Precise reliability analysis base on static pose error of 6 degree of freedom serial robot

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Abstract. Taking the JLRB20 industrial robot as the object, the improved D-H modelling method is used to establish the positioning error model of the robot, the reliability of the static pose error of the robot is analysed, and the reliability evaluation index of the static pose error of the robot is established. By analysing the precise reliability base on static pose error of the robot, it is determined that the joint rotation angle has the greatest influence on the accuracy of the static attitude error of the robot end, which provides a basis for improving the reliability of the static pose error of the robot.

1. Introduction

Errors that affect the end effector of a serial robot include dynamic errors and static errors. Among them, static error is also called systematic error \cite{1,2}, which refers to a deterministic error that does not change with time during the movement. The methods of static error modeling for serial robots mainly include: matrix transfer method, vector product method, perturbation method and Monte Carlo method \cite{3}. A. Kuman and S. Prakash \cite{4} derived the position error mathematical expression containing the structural parameter error of the robot, and completely considered the structural parameter error together with the kinematic variable error. Chi-haur Wu \cite{5} took into account factors such as the joint angle error and structural parameters of the robot, and deduced the mathematical expression of the position error of the end effector. K. Sugimoto \cite{6} used the vector analysis method and the mathematical tool of helical transformation to establish the robot end position error model, and determined that the robot structural parameter error is the main influencing factor of the error model.

The previous models rarely consider the reliability of the static pose error accuracy of the robot end effector, and the evaluation index of the precise reliability base on static pose error of the robot end effector is rarely involved. In this paper, the improved D-H modeling method is used to establish the static pose error model of the JLRB20 series robot, to determine the reliability evaluation index of the robot's static pose error accuracy, and to analyze the effect of obtaining the joint rotation angle on it, in order to improve the static position of the JLRB20 series robot. The theoretical reliability of posture error accuracy reliability is provided.

2. Kinematic description of JLRB serial robot

The JLRB20 series robot is an articulated robot, which uses the D-H modeling method to establish the robot coordinate system. As shown in Figure 1, the coordinate system of D-H parameters of
JLRB20 series robot is established. The angle of rotation $\theta_i$ is the angle between the normal $x_{i-1}$ and $x_i$. From the top of the shaft $z_{i-1}$, the counterclockwise direction is the positive direction. The offset of the joint $d_i$ is the distance between the normal $x_{i-1}$ and $x_i$. The length of the connecting rod $a_i$ is the distance from the axis $z_{i-1}$ to the axis $z_i$. The torsion angle of the connecting rod $\alpha_i$ is the angle from axis $z_{i-1}$ to axis $z_i$.

Using the homogeneous transformation matrix formula between adjacent coordinate systems, we can obtain:

$$
A_i = \text{Rot}(z_{i-1}, \theta_i) \text{Trans}(0, 0, d_i) \text{Trans}(a_{i-1}, 0, 0) \text{Rot}(x_{i-1}, \alpha_{i-1})
$$

$$
= \begin{bmatrix}
c\theta_i & -s\theta_i c\alpha_{i-1} & s\theta_i s\alpha_{i-1} & a_{i-1} c\theta_i \\
s\theta_i & c\theta_i c\alpha_{i-1} & -c\theta_i s\alpha_{i-1} & a_{i-1} s\theta_i \\
0 & s\alpha_{i-1} & c\alpha_{i-1} & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(1)

The homogeneous transformation matrix of the end effector can be further obtained as:

$$
^0T = A_1 A_2 \cdots A_6
$$

$$
= \begin{bmatrix}
n_x & o_x & a_x & p_x \\
n_y & o_y & a_y & p_y \\
n_z & o_z & a_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(2)

Thus, the kinematics model of the JLRB20 serial robot is established. The theoretical values of all the link parameters of the six joints and the range of motion of each joint rotation angle are calculated, as shown in Table 1, where $i$ is the value of each joint of the robot in its initial state.
Table 1. Link parameters of JLRB20 series robot

| Joint | Rotation angle $\theta_i$ (°) | Joint offset $d_i$ (mm) | Link length $a_{i-1}$ (mm) | Torsion angle $\alpha_{i-1}$ (°) | Range of $\theta_i$ |
|-------|-------------------------------|-------------------------|---------------------------|-------------------------------|---------------------|
| 1     | 90                            | 0                       | 0                         | 0                             | -165~165            |
| 2     | -90                           | 0                       | $a_1$                     | -90                           | -80~110             |
| 3     | 0                             | 0                       | $a_2$                     | 0                             | -110~80             |
| 4     | 0                             | $d_4$                   | $a_3$                     | -90                           | -180~180            |
| 5     | 0                             | 0                       | 0                         | 90                            | -110~110            |
| 6     | 0                             | 0                       | 0                         | -90                           | -360~360            |

3. JLRB20 series robot static pose error modelling

There is a slight deviation between the actual link parameters of the robot when it is working and the link parameters in the kinematics theoretical model, and the impact of such small deviations in high-precision situations cannot be ignored.

