Optimizing the structural parameters of the robotic system to ensure the efficiency and reliability of work in the production environment[1*]

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Abstract
In this article, an automated line for cutting splines in ring-shaped workpieces is developed. The design of the line is described, which includes a CNC machine for cutting splines, a mobile industrial robot with a rectangular coordinate system, various types of conveyors, and roller conveyors for transporting workpieces. The basis of the line is a CNC machine tool and a mobile industrial robot equipped with a system of drives and gears. The principles of operation and design features of the robot are detailed, including the system of drives and gears that ensure its mobility and functionality. A numerical analysis of the kinematics of the manipulator was carried out, as well as simulation modeling using software to evaluate the efficiency of the proposed system.

Keywords
Automated line, spline cutting, industrial robot, kinematic analysis, design

1. Introduction

In today's manufacturing environment, where time and accuracy are critical factors, automation is increasingly necessary to achieve high productivity and production quality. Automated lines that combine various technologies and devices become welcome elements in ensuring effective production processes. Robotic systems in the modern production environment play a key role in ensuring the efficiency and reliability of production processes. The rapid development of technologies and the growth of market needs require constant improvement of the designs of robotic systems in order to optimize their functional characteristics.

SMARTINDUSTRY-2024: International Conference on Smart Automation & Robotics for Future Industry, April 18 - 20, 2024, Lviv, Ukraine
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However, there are certain challenges and issues encountered when designing and using robotic systems in a manufacturing environment. Inefficiencies, limited resources, excessive costs and deficiencies in reliability can lead to inefficient production processes and losses for the enterprise.

In this context, this article is aimed at researching methods and approaches to optimizing the structural parameters of robotic systems in order to increase their efficiency and reliability in the production environment. The study highlights the aspects that permit achievement of this goal and improve the functional characteristics of robotic systems.

With the development of industrial automation, the number of manipulator application scenarios is constantly increasing. Jobs are extremely widespread in the conditions of modern society and production. Labor-intensive and tiring industrial tasks such as stamping, engraving, welding, and billet feeding are prevalent in the current assembly line mass production model. Durability, ease of use and efficiency of industrial robots contribute to their wide implementation in various industries. The studies analysed testify to a wide range of scientific research specifically in the field of automated production. Accordingly, there is a growing demand for accuracy, stability and cost-effectiveness of devices during the performance of industrial tasks. [1- 4]

Robotic arms were designed using Solidworks software in the works [5 - 7]. In the research reported in [5], a robotic arm is designed and developed with four degrees of freedom (DOF). The geometry of the arm was designed in [6] using Solidworks software, which was further processed in ANSYS® software and static structural analysis of the robotic arm using Finite Element Analysis (FEA)was performed. The study [7] presents a design alternative and analysis of the structure of the 6 DOF robot arm. This research could be used as references for designing and manufacturing a 6 DOF robot arm with a related robot's structure.

In the next scientific article [8], it is offered useful insights into the current knowledge gaps, emerging trends, and future prospects for the growth of robotic welding in maritime applications are offered following a deep analysis of the several research results.

The study of optimizing the productivity of automated production lines using various technologies is analysed. So, in the article [9] it is demonstrated how a digital/simulation model is demonstrated to predict line performance given stochastic behaviour and how this can be used to analyse the impact of parameter changes on performance. Article shows [10] how metamodels can be used to predict line performance and identify optimal design parameters. The authors also consider the possibility of integrating the metamodel into Digital Twin to optimize production processes. The design problem of a semi-automated assembly line considering energy consumption, smoothness index and total cost and approaches to developing an efficient production line are researched in [11, 12].

The advantages of using an up-to-date digital model of the plant for further optimization and expansion of production, which allows reduction of the reconstruction time and the production line expansion phase, are demonstrated in [13].

Modelling, along with an optimization system, is an invaluable tool for confirming that an automated production line can meet the stated business goals before and after it goes live. Implementing actual changes in equipment to improve reliability can be time-consuming and expensive.

As industrial automation continues to evolve, the integration of sophisticated design tools, simulation models, and optimization frameworks is indispensable. These elements collectively forge pathways towards not only refining current manufacturing capabilities but also paving the way for next-generation industrial robotics. Future research should continue to push the boundaries of what is possible in automation technology, focusing on the development of more adaptable, intelligent, and energy-efficient robotic systems. This will be crucial in maintaining the momentum of innovation and meeting the ever-growing demands of modern industry.

The purpose of this study is to design and optimize the design of an industrial robot for cutting slots in ring-shaped workpieces. Important aspects are also the analysis of manipulator kinematics, and numerical and simulation modeling of its movements.

2. Automated Line Design

The proposed automated line for cutting splines in ring-shaped workpieces is an important unit used in production processes. This line combines advanced decisions to ensure the efficiency and accuracy of manufacturing. The purpose of this line is to automate the cutting process, which ensures an increase in productivity and production quality.

Consider the components of the automated spline cutting line in ring-shaped workpieces (Figure 1), focusing on their functional purpose and features.

