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Application of the FARO laser tracker to the study of selected functional characteristics of a Kawasaki ZD130 industrial robot

Abstract

The paper presents the test results of the following functional characteristics of a Kawasaki ZD130 industrial robot: the accuracy and repeatability of unidirectional positioning, the variance of multidirectional positioning and the accuracy and repeatability of distance. The influence of the speed of movement and load on the values of aforementioned functional characteristics was also examined. Measurements were made with the FARO Laser Tracker Vantage coordinate measuring machine. The research was conducted in accordance with the PN-EN ISO 9283:2003 standard.

Keywords: industrial robots, laser tracker, accuracy, precision.

1. Introduction

Industrial robots constitute a group of devices that automatically perform human manipulative and locomotive activities [1]. They are able to execute programmable movements around multiple axes of rotation. They are used in industry.

Each industrial robot undergoes a quality and accuracy check before being operated in its target workplace. The accuracy of an industrial robot is determined by its functional characteristics [2], the most important of which are the accuracy and repeatability of reaching a position.

Guidelines for testing the accuracy of robots are described by the PN-EN ISO 9283: 2003 standard [3]. Different measuring methods are used for calibration and positioning of these devices [5, 6]. Coordinate measuring machines (CMM) are most frequently used for this purpose [7, 8].

This paper presents the results of an industrial robot accuracy test using a laser tracker. A laser tracker is a tool that enables collection of large data sets in short time and with a sufficiently high accuracy [8, 9]. Among companies that currently produce such equipment the largest are: American FARO, whose product was used in the presented research, and Hexagon Metrology - a part of the Hexagon Group, which also includes Leica Geosystems AG, a Swiss company recognized as a producer of measuring devices.

2. KAWASAKI ZD130 industrial robot

The object of the study was the Kawasaki ZD130 palletizing robot. The device is a part of Z-series robots characterized by a large load capacity. The maximum load for the unit in question is 130 kg.

The robot has 4 axes of rotation, its weight is 1350 kg, and its maximum range is 3255 mm. The repeatability of position declared by the manufacturer is ±0.5 mm [10]. The device highest efficiency is: 1800 cycles per hour with a load of 60 kg or 1,500 cycles per hour at the maximum load (with translocations of 2000 mm in the horizontal plane and 400 mm vertically above the position of collection and placement). Kawasaki ZD130 can operate at temperatures ranging from 0° to 45°C at a relative humidity of 35% to 85% (no dew or frost). The device can be mounted on the floor or on a shelf.

3. FARO laser tracker

A laser tracker is an accurate coordinate measuring machine. The most crucial applications, among many available, are: controlling precisely made prefabricates as well as tools and machine components, testing appropriate production line settings, instrument calibration and reverse engineering with the possibility of acquiring real time corrections to the nominal values [11].

The device is composed of two parts: a laser beam generator with external influence compensating element, and a tracking head. In the course of a measurement, the positions of points being measured are indicated by a spherically mounted retroreflector (SMR), which is constantly monitored by the instrument. The position of the observed marker is presented by the laser tracker in real time.

Two methods of distance measurement are used in such devices. The first is based on an interferometric measurement, while the other on the absolute distance measurement. The device used during the present test (FARO laser tracker) utilizes an innovative measurement solution based on predictive algorithms that compensate for the acceleration and speed of a moving object (without using the interferometer) [11].

In order to obtain high-quality results, which later will enable the construction of a correct object model or a valid analysis of the device positioning accuracy, SMRs have to be placed in points which are distinctive for the observed element. A laser tracker measurement can be made with the SMR held in hand and put to the object in an appropriate place, or by mounting it in a target holder, which has already been fixed to the object by magnets or bolted to it.

When using a target holder, it is possible to return to the previously measured locations, which is useful when - for instance - testing the repeatability of programmed movements of the observed device. The fact that SMRs are made of unbreakable glass is quite important for observations performed in workplaces of other devices. There are however some differences in the size of targets and the measurement accuracy achievable using different reflectors [11].

4. Description of measurements

All measurements were taken at the Krakow headquarters of Astor Sp. z o.o. company. The company specializes in distribution of industrial robots. There are several robots in the company's display hall, including the object of our research. In order to plan the measuring procedure and choose an optimal station of the tracking device, it was necessary to identify the location of the machines in the room before taking measurements. Additionally, the maximum dimensions of the measurement space, the appropriate speed of the robot, as well as the maximum volume of the load were determined.

