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PLANNING TRAJECTORIES OF A MANIPULATION ROBOT WITH A SPHERICAL COORDINATE SYSTEM FOR REMOVING OXIDE FILM IN THE PRODUCTION OF COMMERCIAL LEAD, ZINC

The object of this study is the technological operation of removing the oxide film from the surface of the metal melt, foundry production of commercial lead, zinc. To carry out the robotization of this technological operation, it is proposed to use a manipulation robot with a spherical coordinate system. A kinematic structure of a manipulation robot with six degrees of mobility and two arms is proposed. On the first arm of the manipulation robot, a movable blade is fixed, and on the second arm, a rotary blade is fixed. With the translational movement of the first hand, the movable blade rakes the oxide film onto the rotary blade. Further, the oxide film collected on the rotary blade is thrown into a special container with a rotational movement. Restrictions are introduced on the values of generalized coordinates, velocities, and accelerations for each degree of mobility of the manipulation robot. Taking into account these limitations, for the implementation of this process, software trajectories have been developed for the degrees of mobility of the manipulation robot, which are approximated by quadratic polynomials. Each program movement is divided into three sections, in the first section acceleration with a given acceleration is carried out, in the second section movement with a given speed, in the third section braking with a given acceleration. To assess the reliability of the developed software trajectories, simulations were carried out in the MatLab software environment, version R2015b. The resulting graphs of program trajectories coincide with the calculated values of the generalized coordinates, time intervals, speeds, and accelerations of change in the generalized coordinates in terms of the degrees of mobility of the manipulation robot. The period of time required to remove the oxide film is 15.88 s. On the basis of the results obtained, a cyclogram for controlling a manipulation robot was built to perform the technological operation of removing the oxide film in the production of commercial lead, zinc

Keywords: oxide film, manipulation robot, trajectory planning, program trajectory, quadratic interpolation

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1. Introduction

Commercial lead and zinc are produced in the form of castings called ingots. Metal melts of lead and zinc are poured into molds on carousel-pouring machines. During the pouring of liquid lead or zinc in open air, the surface of the melt is oxidized with the formation of an oxide film [1, 2].

To remove the oxide film from the surface of the metal melt, a technological operation (TO) is performed to collect the oxide film. This TO is monotonous and refers to low-skilled labor; it is performed under conditions that are harmful to the health of the worker. Therefore, in order to carry out the robotization of this TO, it is necessary to conduct research on the development of the kinematics of manipulation robots (MR), planning its software and necessary control sequences. The relevance of the work relates to the need for robotization of TO for the collection of an oxide film from the surface of lead and zinc melts.

2. Literature review and problem statement

Paper [3] reportd the results of a study into the TO of collecting an oxide film from the surface of lead and zinc melts as an object of robotization. This process is considered at various levels, strata. In particular, a hydrodynamic stratum, a description of the process of pouring liquid metal into molds, a heat engineering stratum, a description of the crystallization process of metal poured into molds, a metallurgical stratum, and a description of technological regulations for conducting this TO are singled out. Stratified representation is used as a means of consistently deepening the description of the system, its detailing. The lower we go down the hierarchy of strata, the more detailed the disclosure of the system becomes. The higher we rise, the clearer the meaning and meaning of the whole system becomes. In this case, the casting process is considered as the process of pouring liquid metal into molds, a hydrodynamic stratum. Further, this is the process of cooling the liquid metal poured into the mold, as a result of heat exchange with the mold and the environment. As a result, a solidified ingot, a commodity metal ingot, a heat engineering stratum is obtained. It is necessary to comply with the technological regulations for conducting technological processes, the metallurgical stratum. However, MR kinematic structures have not been developed to perform this TO for collecting an oxide film from the surface of lead and zinc melts.

The proposed kinematic structures of MR, in which it is proposed to collect the oxide film using the translational movement of the movable blades on the rotary blades, is the most appropriate and practically feasible method. However, the location of the collection container opposite the MR, in the case of a lead and zinc foundry, is not applicable. This is due to the fact that the carousel filling machine has a circular design, which excludes the location of the container opposite the MR.

Therefore, the development of the kinematic structure of MR requires the coordination of the process of collecting the oxide film from the surface of the metal melt with TO regulations. It should be possible to collect, dump the collected oxide film into a special container, which must fit into the structure of the carousel casting machine.

In the case of a kinematic structure, it is necessary to develop program trajectories according to the degrees of freedom of MR. This problem is solved with the given design and energy constraints of MR elements.

The use of MR, which has 3 degrees of mobility of translational hinges, is proposed in [4]. In the same work, the location of the oxide film collection tank above the MR was proposed, which allows its use as part of a carousel casting machine. Also, the oxide film is dropped into a special container under a special container almost perpendicular to the bottom surface, which in practical use cannot guarantee the complete removal of the oxide film. It should also be noted that the use of translational hinges from the point of view of practical implementation is a more complex design problem [5].

Automatic generation of program trajectories of MR motion, under conditions of uncertainties, which are refined using an explicit description of the set of relationships of objects in the workspace, are considered in [6]. Based on a meaningful description of the existing objects in MR workspace, using logical algorithms, their explicit geometric description is carried out. Using this description, a set of possible variants of program trajectories of movement of the working body is developed with the fulfillment of the condition of non-collision with existing objects in the MR workspace.

Work [7] proposes a heuristic approach to planning the trajectories of MR motion, taking into account the obstacles described approximately in the working space, taking into account which the inverse kinematics problem is solved. The use of the approaches proposed in [6, 7] is advisable in the case of a change in the movements of the manipulation robot, and in the case under consideration, the program trajectories do not change. Therefore, this approach is redundant.

Training methods, in which the movement of the operator's hand is copied and then reproduced by the exoskeleton, are considered in [8]. This is of interest from the point of view of reproducing the movements of the operator to remove the oxide film from the surface of the metal melt. However, in this case, the cost of developing an exoskeleton, which is much more complex than the proposed MR, will be significant.

In [9], a method for tracking the trajectory of the robot's movement is considered, using the method of learning and realizing the movement, using the ideas of the LFD method. Tracking the robot's trajectory is performed using a three-layer neural network, minimizing position and speed errors in real time. This work is interesting from the point of view of adjusting the MR motion trajectory in case of changing the parameters of the technological operation. However, in the foundry, the motion paths remain unchanged.

