VERIFICATION OF THE PROPERTIES OF AN INDUSTRIAL ROBOT FOR THE NUCLEAR INDUSTRY

JAN SEMJON[1], JOZEF VARGA[2], PATRIK PILAT[2], PETER MARCINKO[1], RUDOLF JANOS[1]

[1]Technical University of Kosice, Department of Production Systems and Robotics, Kosice, Slovakia

[2]Technical University of Kosice, Prototyping and innovation centre FME, Kosice, Slovakia

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jan.semjon@tuke.sk

The article deals with the issue of verification of selected geometric characteristics of a special robot intended for the nuclear industry. The design of the robot is specific in that the robot works in both semi-automatic and manual mode. This leads to frequent collisions of some parts of the robot with fragmented equipment. Therefore, it was necessary to ensure the accuracy and repeatability of the robot after its production and during its operation. Verification of the parameters of the robot after one year of operation was carried out in the controlled zone of the nuclear power plant, which was specific due to the presence of ionizing radiation. The methodology, technique and method of verification had to be adapted to this.

KEYWORDS

Robot, verification of parameters, nuclear industry, repeatability, ISO 9283

1 INTRODUCTION

Verification of the geometric characteristics of robots is one of the important activities before deploying a newly developed robot in industry. Sensing technology or complete devices used to detect the necessary characteristics use different principles [Slamani 2015]. The difference between the individual principles lies primarily in the accuracy of the measured data, the speed of the measurement, the conditions in which the measurement can be performed and, of course, the price level for the purchase of the relevant equipment. Systems used by companies to verify the working characteristics of robots are selected from the available sources. The RoboDyn calibration and inspection system [McGarry 2021] provides comprehensive control that guarantees accuracy, flexibility and intelligence. With the option to calculate the robot base alignment and tool center displacement corrections. It can also compensate for robot parameters, and when supplemented with the Leica Absolute Tracker [Szybicki 2022], this tool is suitable for measuring the working characteristics of robots. To obtain static and dynamic parameters, this software is used with the Leica Absolute Tracker system. With direct connectivity between Leica Absolute Tracker systems and various robot technologies, RoboDyn provides the flexibility needed to connect to virtually any system. Thanks to the open architecture of the RoboDyn system, any user can extend the basic functions of the software by adding their own direct connections and post-processors. Another company that deals with this issue is the company BlueWrist, Robot&vision solutions. This company uses the KinOptim system [Barelle 2014]. It is a complete robot calibration solution fully integrated with comXtream. It uses many parameters including D-H (DenavitHartenberg) parameters, TCP calibration, etc. This method uses laser interference [Biro 2020, Zhang 2019, Heczko 2021]. The use of the optical tracking system and other methods makes it possible to improve the accuracy of the robot used in applications such as riveting, drilling or precise assembly [Liu 2020].

Another method that is used in the verification of some characteristics of robots is the use of a ballbar, which allows identifying changes in the accuracy of the robot based on the deformation of the circular path [Kuric 2020]. Other geometric characteristics that can be verified on robots include path accuracy, where the accuracy of the robot is monitored during its movement, not only at static measurement points [Marcinko 2024]. The oldest way to verify robot parameters is the use of various touch sensors, which can display measured inaccuracies in digital or analog form on appropriate display devices [Keyence 2024].

2 FORMULATION OF THE PROBLEM

The basic parameters of the designed robot were based on the following requirements. The robot must have five rotation axes and must be mounted on a transverse platform, allowing movement in two mutually perpendicular directions. Movement in the transverse direction with a length of min. 4800 mm with repeated stop accuracy of max 1.5 mm. Movement in the longitudinal direction along standard rails with a stopping accuracy of up to 10 mm. This movement is not important from the point of view of accuracy, it is only used to move the robot to individual parts of the steam generator. The carrying capacity of the robot was set at 200 kg. Its vertical reach should reach a value of at least 3 m. It must allow the connection of these tools (CO torch, plasma torch, Saw with basket, saw without basket, extraction pliers, angle grinder). Minimum movement speed 10 mm/min, one-way positioning accuracy without the influence of cutting forces maximum 1.5 mm and positioning repeatability up to 2 mm. Electric robot drives, equipped with resolvers and brakes.