When planning the measuring procedure the influence of various confounding factors on the accuracy of tracker measurement was analyzed. One of them were floor vibrations caused by the movement of the robot arm, which could be transmitted through the ground and tripod to a detector placed in the measuring device. However, a decision was made that the floor with expansion joints and the heavy tripod dedicated to the tracker would limit the possible influence of vibrations on the measuring device (Figure 1).

To achieve the measurement accuracy specified in the standard [3], constant monitoring of changes in temperature and humidity of the workspace was required. These measurements were made with a Comet D4130 thermo-hygro-barometer. The conditions in the hall at the time of the tests were stable. An independent temperature measurement was also taken by a sensor built into the laser tracker. Slight temperature changes were taken into account on an ongoing basis when entering corrections to the observations.

It was therefore concluded that the results of the measurements were not confounded by the conditions inside the hall.

Laser tracker measurements were taken from a freestation. The test began with calibration of the instrument. To this end, 17 points in the testing space were measured. Additionally, a measurement of a meter standard was made. This is a physically prepared portion of an invar tube with clear ends and targets holders in which the SMRs are mounted.

The robot which is the object of the research is used for palletization. Of all the available tests for palletizing robots (Table 1) three were selected and conducted. The tests enabled to determine: the accuracy and repeatability of positioning capabilities of the robot, the variability of accuracy achieved from multiple points and the deviation and repeatability of distance. The course of the paths and the number of measuring cycles were determined using the PN-EN ISO 9283: 2003 [3]. The paths followed by the robot were defined by spatial coordinates (X, Y, Z) of their distinctive points. For each planned robot position Euler angles (φ, ψ, θ), whose values had to be entered when programming the machine, were also established. Spatial coordinates were determined using the PN-EN ISO 9787: 1999 [4].

Fig. 1. Location of the tracker relative to the robot (by A. Cisińska)

Tab. 1. List of tests for palletizing robots

Functional characteristic	No. of cycles	Load test		Speed	
		Nominal load		Nominal speed	
		100%	10%	100%	50% or 10 %
positioning accuracy and repeatability	30	X	O	X	O
variability of accuracy achieved from multiple points	30	X	O	X	O
deviation and repeatability of distance	30	X	-	X	O
time to stabilize a position	3	X	O	X	O
position readjustment	3	X	O	X	O
positioning characteristcs drag	continuous cycles over 8 hours	X	-	X	-
minimal positioning time	3	X	O	X	optimized speed
compliance error	-	-	gradual load	-	-

X – necessary variant
O - optional variant

The studies were conducted using a load weighing about 40 kg, which was attached to the robot arm by a tightening belt and pressed directly to suction cups mounted on the robot wrist.

The first test, the purpose of which was to determine the accuracy and repeatability of positioning capabilities of the robot, was performed using an envelope-shaped path (Fig. 2). Three variants of the test were used: at 100% speed and 40% load, at 50% speed and 40% load, and at 100% speed and 8% load (no load).

The next step was the most complex test, in which the accuracy of achieving a position from a number of points was determined. That required designing a path for which the robot would reach a predetermined position from three mutually perpendicular directions. There was made an assumption that the approach towards extreme points would be held in line with the standards [3], i.e. from the inside to the outside. The test was carried out in three variants: at 100% speed and 40% load, at 50% speed and 40% load, and at 100% speed and 8% load.
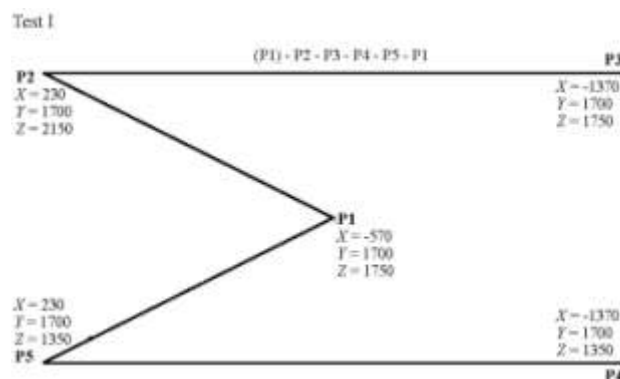

Fig. 2. The run path for test I

The form and idea behind the third of the tests were the simplest, as the path was a segment connecting two points: P_2 and P_4. Shorter segments of various lengths along the path were also measured. The test was carried out in two variants: at 100% speed and 40% load, and at 50% speed and 40% load. That test did not include runs of an unloaded robot. The measurements enabled determining the distance deviation and repeatability of distance covered by the robot.

