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Original Article

Selected problems of design and pre-implementation studies of new types of manipulators

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Abstract: Conceptual development and testing of models and prototypes of manipulators, supporting the work of industrial robots, has become a specialty of the Department of Welding Engineering of the Warsaw University of Technology and ZAP Robotyka from Ostrow Wielkopolski. However, they are not typical devices, so their development requires a detailed analysis of many aspects, both functional and economic. Also the pre-implementation tests are not included in dedicated standards and must be based on previously developed experimental procedures. This article presents selected problems in the design and research of new types of manipulators, created as a result of joint research and development work.

Keywords: positioner; manipulator; running track; external robot axis; FEM; off-line programming

Introduction

An indispensable equipment of many robotic workstations, including welding workstations, are additional manipulating devices supporting the work of the robot – its external axes. This term refers to separate manipulators, controlled by the same system and program as the master robot [1,2]. It is important that the drives and controls used in them allow, for as many axes of manipulation as possible, for full synchronization with the movements of the robot arm, including simultaneous operation. This will translate into the ability to perform complex, spatial working trajectories in the most convenient positions from the point of view of the process, also with regard to objects of significant size.

First of all, positioners are used – machines that manipulate (positioning and/or working movements, even performed simultaneously with robot movements) objects attached to them [3,4]. As part of the joint implementation work carried out in recent years, several such devices have been developed, always in line with current trends and market demand. Among the non-standard solutions were modular constructions [5,6]. Due to the number and arrangement of positioner manipulation axes (usually from one to five), it is possible to achieve various goals.

Usually, the rotating and controlled table can be stationary and, above all, manipulated (tilted) via one or even two additional controlled axes. In this way, the ability for machining, e.g., welding, in the most technologically convenient positions is achieved, or at least access to these locations becomes possible [7].

The stationary or rotating and controlled table, which as before can be stationary or manipulated (tilted) via one or even two controlled axes, has its counterpart on the other, symmetrical side of the positioner. These are the so-called dual positioners – symmetrical. In this case, in addition to the benefits mentioned in the first point (not applicable to symmetrical positioners with fixed and non-tilting table), two additional benefits are achieved – an increased level of safety and efficiency. A two-station positioner, positioned between the robot and the operator, frees the human from the need to enter the range of the robot's arm (into the danger zone) for servicing (loading, unloading). At the same time, the operator and the robot can perform their production tasks simultaneously [8].

The second group of external axes of industrial robots are devices that increase their manipulation capabilities by added locomotion. For this purpose, floor or portal runways (with standing and inverted positions of the attached robot) and movable arms (single- and multi-axis) can be used (Fig. 1).

Fig. 1. Examples of external axes of industrial robots: a) two-axis positioner with Kawasaki FA006E robot in the laboratory of the Department of Welding Engineering, b) two-axis "H" type positioner, ZAP Robotics, c) cantilever with vertical robot locomotion, ZAP Robotics

The paper traces the creative process of the development and research preceding the industrial implementation of manipulator machines covering all the above-mentioned groups of external axes of industrial robots. The results were obtained as part of the research and development work and subsequent additional activities conducted at PPU ZAP Robotyka in Ostrów Wielkopolski in cooperation with the Department of Welding Engineering of the Warsaw University of Technology.

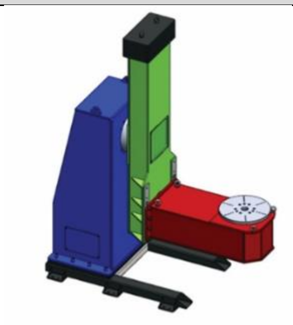
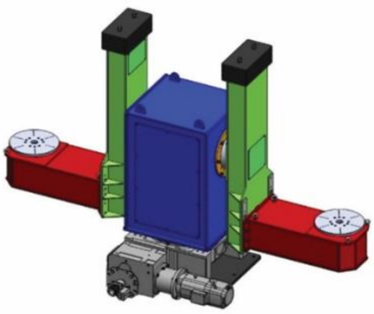
Concept study

The development, in one project of such a diverse group of machines was a serious creative issue, requiring the involvement of specialists from many fields, representing not only designers and management staff of the manufacturer, but also future users (technologists, robot programmers).

The scope of the implementation included three types of manipulator devices – the external axes of an industrial robot:

- "L"-type positioners, both single- and dual-station (Table I). In the basic – single station variant, the rotating table is tilted by means of an "L" shaped arm. This creates favorable conditions for manipulation due to access to the mounted object and its balance. In the five-axis version, two symmetrical conventional systems are connected by a central axis for position swapping. A number of innovative features were assumed, including variable counterweights and the ability to translate the horizontal arm beam for better balancing.

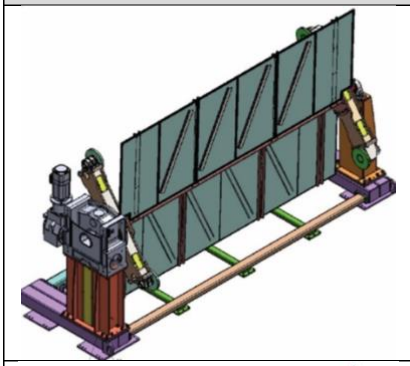
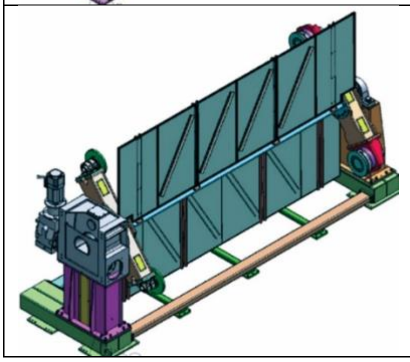
Table I. Variants and main parameters of "L" type positioners developed in the project (preliminary sketches)

<table>
<tr><th>Sketch</th><th>Load capacity [kg]
(dimensions)</th><th>Number of axes</th><th>Number of stands</th><th>Maximum working area [m]</th></tr>
<tr><td rowspan="2"></td><td>250
(2480 mm x 1939 mm x 990 mm)</td><td rowspan="2">2</td><td rowspan="2">1</td><td>1.5x1.5x1.5</td></tr>
<tr><td>500
(2842 mm x 2313 mm x 1120 mm)</td><td>2.0x2.0x2.0</td></tr>
<tr><td rowspan="2"></td><td>250
(2480 mm x 3510 mm x 1468 mm)</td><td rowspan="2">5</td><td rowspan="2">2</td><td>1.5x1.5x1.5</td></tr>
<tr><td>500
(2842 mm x 4219 mm x 1535 mm)</td><td>2.0x2.0x2.0</td></tr>
</table>

- Three-axis, two-station "H" type positioners (Table II). The manipulator formed by combining two symmetrical axis systems in a spindle arrangement with a central axis used for their cyclic replacement. The assumed large loading (working) space forced non-standard solutions – a step change of the H-beam rest angle and a lifting module.
- Track system with a range of additional accessories to extend its functionality (Table III). The design included both floor tracks (standing robot position) and portal tracks with wall-mounted and inverted robot mounting position (optionally standing), in some versions also with the possibility of driving two robots (driving platforms) on one beam. The modular construction included prefabricated: beams, columns, driving platforms, modules for transporting the equipment or changing the mounting position of the robot.