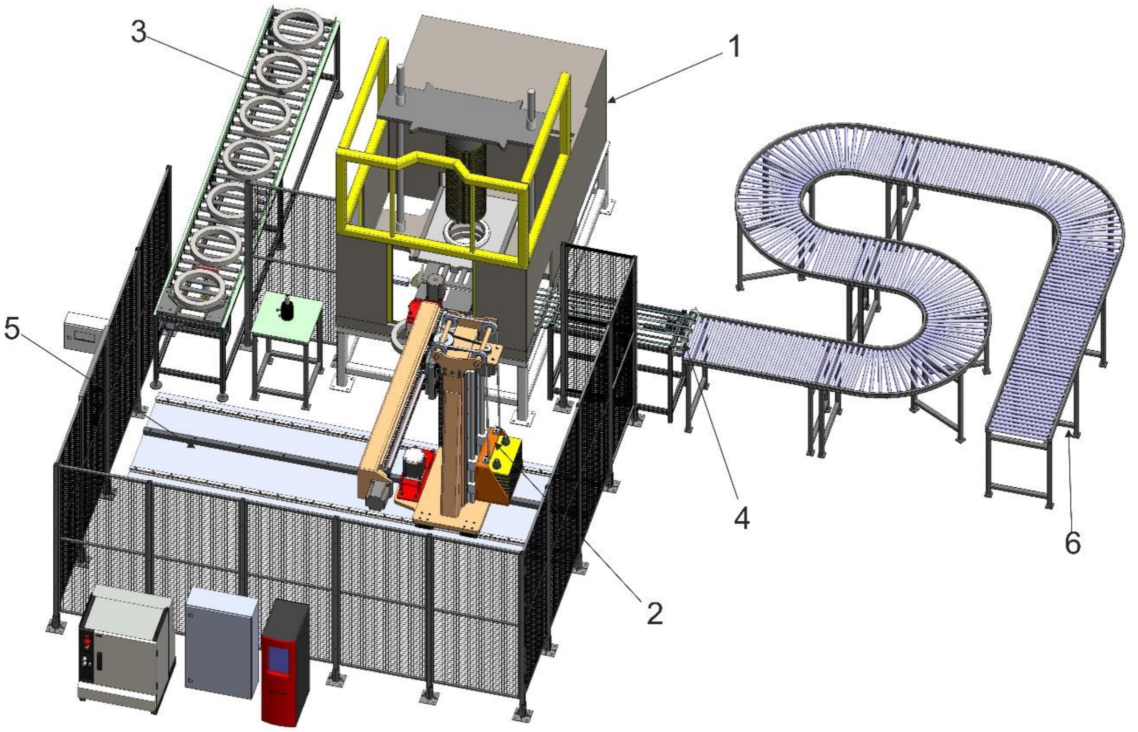


Figure 1: General view of the automated line: 1 - CNC machine; 2 - industrial robot; 3 - gravity roller conveyor for feeding raw workpieces; 4 - chain conveyor for unloading processed parts; 5 - guide for horizontal movement of the robot; 6 - gravity roller conveyor.

The main element of the system is a CNC machine 1, which performs the spline cutting process in ring-shaped workpieces with outer and inner diameters of 450 mm and 355 mm, respectively, a thickness of 65 mm, and a weight of approximately 30 kg. The automated line also includes a mobile industrial robot 2 with a rectangular coordinate system, capable of moving along guides 5; an inclined (gravity) roller conveyor 3 for feeding raw ring-shaped workpieces; a chain conveyor 4 for removing processed workpieces from the CNC machine, and a gravity roller conveyor 6 for inter-operation movement of processed workpieces. The task of the mobile industrial robot 2 is to pick up the workpiece from the roller conveyor 3 and place it into the corresponding chuck of the CNC machine 1. Upon completion of the spline-cutting operation, the chain conveyor 4 unloads the workpiece onto the designated roller conveyor 6. The transportation system, which is part of the automated line, ensures the delivery of raw workpieces to the CNC machine and the removal of processed workpieces after the completion of the process. The robot with a rectangular coordinate system is capable of moving along guides.

The given technical characteristics and design solutions emphasize the peculiarity of desidned automated line. An approach to the implementation of control and optimization of processes gives this system advantages, thanks to the integration of a mobile industrial robot with a system of drives and gears, which allows to increase the mobility and functionality of the robot in the production environment. The use of a rectangular coordinate system provides precise maneuverability between different processing stations, which ensures high efficiency of workpiece movement.

A key feature is also the use of numerical analysis of the manipulator's kinematics and simulation of its operation with the help of software, which allows to optimize all the movements of the robot before starting the production line. This reduces the risk of production errors and increases the reliability of production processes. The designed system provides the possibility of flexible reconfiguration of the robotic line with minimal expenditure of time and resources, which is important for enterprises with variable production needs and, therefore important for modern production, where speed, accuracy, and adaptability of technological processes are important.

3. The Design Solution of the Industrial Robot

3.1. General Construction

A detailed design solution of the industrial robot and its key components, which play a crucial role in ensuring the efficiency and accuracy of the manufacturing process are shown in Fig. 2.

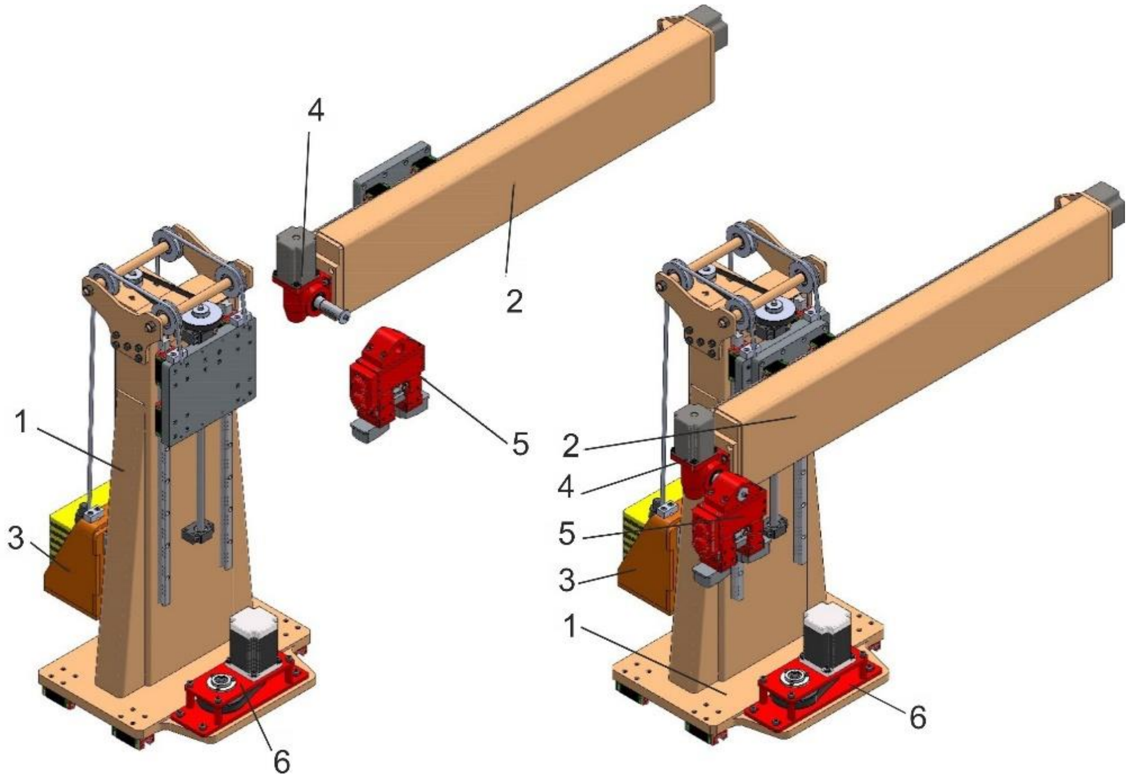


Figure 2: General view of the designed industrial robot: 1 - robot base (column); 2 - extendable manipulator arm; 3 - counterweight; 4 - drive for vertical rotation of the gripper; 5 - gripper; 6 - drive for horizontal movement of the mobile robot.