Apply the MDH modeling method to modify the kinematic model of the robot. An additional rotation parameter $\beta$ (rotation around the Y axis) is used to transform the axis $1_iZ$ to the axis $iZ$ to improve the effect of small deviations (the deviation between actual link parameters and theoretical link parameters) on the robot’s static pose error. The resulting homogeneous transformation matrix is as follows:

$$
\begin{bmatrix}
1 & -1 & -1 & -1 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(3)

The small deviation value of the connecting rod of JLRB20 series robot is expressed by $\Delta \theta_i$, $\Delta d_i$, $\Delta a_{i-1}$, $\Delta \alpha_{i-1}$ and $\Delta \beta_i$. The matrix $T_i^N$ is the homogeneous transformation matrix of the connecting rod $i$ under the effect of nominal parameters, and the matrix $T_i^R$ is the transformation matrix of the actual parameters of the robot. Then:

$$
T_i^N = rot_z(\theta_i)trans_z(d_i)trans_z(a_i)rot_z(\alpha_i)rot_z(\beta_i)
$$

(4)

$$
T_i^R = rot_z(\theta_i + \Delta \theta_i)trans_z(d_i + \Delta d_i)trans_z(a_i + \Delta a_i)rot_z(\alpha_i + \Delta \alpha_i)rot_z(\beta_i + \Delta \beta_i)
$$

(5)

Use $\Delta_i$ to represent the differential transformation relative to the link $i$ coordinate system, then the error model of the link $i$ is:

$$
d(T_i^N) = T_i^R - T_i^N = T_i^N \Delta_i
$$

(6)

To make a complete differential of the kinematics equation, we can get
The nominal transformation matrix between adjacent coordinate systems is $i \rightarrow i+1$, and the differential change caused by kinematic parameter errors is $d i \rightarrow i+1$. In the case of small errors, the total differential of the kinematics equation can be approximated to replace its error equation, so that the position error of the robot end is:

$$d(T_i^N) = \frac{\partial T_i^N}{\partial \alpha_i} \delta \alpha_i + \frac{\partial T_i^N}{\partial \beta_i} \delta \beta_i \tag{7}$$

The posture error of the robot end is:

$$\delta \Phi \approx \sum_{i=1}^{6} \frac{\partial \Phi}{\partial \theta_i} \delta \theta_i + \sum_{i=1}^{6} \frac{\partial \Phi}{\partial d_i} \delta d_i + \sum_{i=1}^{6} \frac{\partial \Phi}{\partial a_{i-1}} \delta a_{i-1} + \sum_{i=1}^{6} \frac{\partial \Phi}{\partial \alpha_i} \delta \alpha_i + \sum_{i=1}^{6} \frac{\partial \Phi}{\partial \beta_i} \delta \beta_i \tag{8}$$

When $i=2$, $\beta_i \neq 0$; when $i \neq 2$, $\beta_i = 0$. Therefore, the expression of the robot's static position and attitude error can be simplified as:

$$\delta P \approx \sum_{i=1}^{6} \frac{\partial P}{\partial \theta_i} \delta \theta_i + \sum_{i=1}^{6} \frac{\partial P}{\partial d_i} \delta d_i + \sum_{i=1}^{6} \frac{\partial P}{\partial a_{i-1}} \delta a_{i-1} + \sum_{i=1}^{6} \frac{\partial P}{\partial \alpha_i} \delta \alpha_i + \frac{\partial P}{\partial \beta_2} \delta \beta_2 \tag{10}$$

$$\delta \Phi \approx \sum_{i=1}^{6} \frac{\partial \Phi}{\partial \theta_i} \delta \theta_i + \sum_{i=1}^{6} \frac{\partial \Phi}{\partial d_i} \delta d_i + \sum_{i=1}^{6} \frac{\partial \Phi}{\partial a_{i-1}} \delta a_{i-1} + \sum_{i=1}^{6} \frac{\partial \Phi}{\partial \alpha_i} \delta \alpha_i + \frac{\partial \Phi}{\partial \beta_2} \delta \beta_2 \tag{11}$$

4. Precision reliability analysis of JLRB series robot

Among the error sources of the static pose error accuracy of the end effector of the serial robot, the geometric parameter error accounts for about 80% [7]. The error model is established according to the transfer matrix method, the accuracy of the robot's terminal pose error caused by static errors is analysed, and the reliability evaluation index of the static pose error accuracy is established to analyse the robot's static pose accuracy error.

