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EXPERIMENTAL INNOVATION TO COMPENSATE POSITIONING INACCURACIES OF INDUSTRIAL ROBOTS WITH HIGH PAYLOAD CAPACITY

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Abstract: *The issue of the absolute accuracy of large and very large industrial robots while handling heavyweights is still a challenge in the world of robotic engineers due to complex structural deformations in the robot joints and control modelling. It is almost impossible to master the reactions of these robots in complex industrial applications, where introducing small variations such as variable weights, variable gauges, and variable part models, positioning accuracy is strongly affected at high working speeds. In this paper is presented a methodology about measuring, compensating, and predicting the positioning errors of end-effector'. Measurements are done with metrologically certified instruments, like spacing measuring instruments, and comparator watches. An error prediction model is constructed to find out the positioning error at the tool center point (TCP) of the robot, for different payloads and different distances of the TCP relative to the robot base system. Tests indicate very good results for payloads above 550 kg, TCP speeds of 1000 mm/s and target points at over 3500 mm from the robot base.*
Key words: *high payload robots, precision, accuracy, flexile robotic cells*
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1. INTRODUCTION

In 1998 the international standard ISO 9283 was released to describe different performance criteria and associated test procedures for industrial robots, among which, accuracy and repeatability of pose, are prominent. [2] Repeatability matters especially in the teach-in programming mode, whereas accuracy matters especially in the off-line programming mode by simulation software.[1][9][10]
In this context, the paper's aim is to put into evidence some issues related to positioning accuracy and repeatability of industrial robots with very high payloads in the context of various external noise factors. [12][21]
In general, positioning error is the result of chained inaccuracies in the whole robotic system, typically categorized as: controller errors (due to the resolution of the axis encoder devices), algorithmic interpolation errors (that take place throughout the movement of the robotic arm) and kinematic errors (which mainly derive from inaccuracies of the kinematic model), dynamic errors (parameters not considered by the dynamics which relate to the servo systems' friction and inertia), manufacturing errors such as imprecision link offsets, joints' wear, gearings backlash, bearings wear, temperature fluctuations and elasticity deviations.[23][24]
When considering large-scale robots, we usually associate them to very large and heavy end-effectors, large and very heavy handling parts, which generate highly static and dynamic forces and torques during robot operation, leading to unacceptable positioning deviations. To keep the cycle times in the limits imposed by the manufacturing processes, the speed of the TCP cannot be lowered, even if we operate with large-scale, high-payload industrial robots. [4][6][8]
Due to the positioning inaccuracies, large scale robots are usually implemented in basic part-handling applications.[20] The challenge occurs when applications require accuracies below 0.5 mm, such as the case of CNC machine-tool loading and unloading. Despite the careful

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design of the robotic cell for machine tending that considers various mechanical constraints, we still meet critical situations where the robot's TCP cannot precisely reach its target.
Usually, this critical case is the loading operation of the CNC machine-tool when the loading target point is at the limit or outside the limit of the nominal working space of the robot. Thus, this paper introduces some experimental researches to solve the aforesaid problems of positioning inaccuracy.[17][19]
For the scope of this paper, we do not consider the problem defined by the perpendicularity of the part to the C axis of the CNC machine-tool. We will focus only on the compensation, positioning, precision, and repeatability of the industrial robot.[14][15]

2. MEASURING POSITIONING ERROR

2.1 Equipment

For the experimental application we used the ABB IRB8700-800/3.50 with a IRC5 Single Cabinet controller. Repeatability is specified at 0.10 mm for a nominal payload of 800 kg. Fig. 1 shows the shape of the working area of this robot, and in Fig. 2 it is illustrated the sensor we have used to perform measurements of the end-effector's position.

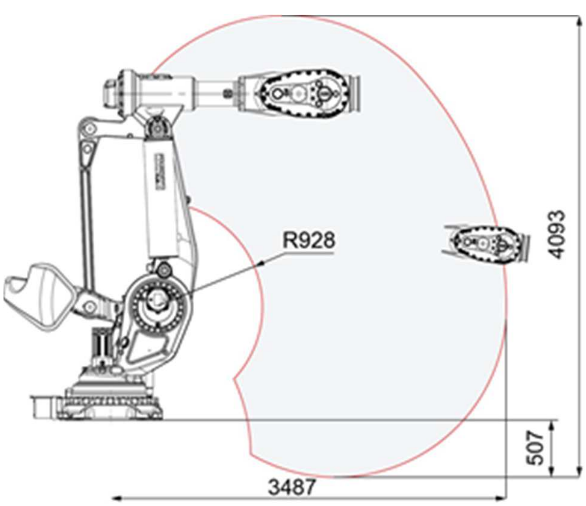

Fig. 1. ABB IRB8700 working area – cross section [source: https://new.abb.com/]

Fig. 3 illustrates the target position of the robot with the heavy part grasped for CNC machine-tool tending. Image is captured from the industrial site, where the application was implemented.

