Advanced Logistic Systems Vol. 9, No. 1 (2015) pp. 69–76.

ACCURACY MEASUREMENTS OF INDUSTRIAL ROBOTS

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Abstract: The robots are frequently used in logistic problems and the increasing quality requirements of the production can be fulfilled only by high positioning accuracy. In this paper we analyse a KUKA KR 15/2 and a Fanuc LR Mate 200iC robot, which are measured by laser interferometer Renishaw XL-80. Both robots are six DOF, articulated manipulator (RRR), and their descriptions of Denavit-Hartenberg parameters are very similar. The measurement are restricted on relatively small working area, i.e., $\pm 50mm$ displacement in X and Y directions. The goal of the measurements is to determining the positioning accuracy and it repetition. In addition to the measurement analytic formulae are given by help of Denavit-Hartenberg parameters. This gives the possibility to compare to joint angles obtained by theoretical formulae and given by controller.
Keywords: *robot, simulation, measurement, inverse kinematics, Denavit-Hartenberg parameters*

1. INTRODUCTION

The robots are frequently used in logistic problems [1], [2]. The increasing quality requirements of the production can be fulfilled only by high positioning accuracy.

The authors of this paper have the possibility to access to two industrial robots, one of them is a 20 years old KUKA KR 15/2 robot and the other one is a 5 years old Fanuc LR Mate 200iC robot. Before their application to machining, it is advisable to check the accuracy of positioning. The laser interferometer provides high accuracy measurements, this method was also used in [3]. The method is well applicable for measurements along straight line motions.

In Section 2 the kinematical description with the Denavit-Hartenberg (DH) parameters and the inverse kinematics are summarized for the two industrial robots [4]–[6]. Measurements with laser measurement system are detailed and demonstrated in Section 3 [7], [8]. Similar series of measurements are performed on the industrial robots, to evaluate repetition accuracy. Some concluding remarks are summarized in Section 4.

2. KINEMATICAL DESCRIPTION OF THE ROBOTS

The DH parameters are well applicable to describe articulated manipulators. The DH parameters are defined as follows:

- a_k is the distance between the axis z_{k-1} and z_k, and is measured along the axis x_k
- α_k is the angle between the axis z_{k-1} and z_k
- θ_k is the angle from x_{k-1} to x_k in a plane normal to z_{k-1}
- s_k is the distance from origin o_{k-1} to the intersection of the x_k axis with z_{k-1} measured along the z_{k-1} axis

The robots, i.e., KUKA KR 15/2 and Fanuc LR Mate 200iC are shown in Figure 1a and Figure 1b, respectively, and the DH parameters are listed in Table I based on [4] and [5].

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Table I

DH parameters of robots Fanuc LRMate 200iC and KUKA KR 15/2

Parameters / Joints	a_k [mm]		α_k [°]		θ_k [°]		s_k [mm]	
	Fanuc	KUKA	Fanuc	KUKA	Fanuc	KUKA	Fanuc	KUKA
J1	75	300	+90°	+90°	0°	0°	330	675
J2	300	650	0°	0°	+90°	+180°	0	0
J3	75	155	+90°	+90°	0°	0°	0	0
J4	0	0	–90°	–90°	0°	0°	320	600
J5	0	0	+90°	+90°	0°	0°	0	0
J6	0	0	0°	0°	0°	0°	140	140

(a) *(b)*

Figure 1. Coordinate systems of (a) KUKA robot and (b) Fanuc robot

The aim of the inverse kinematics of the robots is to determine the accurate values of the joint angles (θ_k) in measured points along prescribed straight lines. It is supposed that the orientation and path of the end effector are given. The six DOF robot are provided by six joints. The angles of the first 3 joints give the position (x_c, y_c, z_c) of the end effector, while the other 3 angles of the joints determine orientation of the end effector. The angle θ_1 can be obtained by the help of x_c and y_c positions. The joint angle θ_2 and θ_3 can be also obtained from simple trigonometry [6] using cosine theorem. Joint angles θ_4, θ_5 and θ_6 can be obtained using transformation matrix given by Euler angles assuming downward vertical orientation of the end effector as shown in Figure 1b. The derived formulae are listed in Table II.

