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Influence of Geometric Errors and Measuring Errors on Positioning Accuracy of an Industrial Robot*

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***Abstract* - This paper discusses the influence of geometric error parameters and measuring error parameters on the positioning accuracy of an industrial robot. Firstly, the kinematic model of a 6-DOF industrial robot based on the modified Denavit-Hartenberg (D-H) parameter method was established. Secondly, the influence of the geometric error parameters on the positioning accuracy of the robot's end-effector is analyzed by simulation experiments in detail, including the link length errors, link twist errors, link offset errors and joint angle errors. And then the influence of measuring error parameters is also discussed. The results show that under individual effect of the linear errors, the length of positioning error of the robot's end-effector is equal to the value of the corresponding error parameter. However, the angle errors have remarkable amplification effects on the accuracy of the robot. Moreover, it should be noted that the influence of measuring error parameters on the positioning accuracy of the robot is on the same order of magnitude as that of the geometric error parameters. Therefore, the measuring errors parameters should be taken into account during kinematic calibration.**

Keyword – Industrial robot, Kinematic model, Positioning accuracy, Geometric errors, Measuring errors.

I. Introduction

With the development of the manufacturing technologies, the demand for industrial robots with higher accuracy has been growing continuously [1, 2]. In general, the repeatability of robotic manipulator is higher than its absolute position accuracy [3, 4]. In the past decade, the poses of the robot end-effector have been manually taught by off-line programming, so the accuracy of a robot is not important. However, on-line robot programming is becoming more and more important for recent flexible manufacture system [5, 6]. Therefore, the calibration of robots must be seriously considered in order to improve the accuracy of the robots.

There are two types of robot calibration method, including kinematic and non-kinematic calibration. The kinematic calibration is based on the identification and compensation of the errors related to robot's kinematic parameters [7]. The source of kinematic error associated with the geometric parameters includes the manufacturing errors, installation errors and encoder errors and so on[8-11]. Previous researches have shown that the geometric error takes a high proportion in the total errors, more than 80%. Thus the kinematic calibration of a robot is mainly to study the geometric error parameters.

The kinematic model for robots, which is widely adopted, is the Denavit-Hartenberg (D-H) model [12, 13]. The model can describe a robot's kinematics using four parameters for each link, including the link length, link twist, link offset and joint angle. However, when two adjacent joints are near parallel, only a small angle deviation between them will causes significant change in the kinematic parameters [14]. To solve the problem, a modified D-H model by introducing a rotation around the y-axis was proposed [15]. And then the S model using six parameters [16], Product of Exponentials (POE) model [17], CPC model [18] were presented.

Recently, the laser tracking measurement system is widely adopted for kinematic calibration of the industrial robots. And it is unavoidable to bring in some measuring errors, such as the errors caused by establishment of measuring coordinate frame and tool coordinate frame where the sphere-cally mounted refection (SMR) is installed.

Therefore, this paper will focus on discussing the influence of the geometric errors and the measuring errors on the positioning accuracy of an industrial robot. To this end, Section 2 of the paper will establish a kinematic model for a 6-DOF robot based on the modified D-H method. In Section 3, the influence of the geometric errors on the positioning accuracy of the robot will be analyzed by simulation in detail. And Section 4 will analyze the influence of the measuring errors on the accuracy of the robot. Finally, the paper will end with a brief conclusion.

II. Kinematic Model for Industrial Robots

Among the existing modeling techniques, a widely adopted approach for kinematic analysis of robots is the D-H model. Hence, this paper chose the model to analyze the positioning error for the end-effector of an industrial robot.

The homogeneous transformation matrix can be used to describe the position and orientation. The position of point P

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with respect to coordination frame $\{A\}$ can be represented as

$$^{A}\mathbf{P} = [P_x \quad P_y \quad P_z \quad 1]^T .$$

The rotational transformation matrices around x-axis, y-axis and z-axis can be described as follows,

$$Rot_X(\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) & 0 \\ 0 & \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$Rot_Y(\theta) = \begin{pmatrix} \cos(\theta) & 0 & \sin(\theta) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$Rot_Z(\theta) = \begin{pmatrix} \cos(\theta) & -\sin(\theta) & 0 & 0 \\ \sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

where, θ is the rotation angle. The translational transformation matrices along x-axis, y-axis and z-axis can be described as

$$Trans_X(d) = \begin{pmatrix} 1 & 0 & 0 & d \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \; Trans_Y(d) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & d \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$Trans_Z(d) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

