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EVALUATION OF ARTICULATED ARM ROBOT ACCURACY USING A LASER INTERFEROMETER

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Abstract: *This article presents the first stage of the work performed by the authors regarding robot accuracy evaluation. This stage focuses on measuring the variations in robot's accuracy values during a linear movement of the tool along a direction parallel to the Y axis of the base frame. The experimental procedures were conducted using a Kawasaki FS 10 E articulated arm robot with six degrees of freedom and the measurements were done using a Renishaw ML10 laser interferometer. The accuracy values at various points on the trajectory were recorded using different movement speeds, in order to evaluate the influence of trajectory speed on the accuracy levels and the speed levels at which the robot can be programmed for precise tasks. Furthermore, the measurements were conducted for both the programmed path along the Y axis of the base frame and for the reversed trajectory. For results analysis, a comparison with previous experimental procedures regarding robot volumetric precision was made, including a study of precision levels across the robot's workspac, which was considered as a basis for these measurements. Future research directions include analyzing the accuracy levels of the robot along the X axis of the base frame and evaluating the repeatability of the arm, with the final goal being to apply a calibration procedure based on the experimental results in order to improve the overall volumetric precision of the robot.*

Key words: *industrial robot, laser interferometer, accuracy, volumetric precision, linear trajectory.*

1. INTRODUCTION

In the field of industrial robotics some of the main functional parameters are the accuracy and the repeatability, considering here the parameters that are taken into account since the first stages of robot integration for an industrial application. This is a natural consequence of the fact that these parameters are contributing to the outlining of the volumetric precision of the robot. Being two of the most important parameters, the field of industrial robotics scientific research has treated extensively both the issue of measuring the behavior of the robot with respect to its precision – taking into account various environmental influence factors – and the issue of robot calibration in order to improve its accuracy and repeatability. These studies have shown that evaluation procedures and calibration methods developed offline have a major disadvantage in that the environmental factors can only be simulated and most of the time cannot be taken into account with enough accuracy. Furthermore, many of the accuracy and repeatability measuring procedures performed online often require complex calibration steps and are not very cost-effective [1].

Historically, repeatability has been the most taken into account of the two parameters previously discussed. This came from the fact that the programs, being mostly developed online, were calibrated on the spot with respect to accuracy, shifting in fact the reference frame of the entire application according to the deviations observed in the first programming stages. Thus, it was more important that, once calibrated, the robot should have a good repeatability in order to perform the same tasks again and again with the same accuracy level. More recently, with the increase of offline programmed applications, the accuracy began to play a more important role. It was essential for the virtual model of the robot to behave as close as possible to the real equipment, and that means that the real robot should have very good accuracy levels in order to follow closely the programmed path - the theoretical one. For these reasons, when the programming is done online, the most important parameters is the repeatability, but when it comes to offline programming, accuracy becomes the main issue [2].

Taking these aspects into account, this article describes a method to evaluate the accuracy of an articulated arm industrial robot with six degrees of freedom which follows a path parallel to the Y axis of the base frame. The accuracy evaluation is performed online and it is done using a laser interferometer. The

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programming method used for measurement – the block programming procedure using point-to-point teaching – is suitable for evaluating the relative accuracy of the robot – the accuracy measured with respect to the first programmed point. Thus, the experimental procedure evaluates the ability of the robot to ensure a good accuracy for applications programmed online.

2. EXPERIMENTAL EQUIPMENT

The measuring procedures were performed on a Kawasaki FS10E industrial robot with six degrees of freedom. The robotic system included the articulated arm and a Kawasaki D series controller, which are shown in Fig. 1. The functional parameters of the robot are shown in Table 1 [3].

The accuracy values were acquired using a Renishaw ML10 laser interferometer, which allows for measurement of geometric and dynamic characteristics of the robot, as well as for calibration procedures. The modular architecture of the laser system allows measurement of these characteristics on different movement axes and for different trajectories. Thus, the flexibility of the device ensures not only a good integration with the kinematic flexibility of an articulated arm robot, but also good options for further analysis and scientific research [4].

Fig. 1. Kawasaki FS10E articulated-arm robot and Kawasaki D controller.

Fig. 2. ML10 laser interferometer system.