All tests started from a known point, i.e. a point involved in the test, but later excluded from the calculation. The ordering of the tests was selected so as to minimize possible errors resulting from mounting the load. Therefore, all the tests with full load of the robot were performed first. 50 kg was assumed as the mass of full load, which represented about 40% of the maximum permissible load of the robot. The mass of the load consisted of the wrist weight - 10 kg, and the weight of cargo - 40 kg. In the following step, each test was performed without the load previously carried by the robot. In this instance, the robot remained loaded by the wrist, which was not dismantled and accounted for about 8% of the maximum load. However size and weight of the load differed from the values specified in the standards applied in research of accuracy of industrial robots [3]. Their values remained highest possible considering the conditions in which the study was conducted. The travel speed with which the robot moved along the programmed paths was set to 100% and 50% of the maximum nominal speed, which - when translated into a physical change of position in time - constituted 1 m/s and 0.5 m/s, respectively.

Additional tests were carried out in order to verify the stability of tracking and accuracy of determining the course of paths by the laser tracker during a fast SMR movement. The performed trials helped to establish the actual time needed to acquire data about the position retroreflector (along with the time to send the observations to a computer and process it by specialized software).

5. Results

Observational data obtained by a laser tracker consist of coordinates of robot positions reached in all of the performed tests. Following a check and ordering of the data, the data sets were divided into subsets corresponding to the performed tests. Erroneous observations were excluded, which facilitated the subsequent processing of the measurements. The results from 30 sets of measurements for each of the tests were averaged and lists of averaged coordinates of points were prepared and transformed to the robot's system from the tracker system. The abovementioned was achieved via isometric transformation. Therefore, the scale of the object, as well as the distances and angles between the transformed points were conserved after the transformation. The necessity of coordinate transformation resulted from the fact that industrial robot accuracy and repeatability tests should be carried out on the basis of nominal positions, whose coordinates are specified in the basic robot system [3].

Before determining the values of functional characteristics of the robot, the mean error of spatial positions of points whose coordinates were recorded by the laser tracker was calculated. The calculations were based on the calibration measurement results and the error amounted to $\sigma_P = \pm 0.040$ mm.

During the study of the accuracy and repeatability of positioning, the robot followed the path set between the following points: P_5-P_4-P_3-P_2-P_1 (Fig. 2). Figures 3 and 4 show the course of the tested path and the average position reached by the robot.
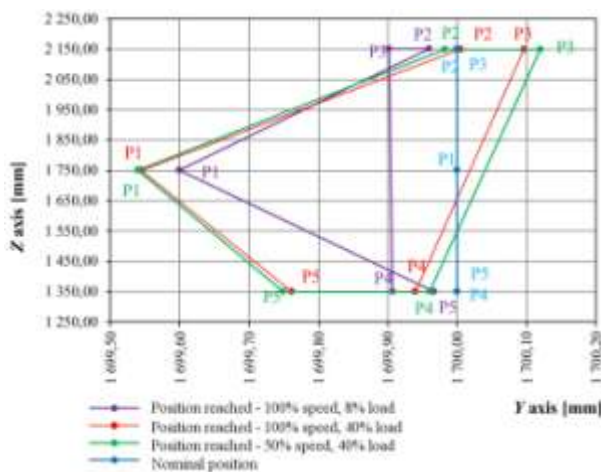

Fig. 3. The set and achieved paths during the test of industrial robot accuracy and repeatability of positioning, projected on the YZ plane
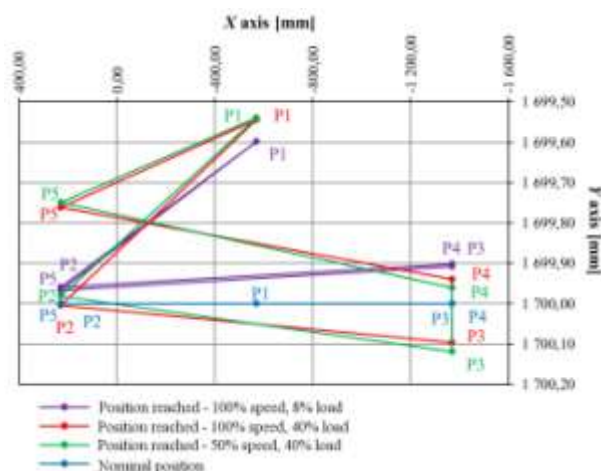

Fig. 4. The set and achieved paths during the test of industrial robot accuracy and repeatability of positioning, projected on the YZ plane

The scales of the axes shown in Figures 3 and 4 have been chosen to allow a comparison between the coordinates of five points reached by the robot in three different operating conditions. When performed at different operation speeds the runs are very similar, however changing the load modulates the path executed by the robot. In each test scenario, reaching the P_1 position deviates the most from the set-point. The smallest deviations were observed for the P_2 position.