Based on these minimum requirements and consultation with the customer, the design of a robot with a carriage and tools was arrived at, where a view of the robot with a carriage and tools is shown in Fig. 1.

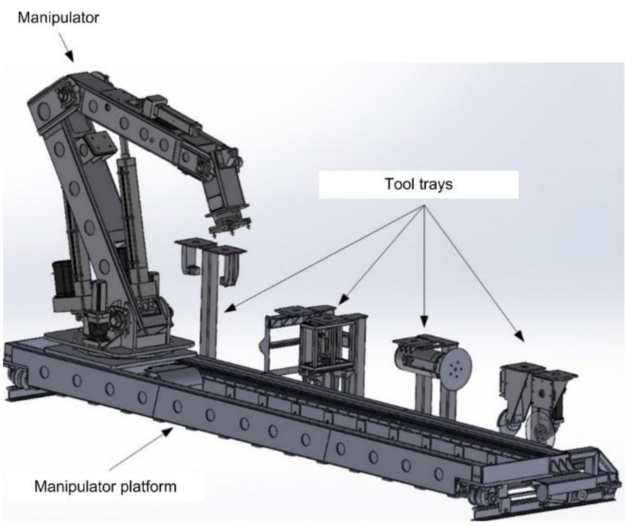

Figure 1. View of the robotic workplace in 3D

The most critical and, from the point of view of accuracy, the most important operation in the fragmentation of the steam generator is the cutting of stainless steel pipes to a length of 700 mm. As a tool, a saw blade with a diameter of 400 mm and a speed of 1400 rpm is used, stored in a specially designed saw.

The mentioned solution is patented by the European patent EP3984673 [Vargovcik 2023]. The saw also includes a collection basket attached to the lower part of the saw to rotate freely. The specially designed saw is in direct contact with the contaminated tubes of the steam generator, and at the same time the teeth of the saw blade gradually wear down. This leads to ongoing checks and subsequent replacement with a new disc. On the basis of these facts and at the same time on the basis of similar measurements carried out on industrial robots, it was agreed with the customer that the verification of the robot parameters will be carried out only on the output flange of the robot (without the presence of a tool - a saw). This will make it possible to achieve similar measurement conditions after the robot is manufactured and after its operation in the required time intervals.

If it is necessary to verify the measured data after the manufacture of the manipulator and subsequent comparison after six months or a year of operation in the premises of the nuclear power plant, the possibilities are quite limited. The need to verify the parameters of the designed manipulator during its operation is based on the requirement of fragmentation of 12 pieces of steam generators weighing 90 tons.

Based on these requirements, a robot with the following characteristics was designed and manufactured, Tab.1.

Table 1. Parameters of the robot with a platform

Parameters	Value	Unit
Number of controlled axes (J1 – J7) + (A1 – A2)	5+2	piece
Weight	2350	kg
Payload	200	kg
Maximum reach of robot	3.2	m
Maximum range of movement of the platform (width x length)	1.1 x 5	m
Maximum speed	100	mm/s
Positioning accuracy	1	mm
Repeatability of robot	1.5	mm

The robot will work primarily in a semi-automatic cycle, that is, collisions of tools or parts of the robot with fragmented parts of the steam generator will be common. This creates the need to check the state of the manipulator in order to be able to detect any backlash or damage.

The priority is to use sensors that will function reliably in an ionizing and excessively dusty environment [Semjon 2023]. At the same time, however, their further use outside the nuclear power plant is prohibited, as they will work in a controlled (contaminated) zone. After using the sensors near the contaminated manipulator, their decontamination is problematic, so they leave the nuclear power plant only as nuclear waste. It will then be stored in closed containers in the nuclear repository.

