Transactions of the VŠB – Technical University of Ostrava, Mechanical Series
No. 1, 2016, vol. LXII
article No. 2009

Darina KUMIČÁKOVÁ[*], Vladimír TLACH[**], MIROSLAV CÍSAR[***]

TESTING THE PERFORMANCE CHARACTERISTICS OF MANIPULATING INDUSTRIAL ROBOTS

TESTOVANIE PRACOVNÝCH CHARAKTERISTÍK MANIPULAČNÝCH PRIEMYSELNÝCH ROBOTOV

Abstract

The article is aimed at an issue of assessment of performance criteria of manipulating industrial robots with focusing on positioning performance. There are presented: the testing of one-directional pose accuracy and repeatability on Robot Fanuc LR Mate 200iC within the Laboratory of the Department of Automation and Production Systems and processing of the measured data. The laser interferometer Renishaw and digital indicator Mitutoyo Digimatic were used for performing the testing experiments.

Abstrakt

Článok je venovaný problematike hodnotenia pracovných charakteristík manipulačných priemyselných robotov so zameraním sa na presnosť a opakovateľnosť polohovania. Prezentované sú metódy merania jednosmernej opakovateľnosti polohy robota Fanuc LR Mate 200iC v laboratórnych podmienkach Katedry automatizácie a výrobných systémov a spôsob ich spracovania. Pre meracie experimenty boli využité dva druhy meracích zariadení: laserový interferometer Renishaw a digitálny odchýlkomer Mitutoyo Digimatic.

Keywords

Manipulating industrial robot, pose accuracy, pose repeatability, experimental methods, laser interferometer, digital indicator

1 INTRODUCTION

Industrial robot as a multi-purpose and re-programmable device is an important element of automated production systems. The purpose of its implementation into automated work cell is not only shortening of a product production cycle but also ensuring required quality of technological and manipulating operations that a robot performs. With coming new robotic applications, the demands for robot´s better positioning performance are growing.

Performance criteria and related test methods for manipulating industrial robots are described in the ISO 9283:1998 norm. There the several performance characteristics are presented: pose

[*] Assoc. Prof., Eng. PhD., Department of Automation and Production Systems, Faculty of Mechanical Engineering, UNIZA, Univerzitná 8215/1, Žilina, Slovakia, (+420) 41 513 2812, darina.kumicakova@fstroj.uniza.sk
[**] Eng., Department of Automation and Production Systems, Faculty of Mechanical Engineering, UNIZA, Univerzitná 8215/1, Žilina, Slovakia, (+420) 41 513 2833, vladimir.tlach@fstroj.uniza.sk
[***] Eng., PhD., Department of Automation and Production Systems, Faculty of Mechanical Engineering, UNIZA, Univerzitná 8215/1, Žilina, Slovakia, (+420) 41 513 2809, miroslav.cisar@fstroj.uniza.sk

accuracy and pose repeatability, multi-directional pose accuracy variation, distance accuracy and distance repeatability, position overshoot, path accuracy and path repeatability, path velocity characteristics, static compliance, etc. The importance of individual performance is given by specific application of the tested robot. The ISO 9283 norm presents the table for selection the performance characteristic for the typical applications of industrial robots. The selection recommendations are related to the way of the robot end-effector movement control (point-to-point or continuous controls) [2]. The robot´s most common tested performance is accuracy and repeatability.

One-directional pose repeatability is ability of the robot to return its TCP (Tool Centre Point) to the same pose (i.e., position and orientation) from the same direction repeatedly, and thus minimize the effect of backlashes within individual joints on the test´s results. Multidirectional repeatability can be twice the unidirectional repeatability or even worse [1].

Accuracy is the ability of the robot to attain a TCP´s programmed pose with respect to the robot´s base reference frame. Because of complexity of this reference frame identifying, accuracy is tested most of all indirectly, through another performance, i.e. the distance accuracy.

The worldwide manufacturers of industrial robots specify only one-directional pose repeatability (*RP*) in the robot´s technical documentation. Industrial robot´s positioning performance is affected by various errors that influenced it´s accuracy and repeatability. Nubiola & Bonev [4] specify five factors that cause robot errors. The geometrical inaccuracies and robot arm stiffness/compliance are the most significant factors influencing the one-directional pose accuracy [1], [5].