Table II

Formulae of the angles to robots

Angle	**Formulae**
θ_1	$\text{arctan2}\ (y_c, x_c)$
θ_2	$\theta_2 = \arctan 2\left(z_c - s_1, \sqrt{x_c^2 + y_c^2} - a_1\right) - - \arctan 2\left(\sqrt{s_4^2 + a_3^2} \cdot \sin(\theta_{30}), a_2 + \sqrt{s_4^2 + a_3^2} \cdot \cos(\theta_{30})\right)$
θ_3	$\theta_3 = \arctan 2\left(\pm\sqrt{1 - D^2}, D\right) - \arctan 2(a_3, s_4)$, where $D = \frac{cc^2 - a_2^2 - \left(\sqrt{s_4^2 + a_3^2}\right)^2}{2 \cdot a_2 \cdot \sqrt{s_4^2 + a_3^2} \cdot \cos(180° - \theta_{30})}$
θ_4	$\theta_4 = 0$
θ_5	$\theta_5 = \theta_2 + \theta_3$
θ_6	$\theta_6 = \theta_1$

3. MEASUREMENT OF THE POSITIONING

Figure 2 shows the layout of the linear measurement, where the table, the linear reflector, the linear interferometer with linear reflector and the laser head are illustrated [7]. The linear reflector is moved by the end effector, while the interferometer and laser head are in a static positions. The resolution of the system is 0.001μm [8].

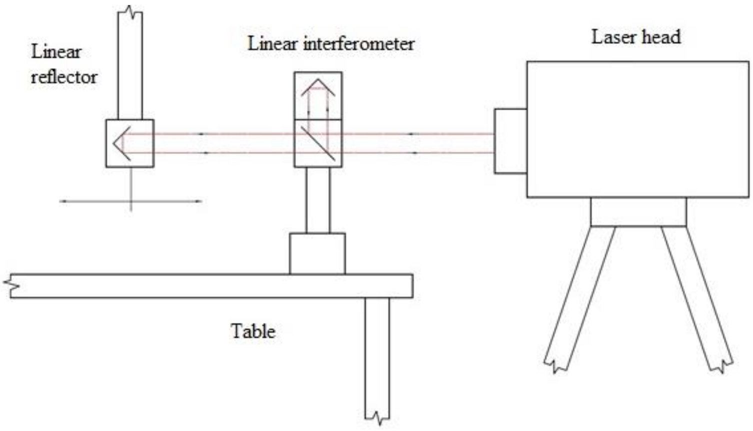


Figure 2. Linear measurement

Due to technical reasons during the measurement the end effector of the KUKA robot is kept in horizontal direction, while in case of Fanuc robot the end effector is kept in vertical direction (see Figure 1). The joint angles of the robots in the starting position are displayed also on Teaching Box (Figure 3).

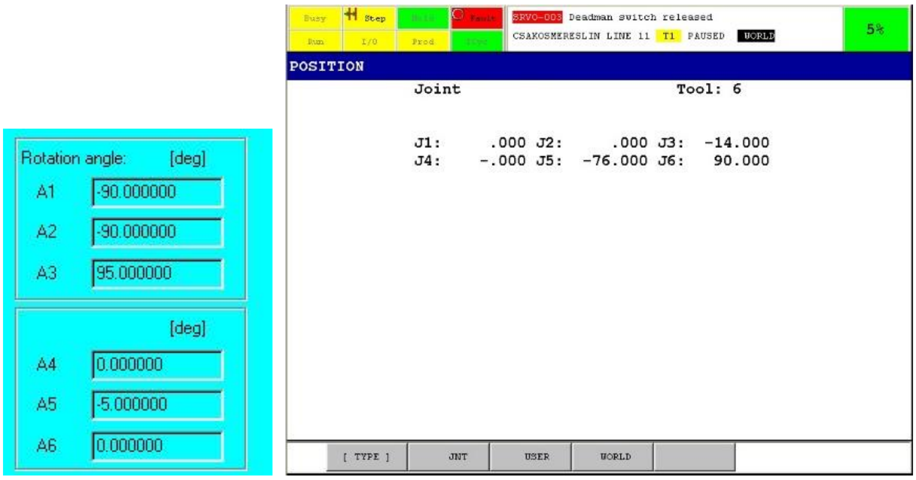
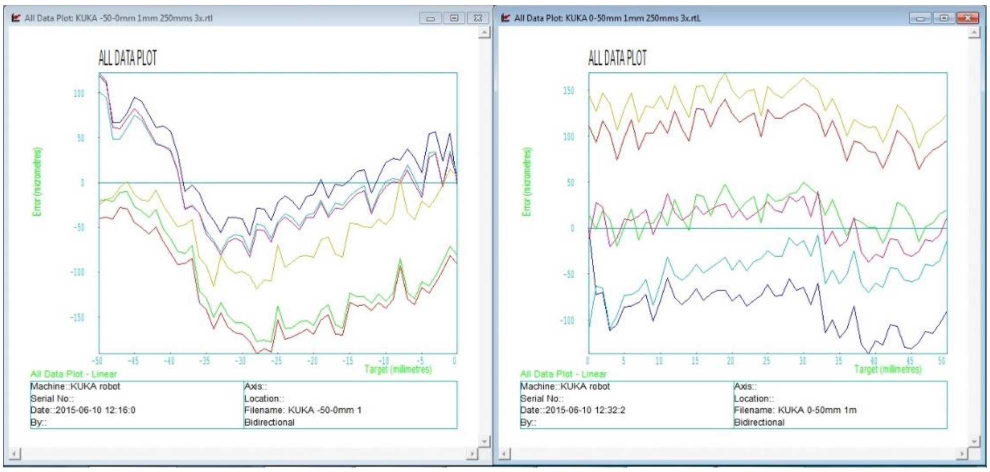