Fig. 2. Keience-type micrometric sensor

Fig. 3. Target position of the robot for machine tending

2.2 Procedure

There are several ways to organize experiments, some of them well-known, such as ANOVA and Taguchi.[18][23] They can indicate, for a set of controlled parameters and noise parameters and their related instances, how many experiments must be done and which combinations of instances have to be used in each experiment.[20] After measuring the resulted standard deviations, various strategies can be used to establish a robust combination of instances for the controlled parameters. [19]
Despite these possibilities, we have considered a more empirical approach, that emerged from discussions with robot operators who were reluctant to adopt sophisticated mathematical formalisms.[3][5] In this respect, we had to innovate. The conflicting problems are: "how to reduce the number of measurements without affecting accuracy", "how to reduce the

complexity of the method without affecting accuracy".[11][16] For both cases we applied TRIZ contradiction matrix, and the following indications occurred: reject and regenerate parts, use simple copies, replace hard systems with soft systems, arrange parts in advance.

With these generic indications we have formulated the following methodology to establish the positioning deviation at the robot target point:

- Establish the number of measurements to be done such as to achieve a reliable result.
- Establish the upper limit speed of the TCP.
- Establish the robot configuration in the target position and the path from the starting point to the target point.
- Run a set of measurements without handling parts, just considering the additional weight of the end-effector.
- Run a set of measurements with handling parts included, but considering different shapes, sizes, and weights.
- Analyze data and adjust the robot path and offsets accordingly to compensate the positioning errors of the robot TCP.

The number of measurements was set to 30 based on the recommendations given by the central limit theorem. It tells that "If the distribution is normal then we need about 30 measurements to properly characterize this distribution". We have considered a normal distribution because the series of measurements are affected by many uncertainty sources.

Thus, we made thirty measurements without any part in the robot gripper; that is, having as additional weight only the end-effector (the mass is 348 kg).

To establish the positioning deviation with the part & end-effector, we measured using different type of parts and different weights.

For each type of part, we made thirty measurements, too. In all situations we used the same settings.

The robot's TCP speed was set to 1000 mm/s, in linear interpolation mode, to meet the cycle time required in the process.

The first group of measurements was executed to find the positioning deviation on the y axis of the robot reference system, in work-object 0. After that the same measurements were made to find the positioning deviation on the z axis, changing only the position of the micrometric sensor.

2.3 Distance between the target point and the effective point with no parts in the gripper

The target point in the experiment, for the given application and for the robot used (see Fig.1) is: "pDesiredPoint=[485.9,-3483.5,1480.5]".

To reach the target, robot must be programmed to follow a linear motion from the home point to the target point.

Firstly, we have identified the deviations of the robot without part handling. Thus, the extra-load was only the end-effector's mass of 348 kg. Results of the measurements along the z axis are shown in Fig. 4.

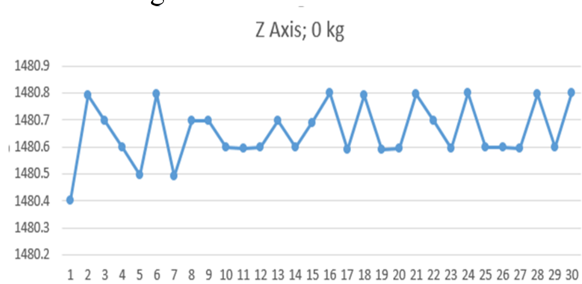

Fig. 4. Deviations of the target position on the z axis with 0 kg load in the end-effector

The next step was to perform measurements of deviations on the y axis, also without additional part handled by the gripper. Results are shown in Fig. 5.

