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Accuracy improvement for 6-axis serial robot using double ball-bar

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Abstract
To increase productivity in manufacturing using a robot, it is required to monitor its performance periodically. Circular test using a double ball-bar (DBB) is one of the simple, and reasonable method to check the robot's performance. For this reason, if the error compensation can be done by the circular test, the productivity can be increased by reducing the costs for maintaining accuracy performance. This work is targeting to improve accuracy of a 6-axis serial robot using a single DBB. This process consists of 3 steps, (1) measuring tool centre point (TCP), (2) estimating kinematic parameters, and (3) verification of the obtained values. At first, the position of the TCP with respect to the end-effector is measured using geometry-based method using DBB. Secondly, a mathematical relation of the kinematic parameters and the distance error is derived. Then the parameters which are redundant or merely affect distance errors are eliminated, and the identifiable parameters are analysed through the mathematical model. The measurement is carried out on a nominal circular path, then the kinematic parameters are calculated from the above method. The validity of the obtained values is determined by checking error reduction after re-measuring with the calibrated values applied. The contribution of this work is suggesting a rapid, simple method to improve the accuracy of a 6-axis serial robot. As this work does not require additional devices for measuring TCP, the whole process can be done only using a single DBB.

Calibration, Error, Measurement, Robot

1. Introduction

Traditional use of industrial robot has not required high accuracy since they were controlled by manual teaching method. However, the growing demand on the products with the complex shapes make the teaching process time consuming as they induces too many teaching points[1]. In this case, offline programming can be a proper solution. However, the method requires not only high repeatability but also high positioning accuracy for precise control[2].

Kinematic error, the deviation between a physical system and its kinematic model, is one of the major sources of robot's positioning error[3]. Therefore, various methods have been tried for calibrating kinematic error[4-6]. Among them, using laser tracker is one of the most-widely-used method due to its simplicity in measurement. However, the laser tracker is generally expensive and has the accuracy issue induced from a 2 DoF(degree of freedom) gimbal structure[7].

A circular test using DBB is a simple, rapid way to check machine's performance by measuring radial deviation while moving the TCP(tool center point) along a circular path.[8] Comparing with the laser tracker, DBB has advantages on its shorter preparing time and affordable price. Furthermore, DBB provides better accuracy in measuring the distance between two points.

This paper proposes a method for improving 6-axis serial robot's positioning accuracy based on circular test. Chapter 2 shows a kinematic model of the 6-axis robot. Chapter 3 discusses overall proposed kinematic error estimation algorithm. Chapter 4 deals with the experimental verification of the suggested method by conducting circular test using a robot. At last, chapter 5, 6 analyzes the result and concludes this work.

2. Forward kinematics

In this work, KUKA KR 60 HA was used as a 6-axis serial robot. Its forward kinematic model is established using DH (Denavit-Hartenberg) parameters. The model and its values are respectively shown in Figure 1 and Table 1.

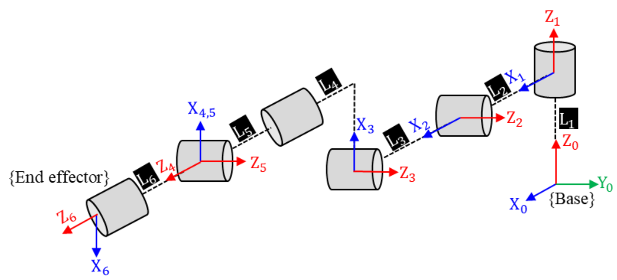

Figure 1. Forward kinematics of the KUKA KR 60 HA

Table 1. Link parameters of the KUKA KR 60 HA

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

Where,
a_i: Offset between $\{i\}^{th}$ and $\{i+1\}^{th}$ axis along $\{i\}^{th}$ Z-axis
α_i: Angle between $\{i\}^{th}$ and $\{i+1\}^{th}$ axis along $\{i\}^{th}$ Z-axis

d_i: Offset between $\{i\}^{th}$ and $\{i+1\}^{th}$ axis along $\{i\}^{th}$ X-axis
θ_i: Angle between $\{i\}^{th}$ and $\{i+1\}^{th}$ axis along $\{i\}^{th}$ X-axis

