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Absolute Positioning Error Modeling and Compensation of a 6-DOF Industrial Robot*

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Abstract **- This paper presents an absolute positioning error modeling and compensation method considering measuring errors for a 6-DOF industrial robot. Firstly, the error modeling of an ABB IRB 120 robot based on the modified Denavit-Hartenberg (D-H) method was established, it took into account not only geometric errors but also measuring errors. And then the compensation method based on the joint angles was introduced. Secondly, the simulation experiments were adopted to verify the feasibility and effectiveness of the compensation method. Finally, the error compensation experiments were conducted, including the measurement, error identification, error compensation. The experimental results show that the accuracy can have a significant improvement of 73.94% after error compensation. Hence, the error modeling and compensation method presented in this study is sensible and effective, and could be used for the error compensation to improve absolute positioning accuracy of the industrial robots.**

Keyword – Industrial robot, Error modeling, Error measurement, Error compensation

I. Introduction

In recent years, the industrial robots have become more and more popular application in the machining field, owning to the benefit of cost efficiency, high flexibility and multi-functionality of industrial robots [1, 2]. Hence, the demand for applications should be programmed through off-line programming is continuously increasing [3-5]. However, in general, industrial robots have high repeatability, but low absolute positioning accuracy [6-9]. Therefore, it is very important to improve the absolute positioning accuracy of industrial robots. There are many factors affecting the absolute positioning accuracy of the robots, one of the main factors is the influence of the robot's geometric errors. Literature review reveals that it takes a high proportion in the total errors, more than 80% [10]. At present, many kinematic models have been proposed for the robot's calibration. The classical Denavit-Hartenberg (D-H) model is widely adopted, but it is not suitable when two adjacent joints are parallel or nearly parallel [11-13]. To overcome the singularity problem, many modified models have been presented, such as modified D-H model, S-model, complete and parametrically continuous (CPC) model, and product-of-exponential (POE) model, and so on [13-17].

Error compensation has become an inevitable and cost-effective way to improve the absolute accuracy of machine [18-20]. There are mainly two methods for compensation of the positioning errors of the robot. One is to compensate the error parameters directly, and the other is to compensate the joint angles indirectly. Most of controllers of the industrial robots can't be accessed to amend the parameter for operators. Hence, the second method is used widely to improve the robot's accuracy. Before error compensation, the error parameters should be obtained by error measurement and error identification. During measurement, it is unavoidable to bring in some measuring errors. How to deal with the measuring errors will affect the accuracy of error identification.

Therefore, this paper will focus on the error modeling and compensation method considering the measuring errors for an industrial robot. To this end, Section 2 of the paper will introduce the D-H parameter method, and then error modeling and compensation method will be established. Section 3 and Section 4 will then verify the feasibility of the presented method by simulation and experiment, respectively. Finally, the paper will end with a brief conclusion.

II. Absolute Positioning Error Modeling and Compensation Method

A. Kinematic Model

For each link of the robot, there are four kinematic parameters based on the D-H method, including link length a_{i-1}, link twist α_{i-1}, link offset d_i ,and joint angle θ_i, where i is the order number of links. The homogeneous transformation matrix (HTM) between the two adjacent links $(i-1)$ and link i can be described by

$$
{}^{i-1}_{i}\boldsymbol{T} = Rot(X,\alpha_{i-1})Trans(X,a_{i-1})Rot(Z,\theta_i)Trans(Z,d_i) = \begin{pmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}. \quad (1)
$$

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where, $Rot(Z,\theta)$ represents the rotation matrix when rotating angle θ around Z-axis, $Trans(Z,d_i)$ represents the translation matrix when moving distance d_i along Z-axis, $s\theta_i$, and $c\theta_i$ are the abbreviation of $\sin(\theta_i)$ and $\cos(\theta_i)$, respectively (the same below).

To explain the modeling method, let us take a 6-DOF industrial robot as an example. The structure of an ABB IRB 120 robot is shown in Fig. 1. Firstly, the coordinate system is established, the relationship of the base coordinate frame $\{0\}$ and other local coordinate frames is shown in Fig. 1. And the nominal D-H kinematic parameters of the robot are shown in Table I.

