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Verification of Selected Performance Parameters of Manipulators - External Robot Axes and the L-type Positioner

Abstract: The creative process ranging from the development of the concept of a complex industrial manipulator through design works, simulation and calculation to the implementation of a finished product is a "mammoth" task. Designers' intentions and users' expectations are confronted with material and equipment-related limitations. Because of the usually special and unique nature of such machines, tests relating to them are not the subject of complex standards and detailed description available in various reference publications but are primarily based on manufacturers' own procedures. The article discusses the verification of a newly developed manipulator design (L-type positioner), the prototype of which was subjected to extensive movement-related and technological tests. The study was developed within a research work concerning new types of machines developed at PPU "ZAP Robotyka" in Ostrów Wielkopolski in collaboration with the Department of Welding Engineering of the Warsaw University of Technology.

Keywords: welding positioner, external robot axes, prototype verification

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Introduction

Manipulators performing functions of external axes of industrial robots usually function as units transporting the robot (robot locomotion) and manipulating workpieces (the so-called positioners). A manipulator-related precondition is its controllability from the same level and by the same task programme as the robot [1, 2]. Such an arrangement enables the free shaping of the robot effector trajectory as well as the complete (and simultaneous) interaction with the axes of an attached manipulator. The obtainment of high functionality requires the satisfaction of numerous conditions, including the following [3, 4]:

- high positioning repeatability, possibly the same as that of the robot (usually not worse than ± 0.2 mm),
- high load capacity (of many tons),
- high rigidity, preventing the exceeding of sag and distortion, potentially leading to permanent deformation or even a failure (not exceeding the yield point of structural materials),

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– possibly the greatest movement range of controlled axes,
– in cases of positioners – possibly the greatest number of axes of manipulation (translated into the available work space).

The obtainment of previously assumed parameters requires the constant monitoring of design works, computational verification of changes and modifications and, finally, the performance of extensive motion-related and technological tests of a prototype. Because of the unique nature of multi-axial positioners, tests of such devices have not yet become the subject of standards and detailed scientific descriptions (except for general tests including checks of insulation resistance or the electric strength of low-voltage circuits). In such a case, checks are based primarily on producer's own procedures and recommendations related to key subassemblies. The aforesaid procedures also result from the specific nature of particular application such as the identification of permissible welding current used by a welding manipulator. Acceptable linear and angular displacements (sagging and torsion) of structural elements can be analysed both in relation to general strength-related requirements (and may verify computational test results of structural models involving the use of the Finite Element Method) and in terms of permissible loads affecting bearings or drive unit hubs. The safe and failure-free operation of devices results directly from the application of recommended parameters [5].

The article discusses the multi-stage complex creative process accompanying the final design-related modifications of an actual prototype as well as its verification and implementation within research works concerning new types of machines developed at PPU "ZAP Robotyka" in Ostrów Wielkopolski in collaboration with the Department of Welding Engineering of the Warsaw University of Technology. In addition to L-type positioners, the project also included the development of other types of manipulators. [5,6].

The study discusses selected results of tests and analyses related to an L-type positioner having a load capacity of 500 kg (in accordance with specifications presented in Table 1). The project also involved developmental works concerning an L-type positioner having a load capacity of 250 kg.

The main axis was made using an Nabtesco RDS-320C reduction gearhead and a FANUC βiS 22 servomotor having the following parameters:

– gear ratio: i=157
– maximum rotation rate of the axis: ~12.7 rpm (maximum input rotation rate: 2000rpm / gear 157)
– nominal torque: 3136 Nm,
– maximum allowed torque: 15860 Nm

The work axis was made using an Nabtesco RDR-200C reduction gearhead and a Fanuc βiS 12 servomotor having the following parameters:

– gear ratio: i=156
– maximum rotation rate of the axis: ~12.8 rpm (maximum input rotation rate: 2000 rpm/ gear 156)

Table 1. Operational parameters of L-type positioners adopted in the project

Function or parameter	Size 1	Size 2
Design	monolithic	
Number of stations/mobile platforms	1 or 2	
Drive unit	electric (dedicated)	
Total number of controlled axes	2/5 (one/two-station)	
Rotation of the work table /control	nx360°/continuous	
Rotation of the L-arm /control	nx360°/ continuous	
Rotation of station change /control	2x180°/discrete	
Load capacity [kg]	250	500
Positioning repeatability [mm]	not worse than ±0.1	
Maximum welding current [A]	not less than 500A	
Maximum work space [m]	1.5 x 1.5 x 1.5	2.0 x 2.0 x 2.0
Drive mounting	universal	

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– nominal torque: 1960 Nm
– maximum allowed torque: 9800 Nm.

The torque-related diagrams and the remaining specifications are contained in related specification sheets.