Table 1

Kawasaki FS10E robot parameters

Architecture	Articulated arm		
DOF	6		
Joint limits and speeds	Joint	Limits	Speed
	1	±160°	200 °/s
	2	−105° – 140°	140 °/s
	3	−155° – 120°	200 °/s
	4	±270°	360 °/s
	5	±145°	360 °/s
	6	±360°	600 °/s
Payload	10 kg		
Wrist load	Joint	Torque	Inertia
	4	21.5 N·m	0.63 kg·m^2
	5	21.5 N·m	0.63 kg·m^2
	6	9.8 N·m	0.15 kg·m^2
Repeatability	±0.1 mm		
Weight	170 kg		
Acoustic level	< 70 db		

The modular structure of the Renishaw ML10 laser interferometer is shown in Fig. 2.

The main components of the laser system are [4]:

- The laser unit, shown in Fig. 3. This is a single frequency laser whose gain medium consists of a mixture of helium and neon. The ML10 laser can be connected to a laptop computer equipped with a PCM20 interface card using a data link cable.
- The EC10 environmental compensation unit, shown in Fig. 4. This unit has the role of compensating the laser beam wavelength taking into account the variations in environmental conditions such as temperature, humidity, etc.

Fig. 3. The ML10 laser unit.

Fig. 4. The EC10 environmental compensation unit.

Table 2

ML10 laser specifications

Laser source	HeNe laser tube (Class II)
Laser power	< 1 mW
Vacuum wavelength	632.9906 nm (nominal)
Laser frequency accuracy	ML10 Gold Standard: ±0.05 ppm Earlier ML10 units: ±0.1 ppm
Outputs	RS485 from 5-pin data link
Power supply	ML10 Gold Standard has Universal Power Supply with auto-sensing input voltage range of 85 V to 265 V. Frequency tolerance: 45-65 Hz Earlier ML10 units had specific power supplies of 100, 110, 220, 240 V. Voltage tolerance: ±10%
Operating temperature	0-40 °C (32–104 °F)
Operating humidity	0–95% non-condensing

Table 3

EC10 environmental compensation unit specifications

Air temperature range	0–40 °C
Air temperature accuracy	±0.2 °C
Air pressure range	750–1150 mbar
Air pressure accuracy	±1.0 mbar
Relative humidity range	0–95% (non-condensing)
Relative humidity accuracy	15% relative humidity
Wavelength compensation accuracy	±0.7 ppm
Material temperature range	0–40 °C
Material temperature accuracy	±0.1 °C
Power supply	EC10 Gold Standard: 120 V, 240 V (user-selectable) Voltage tolerance: ±20% Frequency tolerance: 45-65 Hz Earlier EC10 units had specific power supplies of 100, 110, 220, 240 V Voltage tolerance: ±20% Frequency tolerance: 45-65 Hz

Table 4

Linear measurements specifications

Standard range	0–40 m
Long-range	0–80 m
Accuracy (with EC10)	ML10 and EC10 Gold Standard: ±0.7 ppm * Earlier ML10 and EC10 units: ±1.1 ppm *
Resolution	0.001 μm
Maximum velocity	60 m/min (1 m/s)
Velocity measurement accuracy	±0.05% where *% = percentage of displayed value*

The ML10 laser specifications are shown in Table 2. Also, the EC10 environmental compensation unit specifications, shown in Table 3, are important parameters that should be taken into account in order to determine the environmental conditions in which measurements can be conducted. Furthermore, the environmental compensation unit is used only for linear measurements, which is the case of this research, in order to compensate the refractive index of air. The specifications regarding linear measurements are shown in Table 4 [4].

3. EXPERIMENTAL PROCEDURE

The Kawasaki FS10E industrial robot used for the measuring procedures is equipped for deburring and low-force machining applications using dedicated self-driven tools. Most of robot paths that are directly involved in performing the required tasks are linear or circular movements. Thus, the chosen experimental procedure was that of linear measurement. The scope of this research stage was of evaluating the relative accuracy of robot's linear movement along a direction parallel to the Y axis of the base frame with respect to the first point of the linear path. In other words, all trajectory evaluation points and the corresponding errors were measured relative to the first point of the path. This procedure is consistent with online teaching methods in which the reference frame of the entire program can be calibrated on site and thus any absolute accuracy errors are, for the most part, eliminated.

