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Kinematic parameter calibration method for industrial robot manipulator using the relative position

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Abstract

A new calibration method for industrial robot system calibration on a manufacturing floor is presented in this paper. To calibrate the robot system, a laser sensor to measure the distance between robot tool and measurement surface is attached to the robot end-effector and a grid is established in the floor. Given two position command pulses for a robot manipulator and using the position difference between two command pulses, the relative position measurement calibration method will find the real robot kinematic parameters. The procedures developed have been applied to an industrial robot. Finally, the effects of the models used to calibrate the robot are discussed. This calibration method represents an effective, low cost and feasible technique for the industrial robot calibration in lab. projects and industrial environments.

Keywords: Robot calibration; Relative position; Laser sensor

1. Introduction

When robots were first introduced into the industrial market, the tasks they performed were relatively simple. Most robots required a teaching phase in the programming. Here, the user taught the various positions by moving the robot to the points and then recording them. As long as the robot could repeatedly move back to the taught points, the robot could successfully perform the task.

Robots today are much more sophisticated. The paths to be tracked can be entered directly into the robot controller. However, since the robot is now required to trace a path that is mathematically described rather than taught, a repeatable robot is no longer enough.

In recent years, robotic research has been focused on solving a variety of tasks requiring sophisticated motion in complex environments. Contemporary robot manipulators are capable of efficiently executing a variety of tasks with excellent repeatability. Repeatability refers to the robot's ability to return its end-effector to a position that has been previously “taught”. Absolute accuracy refers to a robot's ability to position its end-effector relative to a fixed reference frame.

A robot normally has high repeatability, but its accuracy is much worse than its repeatability. The challenge, therefore, is how to improve and maintain the system's accuracy in varying manufacturing environments.

Robot calibration is a cost-effective way to improve robot accuracy, and many researchers have devoted efforts to this field. Different models, measurement systems, and algorithms for identification and compensation have been developed as summarized by Roth et al. [1], Hollerbach [2], and Mooring [3].

One method of improving robot accuracy involves identifying the real kinematic parameters by minimiz-

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ing the error between the position and orientation calculated by the robot controller and the actual measured position and orientation. (Driels and Swayze [4], Driels [5], Render et al. [6], Judd and Kaminski [7], Wyatt S. Newman, Craig E. et al [8], Gursel alici and Bijan Shirinzadeh [9])

Other researchers have proposed the use of laser-based measurement systems and vision-based measurement systems. Generally speaking, non-contact systems employing lasers or theodolites are very accurate; however, they are complicated and require highly trained personnel to operate them. (Driels and Pathre [10], Zhuang et al [11], Patrick Rousseau et al [12])

It is the goal of this paper to develop a new calibration method for industrial robot system calibration on a manufacturing floor. To calibrate the robot system, a laser sensor to measure the distance between robot tool and measurement surface is attached to the robot end-effector and a grid plate (an interval of 0.1mm) is established in the floor.

This method can calibrate the robot without calibrating the transformation from the world coordinate system to the robot base coordinate system. This makes the robot calibration easy and convenient to implement on the manufacturing floor. Due to the reduction of measurement number, this method can decrease the time consumption. These devices for calibrated method are easy to use and low cost less than others. Also, this makes the robot calibration easy and convenient to implement on the manufacturing floor.

An experiment using a 6-DOF robot is conducted to show the effectiveness of the proposed calibration algorithm.

2. System model

2.1 Robot model

Since the kinematic model of a robot is used as the foundation for further development of robot error synthesis model, it is briefly reviewed here. The kinematic model is based on the Denavit Hartenberg (DH) convention [13]. The relative translation and rotation between link coordinate frames i-1 and i can be described by a homogenous transformation matrix, which is a function of four kinematic parameters θ_i, d_i, α_i and a_i as shown in Fig. 1.

The homogenous transformation A_i is given in Eq. (1).

