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VERIFICATION OF GEOMETRIC CHARACTERISTICS OF THE ROBOT USING A LASER INTERFEROMETER

This research focused on the verification of selected geometric characteristics of the Yaskawa SDA 10F industrial robot using a Renishaw XL-80 laser interferometer through an experimental method based on the principles of the STN ISO 9283 standard. The theoretical part of the work includes the analysis of the standard and the selection of measurement methods, while the practical part includes the setup, calibration and data analysis. The expected results will verify the compliance of the robot with the technical specifications and suggest potential optimizations to improve its operational properties. Based on the experiment performed, we can also conclude that the verified parameters of the robot are within the expected values and further use of the robot is possible in the case of lower demands on the resulting positioning repeatability.

Keywords: *geometrical characteristics; trajectory; laser Interferometer; STN ISO 9283.*
Fig.: 6. References: 11.

Relevance of the research. Modern development of industrial automation and robotic systems requires increased accuracy and reliability of actuators performing complex technological operations. Industrial robots widely used in various industries must not only be highly dynamic and adaptive, but also exhibit stable kinematic and geometric characteristics, including positioning accuracy and trajectory repeatability. These parameters are critical for assembly processes, precision machining, microelectronic manufacturing and other high-precision technological operations, where even minimal deviations can lead to significant errors and a decrease in product quality.

Problem statement. One of the key aspects of the effective functioning of industrial robots is their metrological control, which provides an objective assessment of operational characteristics. The lack of reliable measurement methods leads to the impossibility of guaranteeing the compliance of actual parameters with the declared technical requirements. In this regard, the use of high-precision measuring instruments, such as laser interferometers, becomes particularly important, which allow for a detailed analysis of linear and angular movements of the manipulator, as well as the detection of potential systematic errors in its operation.

Analysis of recent research and publications. Metrological standards, such as STN ISO 9283, regulate methods for estimating the accuracy characteristics of industrial robots; define permissible errors and methods for their measurement. This standard provides a unified approach to testing manipulators, which allows for the correct interpretation of the obtained results and their comparison with regulatory requirements [1].

Uninvestigated parts of a common problem. In addition to the research objectives, the motivation for performing these measurements also arose from a real technical problem [2]. During previous operations, internal damage to the pneumatic hoses and internal cables running through the hollow structure of the robot's wrist joints (the last two axes) was discovered. This required complete disassembly of the 6th and 7th axes of the Yaskawa SDA-10F robot, replacement of the damaged components, and subsequent reassembly of the system. After reinstallation, deviations were observed when executing previously tested programs, indicating potential changes in the kinematic integrity of the robot. This situation led to the need to verify the geometric performance of the robot [3]. Within the geometric characteristics, which could be compared based on already conducted research in this area, we focused on one-way accuracy and repeatability of positioning. The selection of these characteristics is based on the possibility of comparing the measured data with the data declared by the manufacturer in the robot documentation. At the same time, the measurement task served to evaluate the capabilities of the Renishaw XL-80 laser interferometer for robot diagnostics.

Research objective. The main objective of the study is to experimentally evaluate the accuracy and repeatability of the robot using a Renishaw XL-80 laser interferometer, as well as to analyze the obtained data to decide on the conditions and limitations of its further use [4,5]. To achieve the main objective, it was necessary to perform measurements on one arm of a Yaskawa SDA-10F two-arm robot, while the robot body had to remain stationary. This avoided introducing additional inaccuracies into the measurement due to torso rotation or base movement. In the case of verifying the geometric characteristics of a robot equipped with 15 controlled axes, it is difficult to determine which kinematic pair has the greatest inaccuracy. Therefore, it was necessary to modify the ISO 9283 methodology so that these inaccuracies could be identified. For this reason, we focused on the most damaged robotic arm equipped with 7 controlled drives, where we expected the greatest deviations due to collisions of the arm with part of the workplace. The damage to the arm was also identified by a visual inspection of the arm, where clear signs of a collision were found in the form of scratches and dents.

The statement of basic materials. There is a relatively large number of measuring devices on the market that can be combined with special software for measuring the performance characteristics of robots. For example, the working characteristics of the Fanuc LR Mate 200IC robot were measured using the Renishaw SL-80 laser interferometer. The accuracy of the Renishaw XL-80 laser interferometer is ±0.0005 mm. This type of measurement is based on the movement of a reflector (moving mirror) along a laser beam emitted from a laser light source. This means that the measurement is performed along a line parallel to the laser beam [6].