The optic accessories used for linear measurement are shown in Fig. 5.

The experimental equipment was prepared for operation according to the linear measurement principles. One of the linear reflectors should be attached to the beam-splitter to form the linear interferometer optics. The linear interferometer determines the reference path for the laser beam. The other linear reflector should be place on the axis of movement for which accuracy measurement will be conducted. The setup of the experimental equipment is shown in Fig. 6 [4].

The beam-splitter divides the beam into a reference beam and a measurement beam. The reference beam is directed towards the reflector mounted together with the beam-splitter, while the measurement beam travels to the reflector mounted on the axis of movement. Both reflectors return their respective beams towards the splitter where they are recomposed and directed to the detector placed on the laser unit. This detector measures the interference between the beams. Thus, because one of the reflectors travels with the axis of movement, the measurement of the accuracy is acquired by monitoring the difference between the two beams. This operating principle is illustrated in Fig. 7 [4].

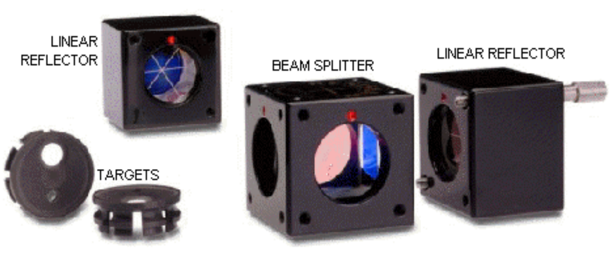

Fig. 5. The optic accessories used for linear measurement.

Fig. 6. The setup of the experimental equipment.

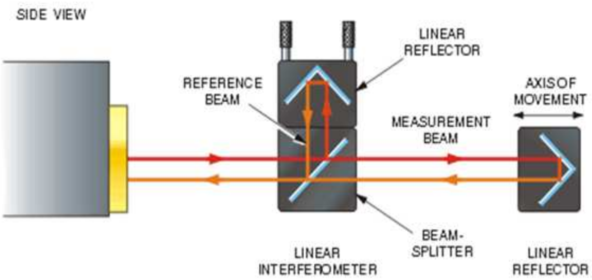

Fig. 7. Linear measurement operating principle.

The only relatively complex task of preparing the experimental equipment is the alignment of the laser beam. The ML10 laser and the optical accessories must be placed and calibrated such as the laser beam should be parallel to the linear axis of travel. This condition is required in order to avoid cosine measurement errors and to avoid losses of signal along the movement path. In order to obtain this alignment, the following steps should be followed [4]:

- The laser should be visually aligned to the axis of movement.
- Without placing the interferometer between them, the axis of movement should be moved close to the laser and a target should be placed on the reflector. The robot should then be moved until the beam forms a red spot on the white point on the target.
- The target should then be removed. If the beam from the reflector does not form a red spot on the centre of the target placed on the laser, the robot should be moved until this condition is met.
- The interferometer should be placed close to the reflector, parallel to its face with an acceptable tolerance of $\pm 2^0$.
- A target with the white spot at the top should be placed at the input of the interferometer. The interferometer should be aligned so that the beam hits the white spot of the target. After that the target should be removed. The beam from the interferometer must reach the white spot of the laser's shutter at the same point as the beam from the reflector placed on the axis of movement. If this condition is not met, the position of the interferometer should be adjusted.

The experimental procedure itself was conducted taking into account that a significant displacement of the axis should take place between the measurement points in order to obtain reliable results. This displacement between the measurement points was chosen to be 20 mm. Also, the total length of the programmed path was 200 mm, resulting in a total of 20 measurement points (considering that the measurements were also conducted by following the path in reverse, from the end to the start point). The first point of the linear path was considered the measurement reference point. Thus, all accuracy errors of subsequent point were measured with respect to this position. In order to obtain this reference, the programming of the robot path was made using the block teaching method, and the target point on the trajectory were recorded by taking into account the coordinates shown on the teach-pendant – thus mirroring the point-to-point teaching method used in online programming. The program used for experimental procedures is shown in Fig. 8. It should be noted that the speed on each trajectory segment was different in order to simulate an actual machining application in which the speed varies on different path segments. Also, the accuracy for path target points was measured both for the programmed trajectory and for the reversed trajectory – the robot was moved 10 mm after the end of the path and then the trajectory was followed again from the end to start. Thus, the accuracy of the robot on the direction of the base frame Y axis was measured in both directions of travel.