4.1. Reliability evaluation index of static pose error accuracy

The pose of the end effector of the serial robot can be represented by a vector $[p_x, p_y, p_z, \alpha, \beta, \gamma]$. Among them, the position error is:

$$P = [p_x, p_y, p_z] \tag{12}$$

Under the X-Y-Z fixed coordinate system, its attitude error is:

$$\Phi = [\alpha, \beta, \gamma] \tag{13}$$

According to the homogeneous transformation matrix at the end of the robot, the generalized coordinate expression of the attitude of the end effector relative to the X-Y-Z fixed coordinate system is as follows:
To quantify and analyze the robot's static pose error, the error should be sampled, the sampled value in the posture error mathematical model of the end effector should be substituting, the posture error of the substituted sample value should be calculating, the probability that the position error of the end effector falls within the error sphere of radius R and the probability of attitude error less than T (given attitude error limit) should be using. That is, the accuracy reliability of static pose error can be used as the evaluation index of the end effector pose error, then the position error and attitude error can be calculated as follows:

$$\delta P_i = P_i - P_t$$

$$\delta \alpha_i = \alpha_i - \alpha$$

$$\delta \beta_i = \beta_i - \beta$$

$$\delta \gamma_i = \gamma_i - \gamma$$

Among them, $x_i$, $y_i$ and $z_i$ represent the coordinate value calculated at the ith sampling of joint variables and structural parameter ($\theta_i$, $d_i$, $a_{i-1}$ and $\alpha_{i-1}$) in the given position, $\alpha_i$, $\beta_i$ and $\gamma_i$ represent the positioning pose angle; $P_t$, $\alpha_t$, $\beta_t$ and $\gamma_t$ represent the ideal attitude value of the device.

Let the position error named $\delta P_i$, attitude error named $\delta \Phi_i = (\delta \alpha_i, \delta \beta_i, \delta \gamma_i)^T$, and the number of samples smaller than the given error R and T is approximately equal to the number of samples $\lambda_p$ and $\lambda_{\Phi}$ divided by the total number of samples. In summary, the calculation formula of the accuracy reliability of the static pose error of the serial robot is as follows:

$$P(\|\delta P_i\| < R) = \frac{\lambda_p}{\lambda}$$

$$P(\|\delta \Phi_i\| < T) = \frac{\lambda_{\Phi}}{\lambda}$$

4.2. Reliability analysis of static pose error accuracy

4.2.1 Analysis of the influence of joint parameters

The parameters of each joint of the robot are shown in Table 2. It is assumed that the joint angle $\theta_i$ and the other three joint parameters $d_i$, $a_{i-1}$ and $\alpha_{i-1}$ follow a normal distribution. The standard deviation of the joint parameters $d_i$, $a_{i-1}$ and $\alpha_{i-1}$ are 0.05mm, 0.05mm, 0.5°, and the standard deviation of the joint angle $\theta_i$ is 0.5°. The overall position rotates from the zero position (initial position) to the final position is $\pi / 6$.

Using equation (2), the four joint parameters of the robot are sub-sampled $10^5$ times to obtain the transformation matrix $^0_6 T$ at the end position of the robot end effector, which $\theta_1 = 2\pi / 3$, $\theta_2 = -\pi / 3$, $\theta_3 = \pi / 6$ is the rotation angle of each joint at point B. The model for solving the position error value and attitude error value of the robot end effector are as follows:
\[
\frac{\partial \Phi}{\partial V_j} = \begin{bmatrix}
\frac{\partial \Phi}{\partial V_j}, 
\frac{\partial \Phi}{\partial V_j}, 
\frac{\partial \Phi}{\partial V_j}
\end{bmatrix}^T
\]

(19)

where \( V_{i1}, V_{i2}, V_{i3}, V_{i4} \) present \( \theta_i, d_i, a_{i-1}, \alpha_{i-1}, i = 1, 2, \ldots, 6, j = 1, 2, 3, 4 \).