Continuously controlled electric drives for the main axes and discrete control (2 x 180°) for the workstation change axes.

Table II. Variants and main parameters of "H" type positioners developed in the project (preliminary sketches)

Sketch	Load capacity [kg] (dimensions)	Number of axes	Number of stands	Maximum working area [m]
	300 (5755 mm x 3142 mm)	3	2	1.5x4.0 (diameter x diameter)
	1000 (6031 mm x 3163 mm)	3	2	

One can notice a very wide, as for a single project, range of developed machines, including the number of their variants and functional variants. It should be noted, however, that this type of equipment is not the subject of mass production, but at most of unit production. Some of the presented solutions may not be used at all, but they will be important material for analysis at the stage of configuration of a production station. On the other hand, the developed concept assumed modular character and prefabrication of many assemblies not only within one type, but the whole project. Consequently, it becomes possible to further extend the system with other variants, depending on individual needs and possibilities of their financing.

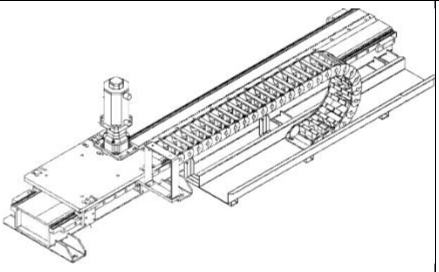
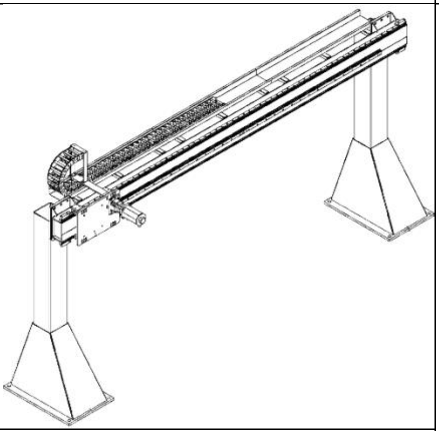
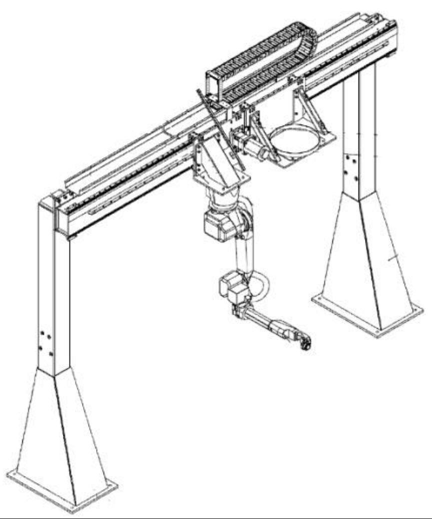
Regardless of the concept adopted, achieving the desired parameters required continuous monitoring of the construction work on the models, motion verification in an off-line programming environment, computational strength analysis (using the finite element method – FEM), and finally, comprehensive motion and technological testing of prototypes built in real scale.

Motion visualizations and simulations

As a result of model design work, a coherent concept of devices was created, which can be used independently (only with a robot) at robotic workstations, but also form mutually complementary sets of high efficiency e.g., from a combination of an "H" type positioner and a runway and a robot. Table IV lists the basic variants of manipulators in typical configurations. Two variants of welding robots, typical for most manufacturers, were assumed to be used: with a standard size (operating radius of about 1400 mm) and with an extended arm (with a range of about 3000 mm). The presented summary became the starting point for the next stage of research work on structural models – visualization and motion simulations in an off-line programming environment.

Motion verification of positioners and runways in confrontation with robot operation can be performed by motion simulations in a virtual off-line robot programming environment [9,10]. For this purpose, the ROBGUIDE system (Fanuc) was used.

Table III. Variants and main parameters of running tracks developed in the project (preliminary sketches, * – variant in illustration)

Sketch (examples of variants)	**Type of track (dimensions)**	**Robot position**	**Load capacity [kg]**	**Beam length (base unit) [m]**	**Number of platforms (in relation to the base module)**
	Floor (2500 mm)	standing	250	2.5*	1
				5.0	
			500	2.5	
				5.0	1 or 2
	Gate (2500 mm x 3747 mm)	wall mounted	250	2.5	1
				5.0*	
			500	2.5	
				5.0	1 or 2
		reverse	250	2.5	1
				5.0	
			500	2.5	
				5.0	1 * or 2

The use of the off-line environment proved to be very effective regarding the design of their structures, which will result in a specific functionality in terms of work on a robotic workstation [11,12]. As a result of the simulations, the advantages of the developed structures were demonstrated, but also several problems were revealed, which were not very troublesome to eliminate at the stage of structural modeling in the graphical CAD environment.

Table IV. Selected combinations of manipulators and welding robots for off-line simulation (M – standard size robot, L – extended arm robot

		L-type positioners		H-type positioners		Runways – robot position: S – standing, N – wall mounted, O – inverted					
		250 kg	500 kg	300 kg	1000 kg	2.5 m			5.0 m		
						S	N	O	S	N	O
Robot only		M, L				M					
L-type positioners	250 kg	–	–	–	–	M, L		–	–		–
	500 kg	–	–	–	–	M, L		–	–		–
H-type positioners	300 kg	–	–	–	–	M, L			M, L		
	1000 kg	–	–	–	–	M, L			M, L		

Testing revealed problems with too low beam position for gate runways with both wall-mounted and inverted robot mounting (Fig. 2). In this case, the inverted robot must be mounted high enough (Fig. 3). Obviously, the presented solution with the stationary robot suspended on the boom with respect to the "H" positioner will provide proper welding conditions only on about half of the frame length. So, once the optimum position for the stationary robot has been found, this height can be transferred to the runway – by raising the mounting of the runway beam accordingly.