Testing the positioning performance of robots is complex metrology problem from the viewpoint of used testing methods and applied measuring equipment. Testing conditions, measuring methods and the performance characteristic calculation for individual performance criteria are describe in norm ISO 9283:1998. The measuring equipment is not specified in this norm and therefore the user of the tested robot can himself decide about this one appropriate type – from the low-cost , such as digital indicator, through laser interferometer and telescoping bar up to excessively expensive laser tracker. The laser tracker is the most common equipment used by robots manufacturers for robot calibration [3] and accuracy assessment. For example, the ABB´s Absolute Accuracy method enables to eliminate the difference between the virtual robot´s precision in the CAD system and the real robot´s one on the factory floor [6]. Utilisation of the FARO Laser Tracker for measuring the position repeatability is described in [1]. Measuring experiments were performed on the robot IRB 1600 and according to conditions specified in the ISO 9283:1998 norm [2]. Results of experiments showed that relatively poor repeatability of the FARO Laser Tracker (of at least 8μm), makes it unsuitable for a comprehensive assessment of the pose repeatability of medium-size industrial robots. Laser interferometer has optimal accuracy (1μm) for evaluating the repeatability of medium-size industrial robots but this one is too accurate and too complex to practical use. The robot´s pose repeatability measuring is possible to perform along a linear path within axis X, Y and Z respectively but none of performance criteria defined in [2] can be measured using a laser interferometer [1]. Dial and digital indicators are measuring equipment frequently used for the robot position repeatability not only at university´s laboratories but also at research workplaces or industrial practice. In comparison with above equipment the indicators are cheaper, they have optimal accuracy and are enable to measure positioning performance as it is described in ISO 9283:1998 norm. For the performance measurement can be used one [7] or more indicators [8] fixed in the special fixture. Digital indicator equipped with data output for connection to computer allows sent them through a data interface into computer and process and evaluate them.

The article presents methodology steps of the position performance testing on the robot Fanuc LR Mate 200iC within the Laboratory of robotization of manufacturing technologies for purpose of preparing the practical training for students of study branch - Automated production systems.

2 ROBOT´S ACCURACY AND REPEATABILITY

Present industrial robots are used in various applications where the different level of their accuracy and repeatability is required. ISO 9283:1998 defines the terms related to one-directional pose accuracy and repeatability. These terms include both position and orientation of a robot´s TCP point. Robot Fanuc LR Mate 200iC is used for automation of handling and assembling operations within the work cell of automated assembly and therefore we will further consider only position performance: position accuracy (*AP*) and position repeatability (*RP*).

2.1 The one-directional position performance characteristics

The one-directional position accuracy (*AP*) represents the deviation between the TCP point´s commanded position (*N*) and the mean value (barycenter; *G*) calculated from the cluster of TCP´s positions reached repeatedly - Figure 1. Number of positions in cluster $j = 1, 2, \ldots, n$. Length dimensions are given in (mm).

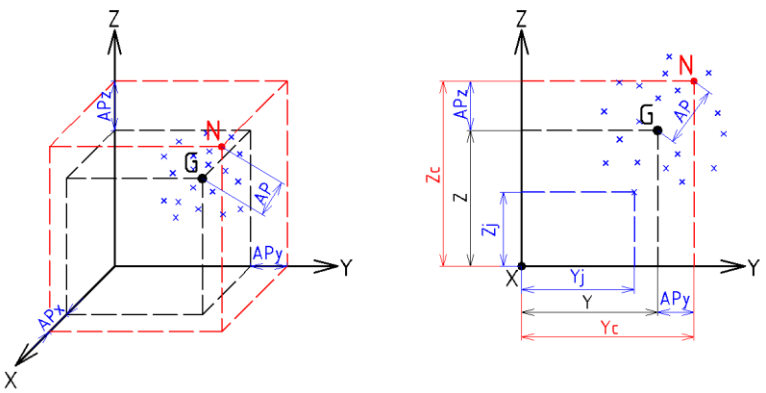


Fig. 1 Graphical displaying of one-directional position accuracy (ISO 9283:1998); G – barycentre $[\bar{x}, \bar{y}, \bar{z}]$, N – commanded position $[x_c, y_c, z_c]$, x - j^{th} reached position $[x_j, y_j, z_j]$

One-directional position accuracy *AP* is given by a general formula:

$$AP = \sqrt{AP_x^2 + AP_y^2 + AP_z^2}, \quad (1)$$

$$AP_x = \bar{x} - x_c, \quad (2)$$

$$AP_y = \bar{y} - y_c, \quad (3)$$

$$AP_z = \bar{z} - z_c, \quad (4)$$

where coordinates of barycentre - mean values obtained from a cluster of repeatedly reached points - are given by formulas:

$$\bar{x} = \frac{1}{n}\sum_{j=1}^{n}(x_j), \quad (5)$$

$$\bar{y} = \frac{1}{n}\sum_{j=1}^{n}(y_j), \quad (6)$$

$$\bar{z} = \frac{1}{n}\sum_{j=1}^{n}(z_j). \tag{7}$$

The variables x_j, y_j, z_j are coordinates of j^{th} position reached by TCP point.