### Table 2. Joint parameters of JLRB20 series robot.

| Joint | Rotation angle (Initial value) | Joint offset (Average value) | Link length (Average value) | Torsion angle (Average value) |
|-------|--------------------------------|-------------------------------|-----------------------------|-------------------------------|
| \( \theta_i \) (rad) | \( d_i \) (mm) | \( a_{i-1} \) (mm) | \( \alpha_{i-1} \) (rad) |
| 1     | \( \pi / 2 \) | 0    | 0    | 0       |
| 2     | \( \pi / 2 \) | 0    | 80   | -\( \pi / 2 \) |
| 3     | 0    | 0    | 780  | 0       |
| 4     | 0    | 835  | 85   | -\( \pi / 2 \) |
| 5     | 0    | 0    | 0    | \( \pi / 2 \) |
| 6     | 0    | 0    | 0    | -\( \pi / 2 \) |

The statistics of all position error values and attitude error values can be seen in Table 3.

### Table 3. The ideal value of the pose error of the robot end effector and the numerical characteristics of the samples.

| Error | Ideal value | Mean | Standard deviation | Maximum | Minimum |
|-------|-------------|------|--------------------|---------|---------|
| \( \delta P \) | 0 | -0.1370 | 2.2018 | 5.0384 | -3.9972 |
| Fixed coordinate system (rad) |
| \( \delta \alpha \) | 0 | 0.0001 | 0.0163 | 0.1194 | -0.0595 |
| \( \delta \beta \) | 0 | 0.0001 | 0.0209 | 0.1086 | -0.0612 |
| \( \delta \gamma \) | 0 | 0.0001 | 0.0357 | 0.1139 | -0.0791 |

The three components \( (\delta \alpha, \delta \beta, \delta \gamma) \) of the position error \( \delta P \) and attitude error \( \delta \Phi \) calculated by the frequency histogram in MATLAB, the position error frequency histogram and attitude error frequency histogram in O-X-Y-Z fixed coordinate system are shown in Figure 2. The component errors of the position error \( \delta P \) and the attitude error \( \delta \Phi \) in the three directions of x, y, and z are fitted by the distribution \( \chi^2 \), and are normally distributed at the significance level when \( \alpha = 0.05 \).
Take the robot's end effector position error limit \( R = 2 \text{mm} \), and take the robot's end effector attitude error limit \( T = 0.01^\circ \). Then, the calculation formula of the accuracy reliability of the static pose error of the robot end effector are as follows:

\[
\begin{align*}
\begin{cases}
P(\delta P < R) = 0.8257 \\
P(\delta \theta < T) = \left( \begin{array}{c}
0.8474 \\
0.8260 \\
0.7945
\end{array} \right)
\end{cases}
\end{align*}
\]  

(20)

Table 4. The accuracy and reliability of the static pose error of the end of the robot

| Standard deviation | Ideal value | Mean | Standard deviation | Reliability (%) |
|--------------------|-------------|------|--------------------|----------------|
| \( \sigma \theta_j = 0.5^\circ, \sigma d_i = 0.05 \) | 0 | -0.1370 | 2.2018 | 82.57 |
| \( \sigma a_i = 0.05, \sigma \alpha_i = 0.5^\circ \) | 0 | 0.1832 | 2.2716 | 82.38 |
| \( \sigma \theta_j = 0.1^\circ, \sigma d_i = 0.05 \) | 0 | -0.0338 | 2.8780 | 100 |
| \( \sigma a_i = 0.05, \sigma \alpha_i = 0.5^\circ \) | 0 | 0.0533 | 2.8780 | 100 |
| $\sigma_\theta$ | $\sigma_\alpha$ | $\sigma_\beta$ | $\sigma_\gamma$ |
|---------------|----------------|----------------|----------------|
| 0.5°, 0.05    | 0.01, 0.5°     | 0.5°, 0.05     | 0.05, 0.1°     |
| 0             | -0.1250        | 2.4714         | 82.46          |
| 0.5°, 0.05    | 0.05, 0.1°     | 0.5°, 0.05     | 0.05, 0.1°     |
| 0             | 0.1362         | 2.3635         | 81.89          |

**Fixed coordinate system $\delta \alpha$ (rad)**

| $\sigma_\theta$ | $\sigma_\alpha$ | $\sigma_\beta$ | $\sigma_\gamma$ |
|---------------|----------------|----------------|----------------|
| 0.5°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0001         | 0.0163         | 84.74          |
| 0.1°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0000         | 0.0105         | 92.58          |
| 0.5°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0000         | 0.0196         | 84.66          |
| 0.5°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0000         | 0.0192         | 84.97          |
| 0.5°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0000         | 0.0186         | 84.23          |