The pose(position and orientation) of the end effector ${}^{0}_{6}\boldsymbol{T}$ with respect to the base coordinate system can be derived using HTM(homogeneous transformation matrix) ${}^{i-1}_{i}\boldsymbol{T}$ and kinematic chain.

$${}^{0}_{6}\boldsymbol{T} = \prod_{i=1}^{6} {}^{i-1}_{i}\boldsymbol{T}$$

3. Algorithm

3.1. Error modelling

The error model is generated by integrating following 2 models.

Model 1 TCP positioning error($\Delta\boldsymbol{p}$) - Radial deviation(ΔR)
Model 2 Robot's kinematic error - TCP positioning error

Model 1 can be derived from a linearized ball-bar equation. A mathematical relation of ΔR, rotation center $\boldsymbol{p_c}$ and TCP position $\boldsymbol{p}$ can be written as follows[9].

$$R\Delta R = (\boldsymbol{p} - \boldsymbol{p}_c)^T(\Delta\boldsymbol{p} - \Delta\boldsymbol{p}_c)$$

Model 2 is derived by linearizing the difference $d\boldsymbol{T}_i$ between nominal ${}^{i-1}_{i}\boldsymbol{T}$ and actual transformation matrix ${}^{i-1}_{i}\boldsymbol{T}_a$ with respect to each kinematic error. Therefore, Taylor expansion is used as described in following equation[10].

$${}^{i-1}_{i}\boldsymbol{T}_a = {}^{i-1}_{i}\boldsymbol{T} + d\boldsymbol{T}_i$$

$$d\boldsymbol{T}_i = \frac{\partial[{}^{i-1}_{i}\boldsymbol{T}]}{\partial a_{i-1}}\Delta a_{i-1} + \frac{\partial[{}^{i-1}_{i}\boldsymbol{T}]}{\partial \alpha_{i-1}}\Delta \alpha_{i-1} + \frac{\partial[{}^{i-1}_{i}\boldsymbol{T}]}{\partial d_i}\Delta d_i + \frac{\partial[{}^{i-1}_{i}\boldsymbol{T}]}{\partial \theta_i}\Delta \theta_i$$

As a consequence of integration, a linear relation matrix $\boldsymbol{U}$ between ΔR and the kinematic error vector $\Delta\boldsymbol{\rho}$ is established.

$$\Delta\boldsymbol{R} = \boldsymbol{U} \cdot \Delta\boldsymbol{\rho}$$

3.2. Identifiable parameter analysis

Some of the kinematic parameters in $\Delta\boldsymbol{\rho}$ are merely affect radial deviation while circular test. It can be checked from the rank deficiency of the matrix $\boldsymbol{U}$. As it can cause significant error in calculating inverse matrix, the problematic parameters should be eliminated. In this case, singular value decomposition(SVD) is generally used. By finding and eliminating the zeros among singular values, $\boldsymbol{U}$ can have full rank. In this way, $\Delta d_1, \Delta d_3, \Delta d_6$are deleted. In addition, Δd_2 is excluded since it diverges while iterating the least squares. The exact reason to this phenomenon should be further studied. Additionally, $\Delta\theta_1 \sim \Delta\theta_6$ are not considered in this work as they are position-dependent values. Consequently, following 12 parameters are chosen as target kinematic parameters $\Delta\boldsymbol{\rho_{target}}$.

$$\Delta\boldsymbol{\rho_{target}} = [\Delta a_1 \sim \Delta a_5, \Delta\alpha_1 \sim \Delta\alpha_5, \Delta d_4, \Delta d_5]^T$$

4. Experiment

In order to check a feasibility of the proposed method, the suggested algorithm was tested on a 6-axis serial robot(KUKA KR 60 HA). The robot has a laser oscillator for DED onto its flange. At the end of the tool, a magnetic tool cup was fixed to attach an end of DBB for installation.