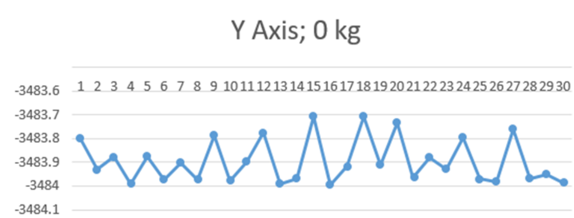

Fig. 5. Deviations of the target position on the y axis with 0 kg load in the end-effector

It is important to highlight that the "pDesiredPoint" point is saved with the robot gripper handling zero loads. If one analyzes the results from Fig. 4 and Fig. 5, it can be noticed that the robot handling 0 kg load is always positioned above the "pDesiredPoint" along z and away along y in the negative direction. Thus, we have to consider that the mechanical elements of the robot have elastic behaviors.

2.4 Distance between the target point and the effective point with parts in the gripper

In order to start the detailed analysis of the robot behavior, it was necessary to test the movement and accuracy with several part models, who had different weights. With each part we performed 30 tests to find the robot deviation from z axis, and 30 tests to find the robot deviation from y axis.

To embed influences of various payloads, we have considered six models of parts. They vary both in size, shape, and weight. Each part is considered a "generic part" for a family of parts. The set of parts is contextual; meaning, number of parts and their characteristics depend on the industrial use case under consideration. Fig. 6 from Fig. 17 show the results of the measurements for the set of six parts, highlighting the resulted deviations along the z and y axes.

Fig. 6. Deviations of the target position on the z axis with 50 kg load in the end-effector

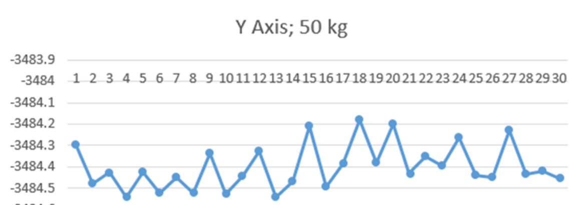

Fig. 7. Deviations of the target position on the y axis with 50 kg load in the end-effector

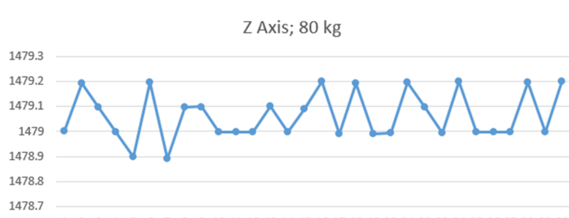

Fig. 8. Deviations of the target position on the z axis with 80 kg load in the end-effector

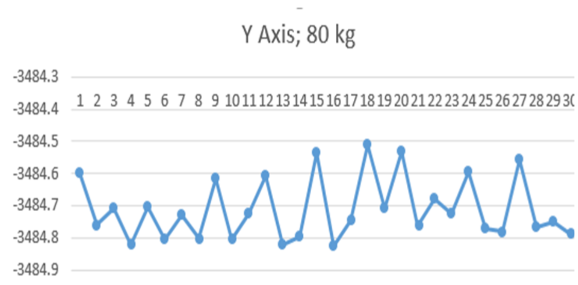

Fig. 9. Deviations of the target position on the y axis with 80 kg load in the end-effector

Fig. 10. Deviations of the target position on the z axis with 100 kg load in the end-effector

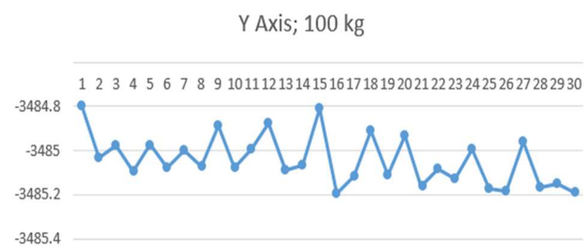

Fig. 11. Deviations of the target position on the y axis with 100 kg load in the end-effector

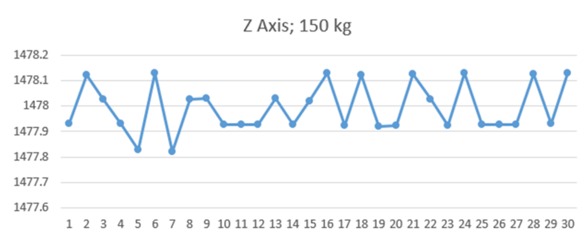

Fig. 12. Deviations of the target position on the z axis with 150 kg load in the end-effector