To obtain high operational functionality, the projected involved two sizes of machines having a stationary cubic-shaped work space located opposite the positioner housing (on the surface of a work table), in the lowest possible position where a manipulated object having dimensions of 1.5 m × 1.5 m × 1.5 m and a load capacity of 250 kg or 2.0 m × 2.0 m × 2.0 m and a load capacity of 500 kg could be placed. The foregoing resulted in significant dimensions of extended beams (ending with the work table) exposed to considerable stresses (potentially leading to deformations). Figure 1 presents the primary dimensions of the L-type positioner having a load capacity of 500 kg. In relation to the above-presented positioner types, the maximum size of a manipulated object would strongly depend on the momentary angular position of both axes of manipulation, the designed position of the rotation axis of the L-arm (1502 mm) and the mounting height of the horizontal L-beam (900 mm).

Final modifications of the L-type positioner

The final form of the L-type positioner, including its dimensions, ranges of movement and adjustment, thicknesses of sheets/plates and structural sections as well as components such as bearings, gears and drives, were the results of numerous structural iterations following CAD model-based motion simulations in the off-line programming environment [7] and FEM-based calculations [8] (discussed in more detail in other publications). Figure 2 presents the initial and the final design (used in the construction of the prototype).

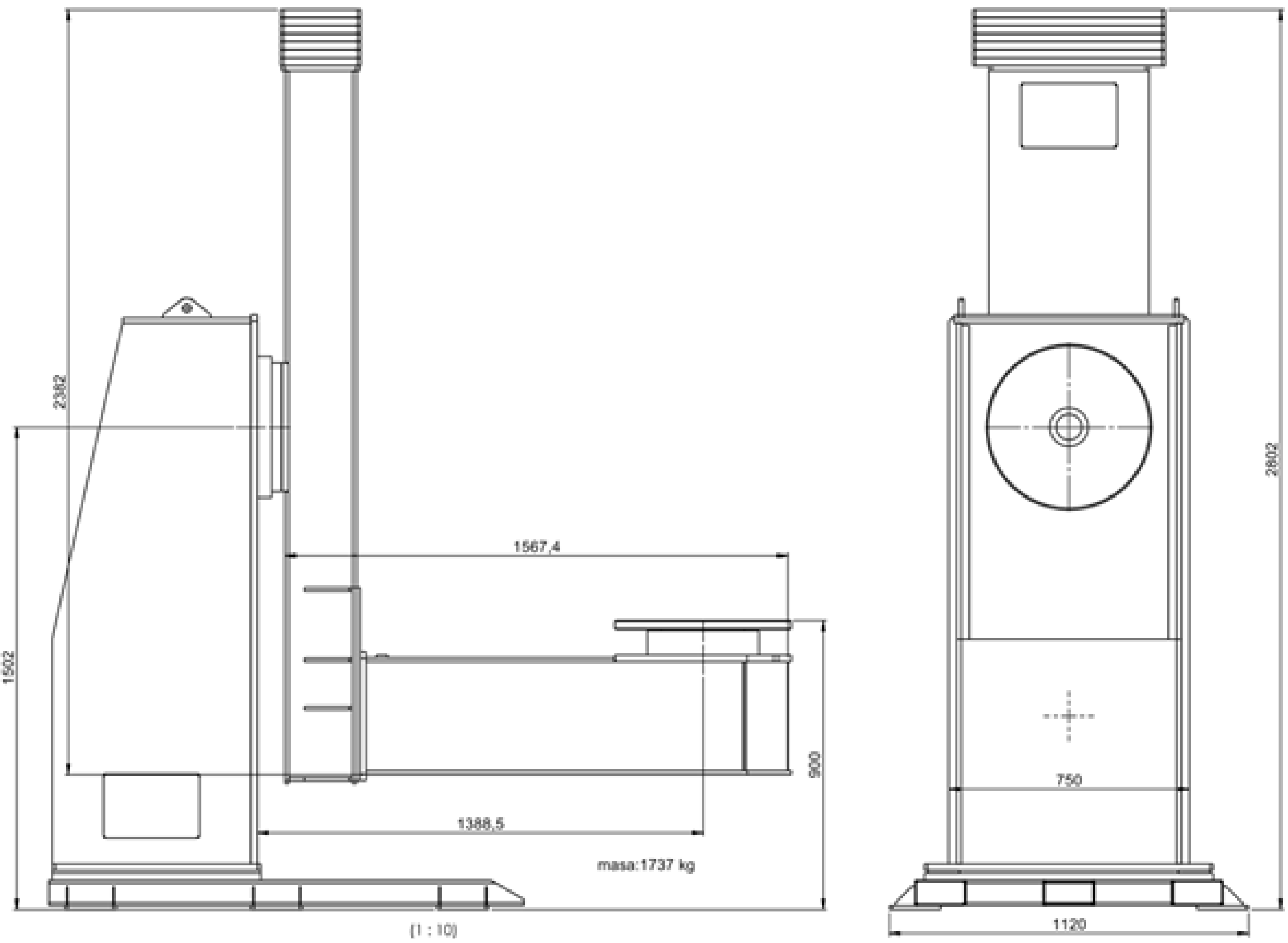

Fig.1. Primary dimensions of the L-type positioner (500 kg)