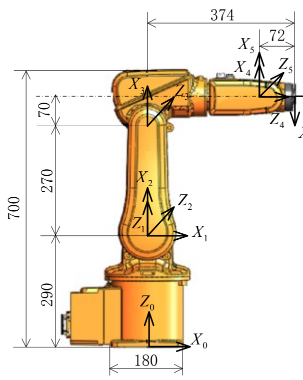

Fig. 1 The structure and the coordinate system of an ABB IRB 120 robot.

TABLE I
THE NOMINAL KINEMATIC PARAMETERS OF THE ROBOT

i	α_{i-1} (°)	a_{i-1} (mm)	d_i (mm)	θ_i (°)
1	0	0	290	0
2	-90	0	0	-90
3	0	270	0	0
4	-90	70	302	0
5	90	0	0	0
6	-90	0	72	180

The overall transformation matrix from the frame $\{6\}$ to frame $\{0\}$ can be represented as

$$ {}^0_6\boldsymbol{T} = {}^0_1\boldsymbol{T}\cdot{}^1_2\boldsymbol{T}\cdot{}^2_3\boldsymbol{T}\cdot{}^3_4\boldsymbol{T}\cdot{}^4_5\boldsymbol{T}\cdot{}^5_6\boldsymbol{T}. \tag{2}$$

According to the Table I, we can obtain bellow matrices

$$ {}^0_1\boldsymbol{T} = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 290 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$ {}^1_2\boldsymbol{T} = \begin{bmatrix} c(\theta_2-90^o) & -s(\theta_2-90^o) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s(\theta_2-90^o) & -c(\theta_2-90^o) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$ {}^2_3\boldsymbol{T} = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & 270 \\ s\theta_3 & c\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$ {}^3_4\boldsymbol{T} = \begin{bmatrix} c\theta_4 & -s\theta_4 & 0 & 70 \\ 0 & 0 & 1 & 302 \\ -s\theta_4 & -c\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$ {}^4_5\boldsymbol{T} = \begin{bmatrix} c\theta_5 & -s\theta_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s\theta_5 & c\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \text{ and}$$

$$ {}^5_6\boldsymbol{T} = \begin{bmatrix} c(\theta_6+180^o) & -s(\theta_6+180^o) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ s(\theta_6+180^o) & c(\theta_6+180^o) & 0 & 72 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

B. *Kinematic Error Model*

In fact, it is inevitably to bring some errors to the robot manipulator, such as manufacturing errors, installation errors, encoder errors, wear, and so on. When two adjacent joints are near parallel, only a small angle deviation between them will causes dramatically change in the kinematic parameters, as shown in Fig. 2. The D-H parameters change from $a_{(i-1)}=l$, $d_i=0$, $\alpha_{(i-1)}=0$ to $a_{(i-1)}=0$, $d_i=l/\sin(\beta)$, $\alpha_{(i-1)}=\beta_i$. That is, Equation (1) is not suitable in this case. To solve this problem, a small rotation β_i about the y-axis is introduced. When the two adjacent joints are parallel, the nominal value $\beta_i=0$. Therefore, the modified transformation matrix ${}^{i-1}_i\boldsymbol{T}$ from frame $\{i\}$ to frame $\{i-1\}$ can be described by

$$ {}^{i-1}_i\boldsymbol{T} = Rot(X,\alpha_{i-1})Trans(X,a_{i-1})Rot(Z,\theta_i)Trans(Z,d_i)Rot(Y,\beta_i)$$
$$ = \begin{pmatrix} c\theta_i c\beta_i & -s\theta_i & c\theta_i s\beta_i & a_{i-1} \\ s\theta_i c\alpha_{i-1}c\beta_i + s\alpha_{i-1}s\beta_i & c\theta_i c\alpha_{i-1} & s\theta_i c\alpha_{i-1}s\beta_i - s\alpha_{i-1}c\beta_i & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1}c\beta_i - c\alpha_{i-1}s\beta_i & c\theta_i s\alpha_{i-1} & s\theta_i s\alpha_{i-1}s\beta_i + c\alpha_{i-1}c\beta_i & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{3}$$

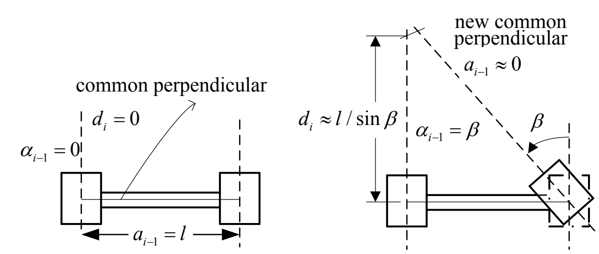

Fig. 2 The Schematic diagram of a small angle deflection between two parallel adjacent joints.