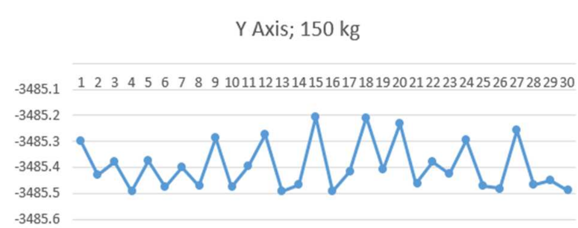

Fig. 13. Deviations of the target position on the y axis with 150 kg load in the end-effector

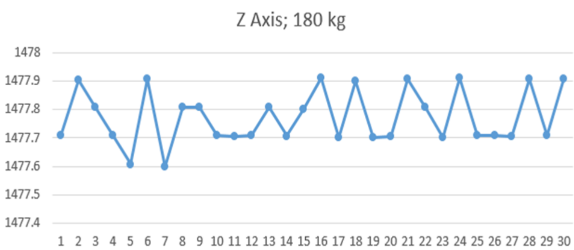

Fig. 14. Deviations of the target position on the z axis with 180 kg load in the end-effector

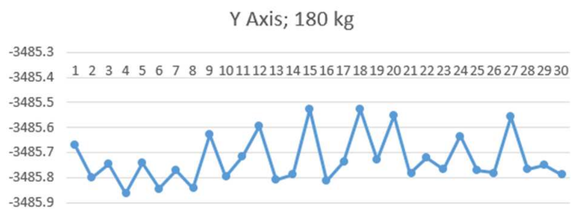

Fig. 15. Deviations of the target position on the y axis with 180 kg load in the end-effector

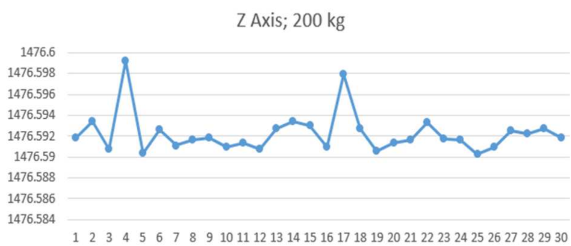

Fig. 16. Deviations of the target position on the z axis with 200 kg load in the end-effector

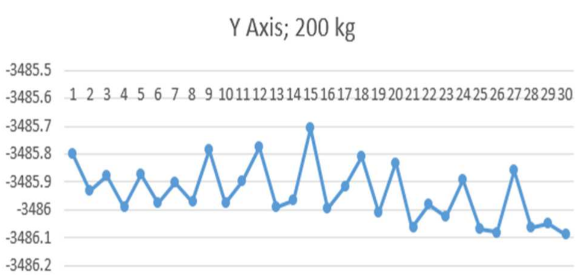

Fig. 17. Deviations of the target position on the y axis with 200 kg load in the end-effector

Fig. 18. The pattern of deviations of the target position on the z axis

Fig. 19. The pattern of deviations of the target position on the y axis

Data from Fig. 4 to Fig. 17 were included in aggregated graphs for z and y axes. Fig. 18 shows the overlapping of the measurements for the z axis and indicates the patterns of deviations, whereas Fig. 19 illustrates this situation for the y axis.

3. POSITIONING ERROR MODELLING

Robot accuracy depends on the values of the joint coordinates, positioning errors due to manufacturing inaccuracies and structural deformation. Moreover, robot axes coordinates are directly associated with the end-effector's Cartesian coordinates through the forward kinematics of the robot's controller. [12][13][7][25]

In view of these situations, a robot programmer would like to know the positioning error of the end-effector that will result when the robot is instructed to approach a position that is specified either by a set of joint coordinates or by the Cartesian coordinates of the end-effector. A robot programmer would need to determine the end-effector's coordinates to be controlled by the program for the end-effector to reach the desired target point in the Cartesian space, considering the positioning error of the robot. [25]

Based on the measurements presented in Section 2 of this paper we must identify the pattern of the error as a function of payload, on the z axis, as well on the y axis. For each payload we must identify the minimum and the maximum error for robot positioning. After that, using mathematical calculations, we must apply a correction formula of the position of the robot (an error-dependent offset).

For the test bench used in this research, the averages of the positioning errors are stated in Fig. 20.