Optimal tracking of software trajectories using differential evolution (DE) optimization methods and a set of MATLAB tools with an applied robot operating system (ROS) is considered in [10]. This makes it possible to develop software trajectories of movement without colliding with existing obstacles in the workspace of the manipulation robot. This approach is interesting in the case of existing obstacles that change their position. In the case of foundry production of commercial lead, zinc, all obstacles are known in advance and their positions do not change.

Paper [11] considers approaches to planning the program trajectories of MR passing through the nodal points with minimization of time and energy costs. Quintic NURBS curves adapt to match the software trajectory to the anchor points while maintaining continuity in position, velocity, and acceleration. This approach can be applied to develop a program MR trajectory with a complex configuration of the motion trajectory. In the case of movement to remove the oxide film from the surface of the metal melt, the trajectories of movement consist of separate sections in which only acceleration, movement at a given speed, and deceleration are required. The complication of the program trajectory is possible when using a manipulation robot with a more complex kinematic structure, which is a separate scientific problem.

The use of finite impulse response filters for the development of a MR program trajectory scheduler was proposed in [12]. In this case, the program trajectory is divided into several separate sections, and for each section its own polynomial is compiled, which takes into account the restrictions on speed, acceleration, while minimizing the time of movement. This approach is interesting in case of changing the tasks of movement along different trajectories, in the example under consideration the trajectory remains unchanged, therefore this approach is redundant in its capabilities.

From the analysis of works [4, 5], we can conclude that it is necessary to develop kinematic structures of MR that meet the requirements of the foundry production of commercial lead, zinc. The use of approaches [6, 7, 9, 12] for solving the problem of planning MR program trajectories for removing the oxide film from the surface of lead and zinc melts is redundant, due to the certainty of MR motion trajectories. The development of an exoskeleton [8] for performing TO of removing an oxide film from the surface of lead and zinc melts is a separate complex problem.

Therefore, it is expedient for the robotization of TO to remove the oxide film from the surface of lead and zinc melts using the simplest kinematic structures of MR that meet the requirements of the foundry production of commercial lead and zinc. To assess the compliance of the developed kinematic structure with the requirements of the foundry production of commercial lead, zinc, develop software trajectories, conduct their simulation, with further development of a control cyclogram. This will make it possible to evaluate the possibilities of the developed kinematic structure of MR for robotization of TO of removing the oxide film from the surface of lead and zinc melts.

3. The aim and objectives of the study

The aim of this study is to plan program trajectories according to the degrees of mobility of MR in the robotization of the process of removing the oxide film from the surface of lead and zinc melts. This will make it possible to robotize low-skilled workers' labor in the process of removing the oxide film from the surface of lead and zinc melts.

To achieve these goals, the following tasks were set:

– to develop the kinematic structure of the manipulation robot with the practical implementation of the process of removing the oxide film from the surface of lead and zinc melts;

– to develop program trajectories according to the degrees of mobility of the manipulation robot, in the form of quadratic polynomials;

– to evaluate the reliability of the obtained program trajectories by modeling them in MatLab;

– to develop a cyclogram for controlling a manipulation robot to perform the technological operation of removing an oxide film from the surface of lead and zinc melts.

4. The study materials and methods

The object of our study is the TO of removing the oxide film from the surface of foundry melts of commercial lead, zinc. Based on the analysis of production processes, the TO of removing the oxide film from the surface of lead and zinc melts was determined as an object of robotization. Taking into account the specific features of the TO of removing the oxide film from the surface of lead and zinc melts, it is necessary to develop the kinematic structure of MR.

After the kinematic structure of MR is selected, a sequence of movements is developed according to the degrees of mobility of the MR. Next, the limits of change in the generalized coordinates are determined, which ensure the performance of MR and TO of removing the oxide film from the surface of lead and zinc melts. Restrictions are imposed on the values of speeds, accelerations according to the degrees of mobility of the manipulation robot.

Based on these data, program trajectories are formed according to the degrees of mobility of the manipulation robot, which, depending on the complexity of the implemented trajectories, can be approximated by various algebraic polynomials. However, it is necessary to take into account the practical feasibility of the developed kinematic control laws.

To check the reliability of the obtained software trajectories, it is advisable to simulate them, for example, in the MatLab software environment. According to the simulation results, adjustments can be made to the mathematical description of the program trajectories.

Further, based on the results obtained, it is possible to build a MR control cyclogram for performing the technological operation of removing the oxide film from the surface of the lead, zinc melt.

5. Results of investigating the problem of robotization of the technological operation of removing the oxide film from the surface of lead and zinc melts

5. 1. Kinematic structure of the manipulation robot and practical implementation of the process of removing the oxide film from the surface of lead and zinc melts

The oxide film from the surface of the metal melt is proposed to be collected using MR. The proposed version of the MR is a two-armed manipulator with fixed blades, having 6 degrees of freedom, the general view of which is shown in Fig. 1. A distinctive feature of this MR, in contrast to the MR proposed in [4], is the maximum use of rotational joints, which are structurally simpler than translational joints and can realize sufficiently high values of the developed moments and forces [5].

The proposed MR consists of a fixed base with a turntable 1, which implements a rotational hinge specified by the generalized coordinate q_1. On it, the second rotary platform 2 is installed, which implements a rotational hinge specified by the generalized coordinate q_2. On this platform 2, a rolling mechanism 3 is installed, which implements a rotational hinge specified by the generalized coordinate q_3. The rolling mechanism 3 is connected to the first arm 4, which is a translational hinge of the linear movement of rod 5. Movable blades 9 are attached to rod 5, the position of which is determined by the generalized coordinate q_4. On the first arm 4, the second arm 6 is also fixed in the form of a rotational hinge, the position of which is given by the generalized coordinate q_5. Rotary hinge 7 is attached to rotary hinge 6, on which rotary blades 8 are fixed, the position of which is determined by the generalized coordinate q_6.