The one-directional position repeatability (*RP*) is defined as “the closeness of agreement between the attained positions after *n* repeat visits TCP point to the same command pose in the same direction”. *RP* represents the radius of a sphere which center is a barycenter *G* – see Figure 2. Number of positions in cluster $j = 1, 2, \ldots, n$. Length dimensions are given in (mm).

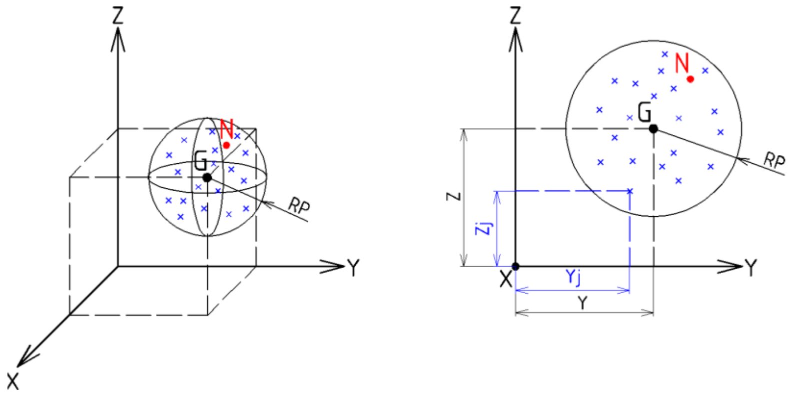


Fig. 2 Graphical displaying of one-directional position repeatability (ISO 9283:1998); *G* – barycentre $[\bar{x}, \bar{y}, \bar{z}]$, *N* – commanded position $[x_c, y_c, z_c]$, *x* - j^{th} reached position $[x_j, y_j, z_j]$

Calculation of *RP* is based on the formula:

$$RP = \bar{l} + 3S_l, \tag{8}$$

where $\bar{l}$ (mm) is mean value of the deviations between the j^{th} reached position [x_j, y_j, z_j] and mean value of reached positions $\bar{x}, \bar{y}, \bar{z}$ that are calculated according to the formulas (5), (6) and (7)

$$\bar{l} = \frac{1}{n}\sum_{j=1}^{n}(l_j), \tag{9}$$

$$l_j = \sqrt{(x_j - \bar{x})^2 + (y_j - \bar{y})^2 + (z_j - \bar{z})^2}, \tag{10}$$

and variable S_l is a sample standard deviation:

$$S_l = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(l_j - \bar{l})^2}. \tag{11}$$

2.2 The measurement procedure

Measurement of both *AP* and *RP* is performed under the same conditions. It means, that *AP* and *RP* calculation can utilize the same data but different calculation methods described within the Sub-chapter 2.1. The measurement procedure is described by ISO 9283:1998. There is defined an imaginary ISO cube with vertices labeled from *C1* to *C8* - Figure 3.

The cube is placed into that robot working space, where a robot´s maximum use is supposed. In addition, the cube must have a maximum available volume and its edges are parallel to axes of a robot´s basic coordinate system which can be identified with the world coordinate system (WCS).

The measured points are arranged within a plane which is placed inside the ISO cube. For 6DOF robots it is inclined plane which is determined by vertices *C1, C2, C7* and *C8* (see Figure 3).

The measurement consists of 30 measuring cycles, within which the TCP point moves to individual points, i.e. tested positions *P5* to *P1*. Each of the points is taken by one-directional approaching of TCP point. Coordinates of each point are measured after reaching its pose and then *AP* a *RP* is calculated.

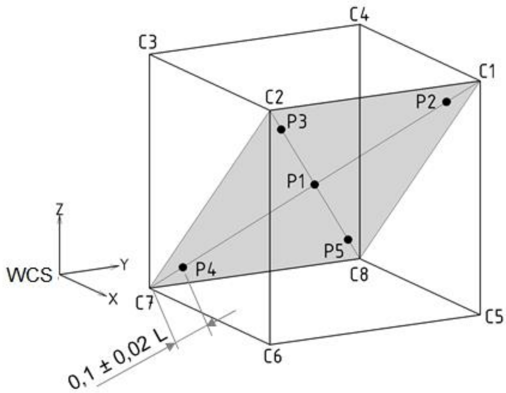


Fig. 3 ISO cube (ISO 9283:1998); *L* – diagonal length (mm)

ISO 9283:1998 norm defines the further conditions for the position performance testing. They are related to ambient temperature, loading of end of robot´s arm and speed of TCP´s movement. Although the norm ISO 9283:1998 was cancelled in the end of 2001 without compensation, the principles of robot´s performance testing continue to be used.