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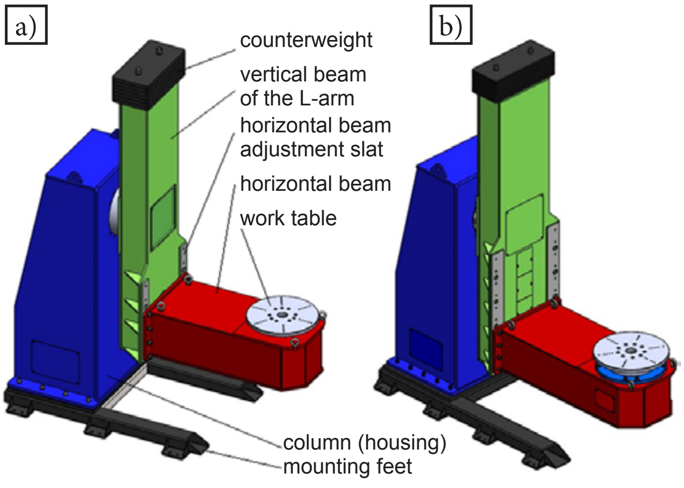

Fig. 2. Three-dimensional models of the L-type positioner obtained using the CAD-based modelling process: a) initial design and b) final design, used in the construction of the prototype [5]

Figures 3 and 4 present exemplary structural changes to the initial design, implemented at the successive stages of the design process. Many modifications (Fig. 3) were concerned with the L-arm horizontal beam, being of key importance as regards positioner functionality and, at the same time, being at risk of deformation (sagging).

A beam adjustment step was changed from 100 mm to 200 mm, whereas the number of positions was reduced from an excessive number of 9 to a number of 4. As a result of the above-presented modifications, the length of the horizontal beam adjustment slat was reduced from 1200 mm to 1000 mm. The subsequent stage involved the reinforcement of the internal beam ribbing, the enlargement of the oval opening being the cable penetration for control and technological cables of the positioner work table (in relation a very large adjustment (mounting) range of the horizontal beam).

The FEM-based analyses revealed unfavourable distributions of stresses in the mounting feet of the positioner. The stability and the rigidity of the manipulator were improved by extending the sections of the mounting feet (constituting the base of the positioner). The above-named modification increased the weight of the base from 170 kg to 257 kg. In turn, the positioner housing was reinforced in the main axis area by, among other things, changing the thickness of the front plate from 20 mm to 30 mm as well as by changing the thicknesses of the side and upper plates from 15 mm to 20 mm (Fig. 3).

The modified model of the L-type positioner was subjected to FEM-based strength-related analysis. Figure 5 presents exemplary results related to distributions of reduced stresses under a load of 300 kg in relation to two positions of the L-arm. The highest stress affecting the positioner in relation to position 0° amounted 40 MPa. In turn, highest stress affecting the positioner in relation to position 45° amounted to 50.7 MPa (Fig. 5b) [3].

The FEM-based analyses also enabled the improvement in terms of distortions and sagging

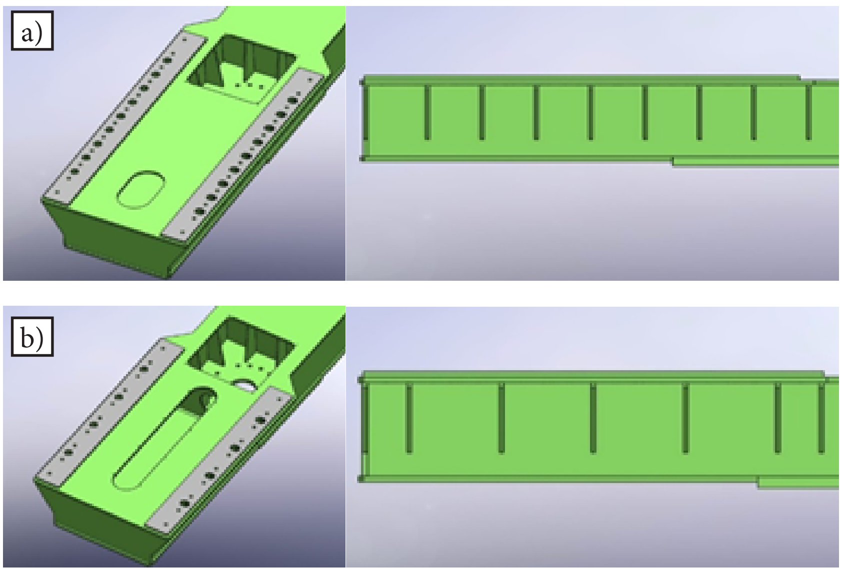

Fig. 3. Modification of the vertical beam of the L-arm: a) before modification and b) new version