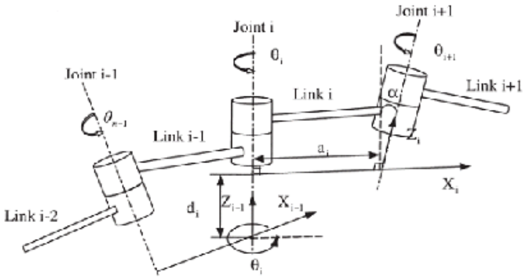

Fig. 1. D-H model diagram.

$$A_i = Rot(Z_{i-1},\theta_i) * Trans(Z_{i-1},d_i) * Trans(X_{i-1},a_{i-1}) * Rot(X_i,\alpha_i) = \begin{pmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

Where $S\theta_i$ and $C\theta_i$ represent sin θ_i and cos θ_i, and $S\alpha_i$ and $C\alpha_i$ represent sin α_i and cos α_i respectively.

As pointed out by Hayti [14], small errors in the end-effector position could not be modeled by small errors in the DH link parameters in the case of two consecutive parallel joints or nearly parallel joints. This causes numeric instability during the identification process. In order to avoid the singularity problem, a small rotation of β about the y-axis, Rot (y, β), is added. As for a robot with two parallel joints or nearly parallel consecutive joints, the homogenous transformation A_i becomes Eq. (2).

$$A_i = \begin{pmatrix} C\theta_i C\beta_i - S\theta_i S\alpha_i S\beta_i & -S\theta_i C\alpha_i & C\theta_i S\beta_i + S\theta_i S\alpha_i C\beta_i & a_i C\theta_i \\ S\theta_i C\beta_i + C\theta_i S\alpha_i S\beta_i & C\theta_i C\alpha_i & S\theta_i S\beta_i - C\theta_i S\alpha_i C\beta_i & a_i S\theta_i \\ -C\alpha_i S\beta_i & S\alpha_i & C\alpha_i C\beta_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2)$$

Where $S\beta_i$ and $C\beta_i$ represent sin β_i and cos β_i respectively.

For a robotic manipulator with N degrees of freedom, the position and orientation of the robot tool frame with respect to robot base frame can be represented by

$$T_N = A_1 \cdot A_2 \cdots A_N = \begin{pmatrix} R_N & P_N \\ 0 & 1 \end{pmatrix} \quad (3)$$

Where R_N is the rotation matrix representing the orientation of the tool frame relative to the base frame and P_N is the displacement vector representing the Cartesian position of the tool frame relative to the base frame.

2.2 Calibration model

The differential change dA_i is estimated as a linear function of the four kinematic errors. Due to the modified kinematics resulting in the homogeneous transformation given by Eq. (2), the differential change dA_i should be estimated as a linear function of the five kinematic errors, assuming the errors are small so that the higher order terms are negligible

$$dA_i = \frac{\partial A_i}{\partial \theta_i}\delta\theta_i + \frac{\partial A_i}{\partial d_i}\delta d_i + \frac{\partial A_i}{\partial a_i}\delta a_i + \frac{\partial A_i}{\partial \alpha_i}\delta\alpha_i + \frac{\partial A_i}{\partial \beta_i}\delta\beta_i \tag{4}$$

The final robot positional and orientational change can be calculated through Eq. (5).

$$\begin{aligned} dT_N &= \frac{\partial T_N}{\partial \theta_1}\delta\theta_1 + \frac{\partial T_N}{\partial d_1}\delta d_1 + \frac{\partial T_N}{\partial a_1}\delta a_1 + \frac{\partial T_N}{\partial \alpha_1}\delta\alpha_1 + \frac{\partial T_N}{\partial \beta_1}\delta\beta_1 \\ &\vdots \\ &+ \frac{\partial T_N}{\partial \theta_N}\delta\theta_N + \frac{\partial T_N}{\partial d_N}\delta d_N + \frac{\partial T_N}{\partial a_N}\delta a_N + \frac{\partial T_N}{\partial \alpha_N}\delta\alpha_N + \frac{\partial T_N}{\partial \beta_N}\delta\beta_N \end{aligned} \tag{5}$$