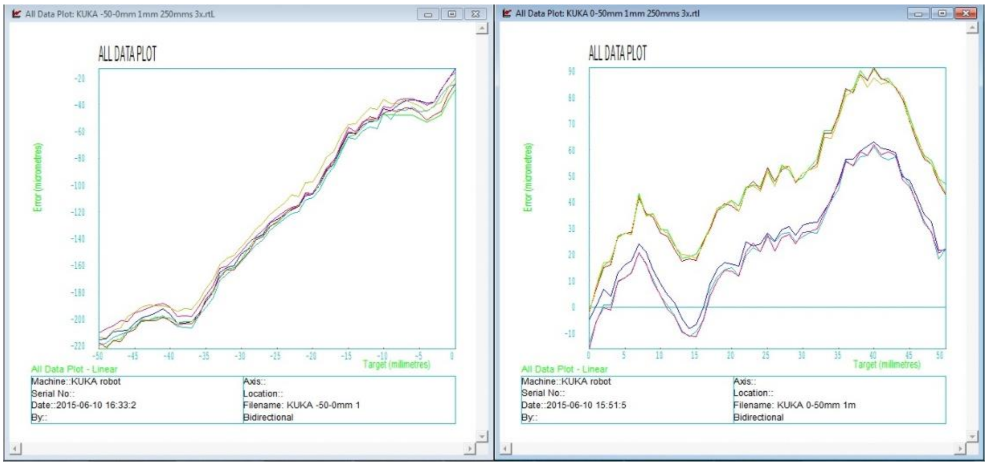
Figure 3. Starting joint angles of robots KUKA KR 15/2 and Fanuc LR Mate 200iC

During the measurements of the robots the end effectors are moved horizontally firstly along X direction thrice then secondly along Y direction thrice with ± 50mm from the starting positions. In both cases the distance steps are 1mm and the velocity of the motions was prescribed to $250\frac{mm}{s}$. The positions have been measured by laser head. The errors of the KUKA robot are shown in Figure 4 and Figure 5 in X and Y directions, and for the motions of Fanuc robot the errors are illustrated in Figure 6 and Figure 7 in X and Y directions, respectively. Diagrams (a) and (b) of Figure 4–7 give the measurements in negative and in positive directions, respectively. In order to evaluate the errors in positioning each curve should be considered relative from the value obtained in a starting zero position.



a) b)