4.1. TCP estimation

Finding accurate TCP position is important for precise control. Although the manufacturer provides 4 point measurement method, the result can be varied since it is based on operator's visual discretion[11]. In this work, DBB is utilized to solve the problem. By measuring the displacement between prior TCP position $\boldsymbol{p}$ and current TCP position $\boldsymbol{p}'$ after moving joint, the $\boldsymbol{p}$ can be calculated from the isosceles triangle as shown in Figure 2. In this case, X and Z position of the TCP is calculated by moving 5 and 6 joint, respectively.

4.2. Measurement & Verification

The measurement path comprises of reciprocal vertical circular path which lies on a nominal hemisphere which has 300 mm radius. Specifically, a path on XY plane was constructed with 100 measurement points, and 57 points on YZ, ZX planes. Then, the DBB was installed between the circular center and the TCP. The robot was commanded to sequentially move to each measurement points, and the corresponding radial deviations were recorded. The process was conducted on 2 different places inside the frequently-used-workspace as shown in Figure 3. After measurement, the target kinematic errors were calculated through the method described in Chapter 3.

In order to verify the obtained values, the calibration was implemented. The calibrated model was generated by updating the model using the obtained parameters values. After recalculating required joint angles on each measurement point, the measurement process is repeated.

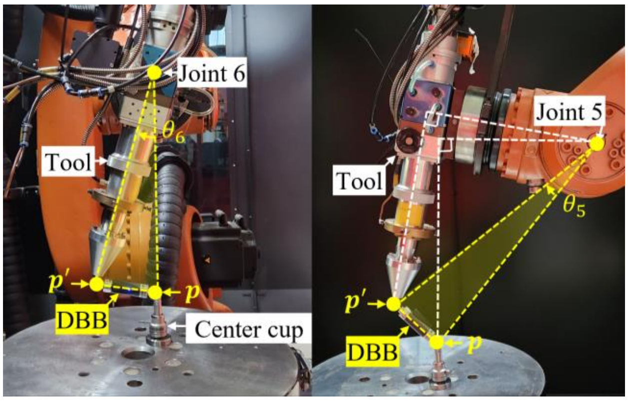

Figure 2. TCP measurement

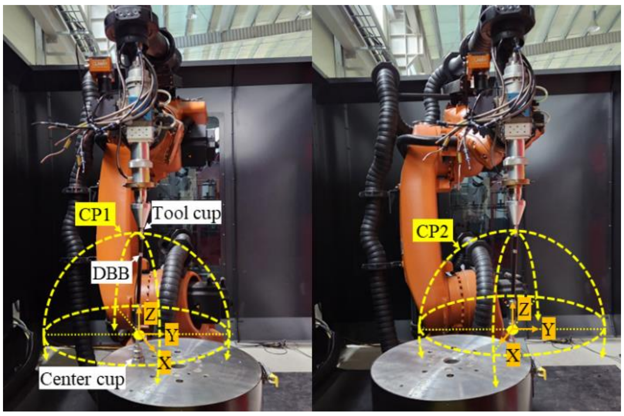