As shown in Fig.1, the joint 2 and joint 3 of the robot are parallel, so ${}^2_3\boldsymbol{T}$ is should be modified according to (3), adding a parameter β_3, the modified ${}^2_3\boldsymbol{T}$ is named ${}^2_3\boldsymbol{T}'$.

In general, the pose accuracy of robots is mainly influenced by the geometric errors, including the errors of link length, link twist, link offset, joint angle and deviation angle, named Δa_i, $\Delta\alpha_i$, Δd_i and $\Delta\theta_i$ and $\Delta\beta_i$. Hence, the kinematic calibration of robots is mainly to identify above error parameters in the current research. And the laser tracker is widely adopted for the robot's calibration. It should be noted that during accuracy calibration, the measuring coordinate frame {m} and tool coordinate frame {t} are needed to established, besides the base frame and local coordinate frame fixed on the each link, as shown in Fig. 3. Because the measuring data is with respect to the measuring coordinate frame. Under the ideal condition, the measuring coordinate frame {m} matches with the base frame {0} of the robot. It fact, however, there are some deviation between them. Therefore, a transformation matrix ${}^m_0\boldsymbol{T}$ from frame {0} to frame {m} is needed to be introduced. Similarly, using the four parameters, ${}^m_0\boldsymbol{T}$ can be described as

$$ {}^m_0\boldsymbol{T}=\begin{pmatrix} c\theta_0 & -s\theta_0 & 0 & a_m \\ s\theta_0 c\alpha_m & c\theta_0 c\alpha_m & -s\alpha_m & -d_0 s\alpha_m \\ s\theta_0 s\alpha_m & c\theta_0 s\alpha_m & c\alpha_m & d_0 c\alpha_m \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{4} $$

where, a_m, α_m, d_0 and θ_0 are the parameters needed to be identified, and their theoretical values are zero, respectively.

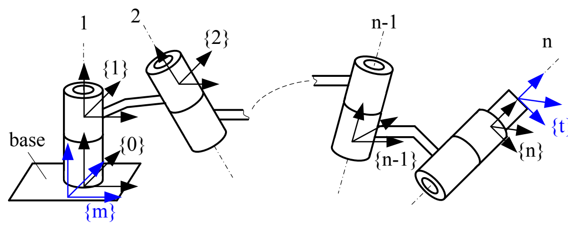

Fig. 3 The measuring coordinate frame and tool coordinate frame.

During measuring, the sphere-cally mounted refection (SMR) of the laser tracker is mounted on the robot's end-effector with the supplementary mounting plate. The tool coordinate frame is established on the center point of the SMR. Similarly, a transformation matrix ${}^6_t\boldsymbol{T}$ is introduced to describe the transformation from frame {t} to frame {6},

$$ {}^6_t\boldsymbol{T}=\begin{bmatrix} 1 & 0 & 0 & p_{xt} \\ 0 & 1 & 0 & p_{yt} \\ 0 & 0 & 1 & p_{zt} \\ 0 & 0 & 0 & 1 \end{bmatrix}^T. \tag{5} $$

where, (p_{xt}, p_{yt}, p_{zt}) is the origin of the coordinate frame {t} fixed on the center point of the SMR with respect to the frame {6}. Hence, the center point P of the SMR with respect to the frame {t} is ${}^t\boldsymbol{P}=[0,0,0,1]^T$. The overall transformation matric for measurement can be represented by

$$ {}^m_t\boldsymbol{T}={}^m_0\boldsymbol{T}\cdot{}^0_1\boldsymbol{T}\cdot{}^1_2\boldsymbol{T}\cdot{}^2_3\boldsymbol{T}'\cdot{}^3_4\boldsymbol{T}\cdot{}^4_5\boldsymbol{T}\cdot{}^5_6\boldsymbol{T}\cdot{}^6_t\boldsymbol{T}. \tag{6} $$

The position of the SMR with respect to the frame {m} can be calculated by

$$ {}^m\boldsymbol{P}={}^m_0\boldsymbol{T}\cdot{}^0_1\boldsymbol{T}\cdot{}^1_2\boldsymbol{T}\cdot{}^2_3\boldsymbol{T}'\cdot{}^3_4\boldsymbol{T}\cdot{}^4_5\boldsymbol{T}\cdot{}^5_6\boldsymbol{T}\cdot{}^6_t\boldsymbol{T}\cdot{}^t\boldsymbol{P}. \tag{7} $$

And the positioning error of the robot can be calculated by

$$ \Delta\boldsymbol{P}=\boldsymbol{P}_{actual}-\boldsymbol{P}_{no\min al}. \tag{8} $$

where, $\boldsymbol{P}_{no\min al}$ represents the theoretical value of position obtained by substituting the nomination values of the parameters into (7), and the $\boldsymbol{P}_{actual}$ represents the actual value of position, which can be obtained by substituting the actual values of the parameters into (7), or by measurement.