Assume that a robot can be treated as a multi-body system composed of a few rigid bodied with a kinematic chain. The coordinate frames are established to the links of the robot in order to describe the kinematic transformation relationship. The four kinematic parameters based on D-H method are used to describe two adjacent links. The definition of D-H parameters is shown in Fig. 1. There are link length a_{i-1}, link twist α_{i-1}, link offset d_i, and joint angle θ_i. The homogeneous transformation matrix ${}^{i-1}_{i}T$ from the link (i) to link $(i-1)$ can be expressed as follows,

$$\begin{aligned} {}^{i-1}_{i}\boldsymbol{T} &= Rot_X(\alpha_{i-1})Trans_X(a_{i-1})Rot_Z(\theta_i)Trans_Z(d_i) \\ &= \begin{pmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} . \end{aligned} \quad (1)$$

where, $s\theta_i$, $c\theta_i$, $s\alpha_{i-1}$ and $c\alpha_{i-1}$ represent $\sin(\theta_i)$, $\cos(\theta_i)$, $\sin(\alpha_{i-1})$ and $\cos(\alpha_{i-1})$, respectively (the same below).

However, when two adjacent joints of the robot are parallel, a small angle deflection with one of joints will bring great position change of the common perpendicular. That is, Equation (1) is singular in this case. Hence, in order to solve this problem, a rotation angle β around the y-axis is taken into account. The transformation matrix between two adjacent parallel joints can be represented as

$$\begin{aligned} {}^{i-1}_{i}\boldsymbol{T} &= Rot_X(\alpha_{i-1})Trans_X(a_{i-1})Rot_Z(\theta_i)Trans_Z(d_i)Rot_y(\beta_i) \\ &= \begin{pmatrix} c\theta_i c\beta_i & -s\theta_i & c\theta_i s\beta_i & a_{i-1} \\ s\theta_i c\alpha_{i-1} c\beta_i + s\alpha_{i-1} s\beta_i & c\theta_i c\alpha_{i-1} & s\theta_i c\alpha_{i-1} s\beta_i - s\alpha_{i-1} c\beta_i & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} c\beta_i - c\alpha_{i-1} s\beta_i & c\theta_i s\alpha_{i-1} & s\theta_i s\alpha_{i-1} s\beta_i + c\alpha_{i-1} c\beta_i & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} . \end{aligned} \quad (2)$$

The above formula is named the modified D-H model.

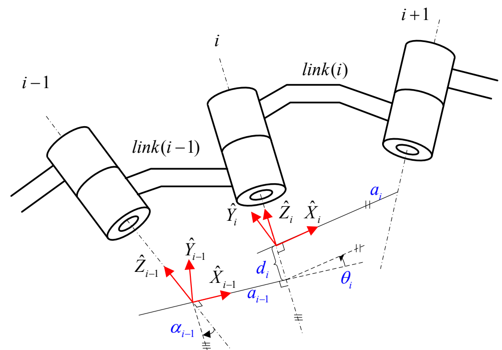

Fig. 1 The definition of D-H parameters.

To explain the modeling approach based on the modified D-H model, a 6-DOF serial robot was taken as an example. Firstly, the coordinate system of the robot was established, is shown in Fig. 2. And the nominal modified D-H kinematic parameters of the robot are shown in Table 1.

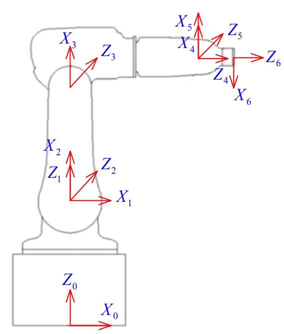

Fig. 2 The coordinate system of the robot.