In order to obtain consistent results, to avoid influences introduced by outlier results and to statistically eliminate extreme experimental values, three measurement sessions were conducted using the same parameters. A fourth measurement session was conducted by increasing the trajectory speed to half the maximum speed of the robot, in order to evaluate the influence of a dramatic speed increase along the trajectory.

Previous volumetric precision measurements performed on the Kawasaki FS10E robot were focused on evaluating the absolute accuracy of the robot in different areas of the workspace, as shown in Fig. 9 [5]. The linear trajectory programmed for the experimental procedure described in this article was placed at a distance of 670 mm from the YZ plane of robot's base frame, taking into account that this distance was within the workspace area that ensured the highest absolute accuracy levels.

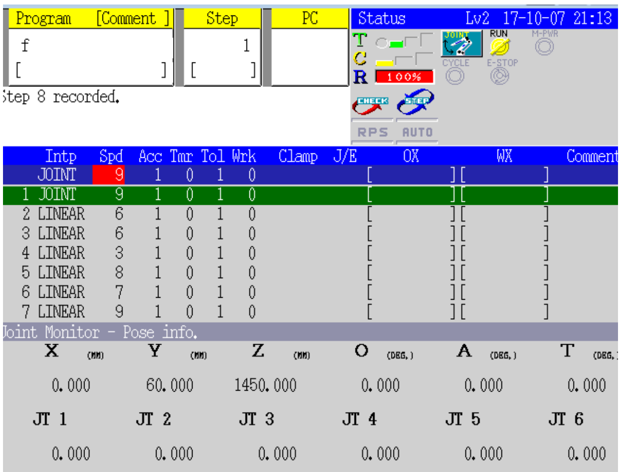

Fig. 8. Programming by block teaching for the measured path.

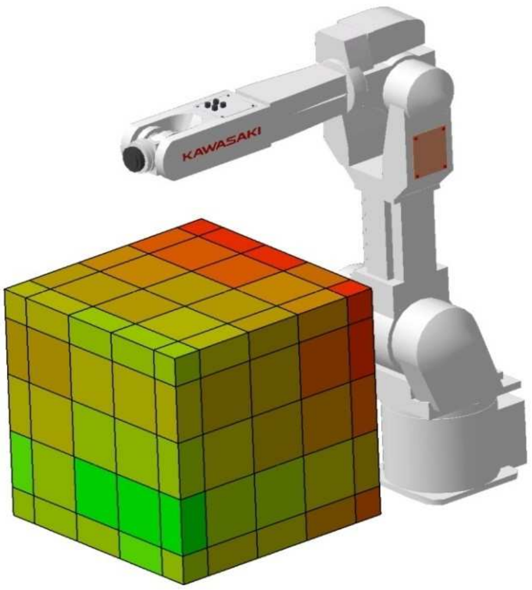

Fig. 9. Accuracy levels across different areas of the workspace for the Kawasaki FS10E.

4. EXPERIMENTAL RESULTS AND GRAPHIC CHART ANALYSIS

The numeric values of the experimental results are shown in Table 5 for the first three measurement sessions conducted at 10% of robot maximum trajectory speed. also, in Table 6 the numeric values of the experimental results for the fourth measurement session, conducted at 50% of robot maximum trajectory speed are shown. The distance along path for each measurement point represents the distance from the reference – the first point of the path. For each point, two accuracy errors were measured, one for the normal path (the trajectory followed from the start point to the end point) and one for the end path (the trajectory followed from the end point to the start point).

The experimental results were analyzed using graphic charts. The graphical representations of the first three measurement sessions – with the trajectory speed at 10% of the maximum robot speed – are shown in Fig. 10. The graphical representation of the fourth measurement session – with the trajectory speed at 50% of the maximum robot speed – is shown in Fig. 11. Also, in Fig. 12, a comparison chart between the median values of the normal path errors and the median values of the reversed path errors – taking into account the first three measurement sessions – is illustrated.