Assume that the geometric errors are small enough, the mapping relationship between the positioning error of robot's end-effect and geometric error parameters can be described by differential equations,

$$ \Delta\boldsymbol{P}=\sum_{i=-1}^{5}\frac{\partial\boldsymbol{P}}{\partial\alpha_i}\Delta\alpha_i+\sum_{i=-1}^{5}\frac{\partial\boldsymbol{P}}{\partial a_i}\Delta a_i+\sum_{i=0}^{6}\frac{\partial\boldsymbol{P}}{\partial\theta_i}\Delta\theta_i+\sum_{i=0}^{6}\frac{\partial\boldsymbol{P}}{\partial d_i}\Delta d_i+\frac{\partial\boldsymbol{P}}{\partial\beta_3}\Delta\beta_3. \tag{9} $$

where, in order to describe easily, the subscripts of parameters of frame {m} are used "-1" instead of "m", for example, a_{-1} replace a_m in description.

Equation (9) can be described in matrix form,

$$ \Delta\boldsymbol{P}=\boldsymbol{J}_\delta\Delta\boldsymbol{\delta}. \tag{10} $$

where, $\Delta\boldsymbol{P}=\left[\Delta p_x,\Delta p_y,\Delta p_z\right]^T$, $\Delta\boldsymbol{\delta}$ is a 29×1 matrix with error parameters, and $\boldsymbol{J}_\delta$ is a 3×29 coefficient matrix,

$$ \boldsymbol{J}_\delta=\begin{bmatrix} \frac{\partial p_x}{\partial a_{-1}} & \cdots & \frac{\partial p_x}{\partial a_5} & \frac{\partial p_x}{\partial d_0} & \cdots & \frac{\partial p_x}{\partial d_6} & \frac{\partial p_x}{\partial\alpha_{-1}} & \cdots & \frac{\partial p_x}{\partial\alpha_5} & \frac{\partial p_x}{\partial\theta_0} & \cdots & \frac{\partial p_x}{\partial\theta_6} & \frac{\partial p_x}{\partial\beta_3} \\ \frac{\partial p_y}{\partial a_{-1}} & \cdots & \frac{\partial p_y}{\partial a_5} & \frac{\partial p_y}{\partial d_0} & \cdots & \frac{\partial p_y}{\partial d_6} & \frac{\partial p_y}{\partial\alpha_0} & \cdots & \frac{\partial p_y}{\partial\alpha_5} & \frac{\partial p_y}{\partial\theta_0} & \cdots & \frac{\partial p_y}{\partial\theta_6} & \frac{\partial p_y}{\partial\beta_3} \\ \frac{\partial p_z}{\partial a_{-1}} & \cdots & \frac{\partial p_z}{\partial a_5} & \frac{\partial p_z}{\partial d_0} & \cdots & \frac{\partial p_z}{\partial d_6} & \frac{\partial p_z}{\partial\alpha_{-1}} & \cdots & \frac{\partial p_z}{\partial\alpha_5} & \frac{\partial p_z}{\partial\theta_0} & \cdots & \frac{\partial p_z}{\partial\theta_6} & \frac{\partial p_z}{\partial\beta_3} \end{bmatrix} $$

$$ \Delta\boldsymbol{\delta}=\left[\Delta a_{-1},\cdots,\Delta a_5,\Delta d_0,\cdots,\Delta d_6,\Delta\alpha_{-1},\cdots,\Delta\alpha_5,\Delta\theta_0,\cdots,\Delta\theta_6,\Delta\beta_3\right]. $$

Equation (10) is named the error model for robot calibration. Therefore, the error parameters can be identified by

$$ \Delta\boldsymbol{\delta}=\boldsymbol{J}_\delta^{-1}\cdot\Delta\boldsymbol{P}. \tag{11} $$

Equation (11) is named the error identification model.