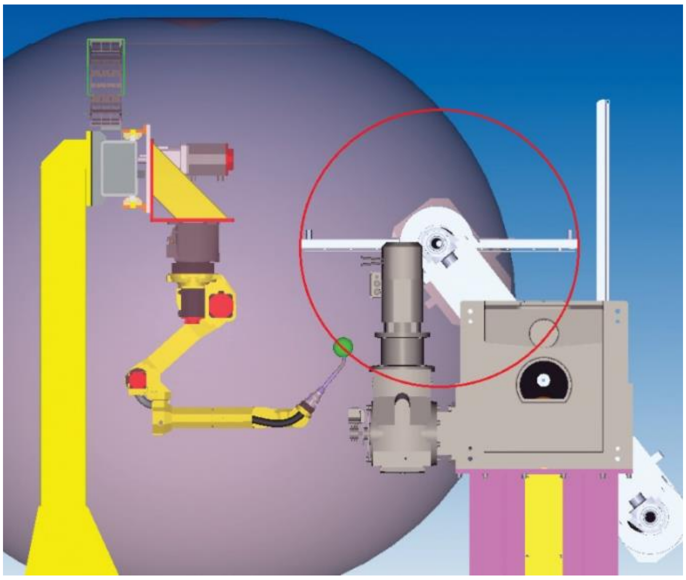


Fig. 2. One of the revealed cases with too low beam position for gate runways - here with inverted robot mounting

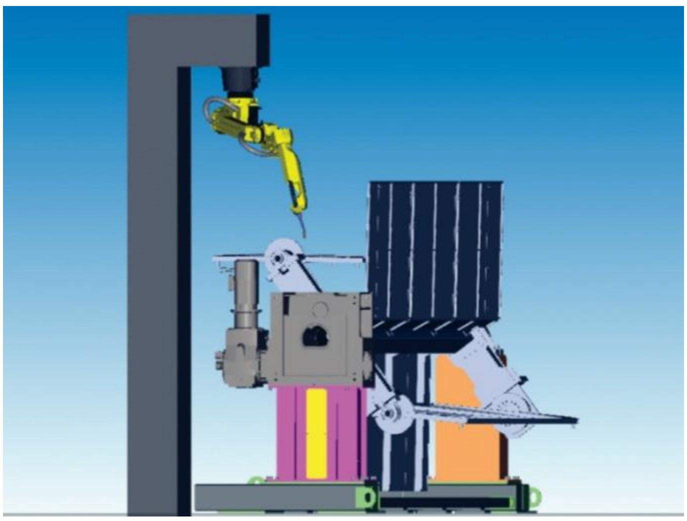


Fig. 3. Simulation of correct interaction of a standard robot (ArcMate 100iC/7L) with a frame-type (flat) manipulation object model mounted on an "H" positioner and ensuring vertical orientation of the electrode axis

Research has shown that sometimes the best working conditions were obtained for the robot mounted in a standing position, but at a considerable elevation (Fig. 4). Unfortunately, as before, when working with large objects mounted on "L" and "H" positioners, this did not guarantee operation in the required area. Therefore, there was a proposal for a new variation of the gate track with a horizontally mounted running beam and a vertical passage of the robot in a standing position (Fig. 5).

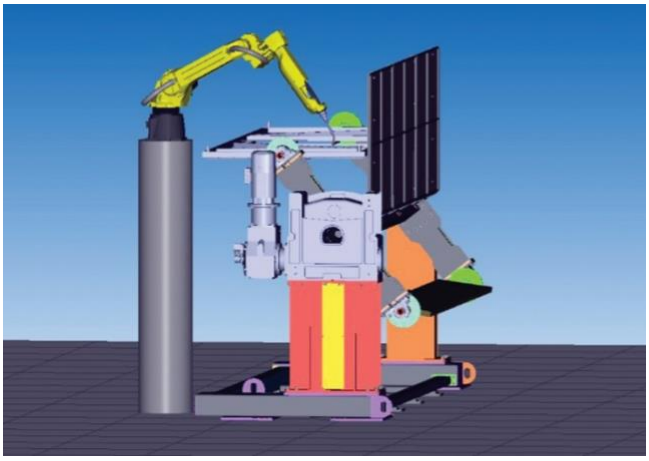


Fig. 4: Simulation of significant elevation of a robot mounted in a standing position

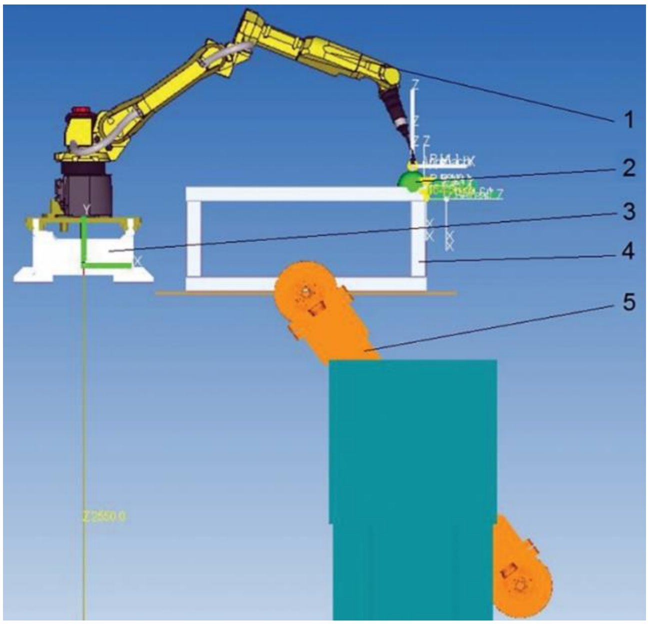


Fig. 5. Proposal of a new variation of a gate runway with the robot traveling in a standing position: 1) robot arm, 2) effector tip, 3) track travel beam, 4) frame model, 5) positioner "H"

Tests conducted in both "H" and "L" type track-positioner collaborations showed the greater utility of wall-mounted over inverted mounting of the robot to the track. In the latter case, it was more often necessary to raise the height at which the running beam was mounted, which can be an additional complication in industrial settings.