5. CONCLUSIONS

This paper described the experimental procedure and the measurement results for the accuracy evaluation of a 6 DOF articulated arm robot. The goal of the research was to evaluate the accuracy levels and to observe robot's behavior along the trajectory.

The first conclusions that can be extracted are linked to the error values measured across the trajectory target points. The values vary between 0.032 and 0.412 mm (including the fourth measurement session), which is outside the rated accuracy for this robot but maintains the same order of magnitude. In this case it must be taken into account the fact that the zero position for each axis was calibrated using the visual marks on the robot's joints, thus generating a significant error level. Yet, this procedure is the calibration method recommended for the manufacturer when high precision operations are not necessary. Also, if the fourth measurement session is not taken into account, the maximum error value is 0.351 mm, which is an acceptable value considering the fact that the robot is equipped with a self-driven tool dedicated for deburring and low-force machining applications.

Table 5

The numeric values of the experimental results for the first three measurement sessions

No.	Distance along path [mm]	Error (normal path) [µm]	Error (reversed path) [µm]	Distance along path [mm]	Error (normal path) [µm]	Error (reversed path) [µm]	Distance along path [mm]	Error (normal path) [µm]	Error (reversed path) [µm]
	1st session			2nd session			3rd session		
1	20	49.101	71.3	20	63.2	56.5	20	46.299	44.3
2	40	145.1	172.9	40	152.199	168.801	40	142.001	151.501
3	60	127	169.301	60	133.701	194.6	60	126.101	166.799
4	80	190.599	196.799	80	172.601	215.501	80	170.299	190.899
5	100	189.4	164.501	100	180.599	153.901	100	170.101	151.801
6	120	187	208.9	120	176.4	199.499	120	193.2	201.9
7	140	113.599	108.301	140	110.5	101	140	97.6	104.399
8	160	262.199	241	160	245.9	224.099	160	254.8	239.9
9	180	351.201	323.2	180	343.101	299.9	180	343.2	313.2
10	200	292.801	284	200	283.2	286	200	293.901	297.299

Table 6

The numeric values of the experimental results for the fourth measurement session

No.	Distance along path [mm]	Error (normal path) [µm]	Error (reversed path) [µm]
1	20	41.199	32.901
2	40	145.199	143.401
3	60	208.999	155.801
4	80	253.799	175.801
5	100	232.001	178.3
6	120	261.099	206.2
7	140	168.801	126.601
8	160	312.801	286.601
9	180	411.3	357.101
10	200	363.2	346.7