When the error parameter $\Delta\boldsymbol{\delta}$ is identified, the actual transformation matrix ${}^m_t\boldsymbol{T}_{actural}$ can be calculated.

C. Error Compensation Model

Most of controllers of the industrial robots can't be accessed to change the parameter for operators directly. Therefore, the error influence of the error parameters, which can't be compensate directly, is equivalent to the influence of the joint angles errors, and then by compensating the joint angles indirectly to improve the robot's accuracy. When the joint angle errors is small enough, the relationship between the positioning errors and the joint angles can be described as

$$ \Delta\boldsymbol{P}=\sum_{i=0}^{6}\frac{\partial\boldsymbol{P}_{actual}}{\partial\theta_i}\Delta\theta_i=\boldsymbol{J}_\theta\Delta\boldsymbol{\theta}. \tag{12} $$

where, $\Delta\boldsymbol{P}$ is a 3×1 matrix, $\boldsymbol{J}_\theta$ is a 3×6 coefficient matrix, and $\Delta\boldsymbol{\theta}$ is a 6×1 matrix, $\Delta\boldsymbol{\theta}=\left[\theta_1,\cdots,\theta_6\right]^T$.

$$ \Delta\boldsymbol{\theta}=\boldsymbol{J}_\theta^{-1}\cdot\Delta\boldsymbol{P}. \tag{13} $$

Therefore, the correction joint angles sent to the robot controller are calculated by

$$ \theta_i'=\theta_i-\Delta\theta_i. \tag{14} $$

Equation (13) is named the error compensation model.

III. Simulation and Analysis

A. Verification of Error Model

To verify the feasibility of the error model, the simulation experiments were conducted.

Firstly, the values of error parameters were given, including the geometric error parameters and the deviation errors of the frame {m}, as shown in Table II.

TABLE II
THE GIVEN VALUES OF THE ERROR PARAMETERS

i	Δa_{i-1}(mm)	Δd_i(mm)	$\Delta\alpha_{i-1}$(rad)	$\Delta\theta_i$(rad)	$\Delta\beta_i$(rad)
0	0.010	0.010	0.0001	0.0001	-
1	0.010	0.012	0.0001	0.0001	-
2	0.015	0.023	0.0001	0.0002	-
3	0.022	0.048	0.0003	0.0004	0.0002
4	0.038	0.062	0.0002	0.0005	-
5	0.052	0.039	0.0005	0.0006	-
6	0.046	0.040	0.0004	0.0006	-

Secondly, 15 robot configurations were selected among the robot's workspace. According to (7) and Table I, the nominal values of robot configurations were obtained, namely $\boldsymbol{P}_{nominal}$. And the actual values of parameters, equal to the summation of the nominal value and the given errors of the each parameter, were substituted into the (7), and the actual values of the robot configurations were obtained, namely $\boldsymbol{P}_{actual}$. Finally, positioning errors of the configurations were obtained according to (8).

Thirdly, according to (9), the presented error model, the another actual values of the robot configurations were obtained, namely $\boldsymbol{P}^{'}_{actual}$. Similarly, the positioning errors $\Delta\boldsymbol{P}^{'}$ of the configurations were obtained. The results are shown in Table III. The maximum of the deviation between the $\Delta\boldsymbol{P}$ and $\Delta\boldsymbol{P}^{'}$ is 0.0003mm, approximately 0.14%. That is, the presented error model in this study is feasible.

TABLE III
THE SIMULATION RESULTS OF THE ERROR MODEL

No.	$\Delta\boldsymbol{P}$ (mm)			$\Delta\boldsymbol{P}^{'}$ (mm)		
	Δp_x	Δp_y	Δp_z	Δp_x	Δp_y	Δp_z
1	-0.2313	0.2549	-0.1106	-0.2315	0.2549	-0.1103
2	-0.1311	0.3066	-0.0882	-0.1313	0.3066	-0.0880
3	-0.2876	-0.1631	-0.0202	-0.2876	-0.1632	-0.0201
4	-0.1482	0.3302	-0.1521	-0.1484	0.3302	-0.1519
5	0.0228	0.2990	-0.1355	0.0225	0.2991	-0.1354
6	0.2943	0.1151	-0.1635	0.2942	0.1153	-0.1634
7	0.3145	0.2052	-0.1937	0.3144	0.2054	-0.1936
8	0.1528	0.3447	-0.2431	0.1527	0.3449	-0.2429
9	0.0279	0.3216	-0.1184	0.0277	0.3217	-0.1183
10	-0.0353	0.3207	-0.2680	-0.0355	0.3208	-0.2677
11	0.2879	-0.3497	-0.2166	0.2882	-0.3495	-0.2166
12	0.1113	0.2953	-0.1090	0.1110	0.2954	-0.1089
13	0.1041	0.2821	-0.1666	0.1038	0.2822	-0.1665
14	0.0101	0.2899	-0.0699	0.0099	0.2899	-0.0698
15	0.2926	-0.2606	-0.0346	0.2927	-0.2604	-0.0346