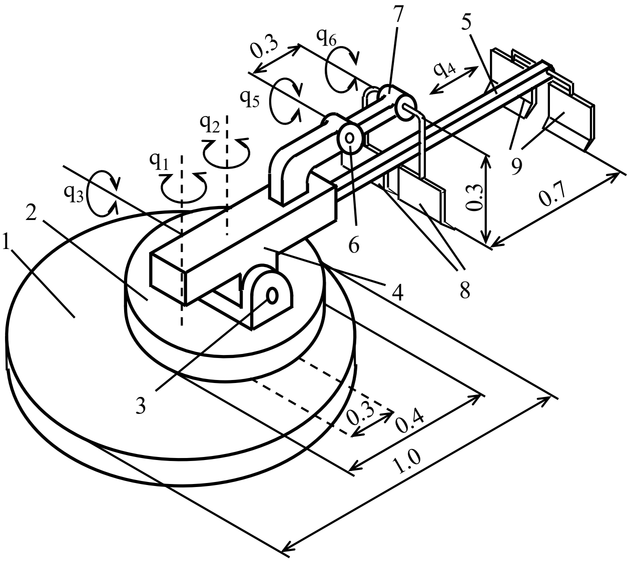

Fig. 1. Manipulation robot for removing the oxide film from the surface of the melt: 1 – fixed base with a turntable, 2 – second turntable, 3 – rolling mechanism, 4 – translational movement mechanism of the first hand, 5 – rod, 6 – swivel joint of the second hand, 7 – rotary hinge of the second hand, 8 – rotary blades, 9 – movable blades

From the analysis of movements by degrees of freedom of the MR, it can be concluded that the drives from 1 to 4 degrees of freedom are electric, and the drives of 5 and 6 degrees of freedom are pneumatic. Consequently, program control systems from 1 to 4 degrees of freedom are positional, and 5 and 6 degrees of freedom are cyclic.

The practical implementation of the process of removing the oxide film in the production of commercial lead, zinc is shown in Fig. 2–5.

In the initial position of the MR, the movable and rotary blades are located in extreme positions relative to each other (Fig. 1). The rolling mechanism 3 is rotated clockwise at a predetermined angle, MP's arms are raised above the mold. Next, the rolling mechanism is rotated counterclockwise by an angle at which the arms of the MP take a horizontal position, corresponding to Fig. 2.

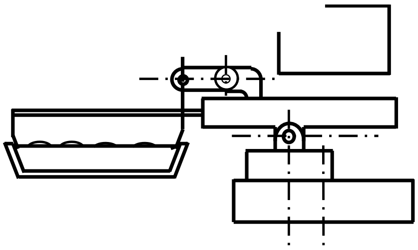

Fig. 2. The starting position of the manipulation robot

At the next step, by the translational movement of the movable blade, the oxide film from the melt surface is collected on the rotary blade. In this position, the rolling mechanism rotates the arms clockwise by a given angle, which corresponds to Fig. 3.

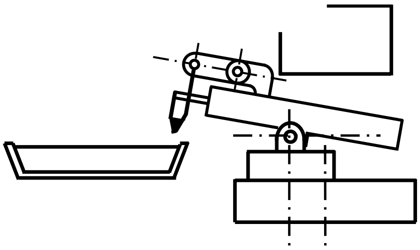

Fig. 3. Position of the manipulation robot with the collected oxide film

Then, at the same time, arm 1 begins a reverse translational movement, and arm 2 of MR rotates clockwise at a given angle, which corresponds to Fig. 4.

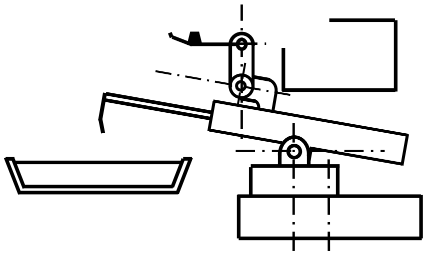

Fig. 4. Position of the manipulation robot with the collected oxide film

With a clockwise rotation, the oxide film is dropped from the rotary blade into a special container, this process is shown in Fig. 5. Now at the same time the rotary vane and the second hand turn counterclockwise, the MP returns to its original position.

The problem is considered when an ingot of commercial lead or zinc has the following geometric dimensions of the surface: length 0.6 m, width 0.4 m (Fig. 6). If the dimensions of the blades are equal to 0.12 m, and the distance between them is 0.07 m, then in this case, in two passes 1 and 2, the oxide film is collected from the surface of the metal melt poured into the mold [3].

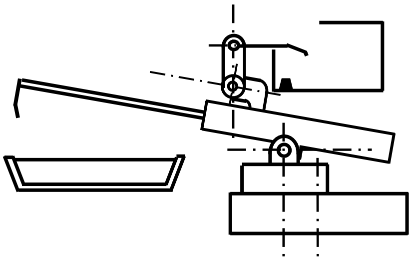

Fig. 5. The position of the manipulation robot when the oxide film is discharged into the container

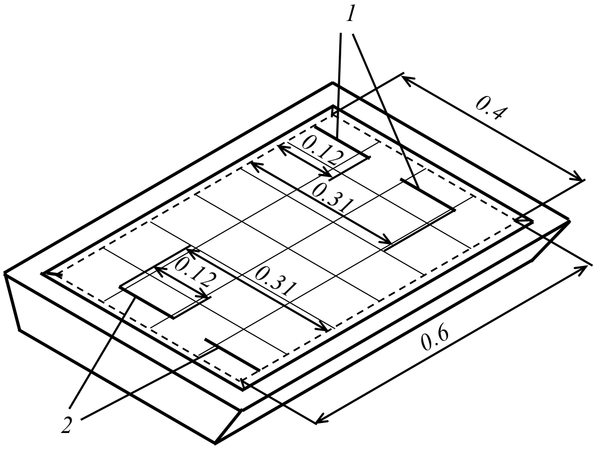

Fig. 6. The geometrical dimensions of the mold and the layout of the blades of the two-armed manipulation robot for removing the oxide film from the surface of the melt:
1 — the position of the molds during the first pass;
2 – the position of the molds during the second pass

This will completely collect all the resulting oxide film from the surface of the metal melt poured into the mold.