Differences between the average coordinates reached by the robot and the theoretical coordinates were calculated for points P_1 - P_5. The results are summarized in Table 2. The highest deviations are seen in the direction of X-axis, and the lowest in the Y-axis direction (except for P_1). This is due to the assumption taken during the measurement, which stated that the movement of the robot was carried out in a vertical plane at a fixed Y-coordinate. The smallest deviation was recorded along the Z axis for P_1, which was set in the middle of the working plane.

A parameter describing the positioning accuracy of the machine (AP_P) was calculated for each point defining the pathway of the robot in the test, based on the previously determined deviations of the robot positions along the axes of the coordinate system (AP_x, AP_y i AP_z).

Tab. 2. Positioning accuracy relative to the axis of the robot coordinate system (X, Y, Z)

	Point	AP_x, mm	AP_y, mm	AP_z, mm	AP_p, mm
100% speed 40% load	P_1	0.314	−0.456	0.011	0.554
	P_2	−0.357	0.005	−0.247	0.434
	P_3	0.230	0.096	−0.213	0.328
	P_4	0.472	−0.060	0.266	0.545
	P_5	−0.366	−0.239	0.349	0.559
50% speed 40% load	P_1	0.313	−0.461	−0.020	0.557
	P_2	−0.017	−0.244	0.171	0.440
	P_3	0.171	0.120	−0.234	0.313
	P_4	0.469	−0.039	0.184	0.506
	P_5	−0.394	−0.251	0.343	0.579
100% speed 8% load	P_1	0.274	−0.401	0.001	0.486
	P_2	−0.270	−0.040	−0.187	0.331
	P_3	0.255	−0.098	−0.090	0.288
	P_4	0.298	−0.093	0.184	0.363
	P_5	−0.368	−0.034	0.162	0.404

Next, the repeatability of positioning of the robot was calculated. It is the parameter used to specify the accuracy of the tested device. The repeatability of positioning (RP_l) is defined as the value of a radius of a sphere with a center of gravity in the barycenter of points reached n times by the robot [2]. The value of this parameter - obtained during the tests - together with intermediate results (ie. l - distance between the position reached and the center of gravity of all the positions reached, and S_l - standard deviation of distance l) is presented in Table 3. The largest dispersion of measurements was seen for P_2, while P_4 had the highest precision. These results probably depend on the path used, because the approach towards P_4 was performed along the segments parallel to the robot axis, while P_2 was approached from P_1 along the diagonal of the working plane.

The variability of accuracy of positioning achieved from multiple points (vAP_P) is the maximum distance between the centers of gravity of a set of points achieved n times en route to the set-point, using three different paths [2]. The planned paths should be directed in parallel to the axis of the robot coordinate system. Table 4 summarizes the calculated vAP_P parameters for points P_1, P_2 and P_4. These are distances between the three different centers of gravity of a set of points reached for these positions.

Tab. 3. The results of positioning repeatability test

	Point	l, mm	S_l, mm	RP_l, mm
100% speed 40% load	P_1	0.040	0.021	0.103
	P_2	0.054	0.024	0.126
	P_3	0.051	0.022	0.117
	P_4	0.035	0.019	0.093
	P_5	0.039	0.021	0.103
50% speed 40% load	P_1	0.026	0.016	0.073
	P_2	0.030	0.017	0.081
	P_3	0.035	0.018	0.089
	P_4	0.029	0.014	0.071
	P_5	0.025	0.016	0.073
100% speed 8% load	P_1	0.034	0.018	0.088
	P_2	0.041	0.023	0.110
	P_3	0.037	0.018	0.092
	P_4	0.030	0.013	0.070
	P_5	0.034	0.018	0.088

The P4 is characterized by the lowest variability in positioning accuracy and it was located in the lower right corner of the working plane. The highest value of this parameter was seen for P2. This point was in the opposite corner of the test-plane.