where,

$$\frac{\partial T_N}{\partial \gamma_i} = A_1 * A_2 * \cdots * \frac{\partial A_i}{\partial \gamma_i} * A_{i+1} * \cdots * A_N \ , \ \frac{\partial A_i}{\partial \gamma_i} = B_{xi}$$

$$\gamma = \{\theta, d, a, \alpha, \beta\}$$

$$\begin{aligned} dT_N = {} & B_{\theta 1} \cdot {}^1T_N \cdot \delta\theta_1 \quad + B_{d1} \cdot {}^1T_N \cdot \delta d_1 + \cdots \\ & + T_1 \cdot B_{\theta 2} \cdot {}^2T_N \cdot \delta\theta_2 + T_1 \cdot B_{d2} \cdot {}^2T_N \cdot \delta d_2 + \cdots \\ & \vdots \\ & + T_N \cdot B_{\theta N} \cdot \delta\theta_N \quad + T_N \cdot B_{dN} \cdot \delta d_N + \cdots \end{aligned} \tag{6}$$

Therefore,

$$\begin{aligned} dT_N = \sum_{i=1}^{N} \{ & (T_{i-1} \cdot B_{\theta i} \cdot {}^iT_N) \cdot \delta\theta_i + (T_{i-1} \cdot B_{di} \cdot {}^iT_N) \cdot \delta d_i \\ & + (T_{i-1} \cdot B_{ai} \cdot {}^iT_N) \cdot \delta a_i + (T_{i-1} \cdot B_{\alpha i} \cdot {}^iT_N) \cdot \delta\alpha_i \\ & + (T_{i-1} \cdot B_{\theta i} \cdot {}^iT_N) \cdot \delta\beta_i \} \end{aligned} \tag{7}$$

(*) $T_0 = {}^NT_N = I$

3. Calibration method

3.1 Position error model

If the position of the end-effector with respect to the base, assuming the position of the manipulator with nominal link parameters is given by P_t, and the real position of the manipulator with kinematic errors is given by P_t^c then the correct position can be expressed as:

$$P_t^c = P_t + dP_t \tag{8}$$

If small errors in the position of the end of the manipulator with respect to the base can be modeled as small variation in the link parameters, then the manipulator position error can be approximated as:

$$\begin{aligned} dP_t = \begin{pmatrix} dP_x \\ dP_y \\ dP_z \end{pmatrix} = \sum_{i=1}^{N} \{ & \begin{bmatrix} (T_{i-1} \cdot B_{\theta i} \cdot {}^iT_N)_{(1,4)} \\ (T_{i-1} \cdot B_{\theta i} \cdot {}^iT_N)_{(2,4)} \\ (T_{i-1} \cdot B_{\theta i} \cdot {}^iT_N)_{(3,4)} \end{bmatrix} \cdot \delta\theta_i \\ & + \begin{bmatrix} (T_{i-1} \cdot B_{di} \cdot {}^iT_N)_{(1,4)} \\ (T_{i-1} \cdot B_{di} \cdot {}^iT_N)_{(2,4)} \\ (T_{i-1} \cdot B_{di} \cdot {}^iT_N)_{(3,4)} \end{bmatrix} \cdot \delta d_i + \begin{bmatrix} (T_{i-1} \cdot B_{ai} \cdot {}^iT_N)_{(1,4)} \\ (T_{i-1} \cdot B_{ai} \cdot {}^iT_N)_{(2,4)} \\ (T_{i-1} \cdot B_{ai} \cdot {}^iT_N)_{(3,4)} \end{bmatrix} \cdot \delta a_i \\ & + \begin{bmatrix} (T_{i-1} \cdot B_{\alpha i} \cdot {}^iT_N)_{(1,4)} \\ (T_{i-1} \cdot B_{\alpha i} \cdot {}^iT_N)_{(2,4)} \\ (T_{i-1} \cdot B_{\alpha i} \cdot {}^iT_N)_{(3,4)} \end{bmatrix} \cdot \delta\alpha_i + \begin{bmatrix} (T_{i-1} \cdot B_{\beta i} \cdot {}^iT_N)_{(1,4)} \\ (T_{i-1} \cdot B_{\beta i} \cdot {}^iT_N)_{(2,4)} \\ (T_{i-1} \cdot B_{\beta i} \cdot {}^iT_N)_{(3,4)} \end{bmatrix} \cdot \delta\beta_i \} \end{aligned} \tag{9}$$