3 TESTING THE PEFORMANCE CHARACTERISTICS ON ROBOT FANUC LR MATE 200iC

Robot Fanuc LR Mate 200iC is implemented at the laboratory workplace of automated assembly (LWAA). There it performs the product final assembly operation and also operations related to the storing of assembled products into the warehouse. Norm ISO 9283:1998 recommends testing of nine performance characteristics for this type of robot´s application. Chosen performance characteristics – one-directional *AP* and *RP* - are two of them.

Robot Fanuc LR Mate 200iC has arm of serial kinematics. It means that accuracy of its TCP´s pose is affected by any deviations occurring in individual joints of the robot arm. These deviations are added together to cause the difference between the reached pose of TCP and the pose that is defined by data obtained from servomotor´s encoders. The aim of calibration is to improve the positioning accuracy of the robot´s TCP within the robot´s workspace.

Five methods of robots Fanuc LR Mate calibration are described in [9]. Each of them is used for the specific causes of the loss of calibration data. The principle of the Quick master method was applied for the robot Fanuc LR Mate 200iC calibration. It means, that the original calibration data was written into the system variable *$REF_COUNT*. The calibration correctness was verified by calculation according to formula (12) and applied for each control axes *J1,…, J6*.

$$J_n = \frac{\beta_n - \alpha_n}{2^{19}} \quad , \qquad (12)$$

where:

β_n – encoder´s value obtained after calibration,

α_n – encoder´s value obtained from original calibration data,

2^{19} – number of pulses per encoder´s one revolution.

Two measuring devices were used for *AP* and *RP* testing: laser interferometer SL-80 Renishaw and digital indicator Mitutoyo Digimatic ID-F including data interface Mitutoyo DMX-1 USB.

3.1 Performance characteristics testing with utilization the laser interferometer

Laser interferometer SL-80 Renishaw enables to perform very accurate measurements. The linear measurement with accuracy ±*0,0005mm* and resolution *1nm* was used for *AP* and *RP* testing. This type of measurement is based on the movement of the reflector (movable mirror) along the laser beam emitted from the laser light source – Figure 4. It means that measurement is performed along a line parallel to the laser beam. Based on this laser interferometer measurement principle the testing method of measurement of five points situated on the diagonal plane of imaginary cube described in ISO 9283:1998 could not be fully respected. Therefore, the modified measurement procedure was proposed for *AP* and *RP* laboratory testing. The imaginary cube with an edge length a = 470mm was implemented into Fanuc robot´s working space – Figure 5a. The measurement was performed in *X*, *Y* and *Z* axes separately with the same starting point *P0* placed into position defined by coordinates: x = 146mm, y = 200mm, z = -194mm with regard to WCS. Five measuring points *P1,..., P5* were placed along the edges of the imaginary cube for each measured axis - Figure 5b.

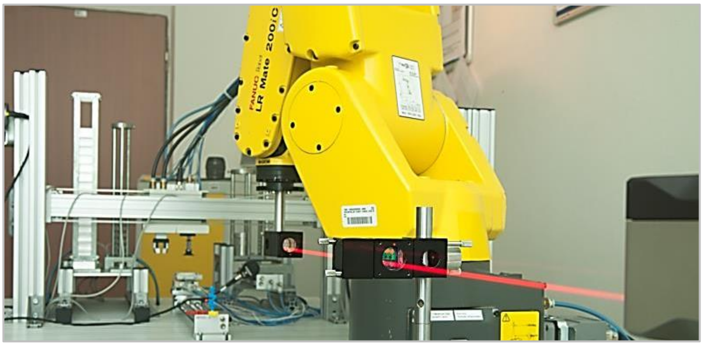
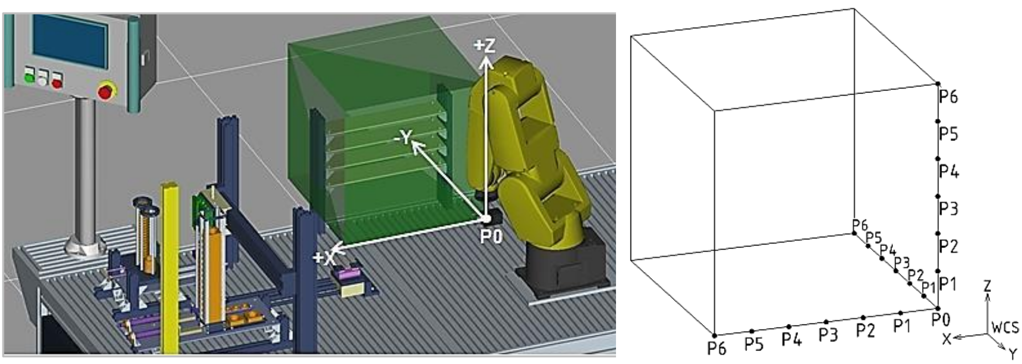


