Volumetric accuracy experimental evaluation and 3D error map generation for a Kawasaki FS 10 E articulated arm industrial robot

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Abstract: - An experimental approach for determining the absolute accuracy of articulated-arm robots with low-to-medium payloads is described in this paper. The accuracy was measured for both positioning performance and trajectory generation of an industrial robot. The research was made using an experimental setup which includes a Kawasaki FS10E articulated-arm industrial robot with 10 kg payload together with a Dynalog CompuGauge system capable of measuring static, kinematic and dynamic performance of spatial mechanisms. The experimental setup was first used to describe the positioning accuracy of the industrial robot using a number of 50 measurement points evenly distributed around a cube-shaped volume which forms the nucleus of the robot's workspace. Based on the experimental results, an error map was built inside the analyzed cube-shaped volume, which can be used to closely estimate the accuracy of the industrial robot in certain areas of the workspace. In the second experimental stage, the same equipment was used to determine the precision and repeatability of circular and rectangular trajectories generated by the industrial robot, the results being analyzed using Dynalog system software. Together, the results obtained from both experiments show the volumetric accuracy of the analyzed industrial robot.

Key-Words: - Industrial Robot, Volumetric Accuracy, positioning error, error map, trajectory accuracy, trajectory repeatability

1 Introduction

Although various measurements have been made in order to determine the positioning and trajectory precision of industrial robots, none has gone far enough to obtain an absolute value regarding this parameter – a value that indicates the total displacement between the absolute position / trajectory coordinates expressed with respect to a fixed global coordinate system and the actual position / trajectory coordinates obtained by the industrial robot [1]. In order to fulfill this gap in industrial robots research field, an experimental setup for determining the absolute volumetric accuracy of articulated-arm robots has been developed.

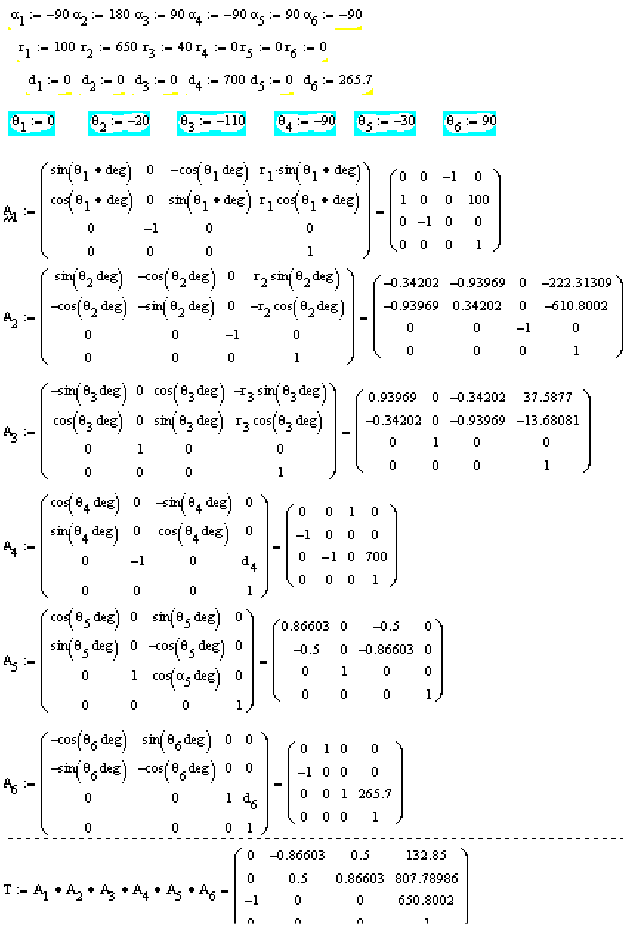
2 The experimental setup

2.1. The industrial robot

The industrial robot used for the research project was a Kawasaki manufactured FS10E model with six numerically controlled axes, 10 kg payload and a repeatability of ±0.1 mm. The robotic system is illustrated in Fig. 1.

Fig. 1. The Kawasaki FS10E industrial robotic system

In order to have a set of control parameters which can be used to validate the statistic calculation of volumetric precision, the direct kinematic model of the robot has been developed [2]. The model algorithm is illustrated in Fig. 2 [3].