Axis	Add Weight 0 kg	Add Weight 50 kg	Add Weight 80 kg	Add Weight 100 kg	Add Weight 150 kg	Add Weight 180 kg	Add Weight 200 kg
z [mm]	-0.4	1.05	1.68	2.11	3.16	3.79	4.22
y [mm]	-0.1	0.9	1.44	1.81	2.71	3.25	3.62

Fig. 20. Robot positioning errors on z and y axes

3.1 Positioning error compensation

The positioning error compensation task is not as simple as it might appear at first glance. With reference to the data from Fig. 20, we need to develop a linearization formula to correct the position of the robot's TCP as function of the payload.

In this respect, considering the minimum weight ($WeightMin$), the maximum weight ($WeightMAX$), the minimum deviation ($DeviationMin$) and the maximum deviation ($DeviationMAX$), the correction ($Correction$) for a given $Weight$ is calculated with the proposed formula from equation (1). This formula is applied both for z and y axes.

$$Correction = \frac{Weight - WeightMin}{WeightMAX - WeightMin} \times (DeviationMAX - DeviationMin) + DeviationMin \qquad (1)$$

3.2 Test and validation

We have applied the linearization formula (1) to test the effects on robot positioning accuracy. Results are shown in the figures 21 to 34. It is important to highlight once again that the payload is added to the mass of the end-effector (which is 348 kg).

Fig. 21. Effect of linearization on robot position on the z axis for 0 kg payload in the end-effector

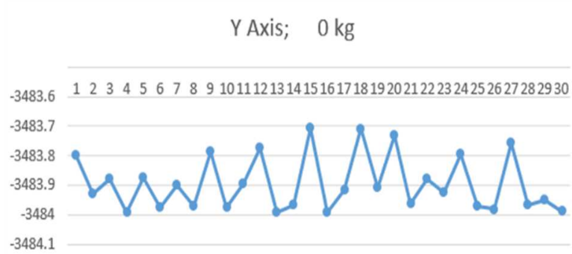

Fig. 22. Effect of linearization on robot position on the y axis for 0 kg payload in the end-effector

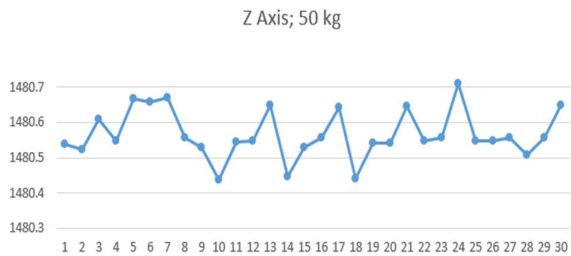

Fig. 23. Effect of linearization on robot position on the z axis for 50 kg payload in the end-effector

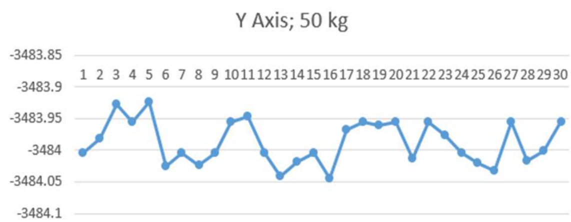

Fig. 24. Effect of linearization on robot position on the y axis for 50 kg payload in the end-effector

Fig. 25. Effect of linearization on robot position on the z axis for 80 kg payload in the end-effector

Fig. 26. Effect of linearization on robot position on the y axis for 80 kg payload in the end-effector

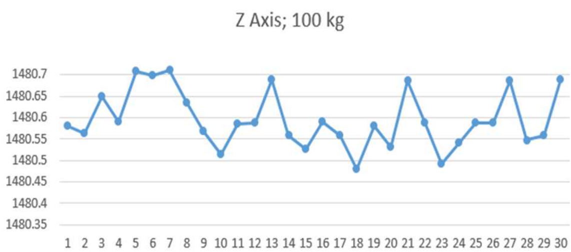

Fig. 27. Effect of linearization on robot position on the z axis for 100 kg payload in the end-effector

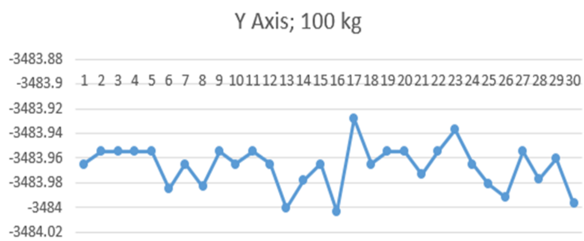

Fig. 28. Effect of linearization on robot position on the y axis for 100 kg payload in the end-effector