Fig. 4 Measurement with laser interferometer utilization along *X* axes



a) b)

Fig. 5 Placement of an imaginary cube and measuring points

Two-directional measuring method was used for performing measuring experiments with utilisation the laser interferometer. This method enables to evaluate not only one-directional *AP* and *RP* but also to observe the effect of the robot manipulator´s joint backlashes on the measured performance characteristics. The principle of one measuring cycle is showed in Figure 6. Robot´s programmed point - TCP - moves along a linear path between points *P0* and *P6* in both positive (+) and negative (-) directions, whereupon stopping in individual positions of measuring points *P1*, *P2*, …, *P5* was performed in both directions. Distance between individual measuring points is equal to 78mm and value of overrun is equal to 79mm.

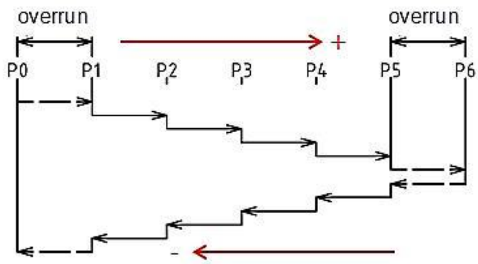


Fig. 6 Principle of two-directional measurement

Two-directional measurement was applied for each axis *X*, *Y* and *Z* separately and 30 times for positive and 30 times for negative directions. Measurements were performed under 10% of end of the robot arm´s maximum loading (m = 0,5kg) and two speeds of TCP´s movement: 100% (v_{100} = 4m.s^{-1}) and 50% (v_{50} = 2m.s^{-1}). Robot Fanuc LR Mate 200iC performed all measuring cycles automatically according to on-line created programs. Measured values were recorded by program Linear Measurement that is intended directly for linear measurement with laser interferometer Renishaw XL-80. Before the measurement, it was necessary to reset the measuring equipment, i.e. to unit zero position of the measuring equipment with the origin of the robot´s base coordinate system labelled as WCS. For this purpose, it was used the special function of Linear Measurement program.

Based on defined conditions of measurements the one-directional *AP* was calculated for each axis separately according to formulas (2), (3), (4). The one-directional *RP* was calculated according to modified formulas, as follows:

$$RP_x = \pm 3S_x = \pm 3\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_j - \bar{x})^2}\ , \qquad (13)$$

$$RP_y = \pm 3S_y = \pm 3\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(y_j - \bar{y})^2}\ , \qquad (14)$$

$$RP_z = \pm 3S_z = \pm 3\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(z_j - \bar{z})^2}\ . \qquad (15)$$

Sorting and processing of the measured values, calculation of the one-directional *AP* and *RP* values for measured points *P1,…, P5* and measurement protocol were done automatically in the program “AP&RP” specially created in Microsoft Visual Basic Express 2010.

Table 1 The one-directional *AP* – results of measurement in positive direction

	AP					
Axis	*X*		*Y*		*Z*	
Speed [%]	50	100	50	100	50	100
AP_{P1} [mm]	-0,0409	-0,0300	0,0038	-0,0254	0,1299	0,1274
AP_{P5} [mm]	-0,4227	-0,4149	0,0526	0,0276	0,1146	0,1044

Results of the one-directional *AP* testing show that this performance characteristic is worsening with increasing the distance between TCP and origin of WCS in the case of measurement in *X* and *Y* axis. Values of deviation for the first and the last measuring points are shown in Table 1. This phenomenon may be caused by the bending moments acting on the robot arm.

Analysis of values calculated for the one-directional *RP* shows that this performance is worsening at movement the TCP point in *X*, *Y* and *Z* axis positive direction (Table 2). However, the calculated average values of the one-directional *RP* were better for measurements in *X*, *Y* and *Z* axis than those indicated in the technical documentation for the robot Fanuc LR Mate 200i C (±0,02mm). The effect of the TCP´s movement speed on the reached one-directional *RP* was not significant.