For this reason, inexpensive touch sensors were chosen to verify the necessary characteristics. These are specifically Heidenhain MT 12 and MT 25 sensors, which have been used in the workplace for a long time [Semjon 2020]. The evaluation units for the mentioned sensors can be stored in a secure box and outside the working area of the manipulator. After preliminary radiation measurements, this means that their contamination will be almost zero and they can leave the controlled zone of the power plant.

The benefit of the research was the selection of a suitable measuring technique and the subsequent verification of the selected geometric characteristics of the robot in the contaminated zone of the nuclear power plant, at the lowest possible costs and ensuring the accuracy of the measurement, which could not be affected by ionizing radiation. Based on the performed measurement, the life of the robot was subsequently extended and it will be used for the fragmentation of steam generators from another decommissioned block of the nuclear power plant.

3 MEASUREMENT METHODOLOGY

One of the main characteristics of industrial robots is their positioning accuracy, which strongly depends on the resolution of sensors and geometric parameters of the robot [Neubauer 2015].

Based on the customer's requirements, measurement tests were designed according to the ISO 9283 standard [ISO 9283 1998]. Tests were selected from the mentioned standard, the implementation of which ensures the identification and comparison of the required characteristics. Before the actual measurement, the basic conditions must be met. The robot must be completely assembled and fully functional.

Before the test, the movements of the robot must be limited as necessary to adjust the measuring instruments. The test must be preceded by a designated heating operation, if specified by the manufacturer. The ambient temperature during the tests should be kept within (20 ± 2) °C. The measured position data (coordinates x_j, y_j, z_j) must be expressed in a coordinate system whose axes are parallel to the axes of the coordinate system of the base of the robot being measured.

The robot position repeatability values were selected as the most important validation parameters. The reason was the need to find out whether the robot is able to continue working on the required manipulation (technological) task while ensuring sufficient movement speed and positioning accuracy [Slamani 2012]. Selected tests with load definition (50% and 100%) of maximum load capacity, maximum output speed of movement and number of cycles are shown in Table 2.

Table 2. Selected tests according to ISO 9283.

Parameters	Load (kg)	Speed (mm/s)	Number (cycles)
Pose accuracy (AP_{50}) Pose repeatability (RP_{50})	100	100	30
Pose accuracy (AP_{100}) Pose repeatability (RP_{100})	200	100	30

3.1 Description of selected characteristics

Pose accuracy (AP) - is the difference between the position we programmed and the average of the positions that the end member of the robot actually reached. The end member of the robot must always approach the programmed position from the same direction. The location of the sensors is realized in three mutually perpendicular axes (X, Y, Z). From the measured values, the one-way position accuracy (AP) in the X, Y, Z axes is calculated according to the relations:

$$AP_x = (\bar{x} - x_c) \tag{1}$$
$$AP_y = (\bar{y} - y_c) \tag{2}$$
$$AP_z = (\bar{z} - z_c) \tag{3}$$

where (x_c, y_c, z_c) are programmed values and (x_j, y_j, z_j) are actual (measured) values. While:

$$\bar{x} = \frac{1}{n}\sum_{j=1}^{n} x_j \tag{4}$$
$$\bar{y} = \frac{1}{n}\sum_{j=1}^{n} y_j \tag{5}$$
$$\bar{z} = \frac{1}{n}\sum_{j=1}^{n} z_j \tag{6}$$

The resulting value of the robot's Pose accuracy:

$$AP = \sqrt{(\bar{x} - x_c)^2 + (\bar{y} - y_c)^2 + (\bar{z} - z_c)^2} \quad (7)$$

Pose repeatability (RP) - expresses the degree of agreement between the locations of the reached positions after n-repetitions of movement to the same programmed position in the same direction. From the measured values, the RP value is calculated as the radius of the sphere whose center is the barycenter according to the relations:

$$RP = \bar{l} + 3S_l \quad (8)$$

where,

$$S_l = \sqrt{\frac{\sum_{j=1}^{n}(l_j - \bar{l})}{n-1}} \quad (9)$$

$$\bar{l} = \frac{1}{n}\sum_{j=1}^{n} l_j \quad (10)$$

$$l_j = \sqrt{\left(x_j - \bar{x}\right)^2 + \left(y_j - \bar{y}\right)^2 + \left(z_j - \bar{z}\right)^2} \quad (11)$$

The coordinates of the barycenter of the reached points for n-repetitions of the same position are calculated according to the relations (4-6).