B. Verification of Error Identification Model

According to (11), the error parameters were identified based on least square method, using the error coefficient matrix $\boldsymbol{J}_{\delta}$ and actual positioning errors $\Delta\boldsymbol{P}$ of the 15 configurations. The identified results are shown in Table IV. Compared with the Table II, most of the error parameters could be identified, except a few parameters.

TABLE IV
THE IDENTIFIED VALUES OF THE ERROR PARAMETERS

i	Δa_{i-1}(mm)	Δd_i(mm)	$\Delta\alpha_{i-1}$(rad)	$\Delta\theta_i$(rad)	$\Delta\beta_i$(rad)
0	0.020	0	0.0002	0.0002	-
1	0	0.022	0	0	-
2	0.015	0.072	0.0001	0.0002	-
3	0.022	0	0.0003	0.0004	0.0002
4	0.039	0.062	0.0002	0.0005	-
5	0.052	0	0.0005	0	-
6	0	0.040	0.0009	0	-

Hence, another simulation experiment was conducted. Another given values and the identified results of the error parameters are shown in Table V and Table VI, respectively.

TABLE V
ANOTHER SET OF THE GIVEN VALUES OF THE ERROR PARAMETERS

i	Δa_{i-1}(mm)	Δd_i(mm)	$\Delta\alpha_{i-1}$(rad)	$\Delta\theta_i$(rad)	$\Delta\beta_i$(rad)
0	0.100	-0.050	0.0010	0.0014	-
1	0.100	-0.050	0.0010	0.0014	-
2	-0.080	0.110	0.0014	-0.0023	-
3	-0.120	0.060	-0.0012	0.0017	0.0002
4	0.030	0.130	0.0017	0.0010	-
5	0.070	-0.040	0.0010	-0.0014	-
6	-0.140	0.050	-0.0010	0.0010	-

TABLE VI
ANOTHER SET OF THE IDENTIFIED VALUES OF ERROR PARAMETERS

i	Δa_{i-1}(mm)	Δd_i(mm)	$\Delta\alpha_{i-1}$(rad)	$\Delta\theta_i$(rad)	$\Delta\beta_i$(rad)
0	0.201	0	0.0020	0.0028	-
1	0	-0.098	0	0	-
2	-0.080	0.179	0.0014	-0.0023	-
3	-0.120	0	-0.0012	0.0017	0.0002
4	0.034	0.127	0.0017	0.0010	-
5	0.069	0	0.0010	0.0005	-
6	0	0.050	-0.0016	0	-

Compared with the Table II and IV, Table V and VI, it was found that,

$$\begin{cases} \Delta a_{-1}^{c} + \Delta a_{0}^{c} \approx \Delta a_{-1}^{n} + \Delta a_{0}^{n} \\ \Delta d_{0}^{c} + \Delta d_{1}^{c} \approx \Delta d_{0}^{n} + \Delta d_{1}^{n} \\ \Delta d_{2}^{c} + \Delta d_{3}^{c} \approx \Delta d_{2}^{n} + \Delta d_{3}^{n} \\ \Delta \alpha_{-1}^{c} + \Delta \alpha_{0}^{c} \approx \Delta \alpha_{-1}^{n} + \Delta \alpha_{0}^{n} \\ \Delta \theta_{0}^{c} + \Delta \theta_{1}^{c} \approx \Delta \theta_{0}^{n} + \Delta \theta_{1}^{n} \end{cases} . \tag{15}$$

where, the superscript c represents the given error value, and the superscript n represents the identified error value.

Because of the redundancy to the parameters, the error model can't identify some error parameters and it will affect the accuracy in the kinematic calibration. This will not be expanded in detail in this paper.