The industrial robot consists of a base, which provides its stability and the ability to move along horizontal guides. In turn, the horizontal guides enable the movement of the industrial robot along the production space through a rack-and-pinion transmission mechanism.

In order to enhance the energy efficiency of the stepper motor responsible for the vertical movement of the manipulator, a design element - a counterweight (Figure 2) - was implemented in the robot's operation. This device is attached to the manipulator using two cables, which are routed through a block system located at the top of the robot's column.

The primary function of the telescopic arm of the manipulator is precise positioning and movement of workpieces in the CNC machine. The use of a telescopic design enables the provision of the required reach and workspace for optimal execution of manufacturing tasks.

The drive of the manipulator arm is based on a screw nut transmission, ensuring precise and stable movement of the manipulator. The use of such a transmission allows for the necessary torque and motion control with high precision.

The gripper is designed for grasping and positioning workpieces on the CNC machine. Its construction allows for the gripping of various types of workpieces with minimal effort and high accuracy.

The control and monitoring system play a crucial role in coordinating the operation of all elements of the system. It is based on advanced software solutions and sensors, providing reliable control and precise positioning of the industrial robot and its components.

Carefully designed construction and efficient synchronization of each element of the system ensure the highest productivity and quality of manufacturing processes.

3.2. Drive for Horizontal Movement

The structural design of the mechanism for horizontal movement of the mobile industrial robot is depicted in Figure 3. The frame 2 of the drive is attached to the column 1 of the robot, and it includes a stepper motor 3, a toothed belt transmission 4, and a rail pair 5. The rail is rigidly attached to the support plate 6, on which guides 7 of linear bearing assemblies 8 are fixed. The column of the robot is capable of moving along the horizontal guides 7 due to paired linear bearing assemblies (two on each side of the column). The movement of the column 1 of the robot is controlled by a specialized control system, which regulates the frequency and direction of rotation of the motor shaft and tracks the position of the column with predetermined accuracy.

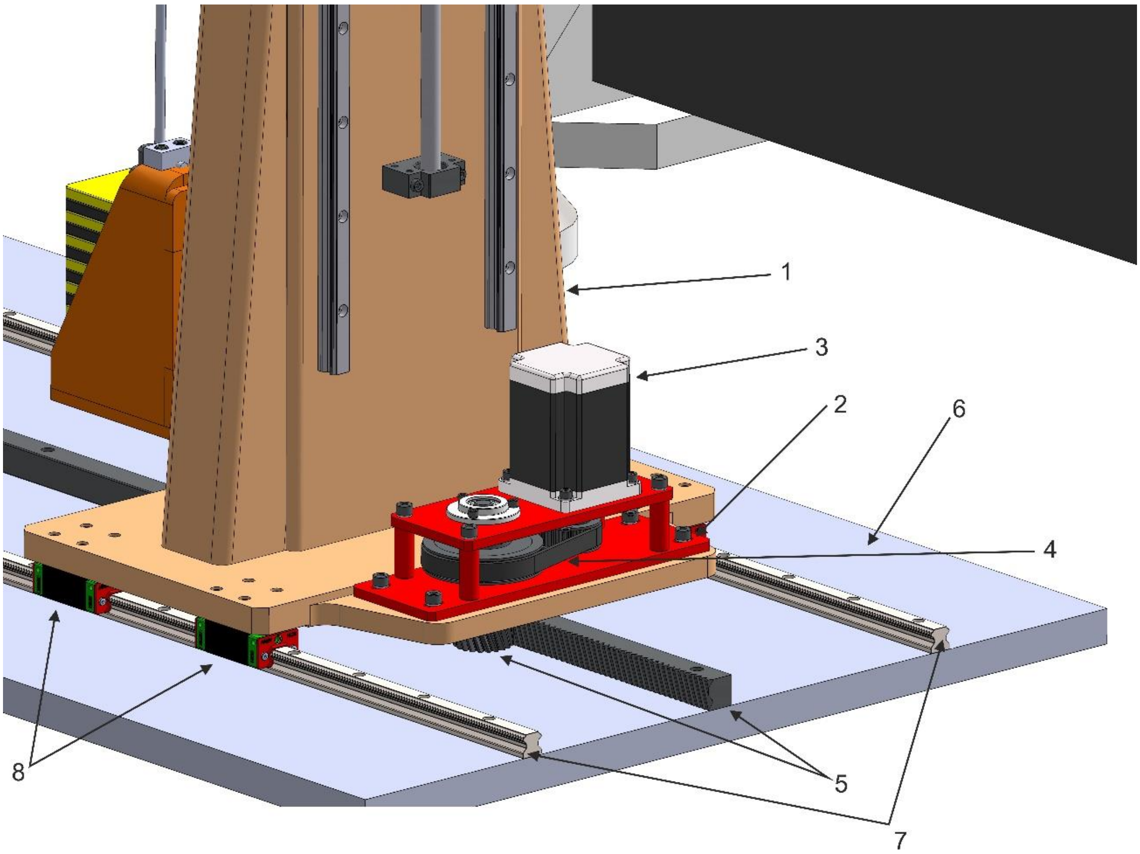


Figure 3: Design of the mechanism for horizontal movement of the mobile industrial robot: 1 - column (base) of the robot; 2 - drive frame; 3 - stepper motor; 4 - toothed belt transmission; 5 - rail transmission; 6 - horizontal support plate; 7 - guides; 8 - linear bearing supports.