3.2 Measurement preparation

To place the measuring cube in the robot's workspace, the following requirements should be met: Five points (P1 to P5) are located on the diagonals of the selected plane. These five points together with the manufacturer's instructions make up the test positions. The test positions must be defined by the coordinates of the base. Point P1 is the diagonal intersection and is the center of the cube. Points P2 to P5 are distant from the ends of the diagonal (10 ± 2)% of the length of the diagonal. If this is not possible, the nearest diagonal point must be chosen. All robot joints must be applied when moving between all test positions [Semjon 2016, Jeswiet 1995]. The location of the measurement points on the measurement cube is shown in Figure 2.

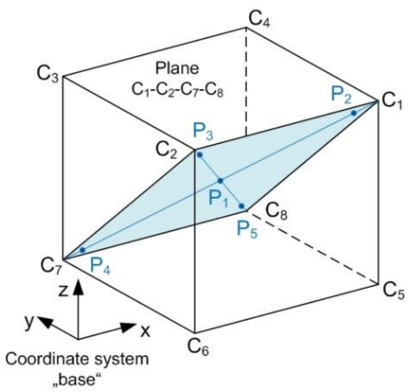

Figure 2. Measuring cube

In order to speed up the measurement, especially in the premises of the nuclear power plant and to ensure the least possible contamination of the sensors, the measuring nest and the operator, only one special measuring point P1 was chosen. This point takes into account the necessity of checking the accuracy of the position of the fragmented steam generator and at the same time minimizing the contamination of the components of the measuring chain. A total of seven drives (A) located in six kinematic pairs were used to move the robot. These were the following drives, Figure 3:

- transverse platform drive A1,
- two drives designed to rotate the base of the robot A2 and A3,
- drive for the linear lift of the first arm of the robot A4,
- drive for the linear lift of the second arm of the robot A5,
- drive for the linear lift of the third arm of the robot A6,
- drive for rotation of the A7 robot flange.