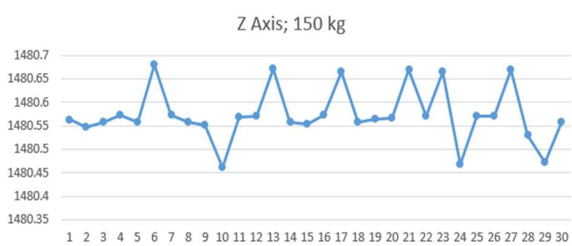

Fig. 29. Effect of linearization on robot position on the z axis for 150 kg payload in the end-effector

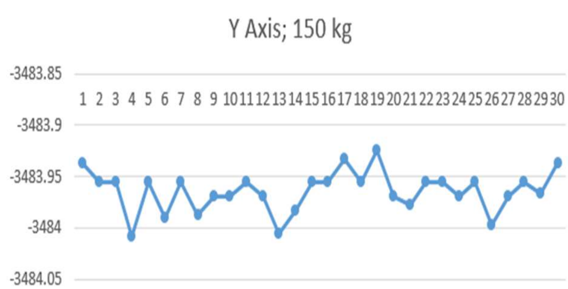

Fig. 30. Effect of linearization on robot position on the y axis for 150 kg payload in the end-effector

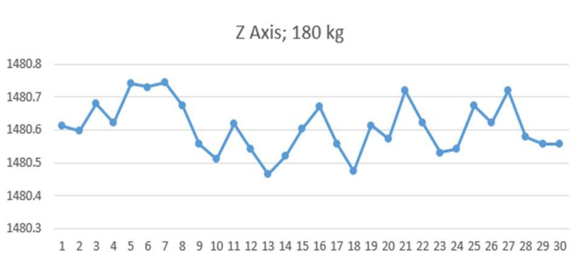

Fig. 31. Effect of linearization on robot position on the z axis for 180 kg payload in the end-effector

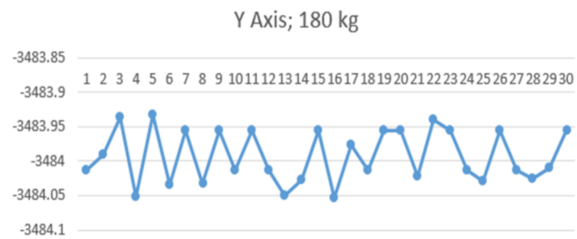

Fig. 32. Effect of linearization on robot position on the y axis for 180 kg payload in the end-effector

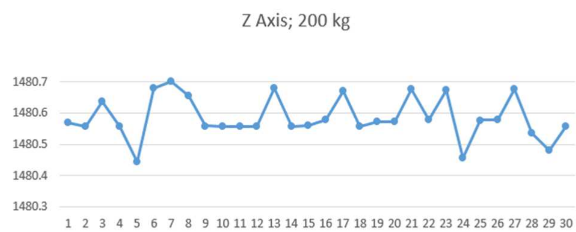

Fig. 33. Effect of linearization on robot position on the z axis for 200 kg payload i
n the end-effector

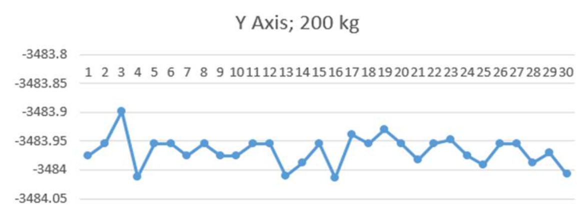

Fig. 34. Effect of linearization on robot position on the y axis for 200 kg payload in the end-effector

Fig. 35. Aggregated results on z axis 0-200 kg

Fig. 36. Aggregated results on y axis 0-200 kg

Fig. 35 and Fig. 36 illustrate the aggregated results on z and y axes. Comparing these results with those indicated in Fig. 18 and Fig. 19, we clearly see a significant improvement in the positioning accuracy of the robot, despite the payload used in the machine tending application.

4. CONCLUDING REMARKS

As one can see from figures 18 and 19 the deviation of the robot relative to the target point is 4.02 mm on the z axis and 3.62 mm on y axis. For the industrial uses case, the accepted deviation is 0.5 mm.

