Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-11-0256

Estimation of Kinematic Parameter Errors of 6-axis Serial Robot through Circular Test

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KEYWORDS: Calibration, Circular test, Kinematic parameter, Serial robot

The accuracy of an end-effector pose of a robot is affected by various sources of error, and they can yield improper motion in case of gripping, machining, and so on. There are lots of studies dealing with calibrating the robot in the way of updating kinematic parameters through measuring the end-effector's pose using laser tracker, dial indicator, photogrammetry, and so on. A circular test is one of the fast, simple, and affordable methods for checking a machine's performance, by measuring radial deviation while moving the tool in a circular way. This work aims to check the viability of estimating kinematic parameter errors of the robot from a circular test via by means of simulation. KUKA KR60HA is chosen as a robot, and the kinematic model is established using DH (Denavit-Hartenberg) notations. The error of the end-effector's position is induced by providing randomly-selected, and normally-distributed values into each kinematic parameter. For the test, measurement points on the pre-determined circular path and corresponding joint angles are calculated through inverse kinematics. At each point, poses of the robot are selected in order to make maximum variation in each joint angles against the prior pose. To identify the value of each kinematic parameter, the mathematical relation between the measured radial deviation and kinematic parameter errors is derived. Finally, the estimated kinematic parameters are compared with the designed one to verify the proposed algorithm. Consequently, this work contributes to show feasibility of applying circular test to a 6-axis serial robot for evaluating performance in accuracy.

NOMENCLATURE

α_i = Angle between $\{i\}^{\text{th}}$ and $\{i+1\}^{\text{th}}$ X-axis along $\{i\}^{\text{th}}$ Z-axis (i =1 ~ 6), rad
l_i = Link offset between $\{i\}^{\text{th}}$ and $\{i+1\}^{\text{th}}$ X-axis along $\{i\}^{\text{th}}$ Z-axis (i =1 ~ 6), mm
θ_i = Angle between $\{i\}^{\text{th}}$ and $\{i+1\}^{\text{th}}$ Z-axis along $\{i\}^{\text{th}}$ X-axis (i =1 ~ 6), rad
r_i = Link offset between $\{i\}^{\text{th}}$ and $\{i+1\}^{\text{th}}$ Z-axis along $\{i\}^{\text{th}}$ X-axis (i =1 ~ 6), mm
$\{\boldsymbol{J}_i\}$ = Coordinate system with respect to $\{i\}^{\text{th}}$ joint (i = 0 ~ 6, t), t stands for a tool's coordinate system
R = radial distance between circular path's center and a measured point.

1. Introduction

With its high demand for improving productivity, industrial robots are widely being used for manufacturing[1]. Simultaneously, as the quality required for the product has increased, high accuracy and repeatability became essential for industrial robots[2]. Thus, it is important to monitor robot's performance periodically. For that, numerous measurement methods have been proposed leveraging various instruments such as laser tracker[3], DBB (double ball-bar)[4], wire encoder[5], and photogrammetry[6].

A circular test with DBB is one of the widely-used-method due to its rapidity, simplicity and affordability[7,8], and there are some commercial products which provide test results based on standards, such as ISO 230-4. However, they only provide evaluation, not calibration. For calibration, the additional measurement should be made using another measurement instruments with professional personnel or the robot should be sent to manufacturer for precise calibration. Both of ways usually cost a lot. Therefore, it is expected that time and budget would be saved if the parameter values for calibration can be identified from the circular test results. Comparing with using pose-based measurement method, the identifiable parameters can be less due to the limited data (distance). Nevertheless, it can contribute to maintain a certain level of accuracy with much lower budget.

The goal of this work is to check the feasibility of estimating kinematic parameters by DBB circular test before practical experiment. In this paper, four steps of this work are presented. First, a forward kinematic model of Kuka KR60HA is proposed. Second, a circular path is generated. At each measurement point on the path, the orientation of TCP (Tool center position) is designed to be moved to get further active angular range for each joint. Then the nominal and actual radial distances are calculated. The actual ones are acquired by adding randomly-generated error values of each kinematic parameter.

Finally, identification of the kinematic parameters is carried out by using a linear relation model derived by *Zhenhua et al* (2014)[9], and identifiable parameters are analyzed.