3.3. Gripper Construction

The gripper of the industrial robot is depicted in Figure 4. It is fixed via a flange on the shaft of the rotary motor installed at the end of the manipulator arm. The two jaws of the gripper are capable of moving along guides using rollers. The gripper mechanism employs a screw-nut transmission, which is actuated by the stepper motor and a spur gear transmission enclosed within a housing. The gripper jaws are designed to grasp ring-like workpieces with dimensions as specified above from the roller conveyor and position them in the corresponding chuck of the CNC machine for further automatic spline cutting.

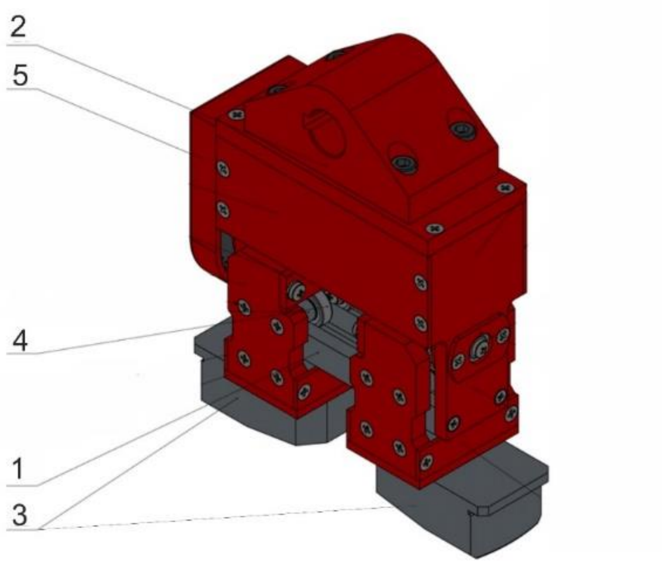


Figure 4: Proposed design of the gripper: 1 - guides, flange 2, 3 - gripper jaws, 4 - rollers, 5 - casing.

3.4. The Assembly of the Drive

According to the proposed construction of the mechanism of horizontal movement of the industrial robot (Figure 2), consider the arrangement scheme of its drive (Figure 5). The torque generated on the shaft of the electric motor 1, on which the drive pulley 3 of the belt transmission 4 is connected through the key 2, is transmitted to the larger (driven) pulley 5. The latter is located on the same shaft as the helical gear 6 of the rail gear of the mechanism of horizontal movement of the robot. According to the proposed construction of the mechanism of horizontal movement of the industrial robot (Figure 2), consider the arrangement scheme of its drive (Figure 5). The torque generated on the shaft of the electric motor 1, on which the drive pulley 3 of the belt transmission 4 is connected through the key 2, is transmitted to the larger (driven) pulley 5. The latter is located on the same shaft as the helical gear 6 of the rail gear of the mechanism of horizontal movement of the robot.

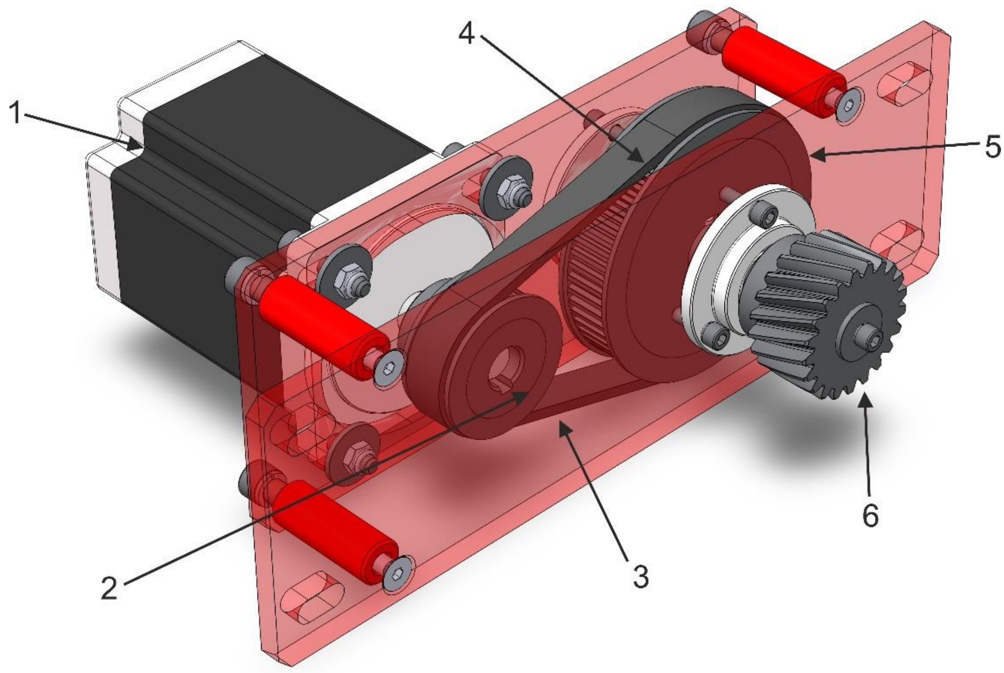


Figure 5: The proposed design of the drive for the horizontal movement of the robot: 1 - the shaft of the electric motor, 2 - key, 3 - the drive pulley, 4 - belt transmission, 5- larger (driven) pulley, 6 - helical gear.

4. The Solution of the Direct Kinematics Problem

Kinematic analysis serves as a fundamental tool in determining the linear aspects of mechanical movement, offering insights into how various components interact and behave over time. At the core of kinematic analysis lies the meticulous definition of symbolic variables and kinematic parameters. These variables encapsulate essential aspects of the system, such as displacements and joint angles, enabling engineers to formulate precise mathematical models. By symbolically representing these parameters, engineers can effectively characterize the behavior of the system under different conditions. One of the most compelling applications of kinematic analysis is the visualization of system trajectories. By defining the trajectory of specific points within the system, engineers gain valuable insights into its motion dynamics. By harnessing the power of kinematic analysis, engineers unlock a deeper understanding of mechanical systems, paving the way for innovation and advancement in various industries. From robotic manipulators to industrial machinery, kinematic analysis serves as a cornerstone in the design, optimization, and operation of line mechanical systems.