$\alpha_1 := -90\ \alpha_2 := 180\ \alpha_3 := 90\ \alpha_4 := -90\ \alpha_5 := 90\ \alpha_6 := -90$

$r_1 := 100\ r_2 := 650\ r_3 := 40\ r_4 := 0\ r_5 := 0\ r_6 := 0$

$d_1 := 0\ \ d_2 := 0\ \ d_3 := 0\ \ d_4 := 700\ d_5 := 0\ \ d_6 := 265.7$

$\theta_1 := 0 \quad \theta_2 := -20 \quad \theta_3 := -110 \quad \theta_4 := -90 \quad \theta_5 := -30 \quad \theta_6 := 90$

$$A_1 := \begin{pmatrix} \sin(\theta_1 \cdot deg) & 0 & -\cos(\theta_1 deg) & r_1 \sin(\theta_1 \cdot deg) \\ \cos(\theta_1 \cdot deg) & 0 & \sin(\theta_1 \cdot deg) & r_1 \cos(\theta_1 \cdot deg) \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 100 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_2 := \begin{pmatrix} \sin(\theta_2 deg) & -\cos(\theta_2 deg) & 0 & r_2 \sin(\theta_2 deg) \\ -\cos(\theta_2 deg) & -\sin(\theta_2 deg) & 0 & -r_2 \cos(\theta_2 deg) \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} -0.34202 & -0.93969 & 0 & -222.31309 \\ -0.93969 & 0.34202 & 0 & -610.8002 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_3 := \begin{pmatrix} -\sin(\theta_3 deg) & 0 & \cos(\theta_3 deg) & -r_3 \sin(\theta_3 deg) \\ \cos(\theta_3 deg) & 0 & \sin(\theta_3 deg) & r_3 \cos(\theta_3 deg) \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0.93969 & 0 & -0.34202 & 37.5877 \\ -0.34202 & 0 & -0.93969 & -13.68081 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_4 := \begin{pmatrix} \cos(\theta_4 deg) & 0 & -\sin(\theta_4 deg) & 0 \\ \sin(\theta_4 deg) & 0 & \cos(\theta_4 deg) & 0 \\ 0 & -1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 700 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_5 := \begin{pmatrix} \cos(\theta_5 deg) & 0 & \sin(\theta_5 deg) & 0 \\ \sin(\theta_5 deg) & 0 & -\cos(\theta_5 deg) & 0 \\ 0 & 1 & \cos(\alpha_5 deg) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0.86603 & 0 & -0.5 & 0 \\ -0.5 & 0 & -0.86603 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_6 := \begin{pmatrix} -\cos(\theta_6 deg) & \sin(\theta_6 deg) & 0 & 0 \\ -\sin(\theta_6 deg) & -\cos(\theta_6 deg) & 0 & 0 \\ 0 & 0 & 1 & d_6 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 265.7 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$T := A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5 \cdot A_6 = \begin{pmatrix} 0 & -0.86603 & 0.5 & 132.85 \\ 0 & 0.5 & 0.86603 & 807.78986 \\ -1 & 0 & 0 & 650.8002 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Fig. 2. Kawasaki FS10E direct kinematic model

2.2. The Dynalog CompuGauge system

Dynalog CompuGage is a system that can be used to measure, view and analyse positioning accuracy / repeatability, as well as cinematic and dynamic performances of industrial robots and spatial mechanisms. The system, was used to determine TCP position and trajectory coordinates in real-time during the experimental applications.

The Dynalog CompuGauge uses two measuring beams and a special robot end-effector. At the end of each beam, an extensible wire with an optical sensor is attached (for a total of four wires). Attached to the robot, the special end-effector is used to connect the measuring wires to the robot and to define the TCP. As the robot moves, each of the four wires expands or collapses. The optical sensors measure the displacement of each wire, and a computer-based program triangulates TCP position. A measuring setup using Dynalog CompuGauge System is illustrated in Fig. 3 and in Fig. 4, the components of Dynalog CompuGauge system are illustrated. It also must be taken into consideration that Dynalog CompuGauge system repeatability has a value of 0.02 mm, which is far less than Kawasaki robot repeatability of 0.1 mm.