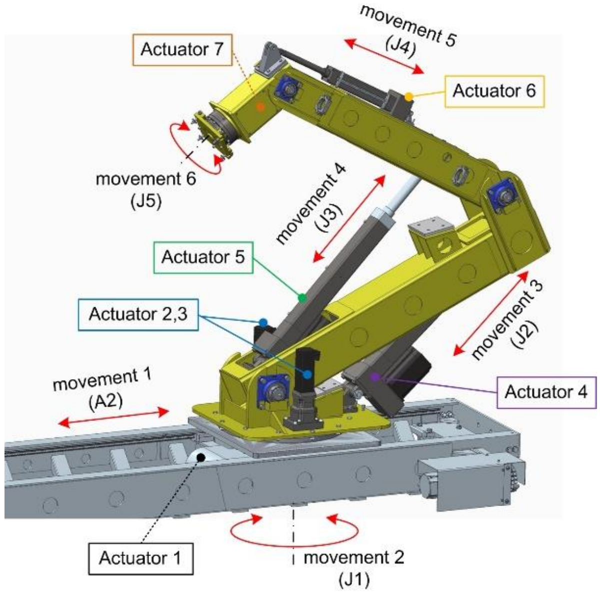

Figure 3. Placement of drives in a robotic workplace

As declared by the ISO 9283 standard, the measurement was carried out at the maximum speed used at the workplace and at two load values. The speed value of 100 mm/s is not the working speed of the saw, but the speed of moving the saw with the basket to the emptying place. There, the bin is opened and its contents are dumped. Sawing speed depends on many factors, such as the number of pipes in the shot (1 to 5), the place of the cut, the direction of movement vertically or horizontally, the presence of other objects around the place of the cut. The load for 50% of the robot's carrying capacity is 100 kg, and the load for 100% of the robot's carrying capacity is 200 kg. The measurement at a load capacity of 10% of the robot's load capacity was not carried out, since this load capacity is minimally used in the real operation of the robot. The location of the load outside the center of the output flange of the robot was chosen due to the calculation of the position of the center of gravity when sawing by the robot with a saw and basket. During the gradual sawing and dropping of pipes into the collection basket, there is a gradual change in the position of the center of gravity up to the value when the basket is filled to maximum capacity. The simulation carried out in the CA environment states that the weight of the full basket, as well as the weight of the saw and other accessories, is 153 kg. The carrying capacity of the robot is 200 kg, which is based on the need to remove heavy objects loosely stored in the steam generator during other robot activities. To the weight of 153 kg, we must also add the action of cutting forces and times caused by the irregular falling of the cut pipes into the collection basket. This creates an assumption of the maximum load of the robot in real operation to an approximate value of 192.5 kg. Figure 4 shows a real view of the robot loaded to 50%. The load at 100% is shown in fig. 5. The shape and material of the load is adapted to the possibilities of the workplace in the nuclear power plant. As mentioned earlier, all material that is in the controlled band for an extended period of time is exposed to radiation. That is why load components were chosen that are already present at the workplace and are also used for other work activities. This choice was therefore conditioned by the minimization of the generation of additional waste. The difference between 50% load and 100% load is given by the addition of a closed 160x160 mm waste-filled profile formed from a 150 mm diameter round rod to the magnetic clamp.

Figure 4. Load placement 100 kg (50% load capacity of the robot)

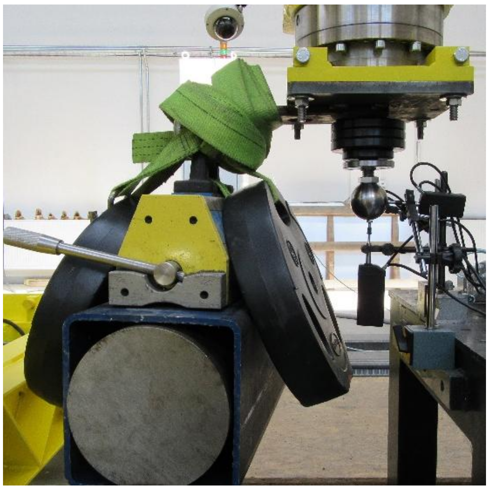

Figure 5. Load placement 200 kg (100% load capacity of the robot)

A precise measuring ball with a diameter of 60 mm equipped with an M20 internal thread was chosen as the measuring component [Semjon 2017, Semjon 2016]. The measuring ball was mounted on an M20 threaded rod, the other end of which was fixed into the thread in the center of the robot's output flange.

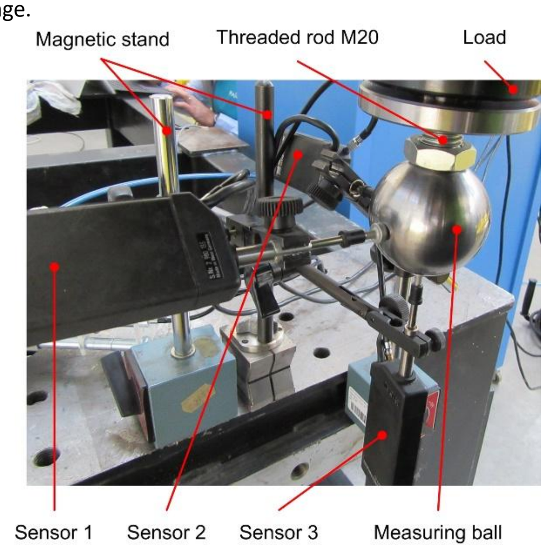

Figure 6. Storage of touch sensors and measuring ball

Smaller weights and lock nuts were also placed on the threaded rod, preventing the measuring ball from loosening. The measuring chain consists of three touch sensors equipped with flat contacts placed perpendicular to each other, Figure 6. Since these are contact sensors, the measuring assembly also included a pneumatic system [Semjon 2019], which allows the contacts to be moved and pushed in so that there is no friction between the contacts sensors and a measuring ball.