Figure 3. Measurement path

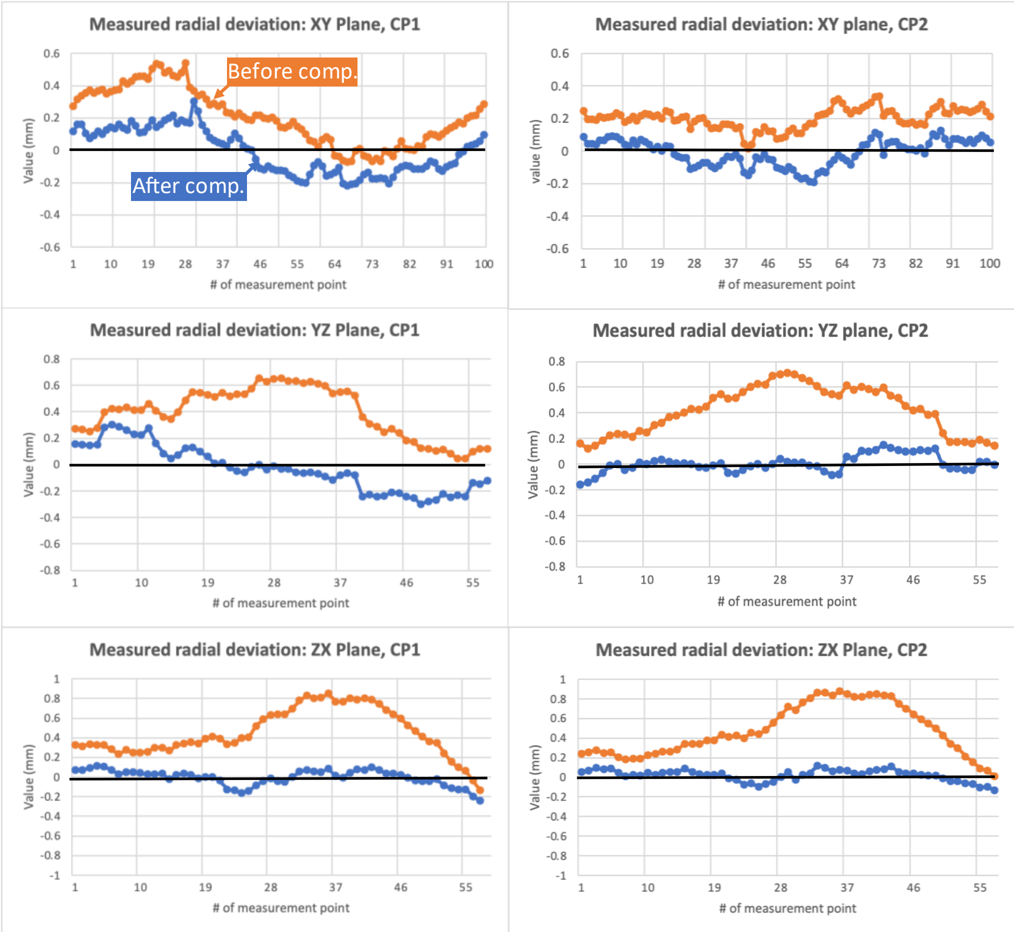

Figure 4. Measured radial deviation without / with calibration

Table 2. Calculated values of kinematic parameters
(length: mm, angle: rad)

Parameter	Value	Parameter	Value	Parameter	Value
Δa_1	-0.9132	$\Delta \alpha_1$	0.0002	Δd_4	0.9112
Δa_2	0.5287	$\Delta \alpha_2$	0.0034	Δd_5	-0.1850
Δa_3	1.2681	$\Delta \alpha_3$	0.0008		
Δa_4	0.1194	$\Delta \alpha_4$	0.0012		
Δa_5	-0.2551	$\Delta \alpha_5$	-0.0006		

5. Result

Figure 4 shows the measured radial deviation before and after calibration, and a significant reduction of the error is observed. The maximum absolute value of radial deviation is decreased by 77.82% and the standard deviation is reduced by 66.4% in maximum. Although this work calibrates only 12 parameters among total 24 parameters, decent performance improvement is shown. The residual errors can be regarded to be related with joint displacement errors, which were not considered in this paper. By finding the way to calibrate them, further improvement in positioning performance can be expected.

6. Conclusion

This work suggests a method for improving positioning accuracy of 6-axis serial robot, and the conculsions are as follows.

(1) The proposed method employs circular test using DBB for simplicity, affordability and high precision.
(2) Although the method does not calibrates the entire parameters, a significant improvement of positioning accuracy is confirmed.
(3) The proposed method can contribute to enhance productivity of the robot by reducing the cost for maintaining high positioning performance

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