For the purpose of the experiment, the following specifications for the Dynalog CompuGauge system must be taken into account (as shown in Table 1).

Fig. 3. A measuring setup using Dynalog CompuGauge System

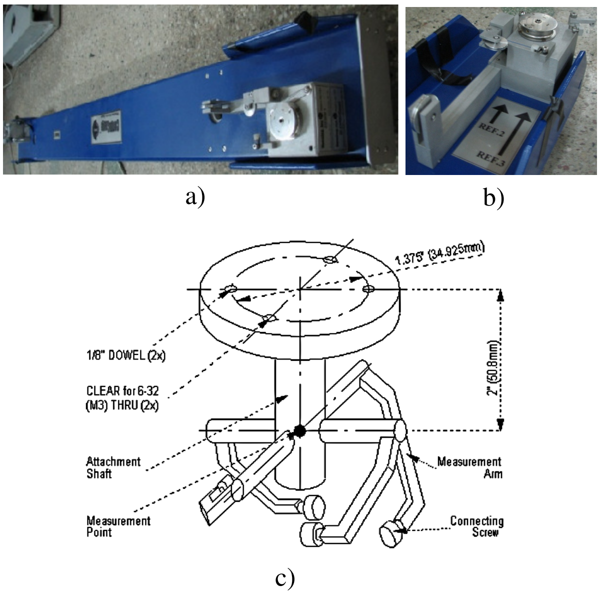


Fig. 4. Dynalog CompuGauge system elements: a) measuring beam; b) an extensible measuring wire attached to the end of a beam; c) the special end-effector

Resolution	0.01 mm
Repeatability	0.02 mm
Accuracy	±0.15 mm
Measurement space	1500x1500x1500 mm
Tracking rate	up to 5 m/s
Sampling frequency	25-100 Hz
Data range	up to 32000 points/file
Measurement time	up to 10 min.

Table 1. Dynalog CompuGauge specifications

3 The experimental procedure

In order to obtain data regarding volumetric accuracy of Kawasaki industrial robot, the distribution in the robot's workspace and the number of measurement points must be established [4]. For this purpose, both Dynalog CompuGauge system measurement space and Kawasaki industrial robot workspace must be taken into account [5].

For Kawasaki industrial robot, the workspace configuration and dimensions are shown in Fig. 5. For Dynalog CompuGauge system, the measurement space is a cube with a dimension of 1500 mm.

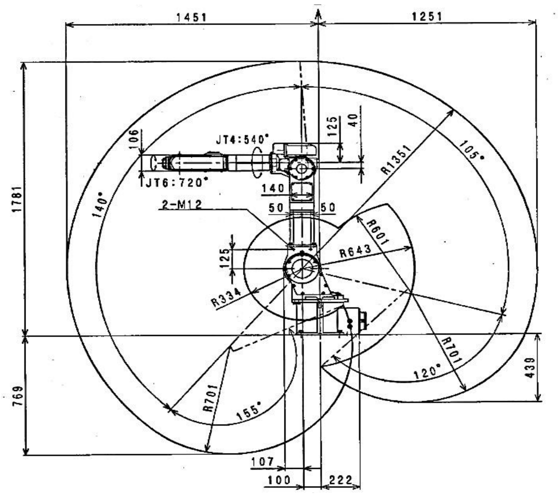


Fig. 5. Kawasaki industrial robot workspace

For the first part of the experiment, based on both above specified workspaces, and also taking into account that, in order to generate a significant change in robot arm configuration, the optimal distance between measurement points, in this case (also considering ISO 9283 and ANS/RIA R15.05 standards), is 150 mm [6], the measurement points have been evenly distributed on the edges of an imaginary cube-shaped volume with the dimension of 600 mm, placed in the centre of robot's workspace (the measurement cube, shown in Fig. 6). This algorithm generates 44 measurement points.