TABLE I

THE NOMINAL MODIFIED D-H KINEMATIC PARAMETERS

Link (i)	α_{i-1} (rad)	a_{i-1} (mm)	θ_i (rad)	d_i (mm)	β_i (rad)
1	0	0	θ_1	290	-
2	- π /2	0	θ_2 - π /2	0	-
3	0	270	θ_3	0	0
4	- π /2	70	θ_4	302	-
5	π /2	0	θ_5	0	-
6	- π /2	0	$\theta_6 + \pi$	72	-

The overall transformation matrix ${}^{0}_{6}\boldsymbol{T}$ from last link to the first link is represented as

$${}^{0}_{6}\boldsymbol{T} = {}^{0}_{1}\boldsymbol{T} \cdot {}^{1}_{2}\boldsymbol{T} \cdot {}^{2}_{3}\boldsymbol{T} \cdot {}^{3}_{4}\boldsymbol{T} \cdot {}^{4}_{5}\boldsymbol{T} \cdot {}^{5}_{6}\boldsymbol{T} . \quad (3)$$

By substituting the data from Table I into the (3), the ideal kinematic model of the robot is obtained. That is, we can calculate the position and orientation of the end-effector with respect to the base frame $\{0\}$.

III. Influence of Geometric Error Parameters on Positioning Accuracy

According to (1), the position of the robot's end-effector is a function of the parameters a_i, d_i, α_i, θ_i and β_i. However, there are some deviations of the parameters between the actual value and the nominal value, caused by manufacturing, installation, wear, and so on. The deviations are expressed as Δa_i, Δd_i, $\Delta\alpha_i$, $\Delta\theta_i$ and $\Delta\beta_i$, and then the actual value of the parameters can be expressed as

$$\begin{cases} a_i^{'} = a_i + \Delta a_i, \ d_i^{'} = d_i + \Delta d_i, \ \alpha_i^{'} = \alpha_i + \Delta\alpha_i \\ \theta_i^{'} = \theta_i + \Delta\theta_i, \ \beta_i^{'} = \beta_i + \Delta\beta_i \end{cases}. \quad (4)$$

To study the influence of geometric error parameters on positioning accuracy, the simulation experiments were adopted. Firstly, the intervals of geometric error parameters were given as shown in Table II.

TABLE II
THE GIVEN INTERVALS OF GEOMETRIC ERROR PARAMETERS

i	Δa_{i-1} (mm)	$\Delta\alpha_{i-1}$ (rad)	Δd_i (mm)	$\Delta\theta_i$ (rad)	$\Delta\beta_i$ (rad)
1	[0, 0.100]	[0, 0.0010]	[0, 0.100]	[0, 0.0010]	-
2	[0, 0.100]	[0, 0.0010]	[0, 0.100]	[0, 0.0010]	-
3	[0, 0.100]	[0, 0.0010]	[0, 0.100]	[0, 0.0010]	[0, 0.0010]
4	[0, 0.100]	[0, 0.0010]	[0, 0.100]	[0, 0.0010]	-
5	[0, 0.100]	[0, 0.0010]	[0, 0.100]	[0, 0.0010]	-
6	[0, 0.100]	[0, 0.0010]	[0, 0.100]	[0, 0.0010]	-

A. *Influence of Δa_i and Δd_i*

A point in the workspace was selected, named P_1, Its joint angles are [30° 45° 30° 45° -30° 60°]. Each of link length error parameter Δa_i changed in [0, 0.100]mm, respectively. And others error parameters were set to zero. According to (3), the ideal position (x, y, z) and actual positions $(x^{'}, y^{'}, z^{'})$ were calculated, and then the positioning accuracy of end-effector was calculated by

$$\Delta p = \sqrt{(x^{'} - x)^2 + (y^{'} - y)^2 + (z^{'} - z)^2}. \quad (5)$$

It also can be named the length of positioning error vector. And the positioning error along the x-axis, y-axis and z-axis can be calculated by

$$E_x = x^{'} - x, \quad E_y = y^{'} - y, \quad E_z = y^{'} - y. \quad (6)$$

The simulation results are shown in Fig. 3 to Fig. 7. According to Fig. 3, it can be seen that the influence of each link length error Δa_i $(i = 0, \cdots, 5)$ on positioning accuracy equal to the value of Δa_i. Namely, the lengths of position error increase with the increase of Δa_i, and it is 1:1 linear relationship. Let's look at the red line, which of legend is Δa in the Fig. 3, it is the positioning accuracy affected by all of the six link length errors simultaneously, it is bigger than that affected by any single error parameter. However, its length isn't the summation of all error lengths influenced by single error parameter respectively. According to Fig. 4 Fig. 6, it can be seen that the positioning error vector, influenced by the all six link length error, approximately equal to the summation of the six error vectors influenced by single error parameter, respectively. The deviations between them are shown in Fig. 7.