5. 2. Construction of program trajectories according to the degrees of mobility of the manipulation robot, in the form of quadratic polynomials

For each degree of MR mobility, the limits of change in the values of generalized coordinates, velocities, and accelerations, limited by the design conditions and energy characteristics of the drives, are set as follows:

$$\begin{cases} -\dfrac{\pi}{2} \le q_1 \le \dfrac{\pi}{2}\,\text{rad}, -\dfrac{\pi}{2} \le q_2 \le \dfrac{\pi}{2}\,\text{rad}, \\ -\dfrac{\pi}{6} \le q_3 \le \dfrac{\pi}{6}\,\text{rad}, \\ 0 \le q_4 \le 0.7\,\text{m}, -\dfrac{\pi}{2} \le q_5 \le 0\,\text{rad}, \\ -\dfrac{\pi}{2} \le q_6 \le \dfrac{\pi}{2}\,\text{rad}. \end{cases} \tag{1}$$

$$\begin{cases} -\pi \le \dot{q}_1 \le \pi\,\text{rad/s}, -\pi \le \dot{q}_2 \le \pi\,\text{rad/s}, \\ -\dfrac{\pi}{2} \le \dot{q}_3 \le \dfrac{\pi}{2}\,\text{rad/s}, \\ -0.4 \le \dot{q}_4 \le 0.4\,\text{m/s}, -\pi \le \dot{q}_5 \le \pi\,\text{rad/s}, \\ -\pi \le \dot{q}_6 \le \pi\,\text{rad/s}. \end{cases} \tag{2}$$

$$\begin{cases} -\frac{\pi}{2} \le \ddot{q}_1 \le \frac{\pi}{2}\,\text{rad/s}^2, -\frac{\pi}{2} \le \ddot{q}_2 \le \frac{\pi}{2}\,\text{rad/s}^2, \\ -\frac{\pi}{3} \le \ddot{q}_3 \le \frac{\pi}{3}\,\text{rad/s}^2, \\ -0.6 \le \ddot{q}_4 \le 0.6\,\text{n/s}^2. \end{cases} \qquad (3)$$

When planning trajectories, we approximate the motion in degrees of mobility of the MR by quadratic polynomials. In this case, the condition for the coincidence of the values of velocities and accelerations at the nodal points of conjugation of sections of the MR motion trajectory is provided [4, 5].

The initial position of MR is given by the values of the generalized coordinates by degrees of mobility $q_{1,1}$=0.258 rad, $q_{2,1}$=–0.258 rad, $q_{3,1}$=0.209 rad, $q_{4,1}$=0.6 m, $q_{5,1}$=0 rad, $q_{6,1}$=–1.57 rad.

At the first step, the process of lowering the blades to the surface of the melt is carried out to collect the oxide film. This process is carried out by changing the value of the generalized coordinate according to the 3rd degree of mobility of MR $q_{3,1}$=0.209 rad to the value $q_{3,2}$=0 rad, then the increment of the generalized coordinate is:

$$\Delta q_{3,1} = q_{3,2} - q_{3,1} = -0.209\,\text{rad}.$$

In this case, you must first accelerate, then perform braking with maximum acceleration. Then the time intervals and increments of the generalized coordinate for acceleration $\Delta q^{p}_{3,1}$ and deceleration $\Delta q^{\text{т}}_{3,1}$ are:

$$\Delta q^{p}_{3,1} = \frac{\Delta q_{3,1}}{2} = -0.1045\,\text{rad},$$

$$\Delta q^{m}_{3,1} = \frac{\Delta q_{3,1}}{2} = -0.1045\,\text{rad}.$$

Hence:

$$\Delta q^{p}_{3,1} = -\frac{\ddot{q}_3 \left(\Delta t_{3,1}\right)^2}{2}, \;\; -0.1045 = -\frac{1.047\left(\Delta t_{3,1}\right)^2}{2},$$

$$\Delta t^{p}_{3,1} = 0.45\,\text{s},$$

where $\Delta t^{p}_{3,1}$ – time to accelerate to the 3rd degree of mobility of MR;

$$\dot{q}_3 = \ddot{q}_3 \Delta t^{p}_{3,1} = 0.47\,\text{rad/s}, \;\; \dot{q}_3 - \ddot{q}_3 \Delta t^{m}_{3,1} = 0, \;\; \Delta t^{m}_{3,1} = 0.45\,\text{s},$$

where $\Delta t^{\text{т}}_{3,1}$ – time to braking to the 3rd degree of mobility of MR.

Therefore, the trajectory of movement in 3 degrees of mobility will be as follows:

$$\begin{cases} t = 0 : q_{3,1} = 0.209\,\text{rad}, \\ \forall t \in [0, 0.45] : q^{p}_{3,1} = 0.209 - \frac{1.0472 t^2}{2}, \\ \forall t \in [0.45, 0.9] : q^{m}_{3,1} = 0.1045 - 0.47 t + \frac{1.0472 t^2}{2}, \\ t = 0.9 : q_{3,2} = 0\,\text{rad}. \end{cases} \qquad (4)$$

Next, the oxide film is collected from the surface of the melt due to the translational movement of the movable blade onto the rotary blade. To implement this movement, the value of the generalized coordinate for the 4th degree of mobility of MR changes from $q_{4,1}$=0.6 m to $q_{4,2}$=0 m, then:

$$\Delta q_{4,1} = q_{4,2} - q_{4,1} = -0.6\,\text{m}.$$

In this case, first, acceleration to a given speed is carried out, then movement at a given speed, and at the end, braking to zero speed is realized. Acceleration is carried out from zero speed to a value $\dot{q}_4 = 0.3\,\text{m/s}$, since the movement of the movable blade at a higher speed can lead to splashing of the melt, then:

$$\dot{q}_4 = \ddot{q}_4 \Delta t^{p}_{4,1}, \;\; \Delta t^{p}_{4,1} = 0.5\,\text{s},$$

where $\Delta t^{p}_{4,1}$ – time to accelerate to the 4th degree of mobility of MR.

Hence:

$$\Delta q^{p}_{4,1} = -\frac{\ddot{q}_4 \left(\Delta t^{p}_{4,1}\right)^2}{2} = 0.075\,\text{m},$$

where $\Delta q^{p}_{4,1}$ is the value of the increment of the generalized coordinate for acceleration along the 4th degree of freedom of MR.

In the case of the braking process, the initial speed is equal to $\dot{q}_4 = 0.3\,\text{m/s}$, and the final speed is equal to zero. From these considerations:

$$\dot{q}_4 = \ddot{q}_4 \Delta t^{m}_{4,1}, \;\; 0.3 = 0.6 \cdot \Delta t^{m}_{4,1}, \;\; \Delta t^{m}_{4,1} = 0.5\,\text{s}.$$

where $\Delta t^{m}_{4,1}$ – time to brake at the 3rd degree of mobility of MR.