The above equation can be written in the following compact form as

$$dP_t = [M\theta]\delta\theta + [Md]\delta d + [Ma]\delta a + [M\alpha]\delta\alpha + [M\beta]\delta\beta \tag{10}$$

where,

$M\gamma = T_{i-1} \cdot B_{\gamma i} \cdot {}^iT_N$

(i-th column, $\gamma = \theta$ or d or a or α or β)

$\delta\theta, \delta d, \delta a, \delta\alpha, and\ \delta\beta$: time invariant constant

3.2 Relative position measurement method

Given two position command pulses for robot manipulator and using the position difference between two command pulses, the relative position measurement calibration method will find the real robot kinematic parameters. Fig. 2 is the block diagram.

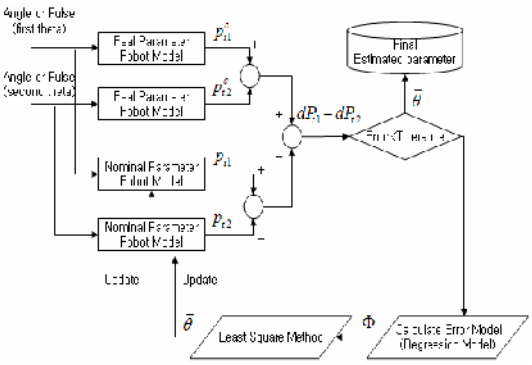

Fig. 2. Relative measurement method block diagram.

The equation of first position command for robot manipulator can be written as:

$$P_{t1}^c = P_{t1} + dP_{t1} \quad (11)$$

The equation of the second position command for robot manipulator can be written as:

$$P_{t2}^c = P_{t2} + dP_{t2} \quad (12)$$

The relative position difference between two position commands results in the following equations.

$$\begin{aligned} P_{t1}^c - P_{t2}^c &= (P_{t1} + dP_{t1}) - (P_{t2} + dP_{t2}) \\ &= (P_{t1} - P_{t2}) + (dP_{t1} - dP_{t2}) \end{aligned} \quad (13)$$

$$(dP_{t1} - dP_{t2}) = (P_{t1}^c - P_{t2}^c) - (P_{t1} - P_{t2}) \quad (14)$$

where,

$dP_{t1} - dP_{t2}$: Relative position error model
$P_{t1}^c - P_{t2}^c$: Real robot relative position (Measurement)
$P_{t1} - P_{t2}$: Nominal robot relative position (Known)

From Eq. (10), the relative position error model is derived:

$$dP_{t1} = [M\theta^1]\delta\theta + [Md^1]\delta d + [Ma^1]\delta a + [M\alpha^1]\delta\alpha + [M\beta^1]\delta\beta \quad (15)$$

$$dP_{t2} = [M\theta^2]\delta\theta + [Md^2]\delta d + [Ma^2]\delta a + [M\alpha^2]\delta\alpha + [M\beta^2]\delta\beta \quad (16)$$

Therefore,

$$\begin{aligned} \therefore (dP_{t1} - dP_{t2}) &= [M\theta^1 - M\theta^2]\delta\theta + [Md^1 - Md^2]\delta d \\ &+ [Ma^1 - Ma^2]\delta a + [M\alpha^1 - M\alpha^2]\delta\alpha + [M\beta^1 - M\beta^2]\delta\beta \end{aligned} \quad (17)$$