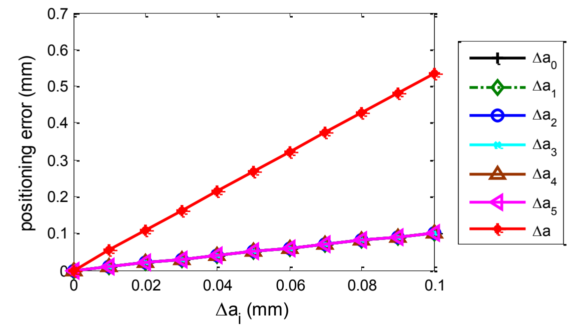

Fig. 3 The positioning accuracy influenced by Δa_i

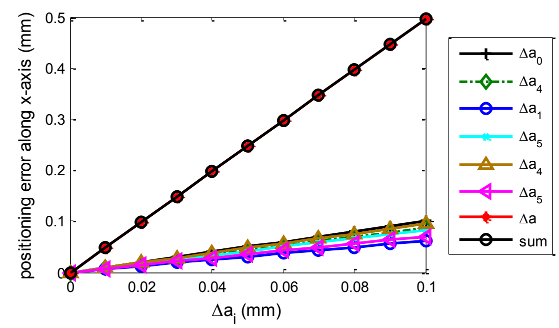

Fig. 4 The positioning error along x-axis influenced by Δa_i

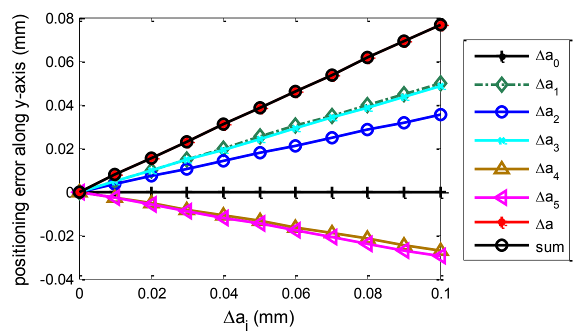

Fig. 5 The positioning error along y-axis influenced by Δa_i

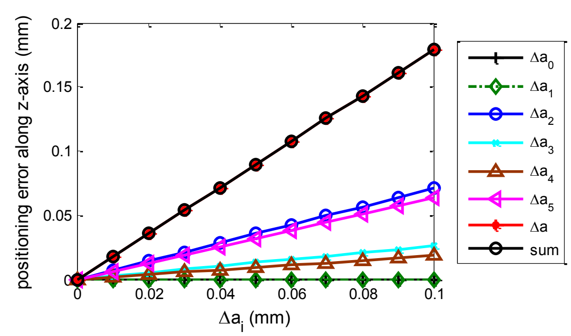

Fig. 6 The positioning error along z-axis influenced by Δa_i

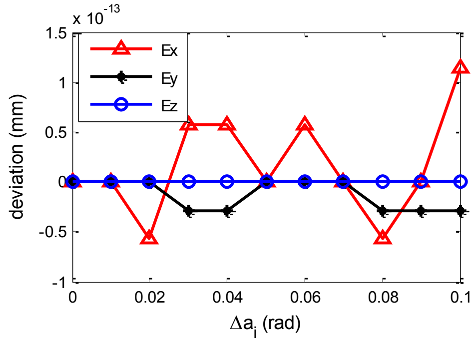

Fig. 7 The deviation of positioning errors along x, y and z-axis

Similarly, the influence of the error parameter Δd_i on positioning accuracy was analyzed by simulation experiment. The same conclusion as the influence of Δa_i was obtained. Under individual effect of error parameter Δd_i, the length of positioning error is equal to the value of Δd_i. Under the common effect of all six error parameter Δd_i, the positioning error vectors are equal to the summation of the error vectors affected by individual error parameter. The positioning accuracy influenced by the error parameter Δd_i is shown in the Fig. 8.