The sensors were placed on magnetic stands, which were then attached to a measuring stand originally made for verifying the parameters of electric actuators. The display units were placed outside the measuring stand, so that constant sensor values could be read. To ensure correct measurements, it was experimentally verified that the minimum time to safely stabilize the sensor values is 2.8 seconds. For this reason, a value of 3 seconds was chosen to settle the values and read out the undisturbed data. The reading of the values was realized by creating one photo of all three display units, Figure 7.

Figure 7. Display units with measured data.

Figure 8 shows a view of the robot and the location of the sensors on the measuring stand in the premises of the production hall, where the robot was manufactured and revived. It is not possible to publish photos from the controlled zone of the nuclear power plant.

Figure 8. A view of the new robot and the location of the sensors

4 RESULTS AND DISCUSSION

The required measurements were also carried out at the workplace, where the robotic device for the fragmentation of steam generators was designed, manufactured and revived. Since the workplace is standardly free of contamination by ionizing radiation, the tests took place without significant restrictions. The only limitation was the realization of the tests at a time when the ambient temperature was (20 ± 2) °C.

During the operation of the device, it was decided that the measurement will be carried out only after the annual operation of the robotic device. The inspection of the equipment after half a year of operation was primarily aimed at adjusting and improving the parameters of the tools used and implementing the obtained data into process optimization. The control measurement after one year was preceded by an annual inspection of the equipment, as well as other tests and measurements required by the operator of the equipment.

4.1 Pose accuracy (AP)

After carrying out 30 measurements at half (50%) and full (100%) load of the robotic workplace and calculating the measured data according to relation (7), we arrived at the following average values of one-way positioning accuracy. The values (AP_{50}) in Table 3 and (AP_{100}) in Table 4 are given for a new robot (designation R0) and for a robot after a year of operation (designation R1). The values $\overline{x}, \overline{y}$ a $\overline{z}$ epresent the average value with 30 measured data in the X, Y and Z directions of the robot R0 and R1 at half load ($\overline{x_{50}}$; $\overline{y_{50}}$; $\overline{z_{50}}$) and full load ($\overline{x_{100}}$; $\overline{y_{100}}$; $\overline{z_{100}}$, according to relation (4 to 6) for AP in chapter 3.1.

Table 3. Calculated AP_{50} values at half robot load

AP 50	Average $\overline{x_{50}}$ (mm)	Average $\overline{y_{50}}$ (mm)	Average $\overline{z_{50}}$ (mm)	AP_{50} (mm)
$R0_{50}$	0.001701	**-0.022267**	-0.001733	**0.022399**
$R1_{50}$	0.001505	-0.028201	-0.005702	**0.028809**

Table 4. Calculated AP_{100} values at full robot load

AP 100	Average $\overline{x_{100}}$ (mm)	Average $\overline{y_{100}}$ (mm)	Average $\overline{z_{100}}$ (mm)	AP_{100} (mm)
$R0_{100}$	0.060001	**-0.006467**	-0.075567	**0.096706**
$R1_{100}$	0.072600	-0.013103	-0.088633	**0.115318**

The measured and subsequently calculated AP_{50} data at half load for the new robot ($R0_{50}$) reached a value of 0.022399 mm. When compared with the required robot accuracy data of 1 mm, we can conclude that the robot after assembly and recovery was sufficiently accurate. The average values of the new robot ($R0_{50}$) in individual axes X, Y and Z reached an absolute value of a maximum of 0.022267 mm. This value is given by the design of the robot, where the greatest flexibility was proposed in the direction of the Y axis, since this direction corresponds to the expected direction of impact of the robot into the steam generator during manual control of the robot.