Tab. 4. The variability of positioning accuracy achieved from many points

Point	vAP_P, mm		
	100% speed 40% load	50% speed 40% load	100% speed 8% load
P_1	0.061	0.106	0.063
P_2	0.064	0.068	0.118
P_4	0.047	0.059	0.078

The last of the functional characteristics determined in the tests was the deviation and repeatability of distance covered by the robot. For this purpose, the machine moved along the path set from P_2 to P_4. The actual distance covered by the robot was calculated on the basis of the obtained point. The differences between the length of the set and covered segment are shown in Figure 5. The chart also indicates the mean values of the differences in the distance covered at different speeds.
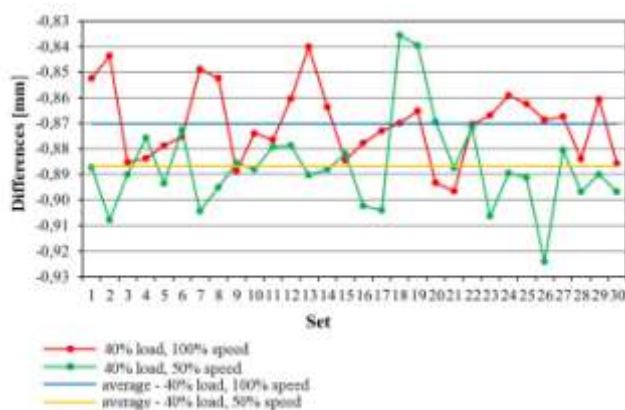

Fig. 5. Differences between the set distance and the distance achieved in the course of 30 trials

The distance positioning accuracy is defined as the deviation of a set segment from the mean of reached segments [2]. The analysis of the collected data shows that the highest deviation of distance is present in the *X*-axis direction, and the lowest in the direction of *Y* axis. It should be noted that the speed of robot movement had little effect on the accuracy of distance positioning.

For the robot in question the value of this parameter amounted to: $AD_P = -0.89$ mm.

The repeatability of the distance determines the degree of correspondence between distances achieved for the same predetermined distance repeated n times in the same direction. For the analyzed P_2-P_4 segment this parameter was calculated based on the sum of the squares of the differences between the distances covered and their mean values. The test results allow concluding that the movement speed of the robot does not affect the repeatability of distance, as this parameter reached $RD = 0.043$ mm.

While testing the accuracy and repeatability of distance, in addition to measuring the P_2-P_4 segment, a measurement of shorter segments of different lengths was also made. It was found that the measured vectors differed from theoretical vectors, both in terms of positioning and orientation. With increasing length of a segment, deviations of the measured lengths from the designed lengths increased. For the shortest segments the accuracy amounted to -0.03 mm, while for the longest ones it reached -0.60 mm. The obtained values of this parameter are lower than the accuracy of the distance for the P_2-P_4 segment. This is due to the fact that the analyzed segments were shorter than the P_2-P_4 segment.

6. Conclusions

The use of coordinate metrology to determine the functional characteristics of industrial robots is justified. The use of the FARO Laser Tracker Vantage coordinate measuring machine enabled determining the measurement error of the spatial position of points which was ±0.04 mm.

The worst positioning accuracy of the tested robot was 0.58 mm and the repeatability reached 0.13 mm. This is a satisfactory result, given that the manufacturer's technical specification of the device states that the positioning repeatability of the tested robot is ±0.50 mm.

The calculations showed that, for the Kawasaki ZD130 robot, the variability of accuracy for reaching a position from different directions does not exceed 0.12 mm. The tested robot completed the set distance with the error of -0.89 mm, which might indicate a scale error in the device.

During the tests the palletizing robot completed the programmed paths at speeds of 1m/s and 0.5 m/s, with a load of 50 kg and 10 kg. Based on the calculation results, it can be concluded that the load influences the positioning accuracy more significantly than the speed of movement. The higher the load, the bigger the robot positioning error.

The tested unit was a training robot used for presentations over a span of about a year, which may have contributed to the high accuracy and repeatability values.

The main advantage of using a laser tracker was maximum increase in measurement automation, which in turn reduced the amount of possible errors occurring during processing of observations. During the collection of measurement data, it was possible to visualize the measured points in dedicated software. The test design also allowed checking whether the laser tracker was useful for measurements of devices in motion. Based on the study one can state that it is possible to conduct position measurement tests under certain conditions (4 second stops of the machine). This measurement technology is not capable of determining such parameters as: time needed to reach a position and time to stabilize a position.

It should be emphasized that the measurement took place in a different working environment than that typical for both the tracker and the robot. Normally, these devices operate in industrial buildings with fairly high air pollution, smoke or dust concentration, and during the operation of other machines and humans. In this case only one robot was used at a time and the number of people in the surroundings was limited to a minimum.

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