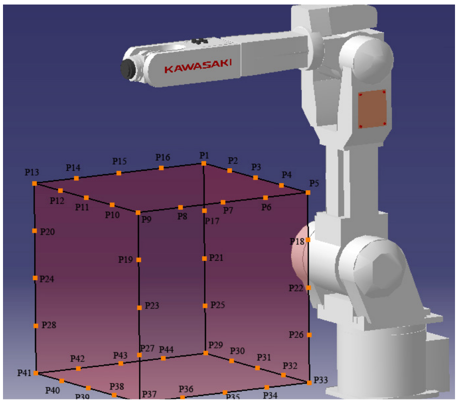


Fig. 6. The measurement cube and the measurement points used for the experimental procedure

To collect the experimental data, the robot was programmed to reach each of the measurement points in sequence. After reaching each experimental point, the program brings the robot back to the "home" position (the configuration shown in Fig. 6). Thus, the "home" position being reached multiple times, it can be used to determine the absolute repeatability of the industrial robot. Using the data obtained from the measurement points, the absolute accuracy of the industrial robot can be calculated. Thus, the following data must be obtained for each measurement point:

- the nominal coordinates of the point;
- the coordinates measured by the Dynalog CompuGauge system;
- the coordinates of the point as shown by the robot's teach-pendant, as well as the parameter of each numerically controlled axis;
- the values obtained by using the NC axes coordinates from the teach-pendant as input data in the direct geometrical model of the industrial robot.

Following the above specified principles, the experimental data for the first part of the experiment was collected. In order to illustrate how these parameters were organized, the experimental data for the first 5 measurement points are illustrated in Table 2. An example for the measuring process for one point is shown in Fig. 7.

As previously specified, the absolute repeatability of the industrial robot is also determined in the first part of the experiment by instructing the robot to return to the "home" position after each measurement point. The experimental data collected for this repeatedly reached point is shown in Table 3.

For the second part of the experiment, it was taken into account that, speaking from a cinematic and trajectory interpolation point of view, the linear and circular trajectory segments are the most difficult to generate, due to the fact that the robot must combine the movement of most of it's numerically controlled axes, making this type of paths are the most error-prone [7]. Thus, the robot was programmed to execute two rectangular trajectories (one in a horizontal plane and one in a vertical plane) and two circular trajectories (also one in a horizontal plane and one in a vertical plane), as shown in Fig. 8. For these basic trajectories, the data for the second part of the experiment was collected using the same setup as in the first case. The results shown by the Dynalog CompuGauge software, based on the values collected by the measurement system, is shown in Fig. 9 (the red path is the nominal programmed trajectory, and the green path is the real trajectory described by the robot).

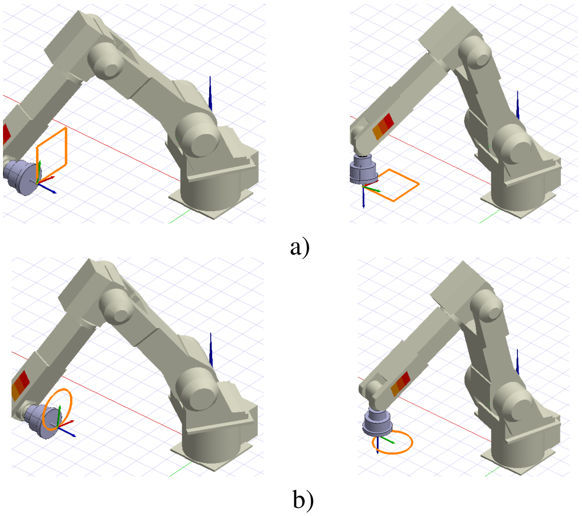
Fig. 7. The measuring process for P1*, P37*, P 41* and P 33* points with Dynalog CompuGauge system and software application

4 Conclusion

For the first part of the experiment, the data was processed by comparing the nominal, teach-pendant and measured sets of coordinates for each point. The coordinates obtained from the direct kinematic model were used as control values, in order to ensure an appropriate statistic calculation [8]. Thus, the following main conclusions can be drawn:

- the total medium displacement between the nominal coordinates and the real coordinates reached by the industrial robot is 1.681 mm. This displacement represents the absolute accuracy of the industrial robot;
- the medium displacement between the teach-pendant coordinates and the nominal coordinates is 0.05 mm. This displacement represents the measurement errors of the position encoders attached to each NC axis;
- the medium displacement between the teach-pendant coordinates and the measured coordinates is 1.678 mm. This displacement represents the errors from the cinematic chain of the industrial robot that accumulates at TCP level.