The solution to the direct kinematics problem of the manipulator involves forming a table of kinematic pairs according to the kinematic scheme of the manipulator (Figure 6), and computing the transition matrices Ai for the proposed manipulator presented in Figure 2. Additionally, the coordinates of the gripper, as functions of the generalized coordinates of the system and the geometric parameters of its links, need to be determined in the coordinate system 0, which is rigidly connected to the stationary base of the manipulator.

In the proposed manipulator, there are three prismatic kinematic pairs. Therefore, the number of degrees of freedom of the manipulator mechanism is three. Axis z_0 passes through the axis of the prismatic pair A, which connects links 0 and 1, that is, through the slider's sliding axis A. Axis z_1 coincides with the axis of prismatic pair B, which connects links 1 and 2, along which link 2 moves relative to link 1. Axis z_2 coincides with the axis of prismatic pair C (links 2 and 3).

Axis z_3 coincides with axis z_2. The directions of axes x_i, as well as the origins of the corresponding coordinate systems, are shown in Figure 6. The types of kinematic pairs, as well as the parameters of the coordinate system transition matrices of the manipulator mechanism, are provided in Table 1.

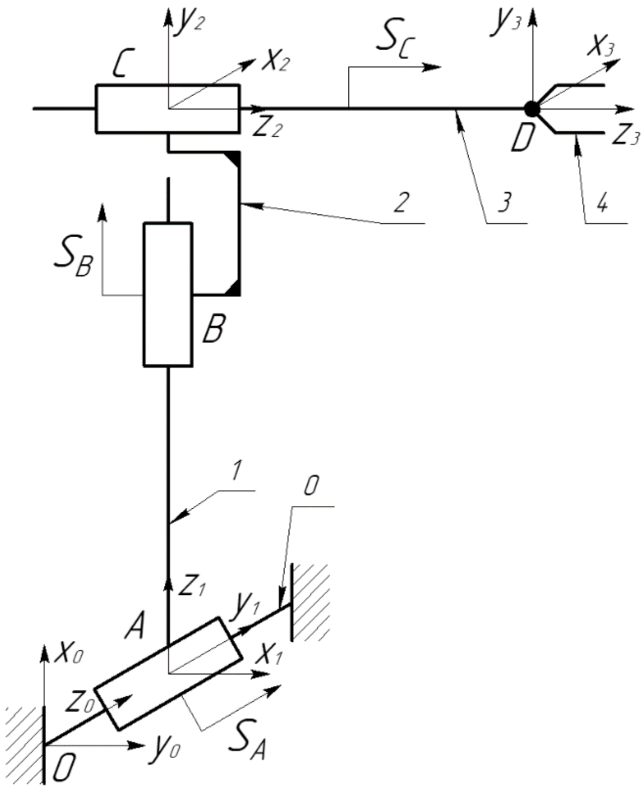


Figure 6: Kinematic diagram of the industrial robot manipulator mechanism.

Table 1
Types of kinematic pairs, and the transition matrices parameters of the manipulator mechanism coordinate systems

Kinematic Pair	Type	Link Number	Parameters			
			θ	α	S	a
A (connects links 0, 1)	Prismatic	1	90°	90°	S_A	0
B (connects links 1, 2)	Prismatic	2	90°	90°	S_B+BC	0
C (connects links 2, 3)	Prismatic	3	0	0	S_C	0

The transition matrices for the respective coordinate systems A_i (1- 3) are as follows:

$$A_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1\cos\alpha_1 & \sin\theta_1\sin\alpha_1 & a_1\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1\cos\alpha_1 & -\cos\theta_1\sin\alpha_1 & a_1\sin\theta_1 \\ 0 & \sin\alpha_1 & \cos\alpha_1 & S_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \tag{1}$$

$$= \begin{bmatrix} \cos 90^\circ & -\sin 90^\circ\cos 90^\circ & \sin 90^\circ\sin 90^\circ & 0\cdot\cos 90^\circ \\ \sin 90^\circ & \cos 90^\circ\cos 90^\circ & -\cos 90^\circ\sin 90^\circ & 0\cdot\sin 90^\circ \\ 0 & \sin 90^\circ & \cos 90^\circ & S_A \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & S_A \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A_2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2\cos\alpha_2 & \sin\theta_2\sin\alpha_2 & a_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2\cos\alpha_2 & -\cos\theta_2\sin\alpha_2 & a_2\sin\theta_2 \\ 0 & \sin\alpha_2 & \cos\alpha_2 & S_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \tag{2}$$

$$= \begin{bmatrix} \cos 90^\circ & -\sin 90^\circ\cos 90^\circ & \sin 90^\circ\sin 90^\circ & 0\cdot\cos 90^\circ \\ \sin 90^\circ & \cos 90^\circ\cos 90^\circ & -\cos 90^\circ\sin 90^\circ & 0\cdot\sin 90^\circ \\ 0 & \sin 90^\circ & \cos 90^\circ & S_B + BC \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & S_B + BC \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A_3 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3\cos\alpha_3 & \sin\theta_3\sin\alpha_3 & a_3\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3\cos\alpha_3 & -\cos\theta_3\sin\alpha_3 & a_3\sin\theta_3 \\ 0 & \sin\alpha_3 & \cos\alpha_3 & S_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \tag{3}$$

$$= \begin{bmatrix} \cos 0^\circ & -\sin 0^\circ\cos 0^\circ & \sin 0^\circ\sin 0^\circ & 0\cdot\cos 0^\circ \\ \sin 0^\circ & \cos 0^\circ\cos 0^\circ & -\cos 0^\circ\sin 0^\circ & 0\cdot\sin 0^\circ \\ 0 & \sin 0^\circ & \cos 0^\circ & S_C \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & S_C \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