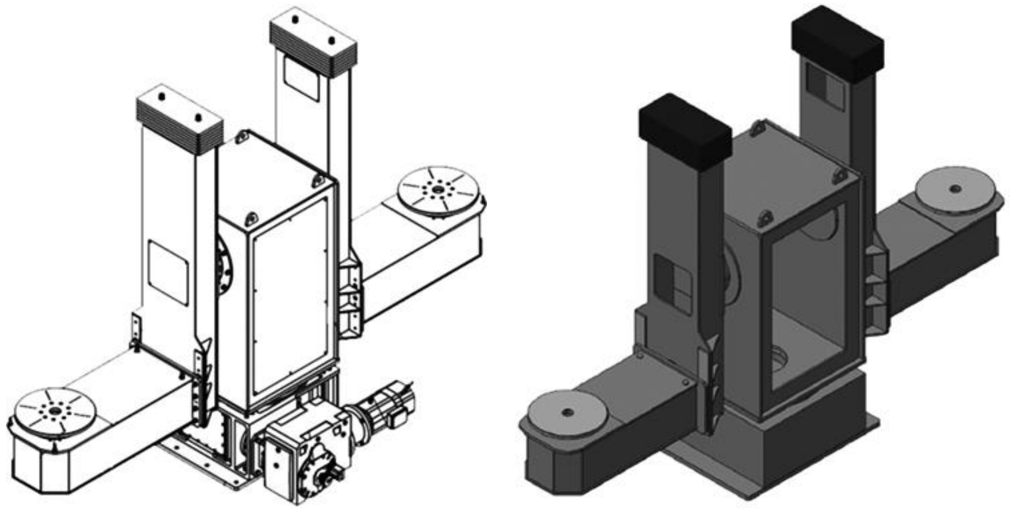
A problem that arises when suspending the robot is that it enters singularities more often than in other configurations due to the ambiguity of the robot's determination of a point in Cartesian space based on angular coordinates. The most common singularity is the alignment of the robot's 5th axis in such a way that axes 4 and 6 coincide. This results in the inability to move the arm further, either manually or by software. In industrial solutions this is quite often encountered difficulty, requiring the robot to be repositioned.

The tests revealed the high usability of the proposed new variation of the gate track with a horizontally mounted running beam and vertical passage of the robot in a standing position (Fig. 5). Additionally, during simulation trials, the robot so positioned entered peculiar points less frequently relative to the wall-mounted and suspended solutions.

In our research we have obtained a conditional usefulness of using an extended arm robot (from ArcMate 710iC series) in configurations with the tested "H" and "L" type positioners and runways in the context of handling medium-size objects. Conditional, however, because some drawbacks of using this type of robots have been demonstrated, including a higher propensity for collisions and difficulty reaching objects close to the robot's mounting location.

Computational testing of models and prototypes

Computer modeling using finite element numerical analysis for L-type positioners has been previously described in papers [13,14]. The functional development of the "L" type positioner is a two-arm “2L” machine, created based on some single-station designs fixed symmetrically on two sides of the central, rotating body (Fig. 6). They allow simultaneous work of elements mounted on two sides. This can increase the efficiency of work on a robotic workstation, moreover, a double-sided design should provide more favorable mass distribution throughout the device, which will be associated with lower deflection values on the positioner arms.



(a) (b)

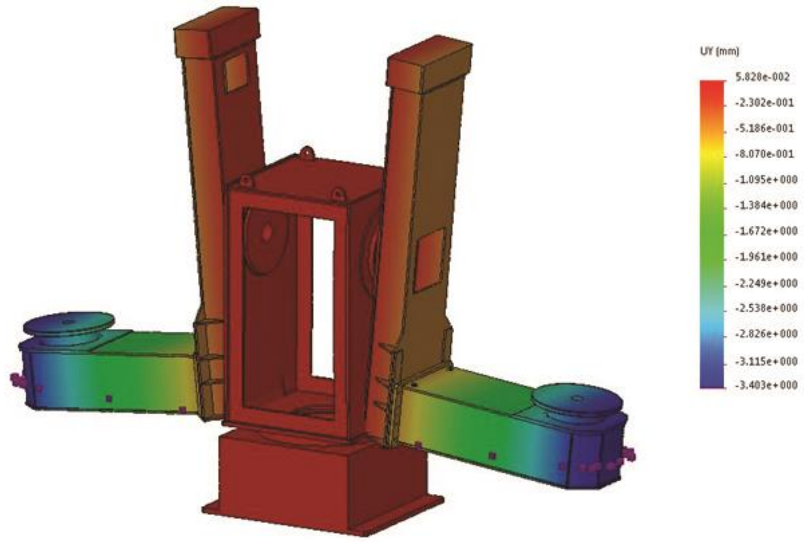
Fig. 6. View of the 2L positioner design (a) and the corresponding 3D positioner model with geometry simplifications (b)

The analysis of the positioner structure behaviour under simultaneous load on both sides in the form of 500 kg mass showed the occurrence of symmetric stress distribution and deflection in both parts of the positioner (Fig. 7). The crucial place showing stress concentration is the area of connection of vertical arms of the positioner with its body. The maximum stress there reaches the value below 60 MPa, which is a safe value in relation to the material yield stress. The shape of the transverse beam and the vertical beam connected with it practically did not change, but only experienced an angle rotation in relation to the place of connection of the vertical beam with the positioner body. This indicates that this location is decisive in terms of the magnitude of the vertical deflection of the positioner crossbeam.

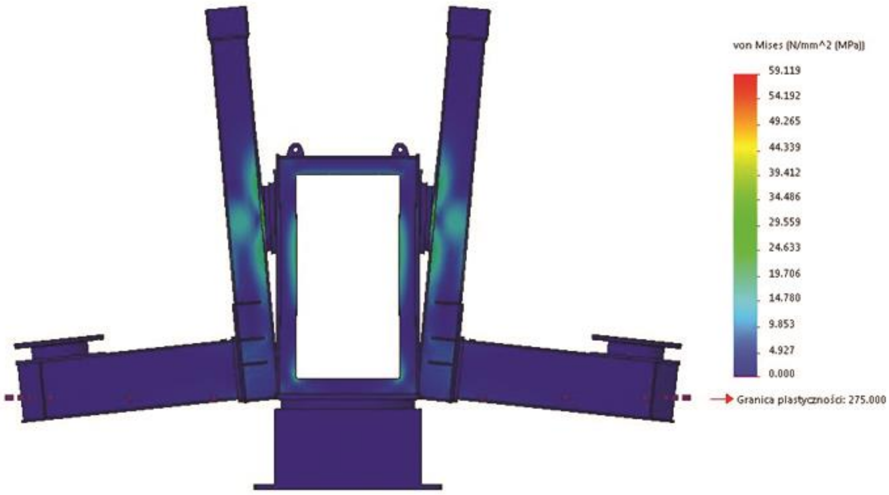
In the case of H-type positioners, the structure also experiences deformation at the connection points from the arms to the body. Figure 8 shows the distribution of the reduced stress (Huber-Mises) in the construction of the positioner loaded unilaterally on the table discs. The maximum stress values do not exceed 24 MPa. The main horizontal beam of the positioner was bent in two planes in the vertical and horizontal directions as shown in Figure 8b. At the same time, the deformation of the positioner elements on the right body side can be seen where the arms are attached to the body. Since the right body is smaller and less rigid than the left body, the deflection of the main horizontal beam is asymmetrical. In most cases, the positioner will operate in a double-sided loading system, where the loads on both sides should balance and protect the crossbeam from excessive torsion. The difference in the amount of torsion of the two beams is due to the fact that the right body of the positioner is less rigid than the left body (it is smaller).