From the above values, it can be observed, regarding the accuracy of the industrial robot, that elastic displacement of the cinematic joints, the components tolerances and the positioning errors that accumulates at TCP level are the main error-generating factors for serial-linked articulated-arm robots [9]. Also, by graphically interpreting the data for all measurement points, a set of error maps can be drawn, dividing the measurement cube, first in precision planes, as shown in Fig. 10, and finally, in precision volumes, as shown in Fig. 11 [10].



a)

b)

Fig. 8. The four paths programmed for trajectory accuracy and repeatability measurement: a) rectangular trajectories; b) circular trajectories

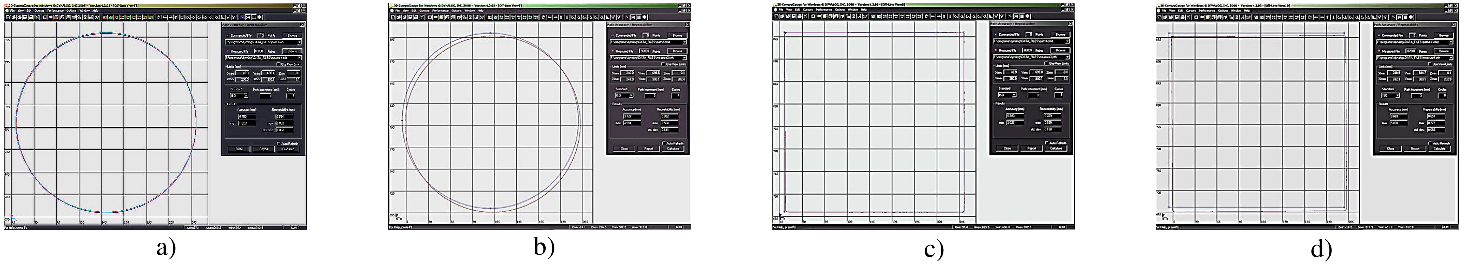

a) b) c) d)

Fig. 9. The experimental results for measuring the trajectory accuracy and repeatability: a) circular trajectory in horizontal plane; b) circular trajectory in vertical plane; c) rectangular trajectory in horizontal plane; d) rectangular trajectory in vertical plane;

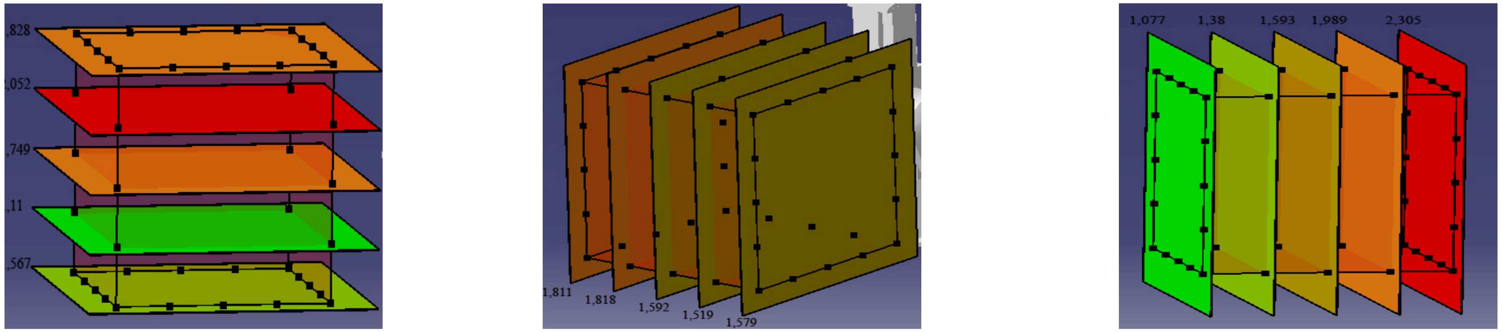


Fig. 10. The measurement cube divided into precision planes (the precision level is shown next to each plane)