Based on the experimental innovation we have proposed in this paper, significant improvements, meaning that we have obtained a maximum deviation of 0.40 mm on the z axis and 0.36 mm on the y axis, which is much better than the accepted one of 0.5 mm. These results are indicated in figure 35 and 36.

Despite its capacity to reach the effectiveness objective (i.e., the positioning accuracy), the applied methodology still has some limitations, such as the time effort required to perform experiments in the industrial field, as well as labor intensive effort to operate in safety conditions large robots and heavy payloads.

Operation with large scale industrial robots is still a less explored area in applied engineering, but with many benefits in various applications, including emerging ones, such as 3D printing of extra-large objects for construction industry, navy industry, etc.

Further research will consider machine learning algorithms, combined with structured design of experiments (e.g., Taguchi method), and scalable modelling to reduce the number of investigations, to increase the area of applicability to a wider set of applications, and a wider variation of the noise factors in the process, as well as the possibility to operate with lower scale robots and afterward to extrapolate to large scale robots.

5. REFERENCES

[1] Pan, H., Polden, J., Larkin, N., Van Duin, S. and Norrish, J., "Recent progress on programming methods of industrial robots", Robot. CIM-Int. Manuf., Vol. 28, No 2, pp. 87–94, 2012.

[2] Berg, J.O., "Robot Accuracy: A Matter of Programming", The Int. J. of Adv. Manuf. Technology, Vol. 7, No. 4, pp. 193-197, 1992.

[3] ISO 9283 - "Manipulating industrial robots. Performance criteria and related test methods", ISO, Geneva 1998.

[4] Elatta, A.Y., Gen, L.P., Zhi, F.L., Daoyuan, Y and Fei, L., "An Overview of Robot Calibration", Inform. Techn. J., Vol. 3. No. 1, pp. 74-78, 2004.

[5] Visher, P. and Clavel, R., "Kinematic calibration of the parallel Delta robot", Robotica, Vol. 16, No 2, pp. 207-218, 1998.

[6] Schröer, K., Bernhardt, R., Albright, S., Wörn, H., Kyle, S., van Albada, D., Smyth, J. and Meyer, R., "Calibration applied to quality control in robot production", Control Eng. Pract., Vol. 3, No. 4, pp. 575–580, 1995.

[7] Wang, S., Miao, X., Yang Y. and Peng, X., "Error Compensation and Calibration of Inter-section Line Welding Robot Based on a Wavelet Neural Network", in: T.-J. Tarn et al. (Eds.): Robotic Welding, Intelligence and Automation, Lecture Notes in Electrical Engineering series, Springer, 88, pp. 33–40, 2011.

[8] Lee, M-S., Kang, D., Cho, Y.-S., Park, Y. and Kim, J.-H., "The effective kinematic calibration method of industrial manipulators using IGPS", in Proc. ICCAS-SICE, 2009, pp. 5059 - 5062.

[9] Cui, H., Zhua, Z., Gan, Z. and Brogardh, T., "Kinematic analysis and error modeling of TAU parallel robot", Robot. CIM-Int. Manuf., Vol. 21. No. 6, pp. 497–505, 2005.

[10] Shiakolas, P.S., Conrad, K.L. and Yih, T.C., "On the accuracy, repeatability and degree of influence of kinematics parameters for industrial robots", Int. J. Model. Simul., Vol. 22, No. 3, 2002.

[11] Gong, C., Yuan, J. and Ni, J., Nongeometric error identification and compensation for

robotic system by inverse calibration", Int. J. Mach. Tool. Manuf., Vol. 40, No 14, pp. 2119-2137, 2000.

[12] Jang, J.H., Kim, S.H. and Kwak, Y.K., "Calibration of geometric and non-geometric errors of an industrial robot", Robotica, Vol. 19, No. 3, pp. 311–321, 2001.

[13] Watanabe, A., Sakakibara, S., Ban, K., Yamada, M., Shen, G. and Arai, T., "A Kinematic Calibration Method for Industrial Robots Using Autonomus Visual Measurement", CIRP Ann. – Manuf. Techn., Vol. 55, No. 1, pp. 1-6, 2006.

[14] Yin, J. and Gao, Y., "Pose Accuracy Calibration of a Serial Five DOF Robot", Energy Procedia, Vol. 14, pp. 977-982, 2012.