Hence:

$$\Delta q^{m}_{4,1} = \dot{q}_4 \Delta t_{4,1} - \frac{\ddot{q}_4 \left(\Delta t^{\text{т}}_{4,1}\right)^2}{2}, \;\; \Delta q^{m}_{4,1} = 0.075\,\text{m},$$

where $\Delta q^{m}_{4,1}$ is the value of the increment of the generalized coordinate for deceleration according to the 4th degree of mobility of MR.

In this case, the value of the distance of movement at a given speed $\dot{q}_4 = 0.3\,\text{m/s}$ is equal to:

$$\Delta q^{d}_{4,1} = \Delta q^{m}_{4,1} - \Delta q_{4,1} - \Delta q_{4,1} = -0.45\,\text{m}.$$

Then:

$$-0.45 = -0.3 \cdot \Delta t^{d}_{4,1}, \;\; \Delta t^{d}_{4,1} = 1.5\,\text{s},,$$

where $\Delta t^{d}_{4,1}$ is the time of movement at a given speed $\dot{q}_4 = 0.3\,\text{m/s}$ according to the 4th degree of mobility of MR.

From here, the trajectory of movement along the fourth degree of mobility will take the following form:

$$\begin{cases} t = 0.9 : q_{4,1} = 0.6\,\text{m}, \\ \forall t \in [0.9, 1.4] : q^{p}_{4,1} = 0.6 - \frac{0.6 t^2}{2}, \\ \forall t \in [1.4, 2.9] : q^{d}_{4,1} = 0.525 - 0.3 t, \\ \forall t \in [2.9, 3.4] : q^{m}_{4,1} = 0.075 - 0.3 t + \frac{0.6 t^2}{2}, \\ t = 3.4 : q_{4,2} = 0\,\text{m}. \end{cases} \qquad (5)$$

At the next step, the process of lifting the blades is carried out, then the program trajectory of movement along the 3rd degree of freedom, similar to the derivation of expression (4), takes the following form:

$$\begin{cases} t=3.4: q_{3,2}=0\text{ rad}, \\ \forall t\in[3.4,3.85]: q_{3,2}^{p}=\dfrac{1.0472t^{2}}{2}, \\ \forall t\in[3.85,4.3]: q_{3,2}^{m}=0.1045+0.47t-\dfrac{1.0472t^{2}}{2}, \\ t=0.9: q_{3,2}=0\text{ rad}. \end{cases} \tag{6}$$

Next, the reverse translational movement of the movable blade is performed, then the program trajectory of movement along the 4th degree of mobility, obtained similarly to expression (5), is written as follows:

$$\begin{cases} t=4.3: q_{4,2}=0\text{ m}, \\ \forall t\in[4.3,4.8]: q_{4,2}^{p}=\dfrac{0.6t^{2}}{2}, \\ \forall t\in[4.8,6.3]: q_{4,2}^{d}=0.075+0.3t, \\ \forall t\in[6.3,6.8]: q_{4,2}^{m}=0.525+0.3t-\dfrac{0.6t^{2}}{2}, \\ t=6.8: q_{4,3}=0.6\text{ m}. \end{cases} \tag{7}$$

In parallel with movement (5) along the 4th degree of freedom, the movement is performed along the 5th degree of freedom – turning counterclockwise to the angle value $q_{5,2}$=1.36 rad. In this case, the time of the start of movement along a given degree of freedom should ensure the condition of mutual non-collision of the rotary and movable blades. The trajectory of movement along the 5th degree of freedom of the MR, taking into account the pneumatic drive, which is not controlled by acceleration, taking into account the speed value given by expression (2), is described as follows:

$$\begin{cases} t=5.0: q_{5,1}=0\text{ rad}, \\ \forall t\in[5.0,5.43]: q_{5,1}^{n}=3.14t, \\ t=5.43: q_{5,2}=1.36\text{ rad}. \end{cases} \tag{8}$$

Next, movement is performed along the 6th degree of mobility, turning counterclockwise at an angle $q_{6,2}$=1.57 rad. This ensures that the oxide film is discharged into a special container. Next, a clockwise rotation is carried out to the value $q_{6,3}$=–1.57 rad. The trajectory of movement along the 6th degree of freedom of the MR, taking into account the pneumatic drive, which is not controlled by acceleration, taking into account the value of the speed given by expression (2), is described as follows:

$$\begin{cases} t=5.43: q_{6,1}=-1.57\text{ rad}, \\ \forall t\in[5.43,6.43]: q_{6,1}^{c}=-1.57+3.14t, \\ t=6.43: q_{6,2}=1.57, \\ \forall t\in[6.43,7.43]: q_{6,2}^{u}=1.57-3.14t, \\ t=6.8: q_{6,3}=-1.57\text{ rad}. \end{cases} \tag{9}$$

At the next step, movement is performed along the 5th degree of mobility, similar to expression (8), the program trajectory of which is equal to:

$$\begin{cases} t=7.43: q_{5,2}=1.36\text{ rad}, \\ \forall t\in[7.43,7.86]: q_{5,1}^{u}=1.36-3.14t, \\ t=7.86: q_{5,3}=0\text{ rad}. \end{cases} \tag{10}$$

After completing the movement in the 4th degree of freedom, it is possible, regardless of the movements for the 5th and 6th degrees of freedom, to transfer the MR to the 2nd trajectory for collecting the oxide film.