C. *Verification of Error Compensation Method*

According to the two sets of given error parameters, as shown in Table II and Table V, the compensation simulation were conducted. The results are shown in Table VII. For the first set, after compensation the mean of the positioning errors is reduced from 0.3747mm to 0.0002mm, and the compensation rate is more than 99.95%. And for the second set, after compensation, the mean of the positioning errors is reduced from 0.8924mm to 0.0017mm, and the compensation rate is more than 99.81%. It can have a significant improvement of accuracy after compensation. That is, the presented compensation method is effective.

TABLE VII
THE SIMULATION RESULTS OF THE ERROR COMPENSATION FOR TWO SETS

Joint angles (°)	The first set		The second set	
	before	after	before	after
(42,11,45,0,26,12)	0.3616	0.0002	0.9667	0.0022
(30,30,30,30,30,30)	0.3450	0.0002	1.0260	0.0019
(111,29,46,33,78,61)	0.3313	0.0002	1.5295	0.0057
(19,22,44,-17,26,54)	0.3926	0.0002	0.8453	0.0015
(14,-3,26,-10,55,21)	0.3291	0.0002	0.4910	0.0005
(-22,42,-44,7,48,-10)	0.3557	0.0003	0.3338	0.0002
(-37,3,43,-1,3,-51)	0.4225	0.0003	0.8444	0.0011
(-15,60,-5,-10,-10,15)	0.4486	0.0002	0.9206	0.0009
(16,30,11,27,8,10)	0.3439	0.0001	0.7202	0.0008
(11,54,-15,-42,45,-2)	0.4194	0.0002	0.7415	0.0006
(-130,-15,55,-26,19,6)	0.5021	0.0005	1.8278	0.0069
(10,10,10,10,10,10)	0.3339	0.0002	0.6059	0.0006
(10,-20,30,-30,40,-40)	0.3437	0.0003	0.6217	0.0008
(22,32,-12,25,41,26)	0.2984	0.0001	1.0125	0.0015
(-80,-20,14,63,24,7)	0.3933	0.0003	0.8996	0.0010

IV. EXPERIMENT AND RESULTS

To verify the feasibility of the above error model and compensation method, an experiment was carried out on a 6-DOF serial robot, an ABB IRB 120 robot. The experiment consisted of three parts: error measurement, error identification, and error compensation. Fig. 4 shows the installation that was used for error compensation of positioning accuracy for an ABB IRB 120 robot with a Leica laser tracker.

Firstly, the measuring coordinate frame {m} was established according to the fitted center line of rotation about

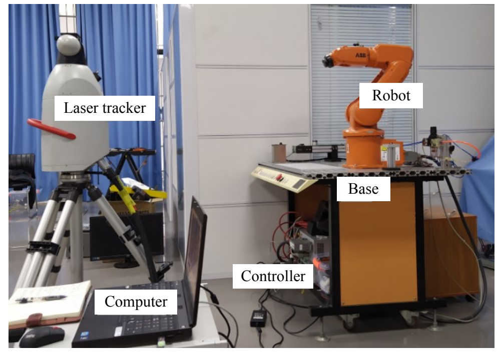

Fig. 4 The experimental setup for the error compensation of the robot.

joint 1, the line generated by translation motion along X-axis with respect to frame {0}, and the setting surface for the robot base. There were some deviations between the frame {m} and frame {0}, which had been discussed in Section II. The four error parameters will be identified with the geometric error parameters.

Secondly, the parameters of the frame {t} were identified. According to the geometric invariance, the distance of the two points in the space is a certain value regardless of coordinate frames,

$$\left|{}^{i}\boldsymbol{P}_1 - {}^{i}\boldsymbol{P}_2\right| = \left|{}^{m}\boldsymbol{P}_1 - {}^{m}\boldsymbol{P}_2\right|. \qquad (16)$$

where, ${}^{i}\boldsymbol{P}$ is the nominal position with respect to the frame $\{i\}$, and ${}^{m}\boldsymbol{P}$ is the measuring position by laser tracker with respect to frame {m}.