Table 2 The one-directional *RP* – results of measurement in positive direction

	RP					
Axis	*X*		*Y*		*Z*	
Speed [%]	50	100	50	100	50	100
RP_{P1} [mm]	±0,0127	±0,01937	±0,0057	±0,00461	±0,088	±0,0246
RP_{P5} [mm]	±0,0278	±0,0234	±0,01491	±0,01143	±0,0157	±0,02095

Analysis of the results of two-directional measurement has shown differences between values measured in positive direction and those measured in the negative one for all three directions *X*, *Y* and *Z*. These differences can be influenced just by the robot manipulator´s joint backlashes. Verification of this finding and determination values of the individual joint backlashes require performing of new measurement that is specified in Fanuc Maintenance manual [10].

3.2 Performance characteristics testing with utilization the digital indicator

The digital indicator Mitutoyo Absolute Digimatic ID-F 543-551-1 including data interface Mitutoyo DMX-1 USB was used for measurement the one-directional *RP*. The indicator´s specification is: accuracy 0,003mm, resolution 0,001mm and range 25,4mm. The structure of proposed measuring system is shown in Figure 7.

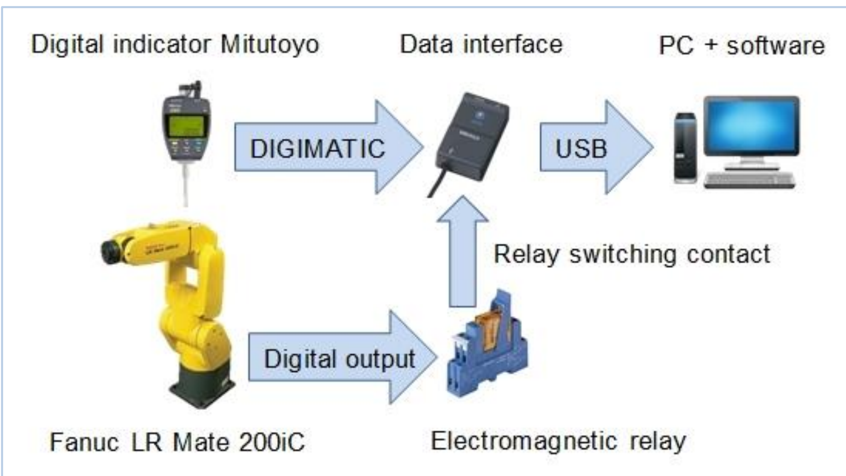
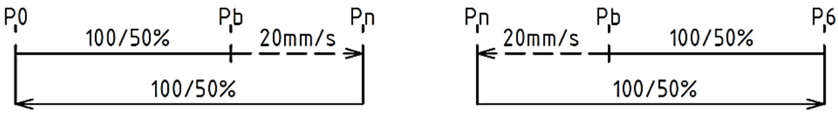


Fig. 7 Structure of the measuring system

The number of measuring points, their placement within the imaginary ISO cube and their positions within measuring axis *X*, *Y* and *Z* were chosen the same as those used at the measurement with the laser interferometer. Difference was only within measurement in *Z*-axes: a smaller number of measuring points (n = 2) and negative direction of TCP movement (from *P6* to *Pn* – Figure 5b). Because of the indicator´s limited range, the measurement in each axis *X*, *Y* and *Z* consisted from separate measurements performed for points *P1, ..., Pn*. Contact point of the indicator´s spindle was always applied to that surface of a flange connecting the end effector with the end of robot´s arm which was the best for the current measuring direction. Conditions of the performance characteristics testing were as follows: number of repeated measurements for each point: 30, speed of the TCP´s movement: 100% and 50%, loading: 20% (m = 1kg). At beginning of each measurement the TCP point is moved to the measuring point and position of the indicator is determined so that contact point applied at the contact surface of the end effector´s connecting flange is in the middle of the indicator´s spindle measuring range. Then, the indicator is reset.

To avoid the digital indicator damaging because of the use of high speeds the new point *Pb* (Figure 8) was defined between *P0* and the measuring point always at a distance 40mm from the point of measurement.



a) b)

Fig. 8 Path of TCP movement for positive (a) and negative (b) direction of measurement

By passing through *Pb*, the set speed (v = 4 m.s^{-1} or 2 m.s^{-1}) is reducing to the safe value v_s = 20mm.s^{-1} at which the TCP will reach the measuring point. The return of the TCP to *P0* runs at the preset speed. Figure 9 shows example of measurement the one-directional *RP* in *X*-axis in Laboratory of robotization of manufacturing processes.