To do this, movement is carried out along degree of mobility 1, similar to expression (4), the program trajectory of which takes the following form:

$$\begin{cases} t=6.8: q_{1,1}=-0.258\text{ rad}, \\ \forall t\in[6.8,7.37]: q_{1,1}^{p}=-0.258+\dfrac{1.57t^{2}}{2}, \\ \forall t\in[7.37,7.94]: q_{1,1}^{m}=0.9t-\dfrac{1.57t^{2}}{2}, \\ t=7.94: q_{1,2}=0.258\text{ rad}. \end{cases} \tag{11}$$

Further, movement is carried out along degree of mobility 2, similar to expression (4), the program trajectory of which will be written as follows:

$$\begin{cases} t=6.8: q_{2,1}=0.258\text{ rad}, \\ \forall t\in[6.8,7.37]: q_{2,1}^{p}=0.258-\dfrac{1.57t^{2}}{2}, \\ \forall t\in[7.37,7.94]: q_{2,1}^{m}=-0.9t+\dfrac{1.57t^{2}}{2}, \\ t=7.94: q_{2,2}=-0.258\text{ rad}. \end{cases} \tag{12}$$

Thus, it is possible to remove the oxide film from the second part of the surface of the melt poured into the mold. First, movement is carried out along the third degree of mobility (4), at $\forall t\in[7.9, 8.84]$. Further, the movement is carried out along the fourth degree of mobility (5), at $\forall t\in[8.84, 11.34]$. At the next step, movement is carried out along the third degree of mobility (6), with $\forall t\in[11.34, 12.24]$. Now it is possible to move along the fourth degree of mobility (7), at $\forall t\in[12.24, 14.74]$. In parallel, movement is performed along the fifth degree of freedom (8), at $\forall t\in[12.94, 13.39]$. Further, the collected oxide foam is dumped into the container, moving along the sixth degree of mobility (9), at $\forall t\in[13.39, 15.39]$. The next step is to move along the fifth degree of mobility (10), at $\forall t\in[15.39, 15.84]$.

At the next step, movement is carried out along the 1st degree of mobility, similar to expression (4), the program trajectory of which takes the following form:

$$\begin{cases} t=14.74: q_{1,2}=0.258\text{ rad}, \\ \forall t\in[14.74,15.31]: q_{1,2}^{p}=0.258-\dfrac{1.57t^{2}}{2}, \\ \forall t\in[15.31,15.88]: q_{1,2}^{m}=0.9t-\dfrac{1.57t^{2}}{2}, \\ t=15.88: q_{1,3}=-0.258\text{ rad}. \end{cases} \tag{13}$$

The program trajectory of movement along the 2nd degree of mobility, like expression (4), is described by the following expression:

$$\begin{cases} t=14.74: q_{2,2}=-0.258\text{ rad}, \\ \forall t\in[14.74,15.31]: q_{2,2}^{p}=-0.258+\dfrac{1.57t^2}{2}, \\ \forall t\in[15.31,15.88]: q_{2,2}^{m}=0.9t-\dfrac{1.57t^2}{2}, \\ t=15.88: q_{2,3}=0.258\text{ rad}. \end{cases} \qquad (14)$$

Thus, the removal of the oxide film from the surface of the poured metal melt into the mold of the carousel casting machine will be ensured over a period of time equal to 15.88 s according to expressions (13), (14).

5. 3. Modeling of program trajectories according to the degrees of mobility of a manipulation robot in MatLab

To check the reliability of our expressions that describe the program trajectories in terms of the degrees of mobility of MR, their simulation was carried out in the MatLab software environment [6]. Program trajectories for degree of mobility 1 are modeled using the *Tr_q*1.*m* program and are built on the basis of expressions (11), (13). The simulation results are shown in Fig. 7.

From the obtained simulation results (Fig. 7), it can be seen that the graph of the change in the value of the generalized coordinate for degree of mobility 1 is a monotonic function. The values of the generalized coordinates and moments of time shown in Fig. 7 coincide with the values given in expressions (11), (13).

Program trajectories for the second degree of freedom are modeled using the *Tr_q2.m* program and are built on the basis of expressions (12), (14). The simulation results are

From the obtained simulation results (Fig. 7), it can be seen that the graph of the change in the value of the generalized coordinate for degree of freedom2 is a monotonic function. The values of the generalized coordinates and moments of time shown in Fig. 8 coincide with the values given in expressions (12), (14).

Program trajectories along the third degree of freedom are modeled using the *Tr_q*3.*m* program and are built on the basis of expressions (4), (6). The simulation results are shown in Fig. 9.

From the obtained simulation results (Fig. 9), it can be seen that the graph of the change in the value of the generalized coordinate for the 3rd degree of mobility is a monotonic function. The values of the generalized coordinates and moments of time shown in Fig. 9 coincide with the values given in expressions (4), (6).

Program trajectories for the fourth degree of freedom are modeled using the *Tr_q*4.*m* program and are built on the basis of expressions (5), (7). The simulation results are shown in Fig. 10.

From the obtained simulation results (Fig. 10) it can be seen that the graph of the change in the value of the generalized coordinate for the 4th degree of freedom is a monotonic function. The values of the generalized coordinates and moments of time shown in Fig. 10 coincide with the values given in expressions (5), (7).

Program trajectories along the fifth degree of mobility are modeled using the *Tr_q*5.*m* program and are built on the basis of expressions (8), (10). The simulation results are shown in Fig. 11.

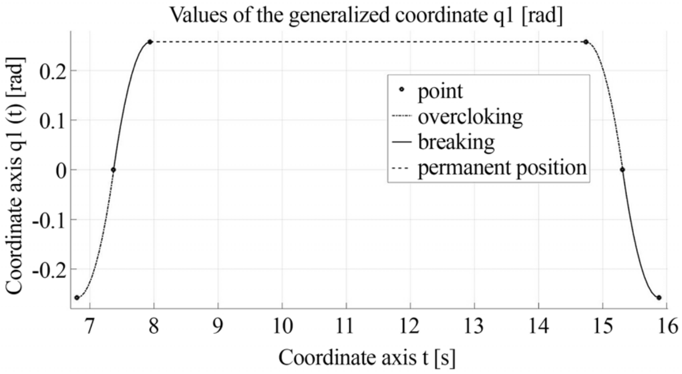

Fig. 7. Program trajectory according to the position of the first degree of mobility of the manipulation robot

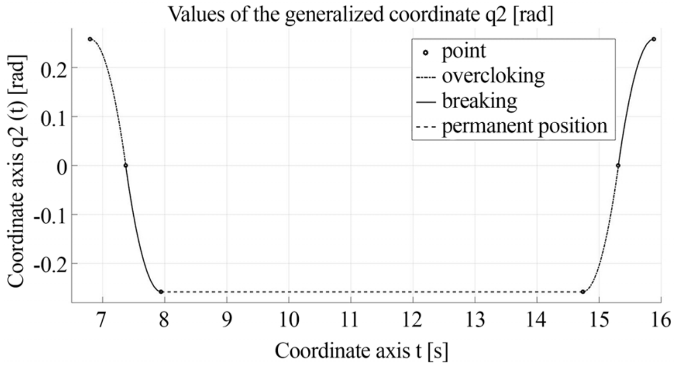

Fig. 8. Program trajectory according to the position of the second degree of mobility of the manipulation robot