[15] Shirinzadeh, B., Teoh, P.L., Tian, Y., Dalvand, M.M., Zhong, Y. and Liaw, H.C., „Laser interferometry-based guidance methodology for high precision positioning of mechanisms and robots", Robot. CIM-Int. Manuf., Vol. 26, No. 1, pp. 74-82, 2010.

[16] Abtahi M., Pendar, A., Alasty, H. and Vossoughi, G., "Experimental kinematic calibration of parallel manipulators using a relative position error measurement", Robot. CIM-Int. Manuf., Vol. 26, No. 6, pp. 799-804, 2010.

[17] Nubiola, A. and Bonev, I.A., "Absolute calibration of an ABB IRB 1600 robot using a laser tracker", Robot. CIM-Int. Manuf., Vol. 29, No. 1, pp. 236-245, 2013.

[18] Alici, G, and Shirinzadeh, B., "A systematic technique to estimate positioning errors for robot accuracy improvement using laser interferometry-based sensing", Mech. Mach. Theory, Vol. 40, No. 8, pp. 879–906, 2005.

[19] Tao, P.Y., Yang G. and Tomizuka, M., "A Sensor-based Approach for Error Compensation of Industrial Robotic Workcells", 2012 IEEE Int. Conf. on Robotics and Automation, Saint Paul, Minnesota, USA, May 14-18, 2012, pp. 5240-5245.

[20] Santolaria, J. and Ginés, M., "Uncertainty estimation in robot kinematic calibration", Robot. CIM-Int. Manuf., Vol. 29, No. 2, pp. 370-384, 2013.

[21] Alici, G., Jagielski, R., Sekercioglu, Y. and Shirinzadeh, B., "Prediction of geometric errors of robot manipulators with Particle Swarm Optimisation method", Robot. Auton. Syst., Vol. 54. No. 12, pp. 956–966, 2006.

[22] Kim, K., Lee, S., Kim, K., Lee, K-Y, Heo, S., Park, K., Jeong, J-I. and Kim, J., "Development of the end-effector measurement system for a 6-axis welding robot", Int. J. Prec. Eng. Manuf., Vol. 11, No 4, pp. 519-526, 2010.

[23] Benardos, P.G. and Vosniakos, G.-C., "Optimising feedforward artificial neural network architecture", Engineering Applications of Artificial Intelligence, Vol. 20, No. 3, pp. 365-382, 2007.

[24] Shiels, Maggie, "Legal milestone for open source" BBC News. Retrieved 2008-08-15 (http://news.bbc.co.uk/2/hi/technology/7561943.stm accessed on May 20, 2018)

[25] Angelidis, A. and Vosniakos, G.C., "Prediction and compensation of relative position error along industrial robot end-effector paths", International Journal of Precision Engineering and Manufacturing (Springer), Vol. 15, No. 1, pp. 63-73, 2014.

Inovaţie experimentală de compensare a abaterilor de poziționare în cazul roboților industriali cu capacitate portantă foarte mare

Rezumat: Când ne referim la roboți industriali începem să ne gândim la o arhitectură de sisteme care, cu ajutorul software-ului care îi completează, reușesc să ne simplifice, să ne ajute sau chiar să ne elimine o multitudine de sarcini cotidiene. Însă când facem referire la un robot industrial de dimensiuni mari, primele lucruri pe care le analizăm sunt de obicei viteza nominală de lucru și precizia de poziționare. Până la un anumit nivel de aplicații care includ manipulare și poziționare, acești roboți sunt suficient de preciși, dar dacă adăugăm unul sau mai multe elemente neprevăzute inițial în etapa de proiectare, ajungem în situații care conduc la ieșirea robotului din intervalul de precizie ("fine"). La viteze și capacități portante foarte mari, robotul nu mai poate gestiona corespunzător precizia de poziționare. Această lucrare introduce o noutate în modul de soluționare a abaterilor de poziționare a roboților industriali cu spațiu de lucru mare și capacitate portantă mare printr-o inovaţie în plan experimental. Teste indică rezultate foarte bune a modelului experimental în cazul unei aplicații industriale în care se manipulează sarcini de 550 kg la flanșa robotului, cu viteze de 100 mm/s și puncte țintă aflate la peste 3500 mm față de baza robotului.

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