Based on the analysis of existing methods for measuring geometric characteristics of industrial robots and taking into account the experience with the implementation of their simpler versions in previous studies, it was decided to use a more demanding, but at the same time more accurate method. The Renishaw XL-80 laser interferometer, which is highly accurate and reliable, was chosen as the main measuring tool. In addition, the Renishaw XL-80 laser interferometer was chosen due to its extensive use in scientific and industrial research, as well as its compliance with the STN ISO 9283 standard. This ensures that the results can be properly compared with other research data and that the methodology can be implemented in real-world industrial robot applications.

During the development of the experimental methodology, it was decided to focus on measuring positioning accuracy and positioning repeatability. This decision was based on the capabilities of the available measurement equipment – a Renishaw XL-80 laser interferometer – and associated optical components, which are best suited for high-precision linear displacement measurements rather than full three-dimensional trajectory tracking [7, 8].

Key equipment includes: (Renishaw XL-80 (for high-precision linear displacement measurements)); (Retroreflectors and mounting fixtures (for attaching the retroreflectors to the robot)) and Data acquisition and analysis software (CARTO Capture & Explore from Renishaw).

As a result, measurements were performed separately along the X and Y axes. This approach not only matched the capabilities of the measurement system, but also allowed for a high level of measurement accuracy and minimized potential systematic errors [9].

To assess the impact of the payload on the robot's performance, measurements were performed under three loading conditions: 10%, 50%, and 100% of the robot's nominal payload, corresponding to 1 kg, 5 kg, and 10 kg, respectively. In addition, all measurements were carried out at 50% of the robot's maximum nominal speed to ensure a balance between dynamic effects and measurement reliability. Operating at reduced speed minimizes potential disturbances such as vibration, overspeed, or mechanical lag that could otherwise distort the assessment of the robot's true geometric characteristics. The article presents only the results at a maximum load of 100% and a speed of 50%, which are the most critical and used in the robot's automatic mode.

All measurements were performed using only one of the two robot arms. The other arm and the torso (central body) of the robot remained stationary throughout the entire testing process. This configuration was chosen to isolate the geometric performance of the selected manipulator and to avoid introducing additional uncertainties caused by the torso or the other arm movements. This approach also reflects the need to verify the accuracy of an arm that has undergone partial disassembly and reassembly for maintenance on its last two axes [2]. The interferometer is positioned on the workbench so that its laser beam can accurately track the robot's trajectory. The installation is performed on a solid surface to minimize the effects of external factors such as vibrations. After installation, an initial calibration of the interferometer is required to ensure its accuracy.

To evaluate the positioning accuracy and repeatability of an industrial robot, a set of discrete reference points were selected in the robot workspace. The workspace itself was calculated based on the ISO 9283 standard and represents a cube in which the center of the robot endpoint is most often located when performing a task [1]. For unidirectional positioning accuracy and repeatability, we used the following formulas:

Pose accuracy (AP) - is the difference between the position that we have programmed and the average of the positions that the actuator end member has actually reached. The actuator end member must always approach the programmed position from the same direction. From the measured values, the Pose accuracy (AP) in the X, Y axes is calculated according to the relationships where $(\bar{x}, \bar{y})$ are the coordinates of the barycenter of the set of points reached after repeating the same position n times:

$$AP_x = (\bar{x} - x_c), \quad (1)$$

$$AP_y = (\bar{y} - y_c), \quad (2)$$

Where (x_c, y_c) are the programmed values and (x_j, y_j) are the actual (measured) values. While:

$$\bar{x} = \frac{1}{n}\sum_{j=1}^{n} x_j, \quad (3)$$

$$\bar{y} = \frac{1}{n}\sum_{j=1}^{n} y_j, \quad (4)$$

The resulting value of the robot's "Pose accuracy":

$$AP = \sqrt{(\bar{x} - x_c)^2 - (\bar{y} - y_c)^2}. \quad (5)$$

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

$$RP = \bar{l} + 3S_l, \tag{6}$$

Where (S_l) is the standard deviation, (l_j) are the actual (measured) values when determining the RP and ($\bar{l}$) are the coordinates of the barycenter of the set of points reached after repeating the same position n times determining the RP:

$$S_l = \sqrt{\frac{\sum_{j=1}^{n}(l_j - \bar{l})}{n-1}}, \tag{7}$$

$$\bar{l} = \frac{1}{n}\sum_{j=1}^{n} l_j, \tag{8}$$

$$l_j = \sqrt{\left(x_j - \bar{x}\right)^2 + \left(y_j - \bar{y}\right)^2 + \left(z_j - \bar{z}\right)^2}. \tag{9}$$

The coordinates of the barycenter of the points reached during n-repetitions of the same position are calculated according to the relations (3-4).