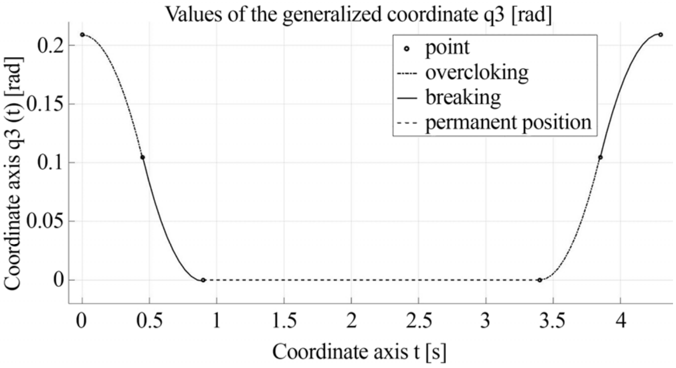

Fig. 9. Program trajectory according to the position of the third degree of mobility of the manipulation robot

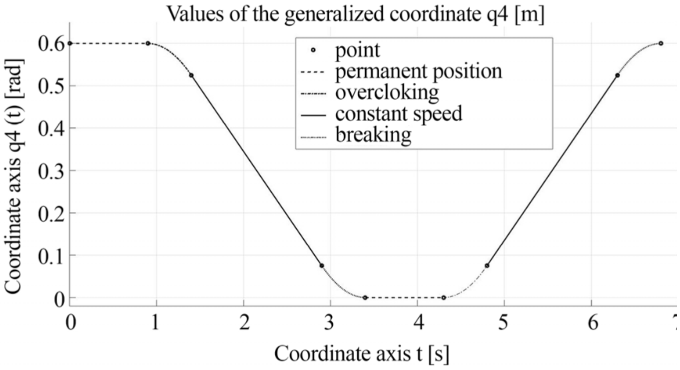

Fig. 10. Program trajectory according to the position of the fourth degree of mobility of the manipulation robot

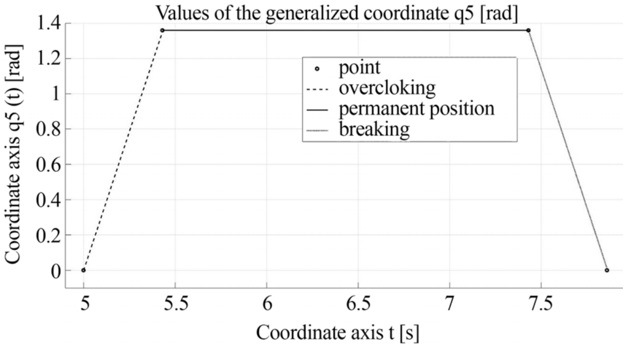

Fig. 11. Program trajectories for the position and speed of the fifth degree of mobility of the manipulation robot

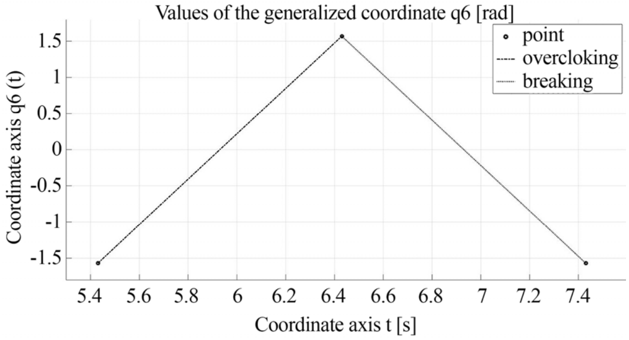

Fig. 12. Program trajectories for the position and speed of the sixth degree of mobility of the manipulation robot

From the obtained simulation results (Fig. 11), it can be seen that the graph of the change in the value of the generalized coordinate according to the 5th degree of mobility is a monotonic function. The values of the generalized coordinates and moments of time shown in Fig. 11 coincide with the values given in expressions (8), (10).

Program trajectories along the fifth degree of mobility are modeled using the *Tr_q*6.*m* program and are built on the basis of expressions (9). The simulation results are shown in Fig. 12.

From the obtained simulation results (Fig. 12) it can be seen that the graph of the change in the value of the generalized coordinate according to the 6th degree of mobility is a monotonic function. The values of the generalized coordinates and moments of time shown in Fig. 12 match the values given in expression (9).

5. 4. Development of a cyclogram for controlling a manipulation robot for removing an oxide film from the surface of lead and zinc melts

Generalizing expressions (4) to (14), as well as the results sshown in Fig. 7–12, a cyclogram for controlling the mobility of the MR for removing the oxide film was constructed, which is shown in Fig. 13. The *y*-axis indicates the transitions in the degrees of mobility of MR. The abscissa shows the time *t*, s.

As can be seen from Fig. 13, for the full cycle of the process of removing the oxide film from the surface of lead and zinc melts, 15.88 s is necessary, which coincides with the obtained values of expressions (13), (14).