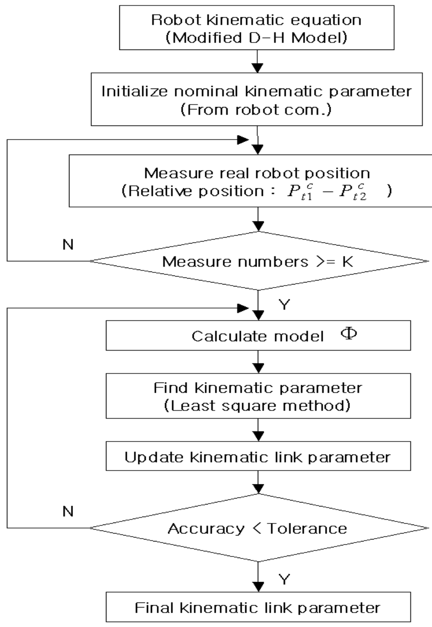

Fig. 3. Calibration process.

The measurement number (K) of relative position can be written as follows:

$$K \geq N \times 5/3 \quad (18)$$

where,

N : Robot joint D.O.F.
5 : Number of modified D-H model parameter
3 : Number of position factor (x, y, z)

To find calibrated robot kinematic parameters, we use the least square method (L.S.M.).

Model equation: $Y = \Phi * \bar{X}$ (19)

$$\therefore \bar{X} = (\Phi^T \cdot \Phi)^{-1} \cdot \Phi^T \cdot Y \quad (20)$$

where,

$$Y = dP_{t1} - dP_{t2} = (P_{t1}^c - P_{t2}^c) - (P_{t1} - P_{t2})$$

$$\Phi = [(M\theta^1 - M\theta^2) \ (Md^1 - Md^2) \ (Ma^1 - Ma^2) \ (M\alpha^1 - M\alpha^2) \ (M\beta^1 - M\beta^2)]$$

$$\bar{X} = [\delta\theta \ \delta d \ \delta a \ \delta\alpha \ \delta\beta]$$

3.3 Calibration process

From the above equations, Fig. 3 is the calibration process.

① Initialize nominal kinematic link parameter
② Relative position measure (K numbers)
③ Least square method
: Find optimal kinematic parameters
④ Update optimal kinematic parameter
⑤ Repeat 2-4 until some minimum value

At this calibration process, using the nominal kinematic parameters with z_{i-1} and z_i parallel (Fig. 1), the errors in d_i and d_{i+1} are dependent since they have the same effect on the reference point position for any manipulator configuration. This dependency will cause a singularity in the matrix of partial derivative used in the calibration equations. Through the pivot check for the matrix of partial derivative, if the pivot is smaller than any tolerance value then the column factor is rejected and that parameter is set zero.

4. Experiment

4.1 System configuration

The experimental system for calibration consists of a six DOF robot (UP20) manufactured by MOTOMAN comp., a laser height sensor manufactured by OMRON, Inc., a grid plate (an interval of 0.1mm) by us, and a PC.

The laser height sensor can conduct height measurement within its field of view and it has a measurement range 80mm-140mm and its resolution is 0.01mm. Using the mechanical height gage (its accuracy is 0.01mm), the calibration for laser height sensor is achieved in Fig. 4.

The grid plate made by CNC machine can conduct xy-axis position measurement and its grid interval is 0.1mm. Namely, the position accuracy of xy-axis is 0.1mm and that of z-axis is 0.01mm.

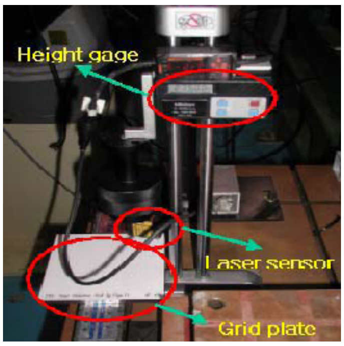

Fig. 4. Calibration for laser sensor.