After measuring the robot after a year of use ($R1_{50}$), at half load of the robot's output flange, we can state that the value of AP_{50} reached the value of 0.028809 mm. Overall, the average deterioration of the accuracy of the robot after a year of use is 22.25%. The stated deterioration still does not exceed the maximum allowed value of the robot's accuracy (0.028809 ≤ 1 mm).

Figure 9 shows a graph showing the value of AP_{50} during 30 measurements with both a new ($R0_{50}$) and year-old robot ($R1_{50}$).

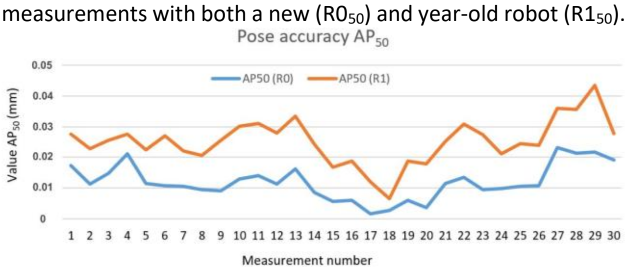

Figure 9. Graphical comparison of AP_{50} on new and used robot

The measured and subsequently calculated AP_{100} data at full load for the new robot ($R0_{100}$) reached a value of 0.096706 mm. When compared with the required robot accuracy data of 1 mm, we can conclude that the robot after assembly and recovery was sufficiently accurate. The average values of the new robot ($R0_{100}$) in individual axes X, Y and Z reached an absolute value of 0.075567 mm at most. This value is based on the assumption of an increase of the load in the direction of the Z axis relative to the world coordinate system of the robot to a double value. Since the robot's structure is made of closed steel profiles, due to the greater weight on the end part of the robot, a slight deformation of the robot's arms occurs.

After measuring the robot after one year of use ($R1_{100}$), with the robot output flange fully loaded, we can state that the value of AP_{100} reached the value of 0.115318mm. Overall, the average deterioration of the accuracy of the robot after a year of use at the maximum load capacity of the robot is only 16.14%. The stated deterioration still does not exceed the maximum allowed value of the robot's accuracy (0.115318 ≤ 1 mm).

Figure 10 shows a graph showing the value of AP_{100} during 30 measurements with both a new ($R0_{100}$) and year-old robot ($R1_{100}$).

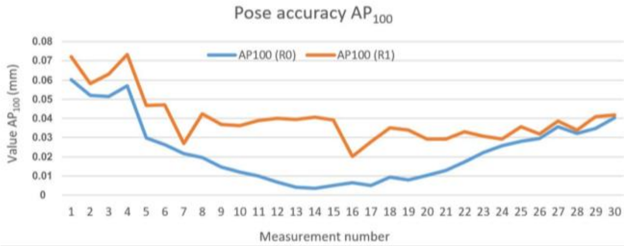

Figure 10. Graphical comparison of AP_{100} on new and used robot.

4.2 Pose repeatability (RP)

For the calculation of the RP, the measured data that we obtained during the detection of the AP were used. By subsequently substituting the obtained data into relations (8 to 11), we obtained the following results, shown in Tables 5 and 6.

Table 5. Calculated RP_{50} values at half load of the robot

RP 50	S_l (mm)	$\bar{l}$ (mm)	RP_{50} (mm)
$R0_{50}$	0.005639	0.011891	**0.028808**
$R1_{50}$	0.007276	0.022515	**0.046985**

The calculated value of RP_{50} at half load of the new robot R0 has a size of 0.028808 mm. After a year of using the R1 robot, the RP_{50} value increased to 0.046985 mm. This represents a year-on-year increase in position repeatability by 38.69%. The detected increase is relatively high, but the detected value does not exceed the permissible value of RP (0.046985 ≤ 1.5 mm).