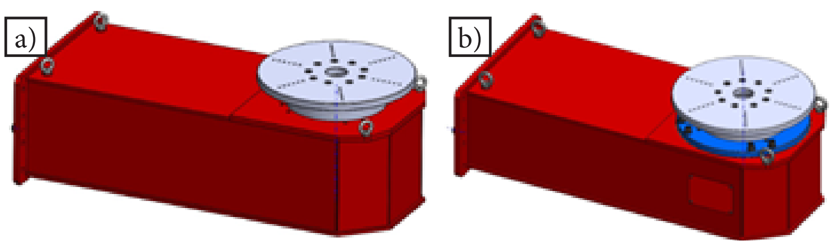

Fig. 4. Horizontal beam of the work table: a) before modification and b) after modification and following the addition of the intermediate flange

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of the positioner arm. For instance, vertical displacement DY was reduced from -1.65 mm to -1.09 mm in relation to an arm position of 0° and a load of 300 kg. In turn, as regard the rotation of the arm by 45°, the maximum sag was reduced from -1.9 mm to -1.6 mm, in relation to a load of 500 kg. The above-presented analysis involved the use of greater counterweight on the vertical beam of the L-arm, the adjustment elevation of the horizontal arm with the work table and the elimination of the technological opening in the vertical beam.

The calculation results indicated slight differences in stresses and sags affecting the positioner. Only after the implementation of all structural changes (referred to in this section), it was possible to significantly improve rigidity and further decrease reduced stresses throughout the structure. The analyses and structural changes resulted in the construction of the L-type positioner having a load (capacity) of 500 kg (Fig. 6). The above-named positioner was subsequently subjected to tests and analyses discussed in the remainder of the article.

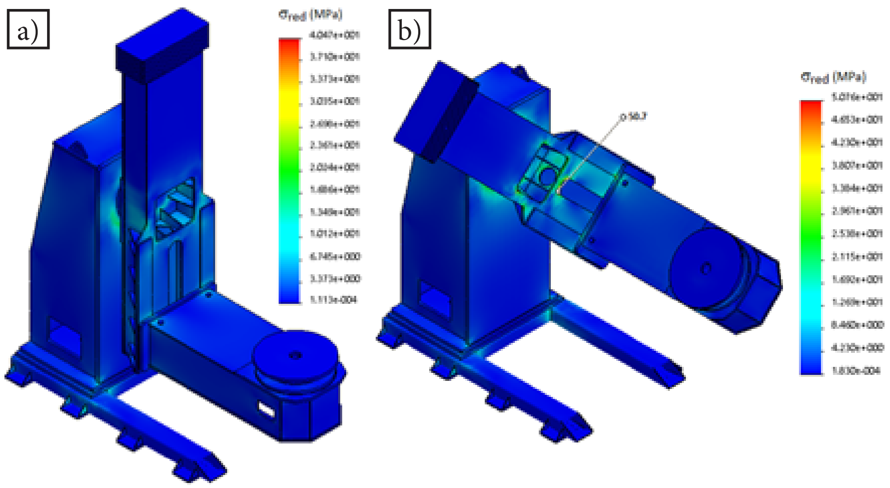

Fig. 5. Distribution of reduced stresses on the complete modified model of the positioner under a load of 300 kg, in relation to two positions of the L-arm: a) 0° and b) 45° [3]

Fig. 6. Prototype of the L-type positioner and the welding robot adapted for operation under a load of 500 kg

Analysis of load torques

The analysis was concerned with the possibility of reducing (by a minimum of 50%) unfavourable load torque in relation to the rotation axis of the L-arm by moving the horizontal beam/or by using additional counterweights. The analysis-related calculations involved the shifting of the horizontal beam of the L-arm along the vertical beam. The shifting of the beam was performed in 4 stages (using a step of 200 mm) – from the maximum extension to the position where the surface of the work table was levelled with the rotation axis of the L-arm.

The tests included the use of additional counterweight balancing the load (in the form of weights located at the top of the vertical beam of the L-arm) in relation to the rotation axis of the L-arm. The weight of a single counterweight amounted to 17.45 kg. The maximum number of placeable weights amounted 15 and weighed 261.8 kg. The calculations and the analysis of the maximum load torque Mo, acting on arm Yc in relation to the rotation axis of the L-arm (Fig. 7), involved taking into account the actual location of the centre of gravity in relation to the resultant load exerted by the weight of

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the arm, counterweight and added load Q = 500 kg (dimension Yc in Fig. 7). Simulations were performed using the CAD Solidworks software. The non-exceedable nominal torque of the L-arm (in accordance with the gearhead specifications) amounted 3136 Nm (maximum torque being 7840 Nm). Simulations involved the prototypical L-type positioner having a load capacity of 500 kg and primary dimensions as presented in Figure 7 (where X0 and Y0 are structural dimensions).