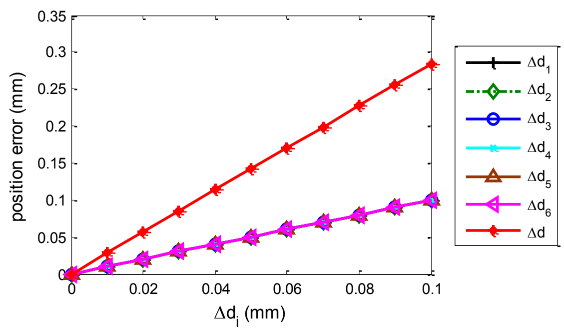

Fig. 8 The positioning accuracy influenced by Δd_i

B. Influence of $\Delta\alpha_i$ and $\Delta\theta_i$

To verify the influence of angle error parameters, the point P$_1$ was selected, again. Each of link twist error parameter $\Delta\alpha_i$ changed in [0, 0.0010]rad, respectively. And others error parameters were set to zero. The positioning accuracy influenced by error parameter $\Delta\alpha_i$ is shown in Fig. 9. It can be seen that the lengths of position error increase linearly with the increase of $\Delta\alpha_i$, The slopes k_i of each line is shown in Table III. It means that a small angle error of link twist will caused big positioning errors, the k_i also can be called error sensitivity coefficient of the selected point.

TABLE III
THE SLOPES OF EACH LINE

$\Delta\alpha_0$	$\Delta\alpha_1$	$\Delta\alpha_2$	$\Delta\alpha_3$	$\Delta\alpha_4$	$\Delta\alpha_5$	$\Delta\alpha$
226.7	138.7	364.2	365.2	62.4	72.0	836.4

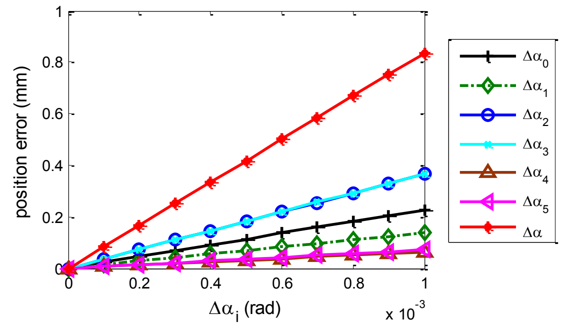

Fig. 9 The positioning accuracy influenced by parameter error $\Delta\alpha_i$

Similarly, the influence of the error parameter $\Delta\theta_i$ on positioning accuracy was analyzed. The same conclusion as the influence of $\Delta\alpha_i$ was obtained. The positioning accuracy influenced by the error parameter $\Delta\theta_i$ is shown in the Fig. 10.

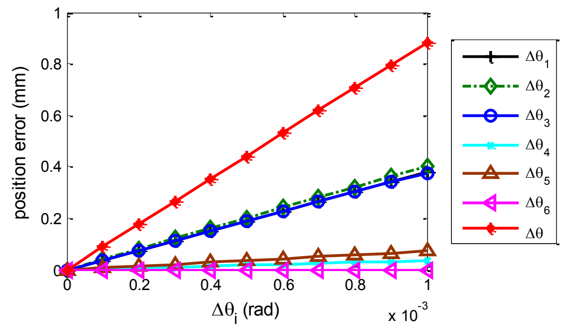

Fig. 10 The positioning accuracy influenced by parameter error $\Delta\theta_i$

C. Influence of $\Delta\beta_i$

Assume that the $\Delta\beta_3$ changed in [0, 0.0010]rad, and others error parameters were zero. The positioning accuracy of the selected points is shown in Fig. 11. The lengths of position error increase linearly with the increase of $\Delta\beta$, and the slope is approximately 98.9.

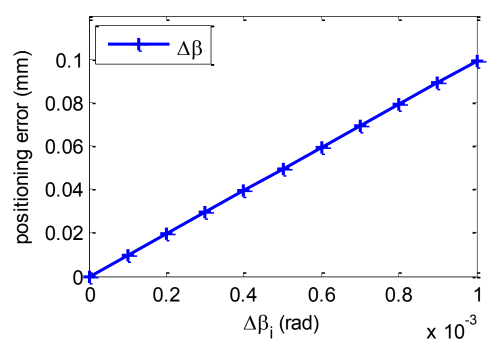

Fig. 11 The positioning accuracy influenced by parameter error $\Delta\beta$

IV. Influence of Measuring Error Parameters on Positioning Accuracy

At present, the laser tracking measurement system is widely used for kinematic calibration of the industrial robots. Before measuring, the measuring coordinate frame {m} must be established, and the sphere-cally mounted reflection (SMR) of the laser tracker should be mounted on the end-effector of robots with the help of the some supplementary tools. There are some measuring errors brought in during measurement. Hence, the influence of the measuring errors on the positioning accuracy was analyzed in detail.