And transition matrix (4) T_3 will be:

$$T_3 = A_1 \cdot A_2 \cdot A_3 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & S_A \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & S_B + BC \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & S_C \\ 0 & 0 & 0 & 1 \end{bmatrix} = \tag{4}$$

$$= \begin{bmatrix} 0 & 1 & 0 & S_B + BC \\ 0 & 0 & 1 & S_C \\ 1 & 0 & 0 & S_A \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Thus, let us determine the coordinates of the gripper center (point *D*) in the zero coordinate system ($Ox_0y_0z_0$):

$$x_D = S_B + BC,\ y_D = S_C,\ z_D = S_A. \tag{5}$$

The corresponding direction cosines of the axes $x_3,\ y_3,\ z_3$ are equal:

$$\begin{array}{lll} \cos(\vec{i}_3 \wedge \vec{i}_0) = 0; & \cos(\vec{i}_3 \wedge \vec{j}_0) = 1; & \cos(\vec{i}_3 \wedge \vec{k}_0) = 0; \\ \cos(\vec{j}_3 \wedge \vec{i}_0) = 0; & \cos(\vec{j}_3 \wedge \vec{j}_0) = 0; & \cos(\vec{j}_3 \wedge \vec{k}_0) = 1; \\ \cos(\vec{k}_3 \wedge \vec{i}_0) = 1; & \cos(\vec{k}_3 \wedge \vec{j}_0) = 0; & \cos(\vec{k}_3 \wedge \vec{k}_0) = 0; \end{array} \tag{6}$$

4.1. Numerical and Simulation Modeling of Gripper Movement in MathCad and SolidWorks Software Products

Based on the defined geometric dimensions of the manipulator links and given laws of generalized coordinate changes, let us find the laws of gripper coordinates (point D) variation in the "zero" coordinate system. We assume the following geometric characteristics of the links and laws of generalized coordinate changes:

$$BC = 326\ mm; \tag{7}$$

$$S_A(t) = \begin{cases} 3600 \cdot t\ (mm);\ if\ \ 0 \le t \le 1\ \text{(s)}; \\ 3600\ (mm);\ if\ \ 1 \le t \le 2\ \text{(s)}; \\ 3600\ (mm);\ if\ \ 2 \le t \le 3\ \text{(s)}; \end{cases}$$

$$S_B(t) = \begin{cases} 0\ (mm);\ if\ \ 0 \le t \le 1\ \text{(s)}; \\ 930 \cdot (t-1)\ (mm);\ if\ \ 1 \le t \le 2\ \text{(s)}; \\ 930\ (mm);\ if\ \ 2 \le t \le 3\ \text{(s)}; \end{cases}$$

$$S_C(t) = \begin{cases} 0\ (mm);\ if\ \ 0 \le t \le 1\ \text{(s)}; \\ 0\ (mm);\ if\ \ 1 \le t \le 2\ \text{(s)}; \\ 960.5 \cdot (t-2)\ (mm);\ if\ \ 2 \le t \le 3\ \text{(s)}. \end{cases}$$

Time dependencies of the generalized coordinate changes applied during the numerical and simulation modeling of the gripper movement are shown in Figure 7.

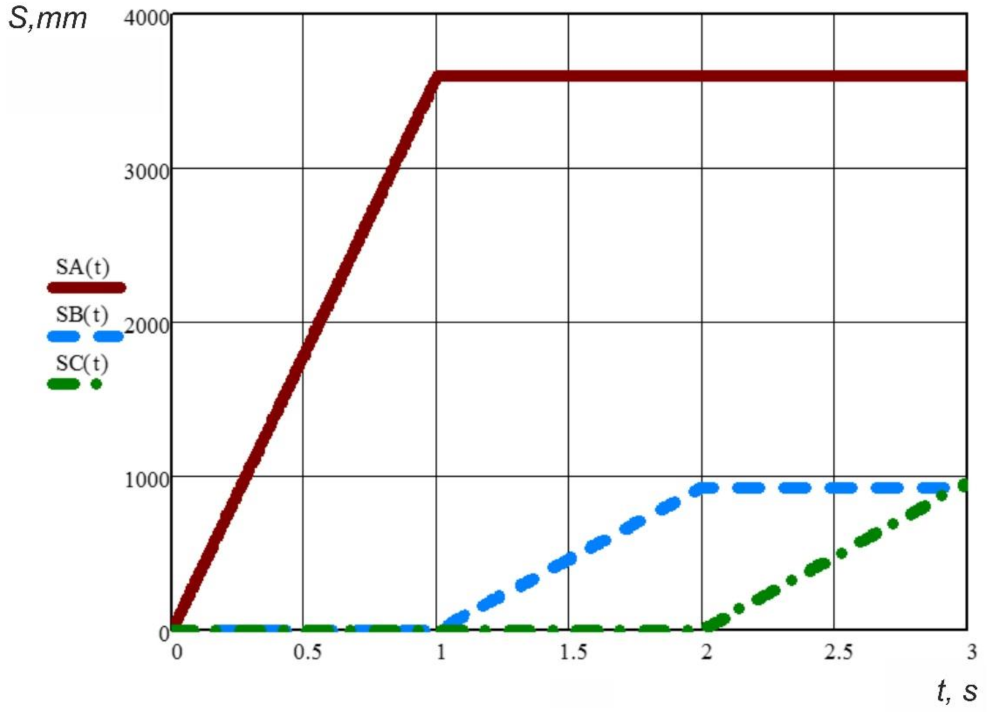


Figure 7 : Time dependencies of the generalized coordinates $S_A(t)$, $S_B(t)$, $S_C(t)$ changes.

The last column of the matrix T_3 given above determines the coordinates of the manipulator gripper center in the zero coordinate system, i.e.:

$$\begin{cases} x_D(t) = S_B(t) + BC = BC + \begin{cases} 0 \ (mm); \ if \ \ 0 \le t \le 1 \ \ (\text{s}); \\ 930 \cdot (t-1) \ \ (mm); \ if \ \ 1 \le t \le 2 \ \ (\text{s}); \\ 930 \ \ (mm); \ if \ \ 2 \le t \le 3 \ \ (\text{s}); \end{cases} \\ y_D(t) = S_C(t) = \begin{cases} 0 \ \ (mm); \ if \ \ 0 \le t \le 1 \ \ (\text{s}); \\ 0 \ \ (mm); \ if \ \ 1 \le t \le 2 \ \ (\text{s}); \\ 960.5 \cdot (t-2) \ \ (mm); \ if \ \ 2 \le t \le 3 \ \ (\text{s}); \end{cases} \\ z_D(t) = S_A(t) = \begin{cases} 3600 \cdot t \ \ (mm); \ if \ \ 0 \le t \le 1 \ \ (\text{s}); \\ 3600 \ \ (mm); \ if \ \ 1 \le t \le 2 \ \ (\text{s}); \\ 3600 \ \ (mm); \ if \ \ 2 \le t \le 3 \ \ (\text{s}). \end{cases} \end{cases} \quad (8)$$

The trajectory of the gripper (point D) movement for the specified motion laws of the manipulator drives, i.e., for the given time laws of generalized coordinates, is built using the MathCad software (Figure 8).