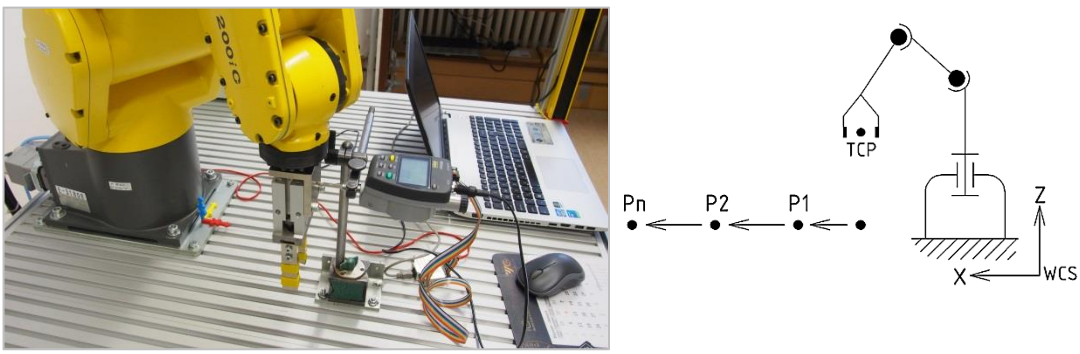


Fig. 9 One-directional *RP* measurement in *X*-axis positive direction

Two programs – the one for positive and the second for negative directions of measurement were created for robot Fanuc LR Mate 200iC. After inputting data specifying the type and conditions of the measurement by user, the programs run automatically without human intervention. Recording and processing of the measured values, calculation of values of the one-directional *RP* for measured points and creation of the measurement protocol were done automatically in the program "AP&RP".

Comparison of the results of testing the one-directional *RP* with utilization of the laser interferometer and the digital indicator show that better repeatability has been reached within the measurement with digital indicator – Table 3, 4 and 5. This anomalous finding could be causing by the following main facts:

- difference between accuracy of used laser interferometer (0,0005mm) and digital indicator (0,003mm),
- differences in applied measurement procedures.

We were unable to unify the conditions for measurement performed with the use of the digital indicator with those used at the measurement with the laser interferometer. Therefore we recommend performing a new measurement with the use of the laser interferometer at conditions specified for the digital indicator. Despite the results of this comparison, we consider the values obtained within measurement by the laser interferometer as the relevant for robot Fanuc LR Mate 200iC performance characteristics assessment.

Tab. 3 Comparison of calculated values of the one-directional *RP* for *X*-axis positive direction

Measuring point	*Laser interferometer*		*Digital indicator*	
	Axis X; speed 50%	*Axis X; speed 100%*	*Axis X; speed 50%*	*Axis X; speed 100%*
P1	±0,0127 mm	±0,01937 mm	±0,00711 mm	±0,00693 mm
P2	±0,00962 mm	±0,01758 mm	±0,00507 mm	±0,00708 mm
P3	±0,01545 mm	±0,01571 mm	±0,00955 mm	±0,00503 mm
P4	±0,01502 mm	±0,01858 mm	±0,00656 mm	±0,00798 mm
P5	±0,0278 mm	±0,0234 mm	±0,02089 mm	±0,00677 mm

Tab. 4 Comparison of calculated values of the one-directional *RP* for *Y*-axis positive direction

Measuring point	*Laser interferometer*		*Digital indicator*	
	Axis Y; speed 50%	*Axis Y; speed 100%*	*Axis Y; speed 50%*	*Axis Y; speed 100%*
P1	±0,0057 mm	±0,00414 mm	±0,00509 mm	±0,00422 mm
P2	±0,00462 mm	±0,00651 mm	±0,0046 mm	±0,00381 mm
P3	±0,00902 mm	±0,00632 mm	±0,00702 mm	±0,00637 mm
P4	±0,01258 mm	±0,00853 mm	±0,01073 mm	±0,00961 mm
P5	±0,01491 mm	±0,01068 mm	±0,01203 mm	±0,01043 mm

Tab. 5 Comparison of calculated values of the one-directional *RP* for *Z*-axis positive direction

Measuring point	*Laser interferometer*		*Digital indicator*	
	Axis Z; speed 50%	*Axis Z; speed 100%*	*Axis Z; speed 50%*	*Axis Z; speed 100%*
P1	±0,00854 mm	±0,01624 mm	±0,00255 mm	±0,00513 mm
P2	±0,00934 mm	±0,01386 mm	±0,00576 mm	±0,00857 mm

Results of testing the one-directional *RP* show that we cannot make a valid conclusion because of:

- the position to which the digital indicator was reset was not the real programmed position but the position reached with certain repeatability,
- each measuring point represents a separate measurement and therefore it is not possible to create connectivity among values of the one-directional *RP*.