The deviation between the base frame {0} of the robot and the measuring coordinate frame {m} are described by 6 parameters, including 3 positioning errors and 3 angle errors, namely, $\delta_{xm}, \delta_{ym}, \delta_{zm}, \varepsilon_{xm}, \varepsilon_{ym}$ and ε_{zm}. The transformation matrix from coordinate frame {0} to frame {m} can be described by

$$ {}_{0}^{m}T = \begin{pmatrix} 1 & -\varepsilon_{zm} & \varepsilon_{ym} & \delta_{xm} \\ \varepsilon_{zm} & 1 & -\varepsilon_{xm} & \delta_{ym} \\ -\varepsilon_{ym} & \varepsilon_{xm} & 1 & \delta_{zm} \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{7} $$

And the transformation matrix from tool coordinate frame {t} to frame {6} can be described by

$$ {}_{t}^{6}T = \begin{pmatrix} 1 & 0 & 0 & \delta_{xt} \\ 0 & 1 & 0 & \delta_{yt} \\ 0 & 0 & 1 & l+\delta_{zt} \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{8} $$

where, l is the offset of SMR along the z-axis of frame {6}, and δ_{xt}, δ_{yt} and δ_{zt} is the positioning errors of the frame {t}.

So the overall transformation matrix for measurement can be represented by

$$ {}_{t}^{m}\boldsymbol{T} = {}_{0}^{m}\boldsymbol{T} \cdot {}_{1}^{0}\boldsymbol{T} \cdot {}_{2}^{1}\boldsymbol{T} \cdot {}_{3}^{2}\boldsymbol{T} \cdot {}_{4}^{3}\boldsymbol{T} \cdot {}_{5}^{4}\boldsymbol{T} \cdot {}_{6}^{5}\boldsymbol{T} \cdot {}_{t}^{6}\boldsymbol{T} . \tag{9} $$

A. The Influence of Measuring Errors on a Position

In order to analyze influence of measuring errors, the same measuring point P_1 was selected as section III. During simulation experiment, l was set to 18mm.

Firstly, the positioning errors of the measuring frame {m} were analyzed. Assume that the errors δ_{xm}, δ_{ym} and δ_{zm} changed in [0, 0.100]mm, or the three errors changed simultaneously. And others error parameters were set to zero. According to the simulation results, the same conclusion as the influence of Δd_i was obtained. Under individual effect of positioning errors of the measuring frame {m}, the length of positioning error of the end-effector is equal to the value of error parameter. Under the common effect of all three positioning errors of the measuring frame {m}, the positioning errors of the end-effector vector are equal to the summation of the error vectors affected by individual error parameter. The accuracy influenced by positioning errors of the frame {m} is shown in Fig.12.

Similarly, the influence of the position error of the frame {t} was analyzed. As shown in Fig.13, the same conclusion was obtained.

Finally, the influence of the angle errors of the frame {m} was analyzed. Assume that the errors ε_{xm}, ε_{ym} and ε_{zm} changed in [0, 0.0010]rad, respectively, or the three errors changed simultaneously. And others error parameters were set to zero. The accuracy influenced by angle errors of the frame {m} is shown in Fig. 14. According to the simulation results, the same conclusion as the influence of $\Delta\alpha_i$ was obtained. It's worth noting that the influence of the measuring angle errors on the positioning accuracy was on the same order of magnitude as that of $\Delta\alpha_i$ and $\Delta\theta_i$, compared with the Fig. 9 and Fig.10.