The third important group of machines included in the external robot axes are the gate tracks. As part of the analysis of the runways, gate tracks were tested in wall-mounted and inverted versions with lengths of 2.5 and 5 m and loads of 250 and 500 kg. The developed structures of the gate track were converted to FEM software. As in previous models, some corrections were required due to rejection of irrelevant elements of the structure or contact corrections on some reinforcing plates of the track columns. The final stage of preparation for the analysis was to apply the finite element mesh consisting of over 500000 elements for the 2.5 m model and over 700000 elements for the 5 m model (Fig. 9).

The 2.5 m running track was also analysed for the case of a load acting in the moving plane of the platform, but also at 500 mm from the plane of the platform, which will lead to more lateral bending of the running track beam.

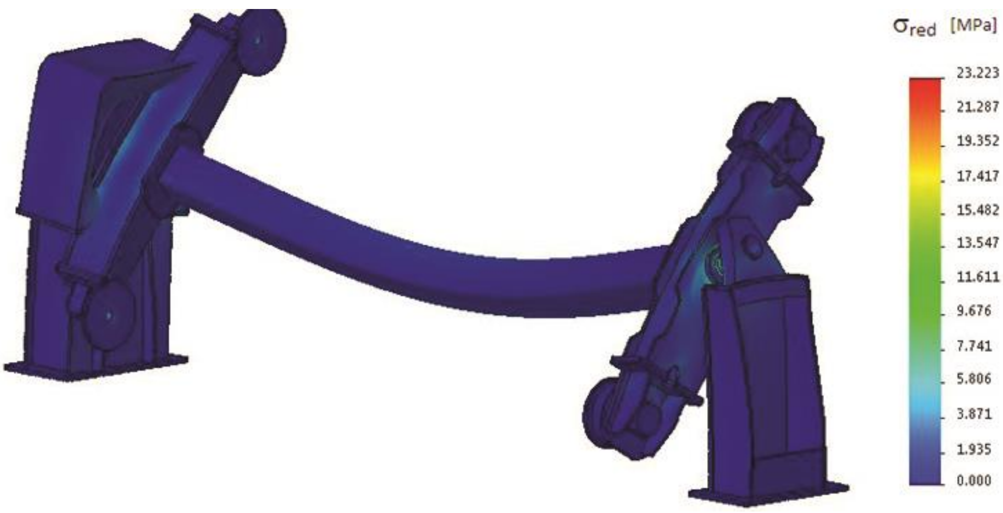


(a)

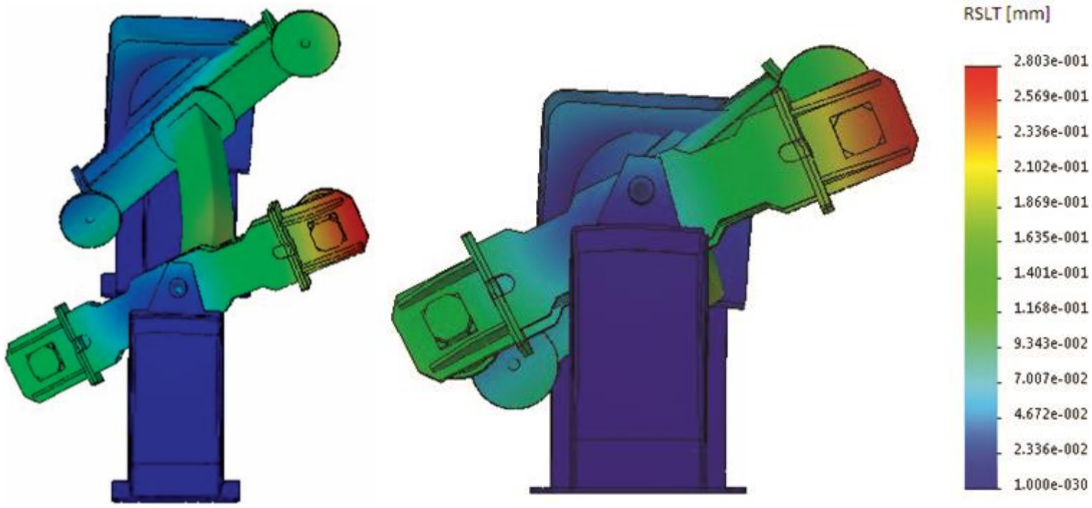


(b)

Fig. 7. Modeling results for a 2L positioner loaded with 500 kg mass on both sides, a) vertical deflection distribution, b) reduced stress distribution (Huber-Mises)

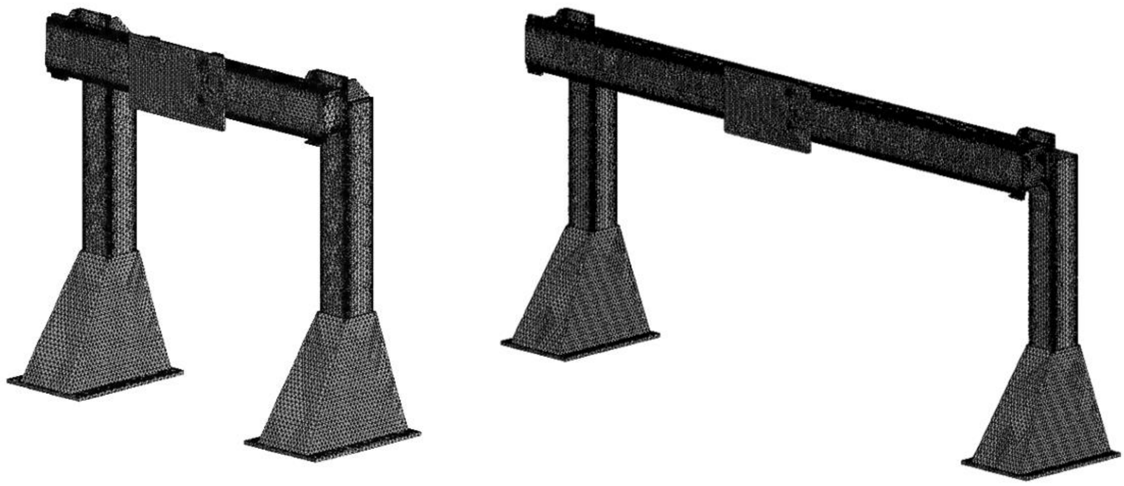


(a)