The points were defined in Cartesian coordinates and were programmed into the robot control system to serve as target positions for measurement.

The positions were chosen to lie along the X and Y axes of the work plane, which corresponds to the direction of propagation of the laser beam in the measurement setup. This allowed for simplified alignment of the Renishaw XL-80 laser interferometer system and maximized the measurement accuracy along each linear axis [10]. The decision to measure each axis separately rather than simultaneously was due to the technical limitations of the optical system and the desire to minimize measurement uncertainty.

An experimental workspace was created to solve our problem, Fig. 1 for measuring selected characteristics of the YASKAWA SDA 10F robot, whose positioning repeatability defined by the robot manufacturer is +/- 0.1 mm [11].

Fig. 1. Experimental workspace for measuring selected geometrical characteristics.

The conditions for installing the necessary optics were created near the robot. The Renishaw XL-80 laser interferometer was mounted on an original Renishaw tripod. The reflective optics were mounted on the robot's end, Fig. 2.

560 measurements were performed in accordance with the proposed method and under the same environmental conditions: air temperature 23.7 [°C], air pressure 994.2 [mbar] and humidity 53 [% relative humidity].

Fig. 2. Reflector mounted on the endpoint of the robot.

Fig. 3 shows a part of the table where there is a sample of the measured data obtained when measuring on the X-axis at 100% of the payload, i.e. at 10 kg. The results at 10% and 50% speed are not given, since the measured deviations were minimal.

In the table you can see the programmed points (targets), i.e. 0, 50, 100, 150 and 200 mm, the cycle number (Run #), the actual position (Position) in the positive direction (+) and the negative direction (-), as well as the deviations between the specified programmed position and the actually reached position (Error) also in the positive (+) and negative (-) directions.

X-AXIS 10kg					
Index	1	2	3	4	5
Targets (mm)	0	50	100	150	200
Run 1 (+) Position	0	50.01509781	100.1934111	150.1828171	200.3105121
Run 1 (+) Error	0	0.015097809	0.193411062	0.18281714	0.310512125
Run 1 (-) Position	0.003320022	50.07110287	100.2188068	150.2940132	200.3044889
Run 1 (-) Error	0.003320022	0.07110287	0.218806769	0.294013198	0.304488885

Fig. 3. Data obtained when measured in the X-axis at 100% of the payload, i.e. at 10 kg.

Fig. 4 shows a part of the table where there is a sample of the measured data obtained when measuring on the Y-axis at 100% of the payload, i.e. at 10 kg.

Y-AXIS 10kg					
Index	1	2	3	4	5
Targets (mm)	0	50	100	150	200
Run 1 (+) Position	0	50.0842829	100.0494497	150.2069388	199.955316
Run 1 (+) Error	0	0.084282896	0.049449725	0.20693877	-0.044683956
Run 1 (-) Position	0.024071875	50.09918669	99.94697458	149.9616797	199.9578225
Run 1 (-) Error	0.024071875	0.099186686	-0.053025421	-0.038320272	-0.042177506

Fig. 4. Data obtained when measured in the Y-axis at 100% of the payload, i.e. at 10 kg.

All the data obtained were used to plot graphs for a clearer visual perception and understanding of the variations in accuracy and repeatability at each individual position (Figs. 5 and 6). Each of the colored lines shown in the graphs represents one run in the positive or negative direction with the control positions.