The positioner was subjected to load (weight) Q = 500 kg. The gravity centre of added load Q overlapped with the rotation axis of the work table (Zc = 0).

The counterweight was adjusted in a manner making it possible to obtain the best possible static balance of the unloaded L-arm. The first four groups of calculations involved the use of a counterweight of 261.8 kg, corresponding to the L-arm in its lowest position, i.e. Y0 = 600 mm (Fig. 7a).

The total weight of the arm and of the counterweight amounted to 1108.9 kg. In the last, i.e. fifth, group of calculations, the counterweight was reduced to 139.6 kg, which corresponded to the unloaded L-arm having a total weight of 986.7 kg and being in its highest position, i.e. Y0 = 0 mm (Fig. 7b).

The mounting height of the horizontal beam of the L-arm was changed within the range of 0 mm to 600 mm in relation to the main rotation axis of the L-arm (dimension Y0 in Fig. 7). The height of the gravity centre of added load Q above the work table surface was changed within the range of 0 mm to 300 mm (0-0.3 m) (dimension Y1 in Fig. 7).

The results of the simulation and calculations of torque Mo are presented in Table 2. The negative values of torque Mo resulted from the negative indications of eccentric Yc, being on both sides of the reference line, i.e. the rotation axis of the L-arm and, during torque identification, were consistent with the general principle of the right-handed screw.

The first parameter to be determined (results in green) was torque Mo in relation to the L-arm alone, also taking into account its mounting position. An increase in the mounting height was accompanied by an increase of the torque from -543.9 Nm (Y0 = 600 mm – the lowest position, balanced by counterweight) to 2066.9 Nm (Y0 = 0 mm). In relation to the

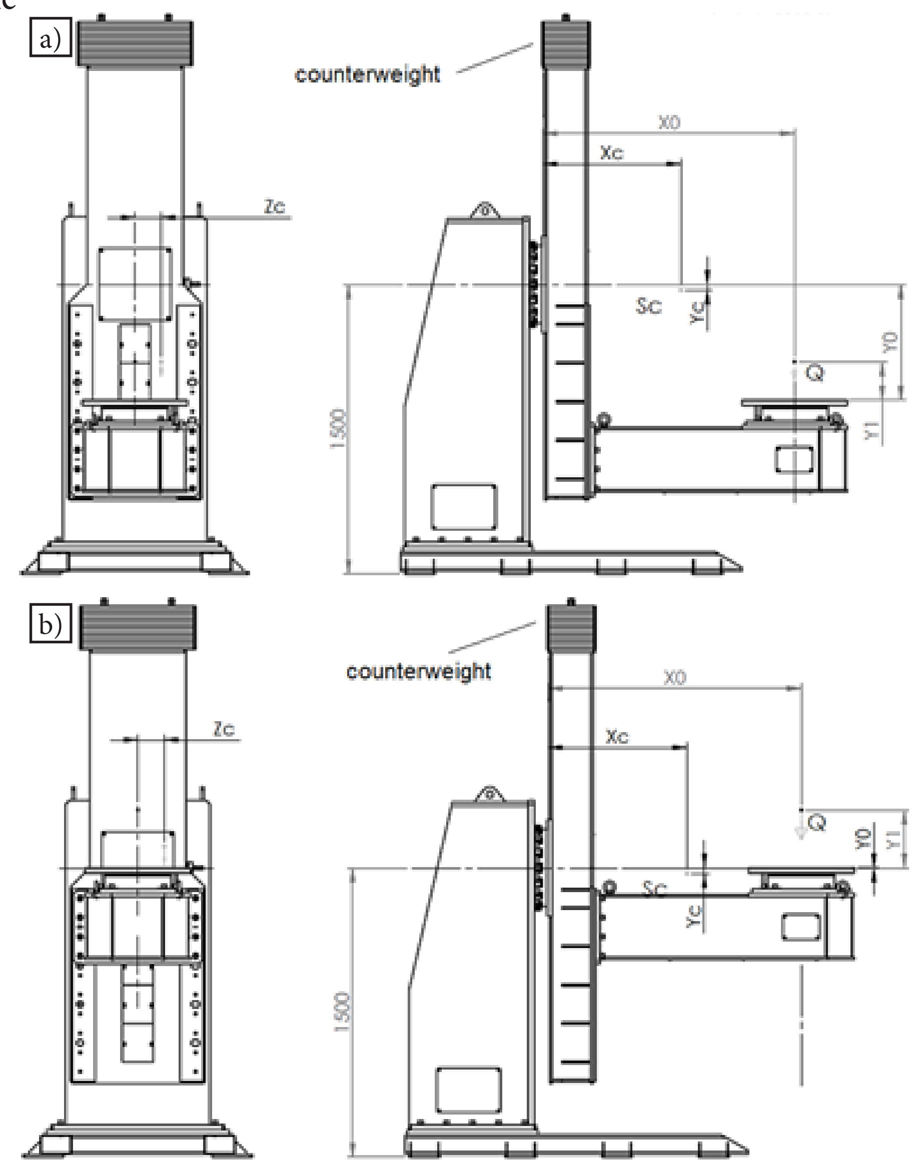

Fig. 7. Geometric parameters of the L-type positioner used in the calculations of torque Mo: a) horizontal arm in its lowest position and b) horizontal arm in its highest position