	Nominal coordinates			Teach-pendant coordinates			Measured coordinates			Coordonates obtained from the direct kinematic model		
	x0 [mm]	y0 [mm]	z0 [mm]	xtp [mm]	ytp [mm]	ztp [mm]	xm [mm]	ym [mm]	zm [mm]	xg [mm]	yg [mm]	zg [mm]
P1	300.000	440.000	300.000	300.014	439.976	299.978	301.393	437.207	300.828	299.998	440.012	300.016
P2	150.000	440.000	300.000	149.999	439.994	299.900	152.364	437.934	300.464	149.998	440.011	300.002
P3	0.000	440.000	300.000	-0.003	439.992	299.945	2.967	439.467	300.181	0.008	440.002	299.948
P4	-150.000	440.000	300.000	-149.984	439.999	300.017	-147.213	441.069	299.670	-149.999	440.016	299.995
P5	-300.000	440.000	300.000	-300.001	439.949	299.929	-298.060	442.111	299.151	-300.000	440.018	300.009

Table 2. Experimental data for the first 5 measurement points

	Nominal coordinates			Teach-pendant coordinates			Measured coordinates		
	x_0 [mm]	y_0 [mm]	z_0[mm]	x_{tp} [mm]	y_{tp} [mm]	z_{tp} [mm]	x_m [mm]	y_m [mm]	z_m [mm]
Pi1	0	800	424.3	-0.05	800.002	424.284	0.667	799.912	424.297
Pi2	0	800	424.3	-0.012	799.999	424.284	0.649	799.938	424.31
Pi3	0	800	424.3	-0.015	799.998	424.288	0.65	799.927	424.315
Pi4	0	800	424.3	-0.002	799.999	424.292	0.644	799.933	424.312
Pi5	0	800	424.3	-0.007	800	424.288	0.618	799.92	424.324

Table 3. Experimental data for robot’s first 5 passes through “home” position

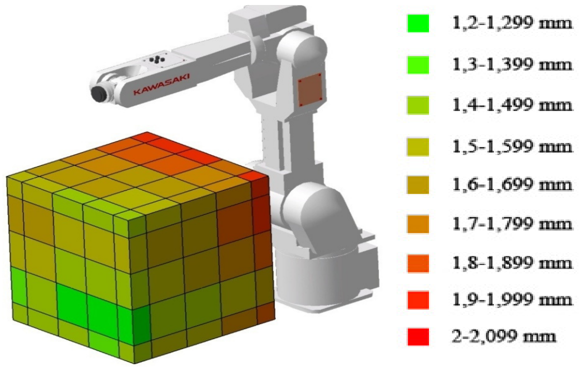


Fig. 11. The measurement cube divided into precision volumes

Observing the measurement cube divided into precision volumes, as shown in Fig. 11, it can be observed that, in the lowest precision zones the lowest accuracy level is 2.1 mm, while in the highest precision zones, the highest accuracy level is 1.2 mm.

Regarding the measurement of the industrial robot repeatability, this was calculated by determining the radius of the sphere that contains all the real points reached by the industrial robot when returning to the “home” position. Thus, using the measurement data obtained from Dynalog CompuGauge system, the repeatability of the industrial robot was calculated at a value of 0.123 mm, which is close to the value indicated by Kawasaki of 0.1 mm.

For the second part of the experiment, regarding trajectory accuracy and repeatability, the following conclusions were drawn based on the data obtained from Dynalog CompuGauge system:

- for the horizontal plane circular path, the medium accuracy is 0.76 mm and the medium repeatability is 0.024 mm;
- for the vertical plane circular path, the medium accuracy is 3.126 mm and the medium repeatability is 0.052 mm;
- for the horizontal plane rectangular path, the medium accuracy is 0.843 mm and the medium repeatability is 0.029 mm;
- for the vertical plane rectangular path, the medium accuracy is 3.683 mm and the medium repeatability is 0.051 mm.

These experimental results show a trajectory accuracy for the vertical planes several times lower than for the horizontal planes. This fact leads to the conclusion that, when it is possible, choosing a trajectory generated in horizontal plane is desirable over choosing a trajectory generated in a vertical plane, in order to obtain a better accuracy. This concept can be used in applications such as machining or arc welding, where a workpiece positioner allows for part orientation (especially through a pitch movement). Also, there is a slight better precision for circular trajectories due to corner errors in the case of rectangular trajectories.

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