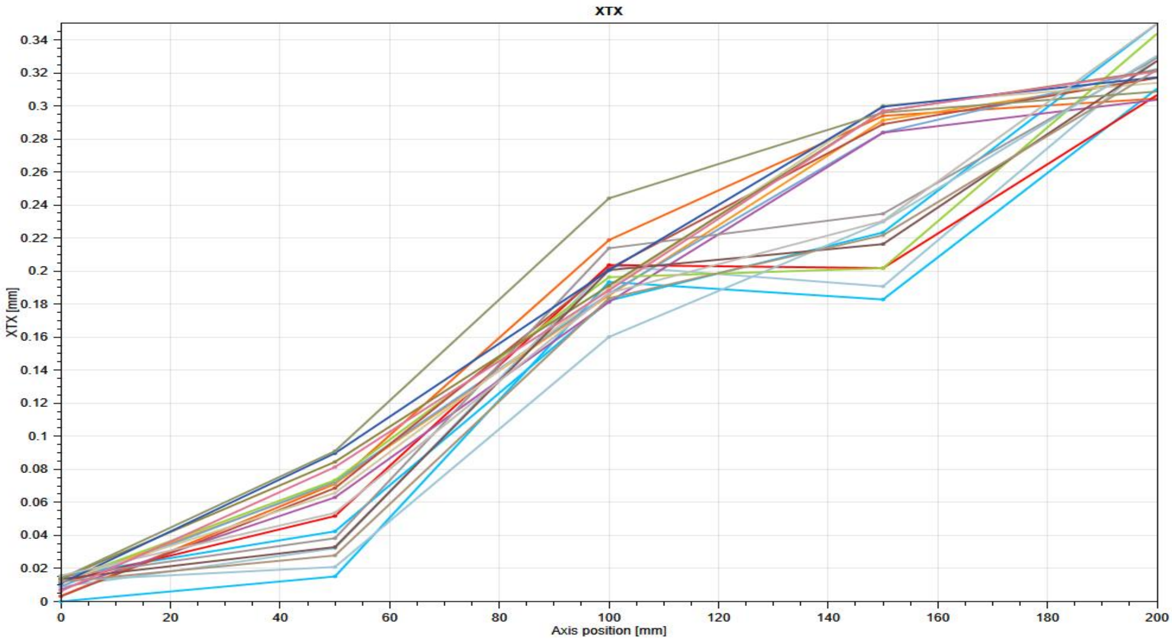

Fig. 5. Graphs of X-Axis measurements with 10 kg payload.

The minimum deviation between the programmed position and the actually reached position was observed at Run 5 (-) and amounted to 0.003080453 mm at 0 mm Position. The maximum deviation between the programmed position and the actually reached position was observed at Run 10 (+) and amounted to 0.349946864 mm at 200 mm Position. The final value of the positioning accuracy of X-Axis APX-100 at 100% payload and 50% speed is 0.349946864 mm. The final value of the positioning repeatability of X-Axis RPX-100 at 100% payload and 50% speed is 0.117493859 mm.

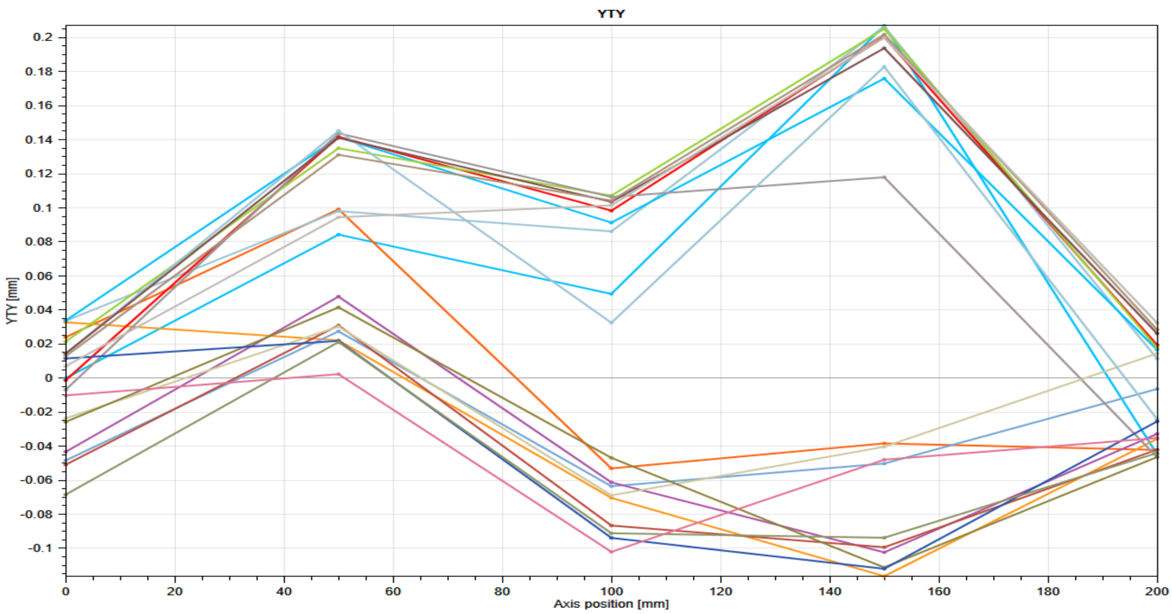

Fig. 6. Graphs of Y-Axis measurements with 10 kg payload.