RS232C serial data communication is set up to integrate the subsystems such as the robot, and the PC into measurement and calibration system. After the robot moves to one position, its controller sends a signal to request that the sensor start measurement. After the measurement is completed the robot moves to the next position. This pattern continues until the whole measurement task (the number of K) is done. Then the robot controller sends all joint pulse readings to the PC, and the sensor sends all the measurements to the person. Based on all these data, the kinematic identification algorithm is used to find the true parameter value.

The overall system figure is shown in Fig. 5.

4.2 Calibration results

4.2.1 Robot model

From the DH model (Fig. 1), the model of a six DOF robot (MOTOMAN UP20) can be given as follows:

Then, nominal robot kinematic parameters are given as in Table 1.

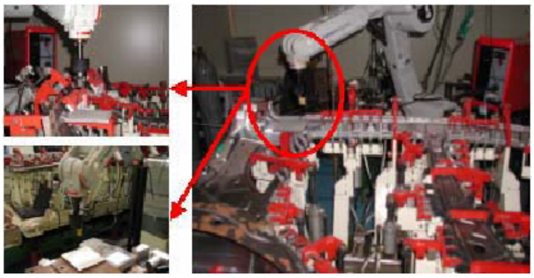

Fig. 5. Overall system for calibration method.

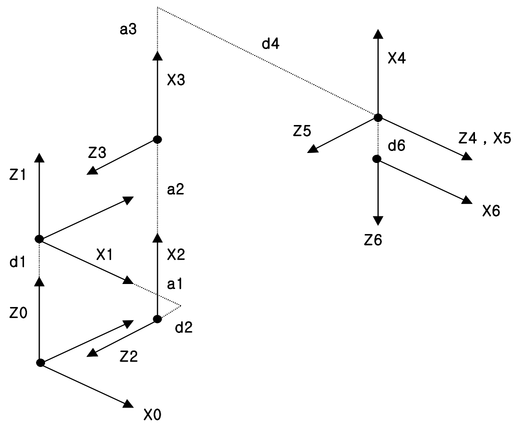

Fig. 6. Robot model.

Table 1. Nominal robot kinematic parameters.

Joint \ Par.	α_i (deg.)	a_i (mm)	d_i (mm)	θ_i (deg.)	β_i (deg.)
1	0	150	535	0	0
2	90	730	0	90	0
3	0	140	0	0	0
4	90	0	765	0	0
5	-90	0	0	-90	0
6	0	0	105	0	0

Table 2. Relative position data (Nominal parameters).

Mea Num (K)	Real robot relative position			Nominal robot model relative position		
	ΔX	ΔY	ΔZ	ΔX	ΔY	ΔZ
1	0.0	-70.0	-0.11	0.04	-69.85	0.03
2	70.1	70.0	0.18	70.00	69.86	0.02
3	-65.0	-5.2	0.01	-64.95	-5.08	0.04
4	0.0	9.8	0.04	0.02	9.78	0.02
5	-10.3	0.0	-11.12	-10.23	-0.02	-11.10
6	0.0	-9.7	4.66	0.00	-9.66	4.68
7	-15.0	-20.5	12.26	-14.97	-20.44	12.29
8	-10.1	-34.6	-0.04	-10.12	-34.51	0.03
9	40.3	19.7	8.84	40.21	19.68	8.78
10	40.3	-14.9	-48.28	40.23	-15.02	-48.19
RMS Error: 0.128						

4.2.2 Robot relative position measurement

The real robot relative position is the measurement data between the laser height sensor and grid plate. The nominal robot model relative position is the calculation data of the kinematic equation from the real robot joint pulses.

Then the measurement number (K) is 10 because $K \geq N(6) \times 5/3 = 10$.