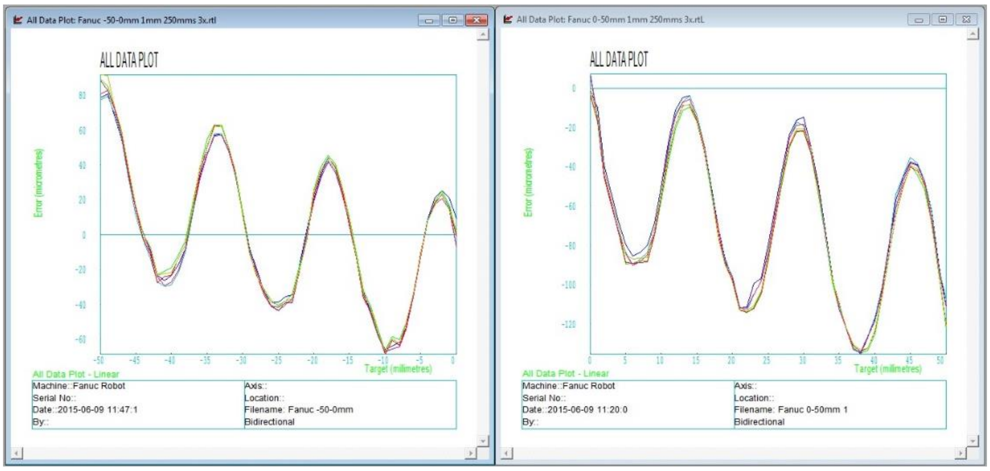
Figure 4. Positioning errors (a) in negative X direction, (b) in positive X direction of the KUKA robot



a) b)

Figure 5. Positioning errors (a) in negative Y direction (b) in positive Y direction of the KUKA robot

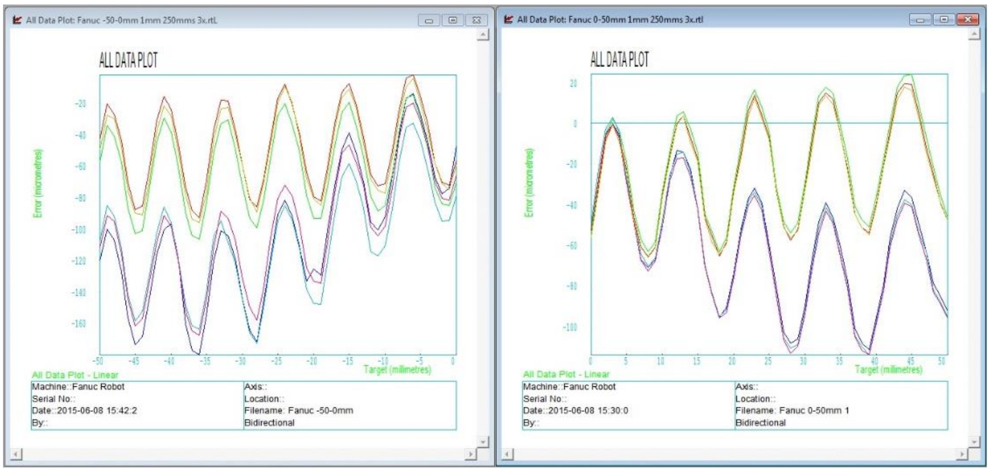
One can see that the relative positioning errors are similar in the repeated measurements. In case of KUKA robot the curves show random tendencies, while in case of Fanuc robot the curves show almost harmonic oscillations. The maximum relative errors of the KUKA robot are ±120μm in X directions and –220μm, +90μm in Y directions. Somewhat smaller maximum relative errors have been detected for the Fanuc robot, i.e., +90μm, –130μm in X directions and –120μm, +70μm.



a) b)

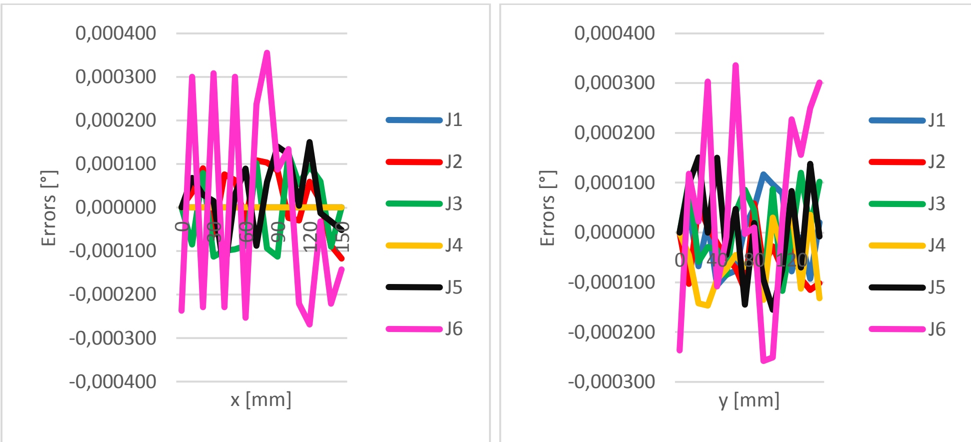
Figure 6. Positioning errors (a) in negative X direction, (b) in positive X direction of the Fanuc robot