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least favourable mounting of the arm, i.e. in the highest position (Yo = o mm, where the work table surface overlapped with the rotation axis of the L-arm), the last series of calculations involved the identification of a new value of counterweight (139.6 kg), which led to the significant reduction of torque Mo (to 484 Nm). The calculations revealed the possibility of the repeated reduction of the unfavourable torque of the L-arm alone, by changing the value of counterweight.

The subsequent stage (results in red) involved the determination of torque Mo in relation to the L-arm with added load Q = 500 kg, the gravity centre of which was located directly on the surface of the work table (Y1 = 0). The above-named case, unfeasible under actual conditions and purely theoretical, only aimed to present the effect of the mounting position of the L-arm on torque Mo. Another, i.e. higher, mounting position of the L-arm reduced the unfavourable torque from -3472.3 Nm (Y0 = 600 mm) to 157.8 Nm (Y0 = 200 mm). The calculated torque increased to 2051.8 Nm (Y0 = 0 mm) – as a result of the unfavourable balancing of the L-arm alone (result was the same as the

Table 2. Calculation results concerning torque Mo in relation to the conditions presented in Figure 6 (four basic series – constant with a counterweight of 261.8 kg and an additional series with a counterweight of 139.6 kg)

Work axis	**Work table**	**Load**		**Centre of gravity**			**Torque**
X0 (m)	YO (m)	Y1 (m)	Q (kg)	Xc (m)	Yc (m)	Zc (m)	Mo (Nm)
1.31	0.6	-	0	0.46	-0.05	0.0	-543.9
1.31	0.6	0	500	0.72	-0.22	0.0	-3472.3
1.31	0.6	0.1	500	0.72	-0.19	0.0	-2998.8
1.31	0.6	0.2	500	0.72	-0.16	0.0	-2525.3
1.31	0.6	0.3	500	0.72	-0.12	0.0	-1894.0
1.31	0.4	-	0	0.46	0.03	0.0	326.3
1.31	0.4	0	500	0.72	-0.10	0.0	-1578.3
1.31	0.4	0.1	500	0.72	-0.07	0.0	-1104.8
1.31	0.4	0.2	500	0.72	-0.04	0.0	-631.3
1.31	0.4	0.3	500	0.72	-0.01	0.0	-157.8
1.31	0.2	-	0	0.46	0.11	0.0	1196.6
1.31	0.2	0	500	0.72	0.01	0.0	157.8
1.31	0.2	0.1	500	0.72	0.04	0.0	631.3
1.31	0.2	0.2	500	0.72	0.08	0.0	1262.7
1.31	0.2	0.3	500	0.72	0.11	0.0	1736.2
1.31	0.0	-	0	0r46	0.19	0.0	2066.9
1.31	0.0	0	500	0.72	0.13	0.0	2051.8
1.31	0.0	0.1	500	0.72	0.16	0.0	2525.3
1.31	0.0	0.2	500	0.72	0.19	0.0	2998.8
1.31	0.0	0.30	500	0.72	0.22	0.0	3472.3
Additional series							
1.31	0.0	-	0	0.50	0.05	0.0	484.0
1.31	0.0	0	500	0.77	0.03	0.0	437.5
1.31	0.0	0.1	500	0.77	0.07	0.0	1020.9
1.31	0.0	0.2	500	0.77	0.10	0.0	1458.5
1.31	0.0	0.3	500	0.77	0.13	0.0	1896.0

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one obtained in relation to the unloaded arm).

After changing the counterweight to the value corresponding to the highest position of the horizontal beam of the L-arm, the value of torque decreased significantly to 437.5 Nm. Only the shifting of the horizontal beam of the L-arm led to more than 20-fold reduction of the unfavourable torque. An additional (and important) adjustment factor was the possibility of changing the value of counterweight (within the range of 0 kg to 261.8 kg).

The primary calculations (results in black) were concerned with the actual-like position of the gravity centre of added load Q (changed from Y1 = 100 to 300 mm). Similar to the previous case, it was possible to observe the significant (repeated) reduction of the unfavourable torque along with the adjustment of the mounting position of the horizontal beam of the L-arm. For instance, in relation to the gravity centre of added load Q being located 200 mm (Y1) away from the work table surface (intermediate distance), torque Mo amounted to 2525.3 Nm in relation to height Y0 = 600 mm and decreased to 631.3 Nm in relation to Y0 = 400 mm.