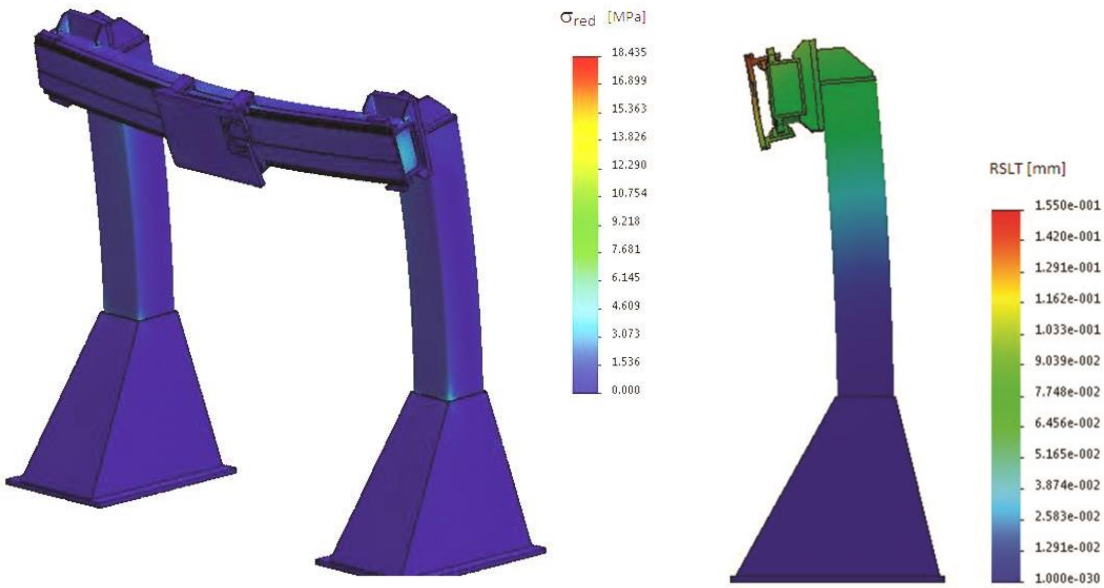
(b)

Fig.8: Distribution of reduced stress and resultant deflection in an H-type positioner loaded unilaterally with a mass of 1000 kg



(a) (b)

Fig. 9. Finite element meshes adopted for calculations in gate models of running track (500 kg) a) 2.5 m, b) 5 m



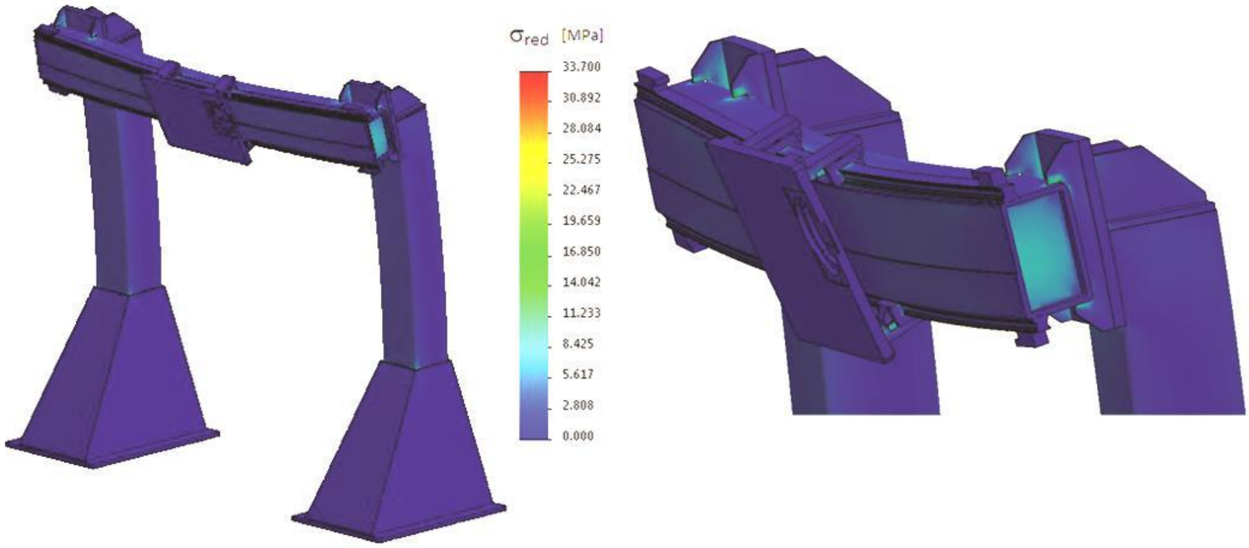
(a) (b)

Fig. 10. Deformation of a 2.5 m long gate track (250 kg) with distribution of (a) reduced stress σ_{red}, b) resultant displacement

Figure 10a shows the reduced stress distribution (Huber-Mises) in a 2.5 m long gate track under a load of 250 kg. The running platform is placed in the wall position at the midpoint of the horizontal beam length. The maximum stress reached a value of 18.4 MPa. The main location of the highest stress in the track structure is the area of the vertical connection between the column and the horizontal beam. The visible deformation of the model indicates the vertical deflection of the horizontal beam and the lateral deflection (Fig.10b) of the same beam. The latter deflection is due to the asymmetrical load applied to the plane of the running platform fixed in the wall position on the horizontal beam.

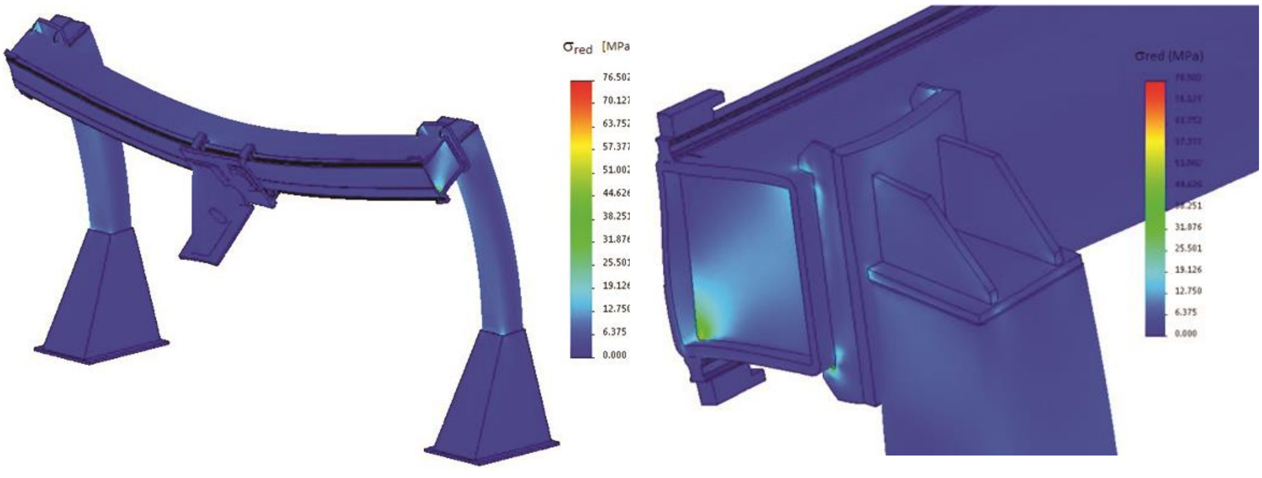
In addition, in the second variant of calculations, the same model was also loaded with a mass of 250 kg but acting at a distance of 500 mm from the plane of the platform (Fig. 11a). Moving the load away from the longitudinal axis of the horizontal beam increased the bending moment of the beam in both the horizontal and vertical planes. The highest reduced stress increased to 33.7 MPa. The running track experienced deflection in the vertical and horizontal planes (lateral deflection). Figure 11b shows an enlarged section of the track where the highest stress accumulation was recorded. It occurs at the connection between the column and the contact track beam. Despite the relatively low values of maximum stresses, possible reinforcement of this area can be considered to eliminate this concentration.