2. Forward kinematic model

Fig. 1 illustrates the forward kinematic model of Kuka KR60HA, and its 24 parameters ($\alpha_{0\sim5}, l_{0\sim5}, \theta_{1\sim6}, r_{1\sim6}$) are presented in Table 1. In addition, it is assumed that the relative position of the DBB from the flange's frame is $[t_x, t_y, t_z] = [30, 20, 10]$(mm). Therefore, the TCP pose with respect to robot's base frame is obtained from (1).

$$A_t^0 = A_1^0 A_2^1 A_3^2 A_4^3 A_5^4 A_6^5 A_t^6 \quad (1)$$

Where,

$$A_i^{i-1} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & l_{i-1} \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_{i-1} & -\sin\alpha_{i-1} & -r_i\sin\alpha_{i-1} \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} & r_i\cos\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Table 1 DH Parameters of Kuka KR60HA

Link (i)	α_{i-1} (rad)	l_{i-1} (mm)	θ_i (rad)	r_i (mm)
1	0	0	$-\theta_1$	815
2	$-\pi/2$	350	θ_2	0
3	0	850	$\theta_3 - \pi/2$	0
4	$-\pi/2$	145	$-\theta_4$	820
5	$\pi/2$	0	θ_5	0
6	$-\pi/2$	0	$\pi - \theta_6$	170

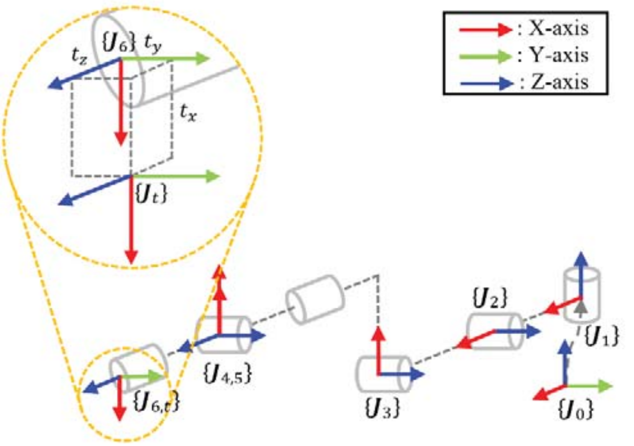

Fig. 1 A schematic of forward kinematics model for Kuka KR60HA

3. Identification of kinematic parameters

3.1. Circular path generation

The generated circular path has 300 mm radius and lies on XY plane with respect to robot's base frame. For measurement, 80 nominal measurement points on the path are selected with constant angular intervals of 0.025π. Also, TCP orientation at each point is commanded to be moved from -45° to 45° in Z, Y, X direction with respect to initial orientation. As a result, significant increase of active range in $\theta_4, \theta_5, \theta_6$ is observed, which used to be rarely moved in case of fixed TCP. This contributes to increase identifiable parameters.

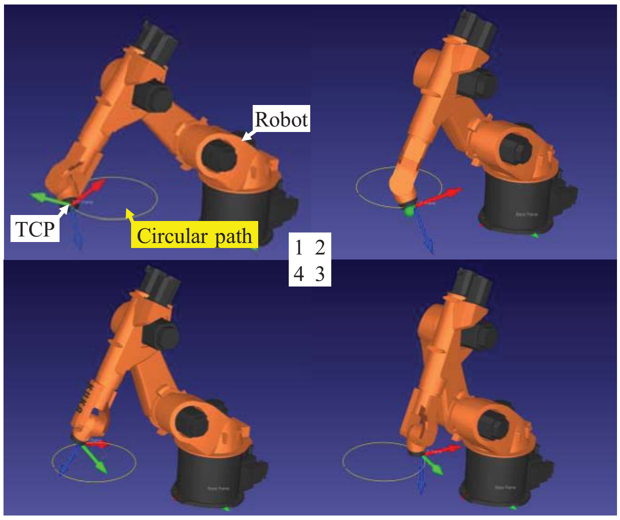

Fig. 2 A schematic of the generated circular path and varying TCP orientation

3.2. Mathematical relation between radial deviation and kinematic parameter

From an error transformation matrix between the frame {i-1} to {i}, (2) is derived using Taylor series. Also, the relation between TCP's position errors ($\Delta\boldsymbol{X}, \Delta\boldsymbol{Y}, \Delta\boldsymbol{Z}$) and corresponding radial deviations $\Delta\boldsymbol{R}$ are modelled as (3) by ignoring higher order terms. Then, the coefficient matrix $\boldsymbol{U}$ in (4) is obtained by applying (2) to (3). As $\boldsymbol{U}$ is not a square matrix, an error vector of the kinematic parameters $\Delta\boldsymbol{\rho}$ can be calculated by pseudoinverse.