The very modification of counterweight performed in relation to Y0 = 0 mm (work table being in its lowest position) also significantly decreased the unfavourable torque. The counterweight could be modified in relation to each mounting position of the horizontal beam and the geometry of applied load.

Analysis of positioning repeatability

An important research-related issue was the identification of the positioning repeatability of the L-type positioner mechanisms in relation to a previously declared value of +/- 0.1 mm. To this end, it was necessary to record dimensional deviations, with which the work table approached an immobile dial gauge. Related measurements were performed after stopping the previously programmed simultaneous rotation of the work table (within the range of 0° to 90° at a rotation rate of 3 rpm) and the horizontal beam of the L-arm (within the range of 0° to 180° at a rotation rate of 6 rpm). The tests involved the performance of three primary measurement series, i.e. with the unloaded work table (102 repetitions) as well as with a load constituting approximately 50% (240 kg, 101 repetitions) and 100% (544 kg, 24 repetitions) of the nominal load. The test load remained unchanged in each series, which corresponded to typical conditions accompanying the operation of such machinery.

Table 3. Results of positioning repeatability measurements in relation to the L-type positioner prototype

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

The measurement results (Fig. 7, Table 3) revealed the lacking effect of the work table load on positioning deviations. Interestingly, the aforesaid deviations decreased in relation to the loaded positioner (if compared with those characteristic of the unloaded positioner). Maximum positioning deviations did not exceed +/- 0.05 mm. The standard deviation of the measurement results was very low and did not exceed 0.014 mm in relation to the unloaded work table. In addition, the aforementioned deviation was (by an order of magnitude) lower in relation to the loaded work table. The analysis of coefficient of determination R2 revealed the lack of measurement data-related correlations. The results obtained in the measurements were significantly superior to a previously assumed repeatability of +/- 0.1 mm. In addition, no overshoots or oscillations of the axis unit in relation to the measurement sensor were observed.

Analysis of horizontal arm sag

The tests also involved measurements concerning the sag of the horizontal arm of the L-type

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positioner, based on the initially developed and subsequently modified design.

The first strength-related analysis concerning the structure of the L-type positioner resulted in the correction of dimensions (reinforcement) of the individual structural elements of the positioner. The corrected design (structure) was subjected to subsequent analysis. The analysis of positioner L500 and L250 took into account the action of forces resulting from the kerb weight of the structure, forces resulting from applied loads (2500 N and 5000 N) as well as forces resulting from the presence of the presence of the drive mounted on the horizontal beam of the L-arm.

The FEM-based modelling results related to the modified, i.e. final, version of the L-positioner revealed that the calculated vertical sag-related values concerning the end of the horizontal L-arm were similar to the average values of sag measured in the prototypical L500 positioner under a load of 240 kg and that of 544 kg (Table 4).

Slightly lower sag values, determined in FEM-based modelling, resulted definitely from the fact that the modelling process did not take into account the presence of the drives. The aforesaid drives were only represented through their weight (used in calculations), yet their complicated design and closed structure precluded the inclusion of their geometry in the design (structure) of the model.