The calculated value of RP_{100} at full load of the new robot R0 has a size of 0.073022 mm. After a year of using the R1 robot, the RP_{100} value increased to 0.077061 mm. This represents a year-on-year increase in position repeatability by 5.24%. The detected increase is low, and the detected value does not exceed the permissible value of RP (0.077061 ≤ 1.5 mm).

Table 6. Calculated RP_{100} values at full robot load

RP 100	S_l (mm)	$\bar{l}$ (mm)	RP_{100} (mm)
$R0_{100}$	0.016644	0.023088	**0.073022**
$R1_{100}$	0.012446	0.039972	**0.077061**

Based on the measurements and subsequent calculations according to ISO 9283, we can state that the values of AP and RP did not exceed the parameters set during the design of the robot. The maximum calculated AP value (0.115318 mm) was smaller than the determined value (1 mm). In the case of the maximum calculated value of RP (0.077061 mm), this value was smaller than the determined value (1.5 mm). If we were to take into account the largest measured value of inaccuracy from the performed measurements, we can state that it was the value of xj (0.109 mm) in measurement no. 60, value yj (- 0.045 mm) when measuring no. 49 and the value of zj (- 0.116 mm) in measurement no. 31. None of the maximum measured values exceeded the maximum AP value (1 mm).

At the beginning of the measurement, it was assumed that the repeatability of RP positioning would show significantly worse values than in the case of AP positioning accuracy. However, this did not materialize as (RP_{max} (0.077061) ≤ AP_{max}(0.115318)), which led to further investigation. Therefore, images of several 12-hour work shifts of the robot were created. Based on the kinematic analysis of the robot's movement in the most frequently used work activities of the robot, the following changes compared to the planned ones were detected:

- change in the design of one T4 tool (separator),
- optimization of the path of movement of the tool T1 (saw with basket),
- addition of another tool T6 (angle saw without basket).

These changes were implemented after half a year of operation of the robot, where tools were adjusted, and the robot's movement was optimized. The mentioned changes led to changes in the action of forces on individual parts of the robot, which had a positive effect in terms of the expected load of the robot. The change in the design of the T4 tool consisted in the addition of a hydraulic cylinder, which significantly reduced the load on the second and third arms of the robot, when pulling out the separation inserts from the steam generator. Optimizing the track on the T1 basket saw when emptying a full basket not only reduced the duration of this process, but is also realized with less extension of the robot's arms, which leads to less stress on them. The addition of another lighter T6 tool with a different center of gravity has led to less use of the heavier T2 tool (a straight saw without a basket). On the basis of the implemented changes during the annual operation of the robot, the assumed sizes and intensity of the load changed, which led to different measurement results than were assumed.

5 CONCLUSIONS

The work deployment of the delivered robot was planned for a maximum of three years. It was due to the fact that the robot was supposed to fragment 12 steam generators. After the completion of the fragmentation of the steam generators, the robot was supposed to be dismantled and taken to the nuclear waste repository. The use of the robot outside the controlled zone of the nuclear power plant is not possible due to its contamination. Another block of the nuclear power plant is currently being liquidated, and the relocation of the said robot to this block is being considered. This is due not only to the fact that the robot has proven itself, but also to the fact that its accuracy and repeatability parameters are satisfactory. We can thus state that thanks to the verification of the robot's geometrical characteristics, it is expected to extend its life and therefore lower the burden on the environment.

Based on the knowledge gained, in the design, production and operation of robotic equipment, the authors of the article also participate in the design and construction of other robots and equipment for the disposal of decommissioned nuclear blocks in Europe.

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CONTACTS:

Jan Semjon, Assoc. Prof. Ing., PhD.
Technical University of Kosice
Faculty of Mechanical Engineering
Department of Production Systems and Robotics
Letna 9, 04200 Kosice, Slovakia
+421556022625, jan.semjon@tuke.sk