partial x_p}{\partial \varphi_i} \varphi_i' + \frac{\partial x_p}{\partial S_3} S_3'; \quad \nu_y^{(P)} = \sum_{i=1}^{4} \frac{\partial y_p}{\partial \varphi_i} \varphi_i' + \frac{\partial y_p}{\partial S_3} S_3';$$

$$\nu_z^{(P)} = \sum_{i=1}^{4} \frac{\partial z_p}{\partial \varphi_i} \varphi_i' + \frac{\partial z_p}{\partial S_3} S_3'.$$

Kinematic models of mounting and finishing robots must include systems of equations to define positions of the degrees of freedom and speeds of their movement, ensuring the preset grasp position and the required speed of its movement. These equations are derived on the basis of the transformation matrix elements T_F, T_R and T_{or} by the way of simultaneous solution of the system of equations and their multiple transformations. To use the methods of successive approximations for solving inverse kinematic problems is not recommended. To simplify the development of kinematic models we suggest using the method of decomposition of the structure, the essence of which is in breaking the architecture into elementary type structures. This allows having transformation matrices for each type module in advance that connects its input and output coordinate systems.

3. MOTION PLANNING AND CONTROL

Mounting and finishing robots' motion planning should be performed in the form of setting motion and velocity vectors in projections on the axis of the robot coordinate system:

$$X_P(t) = [x_P(t), y_P(t), z_P(t)];$$

$$V_P(t) = [\nu_{xp}(t), \nu_{yp}(t), \nu_{zp}(t)].$$

When performing most technological operations by construction robots the velocity module is constantly chosen.

Motion planning of mounting robots first of all, includes design of a component trajectory to handle it to the mounting area. An analysis of the mounting technology has shown that it is most favorable to use trajectories consisting of two or three rectilinear sections. They do include vertical hoisting of the component to the preset height and its horizontal displacement along the straight line to the point of positioning. With high and extended object components, handling can be carried out along the vertical hoist of the component from the cassette. The vertical motion is described by the equations:

$$X_1(t) = [x_0, y_0, z_0 + \nu_z t] \text{ and } V_p = [o, o, \nu_z].$$

When carrying out this motion the vertical position of the component must be preserved. The characteristic feature of mounting robots' motion planning is defining the degrees of freedom, ensuring handling operations and forming control laws for them. For robots with kinematics structure presented in Figure 1, the vertical hoisting of the component without altering its position is provided by the degrees of freedom φ_2, S_3, φ_4:

$$\varphi_2(t) = \frac{\nu_z t}{r_F}; \quad S_3(t) = (\nu_z^2 + r_F^2)^{\frac{1}{2}}; \quad \varphi_4(t) = (\pi + \varphi_2(t)),$$

where $r_F^2 = x_F^2 + y_F^2$.

The horizontal dispacement of the component from the point $H(x_h, y_h, z_h)$ to the point $P(x_p, y_p, z_p)$ of positioning is described by the vector

$$X_2(t) = [(x_h + \nu_x t), (y_h + \nu_y t), z_h]$$

and the components of the velocity vector are equal to

$$\nu_x = \frac{|\nu| \cdot (x_p - x_h)}{l_{Ph}}; \quad \nu_x = \frac{|\nu| \cdot (y_p - y_h)}{l_{Ph}}; \quad \nu_x = 0,$$

where $l_{Ph} = ((x_p + x_h)^2 + (y_p + y_h)^2)^{\frac{1}{2}}$.

For the robot under consideration, such motions are provided by the degrees of freedom Y_1, Y_2, Y_3, Y_4, controlled according to the expressions:

$$\varphi_1(t) = atctg \frac{y_h + \nu_y y}{x_h + \nu_x t}; \quad \varphi_2(t) = arctg \frac{z_p - l_1}{l(t)}; \quad \varphi_4(t) = \varphi_2(t),$$

where $l(t) = (x_h + \nu_x t)^2 + (y_h + \nu_y t)^2$.

Link drive control from the point of component hoisting and displacement to the point of positioning should be carried out along the velocity vector under position control. During this operation one should start with constant acceleration and slowly when coming to the point of positioning according to the law:

$$\nu(t) = \nu_n \exp(-kt); \quad w(t) = w_{\max} \exp(-kt),$$

where k is the coefficient of braking intensity.

The component is reoriented to the point of positioning, the process of its orientation takes place so that the gripping device coordinate system $X_iY_iZ_i$ becomes coaxial with the coordinate system $X_bY_bZ_b$ of the installation. Orienting degree control should be carried out on the basis of the

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synthesized control laws, taking into account inertial characteristics of the component, manipulator and drive links. The most critical and high precision operation is the component fitting after its orientation and requires axis timing. When developing algorithms, the manipulator should be viewed as a multilane mechanism with dynamically connected movements of separate links. The dynamics of the degrees of freedom can be decomposed and the number of calculations can be reduced by introducing adaptive control of robot's actuating mechanisms on the basis of the system decomposition. In this case control is generated in the form of two components: $\overline{U}=\overline{U}_P+\overline{U}_A$. Program control ($\overline{U}_P$) is synthesized with an account of the guide dynamics and the adaptive component ($\overline{U}_A$) with adjustable parameters is determined by the expression $\overline{U}_A=L\overline{X}+K\overline{U}$, where L is the matrix of the adjustable parameters including dynamics and mutual influence of channels, K is stated the matrix of parameters including decomposition of controlling signals, and X is the vector of state parameters.

Finishing robot control includes tool removal into an initial position and its orientation and travel along the prescribed path at the required speed. Tool displacement into the initial position should be carried out along the rectilinear trajectories on the basis of kinematic algorithms. Painting of flat surfaces is performed along the rectilinear trajectories at a constant speed:

$$\overline{X}(t)=\begin{bmatrix} x_0+(1-\zeta)\cdot k\cdot\Delta+\zeta\cdot\nu\cdot t \\ y_0 \\ z_0+\zeta\cdot k\cdot\Delta+\zeta(1-\zeta)\cdot\nu\cdot t \end{bmatrix}.$$

where x_0, y_0 and z_0, are the coordinates of the initial points, Δ is a step of parallel trajectories; k is the number of a step; ζ is a parameter of a trajectory position ($\zeta=1$ for horizontal, $\zeta=0$ for vertical).

For irregular surfaces motion planning should be carried out, using three-dimensional cubic splines.

The process of control algorithm development and control program preparation for construction robots is greatly simplified when computer technology is used. Applying methods of mathematical modeling and computer graphics for the search for optimal trajectories of components handling, one has to carry out simulation of the processes of their installation and orientation, to ensure the decomposition of the surfaces being painted and to determine tool motion trajectories in order to generate a database of reference points.

4. CONCLUSIONS

The presented material was prepared on the basis of the authors' research which was carried out while developing proposals on automation and robotization of operations in residential and industrial construction. The kinematic structures and recommendations on motions planning for mounting and finishing robots proposed here can be used while developing designs for robotization of construction work. Thus we can obtain different robots design solutions. While developing kinematics models we should combine matrix, vector and geometric methods for solving problems of kinematics with the purpose of expressions reducing the mount of calculations. Computer simulations of motion of mounting and finishing robots have shown the efficiency of the described methods of planning motion trajectories and drive control. Therefore the presented approaches can serve as recommendations while developing control algorithms for construction robots.

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