The RMS error is the root mean square between the real robot relative position and the nominal robot model relative position.

4.2.3 Calibrated kinematic parameter

Based on all above data, the kinematic identification algorithm is used to find the true parameter value, and the calibrated kinematic parameters are results in Table 3.

According to the calibration process, Fig. 3, in case of second iteration, the calibration accuracy of second iteration is finer than that of the first iteration.

The number of parameters is the same as the joint number (a six DOF).

Table 3. Calibrated kinematic parameters.

	Calibrated kinematic parameters	
	1-th iteration	2nd iteration
$\Delta\theta$	0, -0.1, -0.195, 0.067, -0.151, 0	0, -0.1, -0.198, -0.067, -0.149, 0
Δd	0, –2.064, 0, 0.377, 0.150, -0.018	0, -2.117, 0, 0.364, 0.147, 0.002
Δa	2, 1.331, 2.943, -0.006, 0, 0.001	2.008, 1.332, 2.984, 0, 0, 0
$\Delta\alpha$	0, -0.063, 0.004, -0.004, 0, 0	0, -0.063, 0, 0, 0, 0
$\Delta\beta$	0, 0, 0, 0, 0, 0	0, 0, 0, 0, 0, 0

Table 4. Relative position data (Calibrated parameters).

Mea. Num (K)	Real robot relative position			Calibrated robot model relative position		
	ΔX	ΔY	ΔZ	ΔX	ΔY	ΔZ
1	0.0	-70.0	-0.11	0.0	-70.0	-0.11
2	70.1	70.0	0.18	70.1	70.0	0.18
3	-65.0	-5.2	0.01	-65.0	-5.2	0.01
4	0.0	9.8	0.04	0.0	9.8	0.04
5	-10.3	0.0	-11.12	-10.3	0.0	-11.12
6	0.0	-9.7	4.66	0.0	-9.7	4.66
7	-15.0	-20.5	12.26	-15.0	-20.5	12.26
8	-10.1	-34.6	-0.04	-10.1	-34.6	-0.04
9	40.3	19.7	8.84	40.3	19.7	8.84
10	40.3	-14.9	-48.28	40.3	-14.9	-48.28
RMS Error: 0.0						

Table 5. Absolute position data from robot base.

		P1	P2	P3
Nominal Data	X	1084.10	947.31	736.89
	Y	430.19	-326.24	181.86
	Z	524.41	563.93	-17.91
Calibration Data	X	1090.18	953.91	741.54
	Y	433.70	-326.54	184.63
	Z	524.21	564.10	-18.18
Measured Data (LTD500)	X	1090.10	953.72	741.16
	Y	433.51	-326.77	184.75
	Z	524.43	563.97	-18.10
RMS Error (Nominal data vs. Measured data)		7.02	6.61	5.42
RMS Error (Calibration data vs. Measured data)		0.30	0.32	0.40

4.2.4 Confirm robot position

Using the calibrated kinematic parameters, we confirmed the improvement of position accuracy. The real robot relative position data is the same as the calibrated robot model relative position data.

RMS error of the relative position data is reduced from 0.128mm to 0.0mm. To find the real absolute error from robot base to tool position, we measured the real absolute error by using the laser tracker device. (LTD500 by Leica Inc.) Then, the residual error was reduced.

Improving the accuracy of the grid plate and the laser height sensor can improve the residual error of robot position.

5. Conclusion

A new low-cost position measurement setup for an industrial robot and the calibration method has been developed. The theoretic derivation of this calibration method shows that the base calibration is not necessary. From the proposed calibration method, the robot kinematic parameters were estimated. Then the position error of robot end-effector was measured below 0.3~0.4mm by Laser Tracker system (LTD500). This unique feature not only makes this calibration method easier to implement, but also shortens the time consumption. Since it is easy and convenient to implement we expect the proposed calibration method will have wide application on the manufacturing floor for robot on-line accuracy enhancement and maintenance.

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