The minimum deviation between the programmed position and the actually reached position was observed at Run 1 (+) and amounted to 0.206938770 mm at 150 mm Position. The maximum deviation between the programmed position and the actually reached position was observed at Run 4 (+) and amounted to -0.001266144 mm at 0 mm Position. The final value of the positioning accuracy of Y-Axis APY-100 at 100% payload and 50% speed is 0.323240680 mm. The final value of the positioning repeatability of Y-Axis RPY-100 at 100% payload and 50% speed is 0.323240680 mm.

Based on the calculation performed according to relations (1 to 9), the following resulting values of RP at a speed of 50% (0.272 mm) and RP at a speed of 100% (0.366 mm) were calculated.

Conclusions. The main objective of this thesis was to experimentally verify selected geometric characteristics of the YASKAWA SDA-10F industrial robot, specifically its positioning accuracy and repeatability, using a Renishaw XL-80 laser interferometer. All measurements were performed in the X and Y directions of the robot workspace at 100% payload at a constant speed of 50% of the nominal speed. The observed deviation on the Y-axis may be due to increased structural bending at higher loads, thermal effects or minor errors in the optical path. Although these results confirm compliance with the specifications along the X-axis, the data on the Y axis highlight the need for constant monitoring or possible mechanical tuning. The manufacturer's defined value for the repeatable positioning accuracy of the new robot is +/- 0.1 mm. The values recorded during the tests (0.272 mm to 0.366 mm) are, however, in line with expectations for a robot of this category and application class, after several years of operation. Based on the experimental verification carried out, it can be stated that even a robot manufactured in 2012, exposed to various collisions, is able to perform the required tasks, assuming lower demands on the resulting positioning repeatability.

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ПЕРЕВІРКА ГЕОМЕТРИЧНИХ ХАРАКТЕРИСТИК РОБОТА ЗА ДОПОМОГОЮ ЛАЗЕРНОГО ІНТЕРФЕРОМЕТРА

Це дослідження було зосереджено на перевірці вибраних геометричних характеристик промислового робота Yaskawa SDA 10F з використанням лазерного інтерферометра Renishaw XL-80 за допомогою експериментального методу, заснованого на принципах стандарту STN ISO 9283. Метою дослідження є оцінка ключових параметрів продуктивності, а саме точності та повторюваності робота, які є вирішальними для високоточних операцій. Теоретична частина роботи включає аналіз стандарту та вибір методів вимірювання, тоді як практична частина включає налаштування, калібрування та аналіз даних. Очікувані результати підтвердять відповідність робота технічним характеристикам та запропонують потенційні оптимізації для покращення його експлуатаційних властивостей. Експериментальна перевірка проводилася за двома взаємно перпендикулярними осями (X, Y). Загалом було проведено 560 вимірювань при трьох розмірах навантаження та середній швидкості. У статті представлені часткові результати в числовій та графічній формі для максимального навантаження та за осями X та Y. Розраховані дані RP (0,272 мм при 50 % швидкості та 0,366 мм при 100 % швидкості) підтверджують припущення, що ґрунтувалися на спостереженнях, зроблених під час роботи робота. Повторюваність по осях X та Y вища за заявлене виробником значення ± 0,1 мм. Перевірку проводили на маніпуляторі робота R2, який був більше навантажений під час роботи, оскільки максимальна вага, яку він обробляв, досягала 9,83 кг. Маніпулятор R1 був навантажений максимальною вагою 5,4 кг. Під час перевірки робот, оснащений загалом 15 керованими осями, використовував лише 7 приводів на маніпуляторі R2, а привід на маніпуляторі R1 та обертання корпусу робота, привод B1, не були задіяні в русі. На основі проведеного експерименту також було виявлено, що необхідно придбати додаткові аксесуари для лазерного інтерферометра, що спростило б та пришвидшило б процес перевірки. На основі проведеного експерименту також можна зробити висновок, що перевірені параметри робота знаходяться в межах очікуваних значень, і подальше використання робота можливе у разі зниження вимог до результуючої повторюваності позиціонування.

Ключові слова: *геометричні характеристики; траєкторії; лазерний інтерферометр; STN ISO 9283.*

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