In order to investigate the sources of the positioning errors, the theoretical values of the joint angles (see Table II) are compared to the data provided by teaching boxes of the robots. The discrepancies of the two values are shown in Figure 8 and Figure 9 for the KUKA and Fanuc robots, respectively. The data of joint angles are given with six decimal precision by the controller of KUKA robot and three decimal precision by Fanuc robot. Results show that the errors in angles are practically negligible and it may cause errors in positioning only a couple of µm.



a) b)

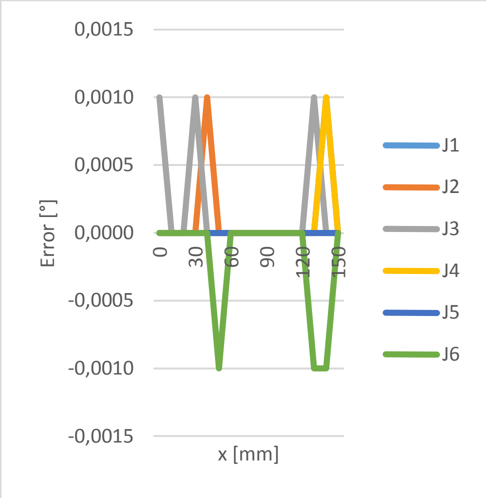
Figure 7. Positioning errors (a) in negative Y direction (b) in positive Y direction of the Fanuc robot



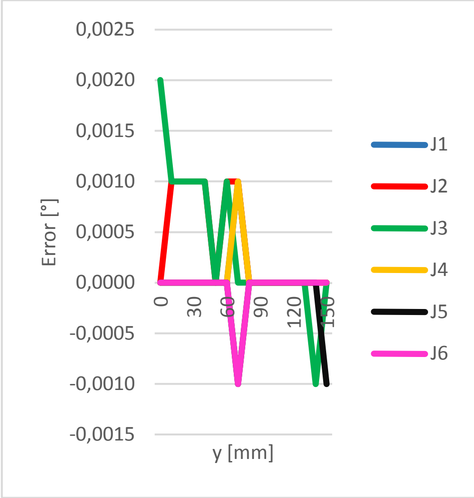
a) b)

Figure 8. Discrepancies in joint angles of KUKA robot comparing values provided by the controller and the theoretical formulae during the motions are (a) in X direction (b) in Y direction

It is likely that the lion part of the positioning errors shown in Figure 4–7 are resulted from the flexibility of the driving systems of the joints, which requires further investigation.



a)



b)

Figure 9. Discrepancies in joint angles of Fanuc robot comparing values provided by the controller and the theoretical formulae during the motions are (a) in X direction (b) in Y direction

4. Conclusions

Repeated positioning accuracies of two industrial robots have been measured and analysed in this paper. The measurements of a robot KUKA KR 15/2 and a robot Fanuc LR Mate 200iC have been carried out with Renishaw XL-80 type laser system. Horizontal displacements of the end effector were examined. The magnitude of the errors in positioning were higher than 0.1mm during the motions in X and Y directions within the range of $\pm 50mm$. It was shown that the positioning errors for the KUKA robot oscillate randomly, while almost regular oscillations can be seen for the Fanuc robot. Since the errors larger than 0.1mm in positioning the investigated robots are not applicable for highly precise assembly problems.

In order to find the possible sources of the error, the joint angles were evaluated by the help of analytical formulae. The results were compared to angle values provided by the robot controllers. It was found that the discrepancies in joint angles are negligible. It means that the detected errors derive from the flexibility of the kinematical chain.

Acknowledgements

This research was carried out in the framework of the Center of Excellence of Mechatronics and Logistics at University of Miskolc.

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