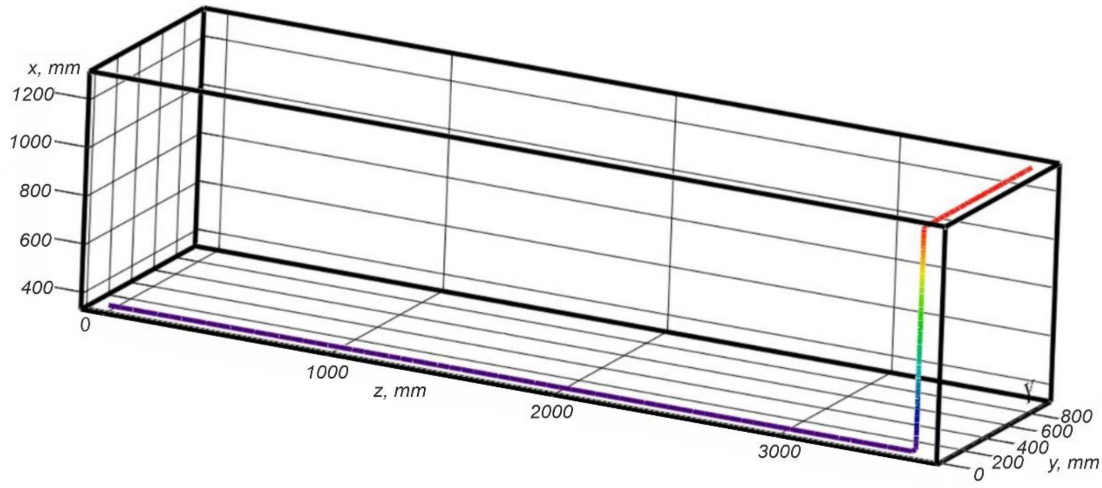


Figure 8: The trajectory of the gripper's movement (point D), constructed using the derived analytical formulas in the MathCad software.

To analyze the correctness of the derived analytical formulas describing the gripper's movement, based on the solid-state model of the manipulator implemented in the SolidWorks program, simulation modeling of the gripper's movement was carried out using the SolidWorks Motion software application. The results of the simulation modeling, presented in the form of the gripper's trajectory, are shown in Figure 9.

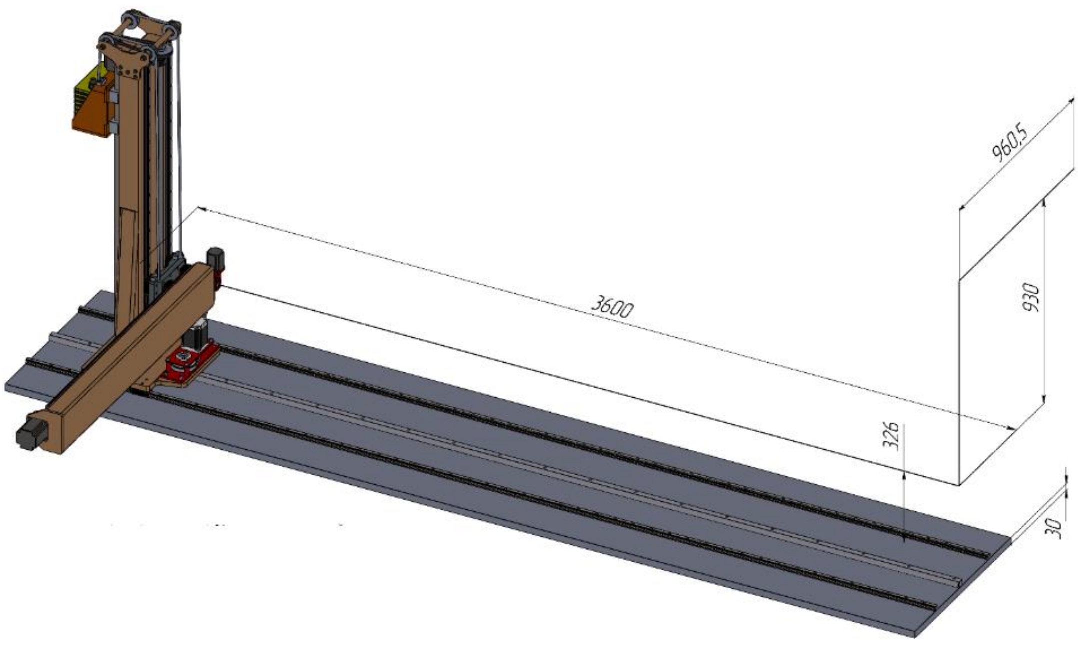
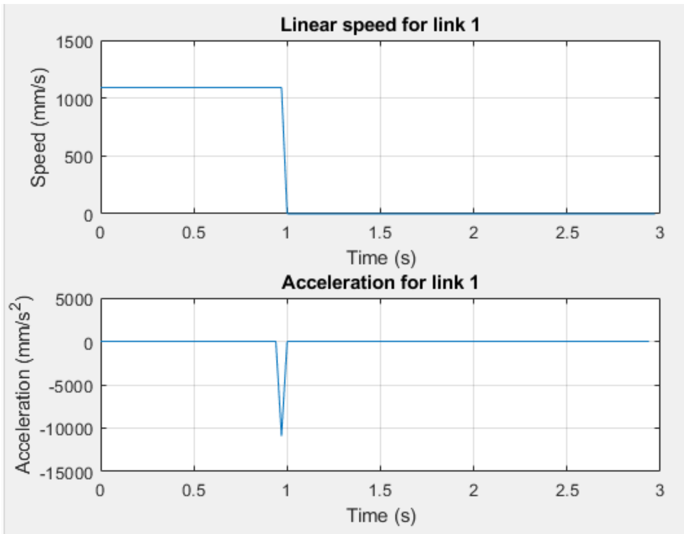
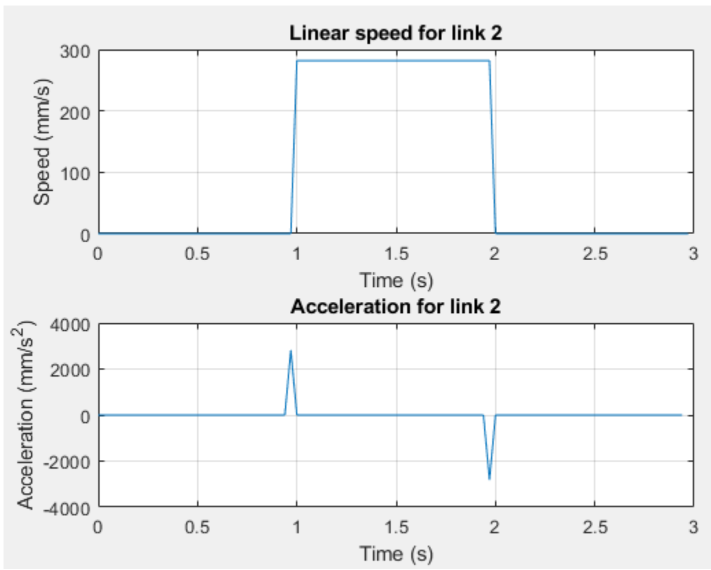