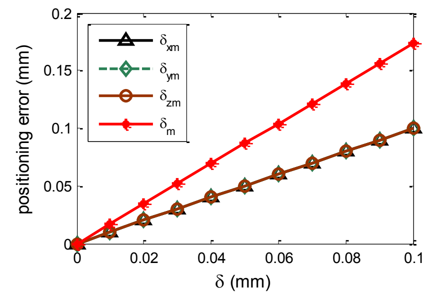

Fig. 12 The accuracy influenced by positioning errors of the frame {m}

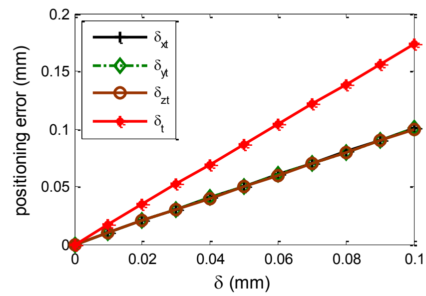

Fig. 13 The accuracy influenced by positioning error of the frame {t}

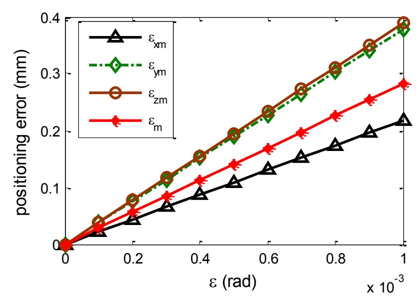

Fig. 14 The accuracy influenced by angle errors of the frame {m}

B. The Influence of Measuring Errors on the Workspace of Robots

To analyze the influence of measuring errors, the 245 points, evenly distributed in the workspace of the robot, were selected. The workspace was 250mm×400mm×500mm.

Each of the positioning error parameters was changed in [0, 0.100]mm, or each of the angle error parameters was changed in [0, 0.0010]rad, respectively, or all 9 measuring errors changed simultaneously. And other error parameters were set to zero. According to the (9), the ideal and actual positions of the points were calculated, and then the positioning accuracy was obtained according to (5). The mean and maximum positioning errors caused by the measuring error parameters, respectively and simultaneously, are shown in Table IV. The positioning errors of the end-effector affected respectively by the positioning error parameters are equal to the values of the corresponding parameters. And the mean positioning errors caused by the angle error parameters are 0.287mm, 0.477mm and 0.411mm, and the maximum are 0.574mm, 0.708mm and 0.996mm. That is to say it has a remarkable amplification effect on the positioning error of end-effector.

The positioning errors caused by the all the measuring error parameters simultaneously are shown in Fig. 15, the mean and maximum errors are 0.477mm and 0.708mm. These clearly show that the measuring error parameter should be considered seriously during kinematic calibration, in order to improve the accuracy of the parameter identification. Only in this way can the positioning accuracy of robots be enhanced effectively.

TABLE IV
THE INFLUENCE OF MEASURING ERRORS BASED ON 245 POINTS

Parameter	δ_{xm}	δ_{xm}	δ_{xm}	ε_{xm}	ε_{ym}
Mean	0.100	0.100	0.100	0.287	0.477
Maximum	0.100	0.100	0.100	0.574	0.708
Parameter	ε_{zm}	δ_{xt}	δ_{xt}	δ_{xt}	all
Mean	0.411	0.100	0.100	0.100	0.696
Maximum	0.996	0.100	0.100	0.100	1.131

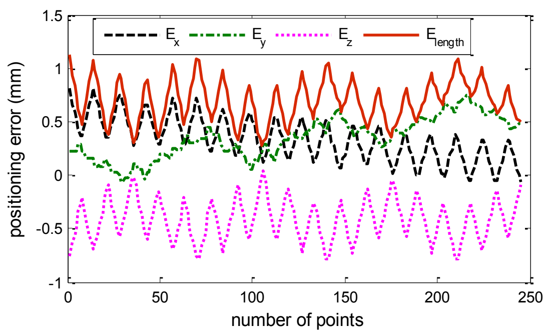

Fig. 15 The accuracy influenced by measuring error parameters.

V. CONCLUSIONS

In this paper, the influence of the geometric error parameters and the measuring error parameters on the positioning accuracy of robots was analyzed in detail. Firstly, the kinematic modeling method of robots based on modified D-H parameters was introduced, and then took a 6-DOF serial robot as an example, the kinematic model was established. Finally, the influences of the geometric error parameters and the measuring error parameters on the positioning error of the robot's end-effector were analyzed in detail. The simulation results bring about the following major conclusion:

1) Under individual effect of linear errors (including link length errors, link offset errors, and positioning error caused by measuring), the length of positioning error is equal to the value of the corresponding error parameter.

2) Under the common effect of the error parameters (including geometric error parameters and measuring error parameters), the positioning error vectors are equal to the summation of the error vectors affected by error parameters, respectively.

3) The angle error parameter, including link twist errors, joints angle errors, and angle errors caused by measuring, has remarkable amplification effect on the poisoning errors of the robot's end-effector.

4) The influence of measuring error parameters on the positioning accuracy of the robot is on the same order of magnitude as that of the geometric error parameters.

Therefore, the measuring errors parameters should be taken into account during kinematic calibration.

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