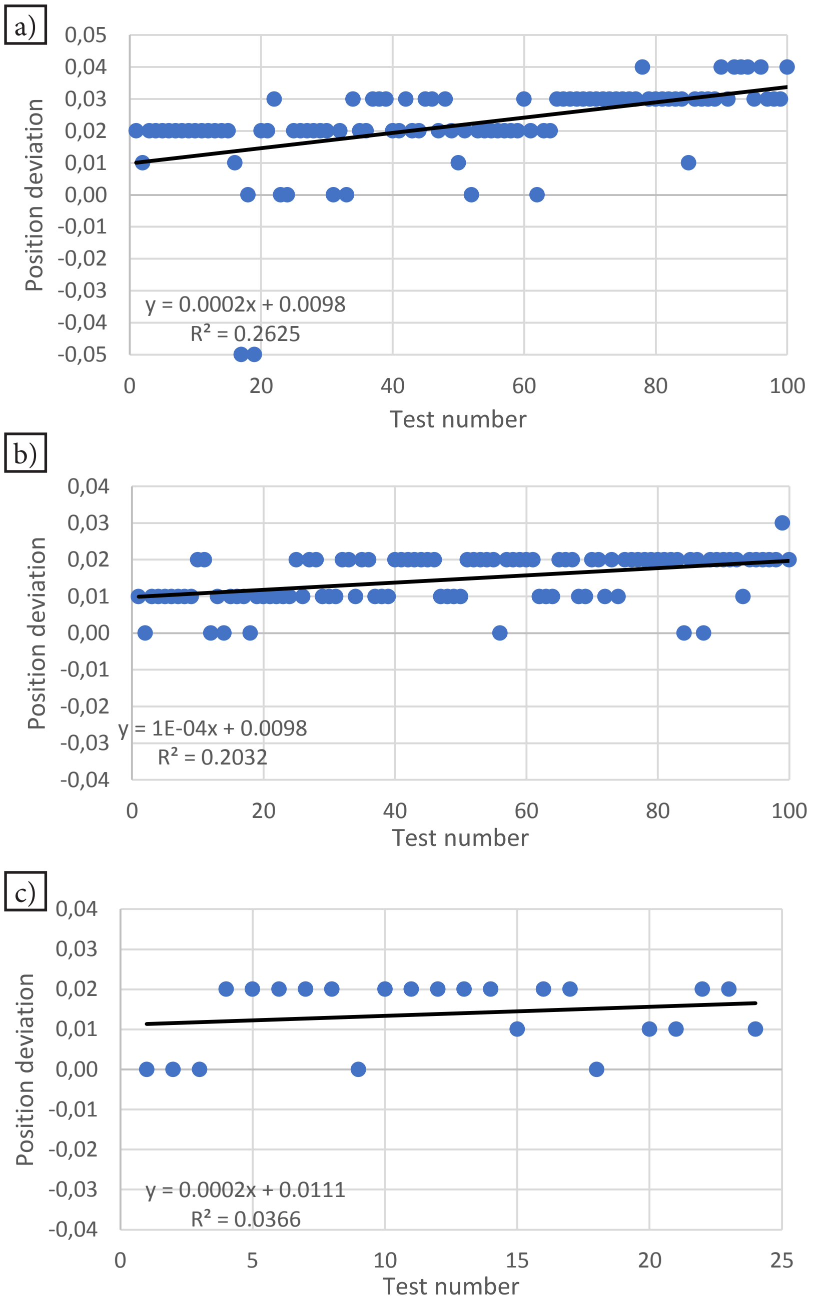

Fig. 7. Characteristics of the positioning deviations of the prototypical L-type positioner during the verification of interaction with the robot: a) without the load, b) under a load of 240 kg and c) under a load of 544 kg

Table 4. Results of the measurements and numerical calculations concerning the vertical sag of the L-type positioner arm

Load (kg)	Measurement	FEM-based calculations (modified model)	FEM-based calculations (initial model)
	Maximum vertical sag (mm)		
250	-1.54 ±0.08 (240 kg)	-1.26	-2.37
500	-3.93 ±0.19 (544 kg)	-2.90	-6.19

Summary

The previously performed strength-related analysis concerning the L-type positioners revealed the presence of slight accumulations of stresses in the entire structure as well as sags at the end of the horizontal arm, the value of which was the sum of sags related to the drives, the housing as well as the area where the drive and the housing were connected with the positioner arm. The calculation results related to the initial models

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of the L-type positioner were used to perform structural modifications in the area where the housing was connected with the arm and where the housing was connected with the positioner base. Asa result, it was possible to obtain the reduction of both stresses and displacements (which translate into overall structural deformation). It was also possible to further reduce the total sag of the positioner arms through the structural stiffening of the area where the housing was connected with the positioner arm.

It is also probably possible to further reduce the total sag of the positioner arms through the structural stiffening of the area where the housing is connected with the positioner arm. The above-presented strength-related modelling concerning the L-type positioner proved to be an indispensable tool when designing new manipulators as it enables the identification of potentially dangerous areas in the structure and perform necessary modifications in order to stiffen the structure and prevent the unfavourable distribution of stresses and bending moments.

In relation to the previously adopted assumption concerning the possible reduction (by a minimum of 50%) of the unfavourable load torque in relation to the rotation axis of the L-arm, the tests revealed the possibility of the significantly greater reduction of the aforesaid torque through simultaneously changing the height of the position of the horizontal beam of the L-arm and the value of counterweight. The counterweight used in the tests to balance the arm alone could be adjusted to the resultant weight of the arm and a load, and, combined with the change of the mounting position of the horizontal beam of the L-arm, could offer nearly unlimited possibilities in terms of reducing unfavourable torque.

The above-presented tests revealed the possibility of the significant reduction of the unfavourable load torque in relation to the rotation axis of the L-arm by using additional counterweights and through the innovative displacement of the horizontal beam with the work table. In specific cases, the aforesaid unfavourable torque could be reduced entirely.

Similarly positive were the results of the tests concerning the positioning repeatability (significantly superior to previously assumed +/- 0.1 mm). The measurements of the sags of the horizontal positioner arm under a load of 240 kg and that of 544 kg fully confirmed the high rigidity of the prototypical positioner and did not differ significantly from the results obtained in the FEM-based numerical modelling process. The FEM-based modelling results concerning the modified version of the L-type positioner revealed that the values of the vertical sag related to the end of the horizontal L-arm were slightly lower than the values of the actual sags. The foregoing resulted from the fact that the computational models did not take into account the presence of the drives, which were only represented through their weight at the mounting point. However, their complicated design and closed structure precluded the inclusion of their geometry in the design (structure) of the entire positioner model. Slight differences of the load values during the measurements could also be responsible for slight differences in relation to the results obtained in the measurements and in the modelling process.

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