In the case of the 5 m long gate track, a clear increase in the maximum stress and deflection of the transverse beam is evident. The stress in the model with offset load already reaches the maximum value of 168.8 MPa, but still below the yield point of the structure material.



(a) (b)

Fig. 11. Deformation of a 2.5 m long (250 kg) gate track with reduced stress distribution σ_{red}



(a) (b)

Fig. 12. Deformation and reduced stress distribution in a 5 m (500 kg) gate track: (a) whole structure results, (b) enlarged connection area between horizontal beam and vertical column

A more favourable stress distribution occurs for a 5 m long gate track with an inverted platform (Fig. 12). Attaching the robot to the platform from below will also reduce the lateral bending of the beam and the bending moment. The maximum stress reached values of 76.5 MPa at the connection between the vertical column and the track running beam. The stress value is well below the yield strength of the structure material.

With a gate track length of 5 m, similar behavior of the structure under 250 and 500 kg load is obtained. The vertical deflection in the middle of the horizontal beam was for a 250 kg load DY=-0.4 mm, (side deflection DZ=0.26 mm) and for a 500 kg load DY= -0.61 mm, (side deflection DZ= 0.238 mm). Moreover, the applied structural design at the junction of the vertical column with the horizontal beam differs from that designed for the 2.5 m long track and it appears that it will require modification to increase the stiffness of the entire gate track. The considerable size of both vertical and lateral deflection visible for the 5 m long track indicates that in this design variant it will be difficult to ensure the appropriate stiffness of the entire system by making structural changes to the applied connections or beam cross-sections. It seems advisable to modify the gate track by introducing a vertical column in the middle of the track length to stiffen the running track and ensure lower deflection values at this location.

On-site testing of prototypes

Due to their special, unique nature, testing and evaluation of these types of devices are not covered in dedicated standards. They are also not the subject of detailed literature discussions. In such a situation, apart from actions of general nature, such as checking the insulation resistance, verification is based primarily on the manufacturer's own procedures, combined with recommendations formulated for key components (if available). Additional evaluation criteria may also result from the specific application of a particular device, e.g. testing of the allowable welding current for welding positioners.

The following proprietary research program was conducted as part of the on-site research:

1. General testing:
   - verification of correctness of construction designs, including compliance with documentation,
   - external visual inspection,
   - electrical, mechanical and operation tests without starting the drives.
2. Operational tests:
   - start-up and initiation of prototypes,
   - functional tests of prototypes in combination with an industrial robot,
   - comparison of tested properties with those defined as desired.
3. Technological tests:
   - MIG/MAG arc welding tests to evaluate the effect of process disturbances on the movement of individual axes of the prototypes under test, welding current transfer, etc.,
   - comparison of the tested properties with those defined as desired.

Two Fanuc standard universal anthropomorphic six-axis industrial robots (Arc Mate 120iC, Arc Mate 120iC/12L) were selected for testing positioner and gate track prototypes.

Figure 13 shows images of the robotic welding station consisting of the built prototype L-type positioner that was tested.

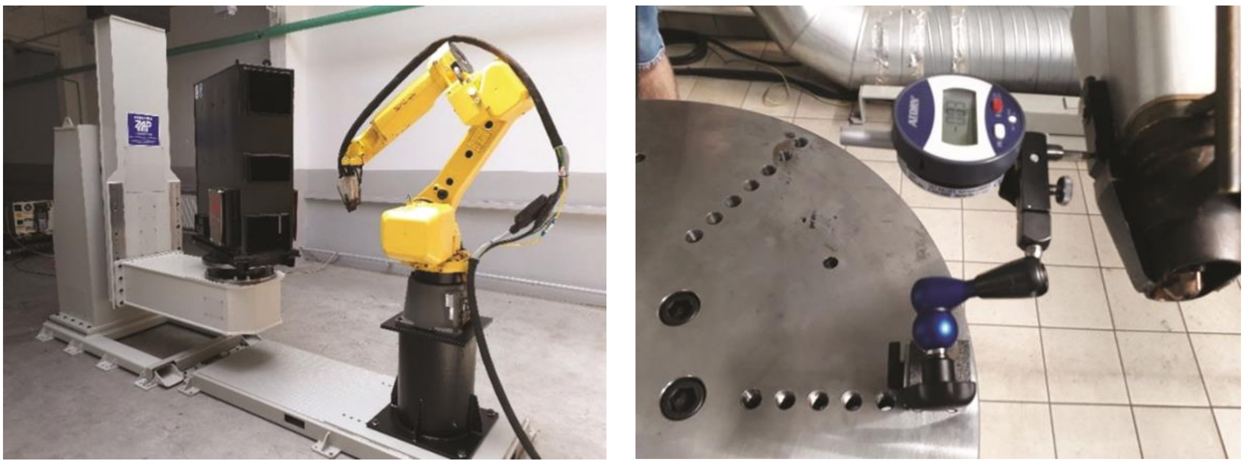


Fig. 13. Prototype of a two-axis, single-station "L" type positioner with 500 kg load capacity prepared for testing

One of the most important motion tests of the positioners was to check the repeatability of positioning, which in case of the L-type positioner was carried out in the range of 24 to 100 cycles. Three main measurement series were performed – with no load on the working table and at ca. 50% and 100% of the nominal load – for different combinations of 240 and 304 kg weights. The measurement took place after stopping the programmed, simultaneous movement of the working table and the horizontal beam of the "L" arm (in the lowest position). The results of the measurements are summarized in table V. Repeatability measurements were performed for different loads, in the range of rotation of the main axis 0÷90° and the working axis 0÷180°.