To reduce influence of errors, the single axis movement was selected during measurement for parameter identification of the frame {t}. In this study, the joint 5 was selected, other joint angles were set to zero, when rotation of the joint 5, the SMR was rotating follow the frame {5}. And the relationship was described with respect to the frame {4},

$$\left|{}^{4}_{5}\boldsymbol{T}(\theta_1)\cdot{}^{5}_{6}\boldsymbol{T}\cdot{}^{6}_{t}\boldsymbol{T}\cdot{}^{t}\boldsymbol{P} - {}^{4}_{5}\boldsymbol{T}(\theta_2)\cdot{}^{5}_{6}\boldsymbol{T}\cdot{}^{6}_{t}\boldsymbol{T}\cdot{}^{t}\boldsymbol{P}\right| = \left|{}^{m}\boldsymbol{P}_1 - {}^{m}\boldsymbol{P}_2\right| \quad (13)$$

where, ${}^{m}\boldsymbol{P}_i$ represents the measuring value of the point P_i by the laser tracker, ${}^{4}_{5}\boldsymbol{T}(\theta_i)$ represents the transformation matrix from frame {5} to frame {4}, when the joint angle of joint 5 rotates θ_i, $\theta_1 = 0^o$, $\theta_2 = 90^o$. The measured data were obtained, ${}^{m}\boldsymbol{P}_1 = [391.15, 0.92, 633.09]$ and ${}^{m}\boldsymbol{P}_2 = [301.70, 0.68, 542.92]$. Therefore, the parameters of the frame {t} was obtained, ${}^{6}_{t}T = [0, 0, 17.8109, 1]$.

Thirdly, two sets of robot configurations were measured by laser tracker, each set included 15 robot configurations distributing in the robot's workspace. One set was used to identify the error parameters, and the other was used as supplement data to verify the effectiveness of the compensation. The position commands sent to the robot were joint angles using the instruction MoveAbsJ. And then the error parameters were identified using the data of the first set according to (11).

Fourthly, the compensation experiment was conducted. By substituting the actual geometric parameter into (7), the function $\boldsymbol{P}_{actual}$ about θ_i were obtained. According to (13) and (14), the correction joint angles $\theta_i^{'}$ of the two sets of configurations were calculated, respectively.

Finally, the correction joint angles of the two sets were set to the robot's controller and the positions were measured again, respectively.

The positioning errors of two sets before and after compensation are shown in Fig. 5. The measured results were compared, as shown in Table VIII. It can be seen that for the first set, after compensation, the mean/maximum of positioning error is reduced from 0.9509mm/0.8080mm to 0.1912mm/0.1300mm, the mean of compensation rate is more than 79.89%, and the maximum is 83.91%. For the second set, after compensation, the mean/maximum of positioning error is reduced from 0.8996mm/0.7669mm to 0.2345mm/0.1655mm, the mean of compensation rate is more than 73.94%, and the maximum is 78.42%. These clearly show that the presented error model and compensation method are effective, and thus can be readily used to improve the robot's accuracy.

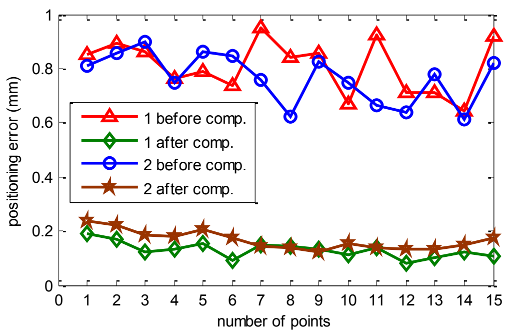

Fig. 5 The positioning errors of two sets before and after compensation.

TABLE VIII
COMPARISON OF MEASURED RESULTS BEFORE AND AFTER COMPENSATION

errors	The first set			The Second set		
	before	after	rate(%)	before	after	rate(%)
mean	0.9509	0.1912	79.89	0.8996	0.2345	73.94
max	0.8080	0.1300	83.91	0.7669	0.1655	78.42

V. CONCLUSIONS

This paper presented an absolute positioning error modeling and compensation method considering measuring errors for a 6-DOF industrial robot. Firstly, the error modeling of a 6-DOFserial robot based on the modified D-H method was established, it took into account the geometric errors and measuring errors. And then the compensation method based on the joint angles was introduced. Secondly, the simulation experiments were adopted to verify the feasibility and effectiveness of the compensation method. Finally, the error compensation experiments were conducted, including the measurement, error identification and error compensation. The results show that after compensation, the compensation rate is more than 73.94%. The accuracy of the robot can have a significant improvement. Hence, the error modeling and compensation method presented in this study is sensible and effective, and could be used for the error compensation to improve absolute positioning accuracy of the industrial robots.

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