4 CONCLUSIONS

The article presents the problem of a robot performance characteristics testing. The attention was focused on the one-directional *AP* and *RP* testing on robot Fanuc LR Mate 200iC with the use of two different measuring devices: the laser interferometer Renishaw applied for non-contact measuring method and the digital indicator Mitutoyo applied for contact measuring method. Results of both measuring methods show some problems related to relevance of values measured for the one-directional *AP*. The main problem is the method of reset of used measurement equipment performed before a measurement starting. In both cases the programmed position was unified with position reached by the TCP point that was affected by the robot´s repeatability. It means that calculated values of the one-directional *AP* have no relevance on robot Fanuc positioning accuracy assessment.

For the purpose of implementation the experimental measurements into educational process, the proposed methodology of measurement the performance characteristics on manipulating industrial robots will be applied only for the one-directional *RP* testing. The digital indicator will be used for a practical training despite the fact that it does not offer such measuring possibilities and accuracy as the measurement by the laser interferometer. But from a practical viewpoint, a preparation of the measurement with utilization the digital indicator is performed in relatively short time and setting of this one before the measurement process is not so complicated that could not be done by students within the laboratory training. Students prepare a measuring workplace for testing the performance characteristic on the robot Fanuc LR Mate 200iC and perform the real measurements for specified measurement conditions. Implementation of the measurement system (Figure. 7) enables to reach the main goal of this laboratory training, that is: to introduce students to the principles of the proposed methodology for testing the one-directional *RP*, collection and evaluation of the measurement data.

REFERENCES

[1] SLAMANI, A. & NUBIOLA, A. & BONEV, I. A. Assessment of the Positioning Performance of an Industrial Robot. *Industrial Robot.* 2012, Vo. 39. No. 1, pp. 57-68. ISSN 0143-991X.

[2] STN ISO 9283 Manipulačné priemyselné roboty. Pracovné charakteristiky a zodpovedajúce skúšobné metódy. (Manipulating Industrial Robots – Performance criteria and related test methods.). 1.vydanie. SÚTN Bratislava 1995, pp.60.

[3] KIHLMAN, H. at all. Metrology-integrated Industrial Robots – Calibration, Implementation and Testing. In *Proceedings of the 35th ISR (Industrial Symposium on Robotics)*. Paris-Nord Villepinte, France. 23-26 March 2004, pp. 130. [online] Available on Internet: http://liu.diva-portal.org/smash/get/diva2:471369/FULLTEXT01.pdf (2016-05-2).

[4] NUBIOLA, A. & BONEV, I. Absolute calibration of an ABB IRB 1600 robot using a laser tracker. *Robotics and Computer-Integrated Manufacturing.* 2013. Vol. 29, No. 1, pp. 236-245. ISSN 07365845.

[5] SHIAKOLAS, P.S. & CONRAD, K.L. & YIH T.C. On the Accuracy, Repeatability, and Degree of Influence of Kinematics Parameters for Industrial Robots. *International Journal of Modelling and Simulation.* 2002, Vol. 22. Vo. 3, pp.245-254. ISSN 0228-6203

[6] ABB Robotics_Vasteras_CS_en.pdf. [online] Available on Internet: http://www.leica-geosystems.de/downloads123/m1/metrology/general/case%20studies/ABB%20Robotics_Vasteras_CS_en.pdf

[7] ŞIRINTERLIKÇI, A, et all.. Repeatability and Accuracy of an Industrial Robot: Laboratory Experience for a Design of Experiments Course. *Technology Interface Journal.* 2009, Vol. 9. Nr. 2, ISSN 1523-9926. [online] Available on Internet: https://www.researchgate.net/profile/Murat_Tiryakioglu/publication/260336817_Repeatability_and_Accuracy_of_an_Industrial_Robot_Laboratory_Experience_for_a_Design_of_Experiments_Course/links/0a85e530ccb260ae2a000000.pdf

[8] DANDASH, D, et all. Micrometre Scale Performances of Industrial Robot Manipulators. *International Journal of Advanced Robotic Systems.* 2012, Vol. 9. ISSN 1729-8814. [online] Available on Internet: http://www.intechopen.com/books/international_journal_of_advanced_robotic_systems/micrometre-scale-performances-of-industrial-robot-manipulators

[9] FANUC R-J3*C Handling Tool. Manual handling. B-82284CS-2/01

[10] FANUC Robot LR Mate 200iC. Maintenance manual. B-82585EN/04