$$dA_i^{i-1} = \frac{\partial A_i^{i-1}}{\partial\alpha_{i-1}}\Delta\alpha_{i-1} + \frac{\partial A_i^{i-1}}{\partial l_{i-1}}\Delta l_{i-1} + \frac{\partial A_i^{i-1}}{\partial\theta_i}\Delta\theta_i + \frac{\partial A_i^{i-1}}{\partial r_i}\Delta r_i \quad (2)$$

$$\boldsymbol{R}\Delta\boldsymbol{R} = \boldsymbol{X}\Delta\boldsymbol{X} + \boldsymbol{Y}\Delta\boldsymbol{Y} + \boldsymbol{Z}\Delta\boldsymbol{Z} \quad (3)$$

$$\Delta\boldsymbol{R} = \boldsymbol{U}\Delta\boldsymbol{\rho} \quad (4)$$

Where,

$$\Delta\boldsymbol{\rho} = [\Delta\alpha_{0\sim5} \quad \Delta l_{0\sim5} \quad q_{1\sim6} \quad r_{1\sim6}] \quad (5)$$

3.3. Analysis of identifiable parameters

Before identification, the redundant and dependent columns in $\boldsymbol{U}$ are figured out. Those columns can be found by checking echelon form of $\boldsymbol{U}$. As a result, the parameters of $\Delta\alpha_0, \Delta l_0, \Delta r_1$ are eliminated as redundant parameters. Also, it is found that $\Delta r_2, \Delta r_3$ are codependent. $\Delta q_{1\sim6}$ is not considered in this work, since they are position-dependent elements. Thereafter, the identification is conducted by the following steps.

1. Randomly selected values are provided to each parameter. Values within $\pm$0.2mm, $\pm$0.005rad are given to offsets, and angular errors, respectively.
2. Actual measurement points on the circular path and corresponding radial distances are calculated. $\Delta\boldsymbol{R}$ is calculated as a difference between actual and nominal radial distance.
3. $\Delta\boldsymbol{\rho}$ is calculated by (4), then $\boldsymbol{\rho}$ is updated until the norm of the updated parameter become less than the tolerance ($\|\Delta\boldsymbol{\rho}\| <$ 0.0001).

$$\boldsymbol{\rho}_{i+1} = \boldsymbol{\rho}_i + \Delta\boldsymbol{\rho} \tag{6}$$

However, it is confirmed that the estimation does not give accurate results if one of Δr_2 and Δr_3 is included. The reason is inferred to be related with their codependency, but the further study is required. The entire process is repeated without both 2 parameters and total 13 parameters ($\Delta\alpha_{1\sim5}, \Delta l_{1\sim5}, \Delta r_{4\sim6}$) are successfully estimated. Their values are shown in Table 2.

Table 2 Comparison between the designed and calculated kinematic parameters through the simulation ($\Delta l_i, \Delta r_i$: mm, $\Delta\alpha_i$: rad)

Para.	Designed	Calculated	Para.	Designed	Calculated
$\Delta\alpha_1$	-0.0049	-0.0049	Δl_1	0.1391	0.1376
$\Delta\alpha_2$	0.0031	0.0031	Δl_2	0.0331	0.0327
$\Delta\alpha_3$	0.0011	0.0011	Δl_3	0.0345	0.0359
$\Delta\alpha_4$	-0.0002	-0.0002	Δl_4	0.1703	0.1698
$\Delta\alpha_5$	-0.0023	-0.0023	Δl_5	0.0300	0.0305
Δr_4	-0.0968	-0.0957			
Δr_5	-0.0076	-0.0051			
Δr_6	-0.1091	-0.1095			

4. Conclusions

In this paper, the feasibility of estimating kinematic parameters of a 6-axis serial robot by performing circular test is checked through a simulation. For simulation, after randomly generated error values are added to the nominal kinematic model, the corresponding radial distance is calculated. From the deviation between actual and nominal distance, the kinematic parameters are obtained using a linear model. As a result, it is confirmed that 13 among 15 parameters are successfully identified. The reason why some parameters are not identified should be studied further. In follow-up studies, the proposed method will be applied to a practical industrial robot and the performance will be tested.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Education, Science and Technology (MSIT) (No. 2019R1A2C2088683, 2-2-R1C1C100330011)

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