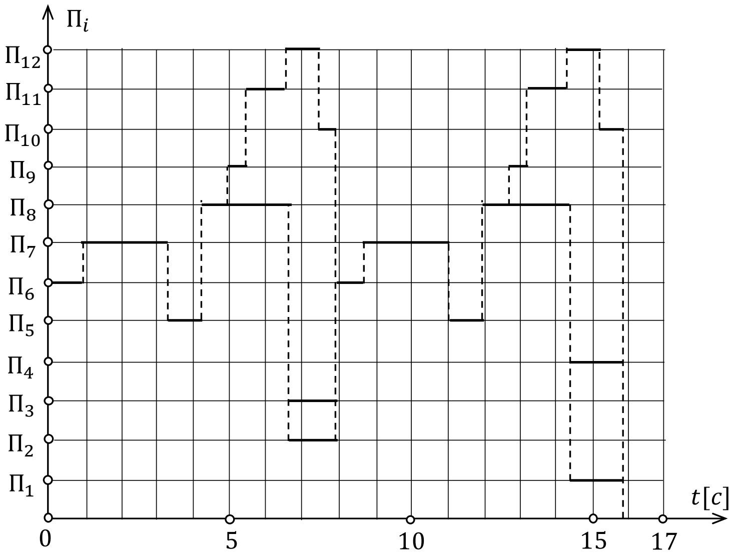

Fig. 13. Control cyclogram according to the degrees of mobility of the manipulation robot for removing the oxide film:
Π_1 — turn counterclockwise of the 1st degree of mobility,
Π_2 — turn clockwise of the first 1st degree of mobility,
Π_3 — turn counterclockwise of the 2nd degree of mobility,
Π_4— turn clockwise 2 degree of freedom,
Π_5 — turn counterclockwise degree of freedom 3, Π_6 — turn clockwise degree of freedom 3,
Π_7 — retraction of the movable blades of degree of freedom 4,
Π_8 — extension of the movable blades of degree of freedom4,
Π_9 — turn counterclockwise of degrees of freedom 5,
Π_{10} — turn clockwise of the 5th degree of freedom,
Π_{11} — turn counterclockwise of the 6th degree of freedom,
Π_{12} — turn clockwise of the first 6th degree of freedom of the manipulator

6. Discussion of results of robotization of the process of removing the oxide film from the surface of lead and zinc melts

For robotization of the TO of removing the oxide film from the surface of lead and zinc melts, a kinematic structure of a two-armed MR with 6 degrees of freedom, shown in Fig. 1, is proposed. 1. In this case, the features of the process of collecting the oxide film, described in [3], are taken into account.

Of interest is the use of the kinematic structure of the exoskeleton [8], which can open up new approaches to collecting an oxide film from the surface of a metal melt. In this case, the approaches to the development of program trajectories proposed in [9, 10] will be useful. The limitation of the use of the exoskeleton is its kinematic redundancy and high cost. Therefore, it is necessary to develop an exoskeleton focused on the performance of this technological operation, which will simplify the kinematic structure and cost of the exoskeleton.

The oxide film is collected by the translational movement of the movable blades onto the rotary blade, as proposed in [4]. The geometric interpretation of the process of collecting metal melt from the surface and dumping the collected oxide film into a special container is shown in Fig. 2. With the given dimensions of the lead, zinc ingot, the collection of the oxide film is carried out in 2 stages [4], which are shown in Fig. 6.

Also, a distinctive feature of the kinematic structure of the proposed MR is the use of two rotational hinges, instead of one translational lateral displacement hinge [4]. In this case, additional restrictions arise on the accuracy of the mechanism and drives of the degrees of freedom of the manipulation robot.

When collecting the oxide film by the translational movement of the movable blade onto the rotary blade, then lifting the collected oxide film from the surface of the metal melt (Fig. 2, *b*) (Fig. 3), further return of the movable blade may not guarantee the fall of some fragments of the oxide film back into the mold. This will require choosing a blade shape that avoids this occurrence. This disadvantage will require additional research in the field of hydrodynamics of the process of collecting an oxide film from the surface of lead and zinc melts.

The process of dumping the oxide film into a special container also has its own difficulties. It is necessary to ensure complete shedding of the oxide film; this may not happen due to the build-up of the oxide film on the surface of the turning blade. Therefore, it is necessary to select such a material for the manufacture of a rotary blade on which an oxide film does not stick.

To improve the process of dropping the oxide film into the kinematic structure of MR, a rotary hinge 6 (Fig. 1) was added, which preliminarily raises the blades to the horizontal position of the rotary blade (Fig. 2, *c*) (Fig. 4). Then, by turning, the collected oxide film is dropped into a special container (Fig. 2, *d*) (Fig. 5). This is an addition to the kinematic structure of the MR proposed in [4].

Program trajectories are described by algebraic polynomials of the second order, taking into account restrictions on the position values, given values of generalized coordinates, speed, acceleration for each degree of mobility. Further complication of the kinematic structure, for example, replacement of the translational joint with two rotational joints, as in Delta robots, will lead to the need to develop software trajectories using the methods described in [11, 12]. At the same time, the complexity of the rotational movements performed, and their high accuracy should be noted. These limitations can be eliminated by using high-precision drives and contour control systems for the movement of a manipulation robot.

The MR control cyclogram is a relationship between the sequence of performing movements according to the degrees of MR mobility and the time intervals necessary for the implementation of this movement. It takes 15.88 s for a full cycle. This is a fairly large time interval. This is due to the fact that the removal of the oxide film requires two passes over the surface of lead and zinc melts (Fig. 6). The removal of the oxide film in one pass cannot be realized with the given kinematic structure of MR. Even in the case of an increase in the size of the movable and rotary blades to a value of 0.4 m, this will complicate the solution of the problem of collecting the melt from the surface and dumping the oxide film into a special container.

For this reason, it is necessary to conduct experimental studies of the proposed version of the kinematic structure of the MR, the design of the elements of which must satisfy the condition of resistance to an aggressive environment. An aggressive environment is formed by acid vapors that remain in the metal melt. This disadvantage will require the use of materials resistant to aggressive environments. It is also necessary to devise approaches to protect the drives of the manipulation robot from the effects of aggressive environments.

7. Conclusions

1. To carry out the robotization of the considered TO, a new kinematic structure of a two-armed MR is proposed, which has 6 degrees of freedom, which, with the help of blades, collects and dumps the oxide film into a special container. A distinctive feature of this MR is the use of rotary joints for lateral displacement, an additional rotary joint to improve the process of shedding the oxide film.

2. Software trajectories have been developed for 6 degrees of mobility of the MR to perform the TO of removing the oxide film from the surface of lead and zinc melts, which are approximated by quadratic polynomials. Each program trajectory contains sections of acceleration, movement at a given speed and deceleration.

3. The reliability of the developed software trajectories was assessed by modeling in MatLab. It showed that the obtained graphs of program trajectories coincide with the calculated values of generalized coordinates, time intervals, velocities, and accelerations of change in generalized coordinates in terms of degrees of freedom of the manipulation robot.

4. A cyclogram for controlling a 6-degree two-handed MR has been constructed to perform TO for removing the

oxide film in the production of commercial lead, zinc: the execution cycle is 15.88 s.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The manuscript contains data included as additional electronic material.

The data will be provided upon reasonable request.

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