Table V. Results of positioning repeatability measurements of the prototype positioner "L"

Deviation type [mm]	Load 0 kg	240 kg	544 kg
Average	0.022	0.015	0.014
Maximal	0.040	0.030	0.020
Minimal	-0.050	0.000	0.000
Standard deviation	0.014	0.006	0.008

The research has shown that there is no effect of the working table load on the positioning deviations, and in fact their reduction for the loaded positioner compared to the unloaded one. The maximum deviation of positioning did not exceed 0.05 mm, and the standard deviation of the obtained results was very small and did not exceed 0.014 mm for the unloaded table, which is an order of magnitude smaller than for the loaded table.

Repetitive positioning measurements were also made when the prototype interacted with the robot. This was realized by repetitively positioning the tip of the robotic arm relative to a point on the worktable surface over a wide range of motion. This was measured using a digital dial sensor after stopping the programmed simultaneous motion of the worktable and the horizontal arm bar "L" (in the lowest position). The measurement results are summarized in table VI. The maximum positioning deviation did not exceed 0.02 mm, and the standard deviation of the obtained results is very small and does not exceed 0.014 mm. The deviations of the interaction inaccuracies of the industrial robot and the prototype positioner measured with the dial sensor are well below the summed declared positioning inaccuracies of both machines (± 0.1 mm positioner and ± 0.03 mm robot).

Table VI. results of measurements of the interaction of the prototype positioner "L" with the industrial robot

Deviation type	Determined value [mm]
Average	- 0.004
Maximal	0.020
Minimal	- 0.040
Standard deviation	0.014

Also, for the H-type positioner, positioning repeatability measurements were performed (100 test cycles). Figure 14 shows a photo of the workstation with prototypes of the H-type positioner and the gate track with the platform in the wall position, and the digital dial sensor mounted in the robot's wrist. The measurement occurred when the programmed motion of the "H" frame and the worktable stopped. There were 2 main measurement series performed – with no load on the worktable and with asymmetric load of the frame "H" – 365 kg (measured side) and 433 kg, obtained from the assembly of the mass of beams and weights 240 and 308 kg. The measurement results are summarized in table VII.

Table VII. Results of positioning repeatability measurements of the prototype "H" positioner

Deviation type [mm]	Load Unloaded	Loaded
Average	-0.013	0.002
Maximal	0.020	0.050
Minimal	-0.050	-0.030
Standard deviation	0.013	0.017

Fig. 14. Prototype gate runway with additional module for transporting accessories during assembly phase

No effect of the worktable load on the positioning deviations was observed, and even a decrease in the average value for the loaded positioner compared to the unloaded one. The maximum positioning deviations did not exceed 0.05 mm, and the standard deviation of the obtained results was low and did not exceed 0.017 mm for the loaded positioner. As with the prototype "L" positioner, results were obtained significantly better than the assumed ±0.1 mm repeatability. No overshooting or oscillation of the tested axis assembly with respect to the measurement sensor was observed.

For the gate track, the positioning accuracy was also measured during 100 measurement cycles. A sensor attached via an articulated boom to the gate running platform (cart), to which the robot was attached, arrived at a fixed base on the placed track. The measurement took place after stopping the programmed movement of the driving platform (cart) with the mounted robot. One series of measurements was performed at 100% nominal load, including: the robot with a mass of 250 kg, the mobile platform of the robot (the cart) and the loaded module transporting accessories.

The measurement results are summarized in table VIII. The maximum deviation of positioning did not exceed 0.02 mm. The standard deviation of the obtained results is very low and does not exceed 0.004 mm. For the track cooperating with the robot, a positive correlation was observed. As in the case of prototypes of "L" and "H" positioners, results significantly better than the assumed repeatability of ± 0.1 mm were obtained.

Table VIII. Results of positioning repeatability measurements of the running track prototype

Deviation type [mm]	Determined value [mm]
Average	-0.018
Maximal	-0.020
Minimal	-0.010
Standard deviation	0.004

Other tests performed on the positioners also yielded positive evaluations, including the results of deflection measurements on the positioner's worktable, which were confirmed with the results of the finite element strength analysis.

Conclusions

As a result of the analyses carried out at the design stage, and then the motion tests of L- and H-type positioners and the running track in combination with an industrial robot and during the implementation of the technological process (welding), the high-performance parameters of the manufactured prototypes of manipulator machines were confirmed.

The analysis shows that at the stage of design studies of new types of manipulators it is reasonable, in addition to the execution and analysis of CAD structural models and their strength calculations FEM, also to carry out virtual motion tests in an off-line environment. This will eliminate the need to build real, expensive models, accelerating the development and construction of prototypes. Only the phase of the final motion tests of the prototypes will entail significant costs, but will provide the final, authoritative confirmation of the quality of the adopted solutions.

Based on the research conducted, the following conclusions can be drawn:

- With respect to the prototype "L" type positioner, of particular note is the confirmation of the possibility of at least 50% reduction of adverse torque from loading relative to the axis of rotation of the "L" arm, by manual repositioning of the horizontal beam and/or additional counterweights. Carried out tests and simulation-calculation studies have shown the possibility of a much more effective than originally assumed, even multiple reduction of the adverse moment.
- For the "H" type positioner, it is ensured that the assumed very large working space (cylindrical shape with a diameter of 1.5 and length of 4.0 m) is achieved in two directions, and free movement of the axis of change of "H" frame positions is possible.
- For all prototypes built, the assumed ranges of motion and the achievement of positioning repeatability no worse than ± 0.1 mm were confirmed.
- The deviations of the interoperability inaccuracies measured with the dial gauge are much below the total, declared inaccuracies of the positioning of the tested machines (± 0.1 mm for the positioners and ± 0.03 mm for the robots). Very good repeatability of positioning of the built prototypes was obtained. Also, the deflection measurements fully confirmed the high stiffness of the prototypes and verified the results obtained during the previously conducted modeling with FEM numerical analysis.
- The operation and functionality of prototypes were checked during the realization of the technological process, in conditions similar to industrial ones using tests carried out on MAG arc welding. Conduction of high values of welding current through the construction of the positioner can disrupt its operation, and even lead to failure and immobilize the machine. Technological tests carried out on all built prototypes have obtained positive results.
- No significant construction and execution errors of the tested prototypes were found, and all minor imperfections were corrected during implementation of particular tasks. The developed and constructed prototypes were fully recommended for inclusion in the beneficiary's commercial offer and for industrial production.

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