Figure 9: The trajectory of the gripper's center movement, constructed during the simulation modeling process in the SolidWorks software.

4.2. Simulation Modeling of Gripper Movement in MatLab

Through visualization, engineers can discern patterns, identify potential inefficiencies, and optimize system performance. In our research, we used different tools to analyze and model the kinematic properties of a robotic system. In particular, we used MATLAB for symbolic analysis of kinematics, determination of kinematic parameters, and calculation of coordinates of point D in space for different time values. This approach allows us to obtain a comprehensive understanding of the operation and properties of the robotic system in the production environment. The use of MATLAB allowed us to perform an analysis using symbolic methods, which allowed us to understand the kinematic properties of the system.





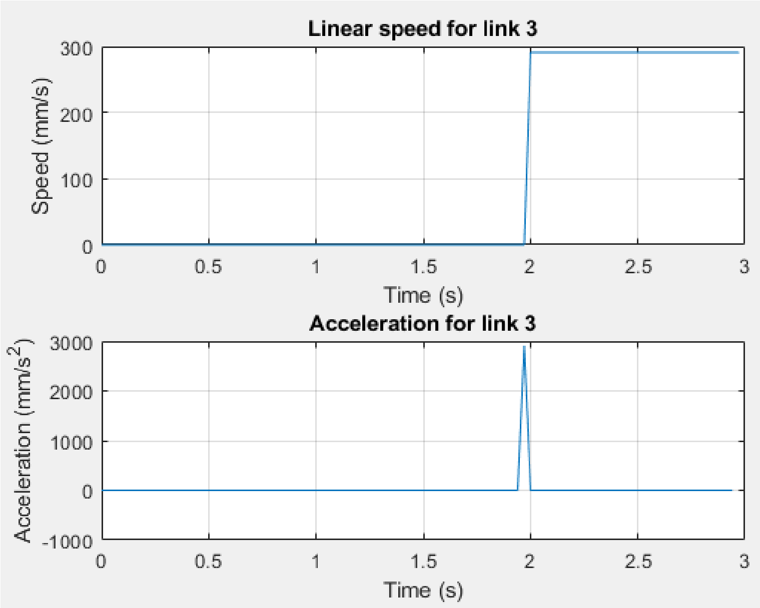


Figure 20: Velocity and acceleration charts.

The kinematic model of the robotic system was analyzed using symbolic calculations and numerical methods. The main steps that were performed were: definition of symbolic variables, calculation of transition matrices to determine the kinematics of the system, determination of the coordinates of point D as a function of time, and calculation of the values of the coordinates of point D using numerical methods for different values of time.

In the course of analysis that followed using Matlab, each link of the mechanism corresponds to a transition matrix that describes the transformation of coordinates between the starting system and the system associated with this link. The general transition matrix T_03, which reflects the kinematics of the mechanism as a whole, is used to calculate the position and orientation of the mechanism in space. The vector t is a sequence of time points and 100 values uniformly distributed in the interval from 0 to 3 seconds. After calculating the theoretical values of speed and acceleration for each link of the mechanism, graphs of theoretical speed and acceleration were built for each link separately. These graphs help to visualize and analyze the dynamic characteristics of each link.

In general, the analysis of the velocity and acceleration graphs confirms that the model is consistent with physical laws and reproduces the expected motion characteristics for each link.

5. Conclusion

A general view of an automated line for cutting splines in ring-shaped workpieces was developed. The main element of the line is a CNC machine tool, which cuts slots in ring-shaped workpieces with an outer and inner diameter of 450 mm and 355 mm, respectively, a thickness of 65 mm, and a weight of about 30 kg. The line also contains a mobile industrial robot with a rectangular coordinate system that can move along the guides, an inclined (gravity) roller conveyor for feeding unprocessed ring-shaped blanks, a chain conveyor for removing processed blanks from the CNC machine, and a gravity roller conveyor for inter operational movement of processed blanks.

We also proposed a constructive solution of an industrial robot. The robot is composed of a base that can move along two horizontal guides due to a rail transmission with the use of a drive mechanism. In order to reduce the nominal power of the stepper motor driving the vertical movement of the manipulator, it is proposed to use a counterweight in the design of the robot, which is connected to the manipulator by two ropes thrown over a system of blocks, which are placed in the upper part of the robot column. The jaws of the gripper are designed in such a way as to be able to grab ring-shaped workpieces from the roller conveyor and position them in the corresponding chuck of the CNC machine for further automatic slitting.

An analysis of the kinematics of the manipulator was carried out, which made it possible to obtain analytical expressions for the description of the movement of the gripper according to the defined laws of change of generalized coordinates. Numerical and simulation modeling of manipulator movement was also performed using MathCad, MATLAB and SolidWorks software packages.

Based on the obtained by numerical and simulation modelling during the theoretical calculation and solid-state design of the manipulator, it is possible to state the satisfactory convergence and correctness of the obtained analytical dependencies of the gripper movement.

Acknowledgements

None

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