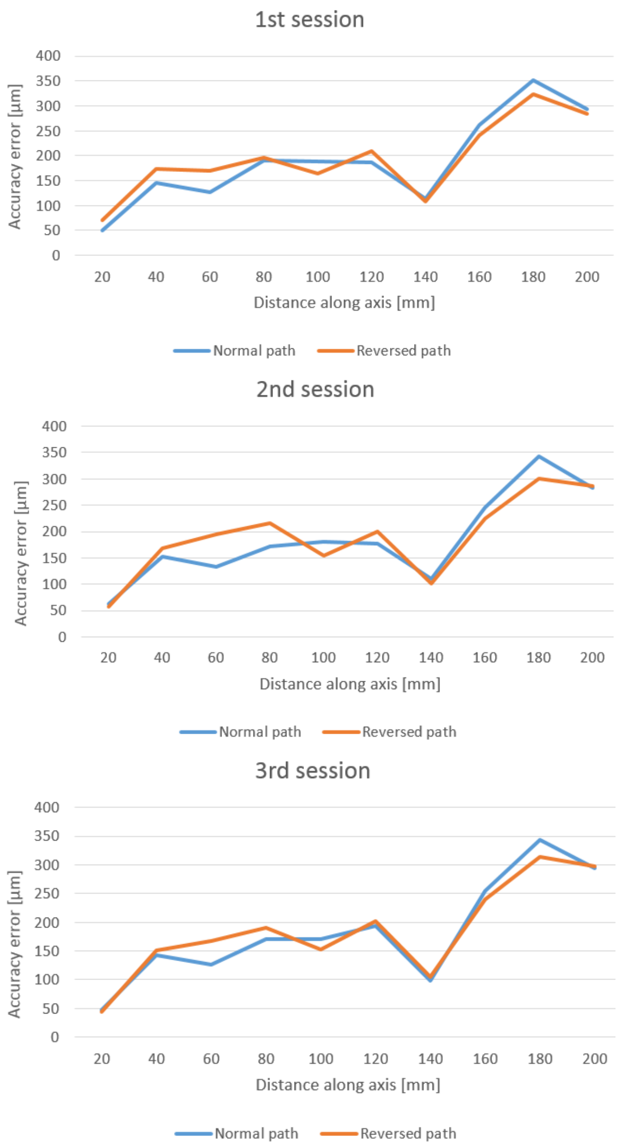

Fig. 10. Graphic chart analysis for the first three measurement sessions.

Regarding the behavior of the robot across the measurement trajectories, it can be observed that the error values are lower if the corresponding target points are closer to the reference point, a fact that is true for both the normal path and the reversed path. This indicates a cumulative error at each path segment.

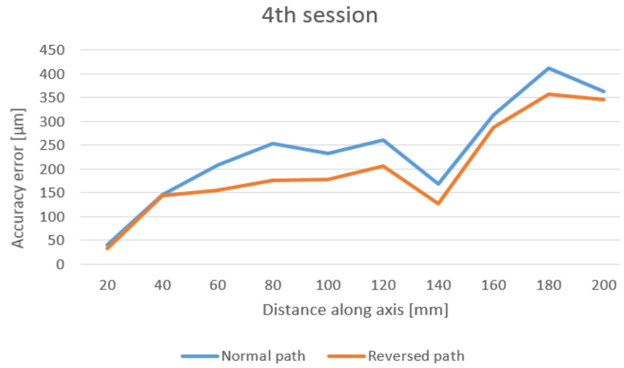

Fig. 11. Graphic chart analysis for the fourth measurement session.

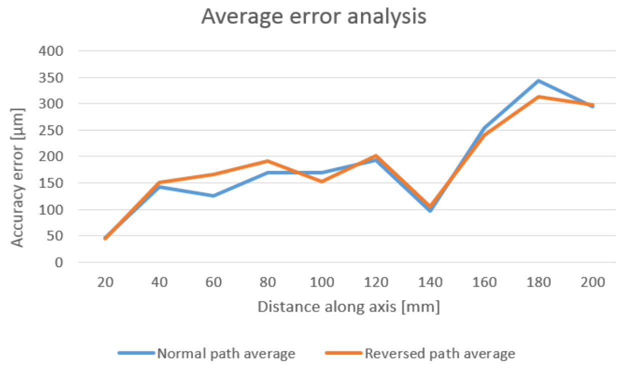

Fig. 12. Comparison between median values of normal path and the median values of reversed path errors.

Also, the comparison of the median values of the normal path errors and the median values of the reversed path errors shows that, at the start of each trajectory direction, the corresponding points errors are lower than the same points analyzed for the other direction – in other words, closer to the reference point the errors corresponding to the normal trajectory points have lower values, and in the opposite direction the errors corresponding to the reversed trajectory points have lower values. This is also an argument that shows a cumulating of errors for each trajectory segment, starting from the first point of the path and generating lower accuracy levels as the robot moves further. By linking this data to previous experimental results, it can be concluded that, for better accuracy results, a more precise calibration of the robot is needed.

REFERENCES

[1] H.N. Nguyen, J. Zhou, H.J. Kang, *A New Full Pose Measurement Method for Robot Calibration),* Sensors. Vol. 13, No. 7, 2013, pp. 9132–9147.

[2] A. Nicolescu, *Roboti Industriali*, EDP, Bucharest, 2005.

[3] `https://robotics.kawasaki.com`, accessed: 2017-06-23.

[4] Renishaw, `http://www.renishaw.com/` , accessed: 2017-03-15.

[5] A. Ivan, *Research regarding optimization of industrial robots for machining applications,* PhD Thesis, University "Politehnica" of Bucharest, 2011.