**Fixed coordinate system $\delta \beta$ (rad)**

| $\sigma_\theta$ | $\sigma_\alpha$ | $\sigma_\beta$ | $\sigma_\gamma$ |
|---------------|----------------|----------------|----------------|
| 0.5°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0001         | 0.0163         | 82.60          |
| 0.1°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0000         | 0.0102         | 91.64          |

**Fixed coordinate system $\delta \beta$ (rad)**

| $\sigma_\theta$ | $\sigma_\alpha$ | $\sigma_\beta$ | $\sigma_\gamma$ |
|---------------|----------------|----------------|----------------|
| 0.5°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0000         | 0.0154         | 82.38          |
| 0.5°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0000         | 0.0162         | 81.96          |
| 0.5°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | 0.0000         | 0.0149         | 82.85          |

**Fixed coordinate system $\delta \gamma$ (rad)**

| $\sigma_\theta$ | $\sigma_\alpha$ | $\sigma_\beta$ | $\sigma_\gamma$ |
|---------------|----------------|----------------|----------------|
| 0.5°, 0.05    | 0.05, 0.5°     | 0.5°, 0.05     | 0.01, 0.5°     |
| 0             | -0.0001        | 0.0357         | 79.45          |
It can be seen from Table 4 that when the standard deviation of the joint rotation angle error is reduced by 5 times, the accuracy reliability of the static pose error of the robot end is improved. The reliability of the robot's position error has been improved from 82.57% to 100%, and the three component errors of $\delta\alpha$, $\delta\beta$, $\delta\gamma$ have been improved from 84.74%, 82.60%, and 79.45 to 92.58%, 91.64% and 95.17% respectively. In addition, the error distribution of the other three joint parameters has little effect on the reliability of the position accuracy and attitude accuracy of the robot tip. It can be seen that the factor that has the greatest impact on the accuracy of the position and attitude error accuracy of the robot end is the error of the joint rotation angle.

4.2.2 Sensitivity analysis of joint rotation angle

The standard deviations of the six joint parameter errors are successively reduced by 5 times, and the accuracy and reliability of the pose error of the end effector of the robot is analysed to determine its sensitivity to the pose and error accuracy reliability. The specific results are shown in Table 5.

| Standard deviation | Ideal value | Mean | Standard deviation | Reliability (%) |
|--------------------|-------------|------|-------------------|-----------------|
| $\sigma_{\theta_1} \sim \sigma_{\theta_6} = 0.5$ | 0 | -0.1370 | 2.2018 | 82.57 |
| $\sigma_{\theta_1} = 0.1$ | 0 | 0.0054 | 2.5150 | 83.32 |
| $\sigma_{\theta_2} = 0.1$ | 0 | -0.0037 | 2.3601 | 88.59 |
| $\sigma_{\theta_3} = 0.1$ | 0 | -0.0098 | 2.2290 | 96.43 |
| $\sigma_{\theta_4} = 0.1$ | 0 | 0.0072 | 2.2826 | 83.09 |
| $\sigma_{\theta_5} = 0.1$ | 0 | 0.0102 | 2.2532 | 82.64 |
| $\sigma_{\theta_6} = 0.1$ | 0 | -0.0083 | 2.2789 | 82.13 |

| Fixed coordinate system $\delta\alpha$(rad) | |
| $\sigma_{\theta_1} \sim \sigma_{\theta_6} = 0.5$ | 0 | 0.0001 | 0.0163 | 84.74 |
| $\sigma_{\theta_1} = 0.1$ | 0 | 0.0000 | 0.0158 | 88.72 |
| $\sigma_{\theta_2} = 0.1$ | 0 | 0.0000 | 0.0184 | 84.99 |
| $\sigma_{\theta_3} = 0.1$ | 0 | 0.0000 | 0.0186 | 85.62 |
It can be seen from Table 5 that when the standard deviation of each joint parameter is reduced by 5 times, the reliability of the position error is greater and the reliability of the three component errors of the attitude error is smaller in the O-X-Y-Z fixed coordinate system. Among them, when the standard deviation of the rotation angle of joint 3 is reduced by 5 times, the reliability of the position error is increased from 82.57% to 96.43%; when the standard deviation of the rotation angle of joint 2 is reduced by 5 times, the reliability of the position error is increased from 82.57% to 88.59%; the rotation angle errors of other joints (joints 4, 5, 6) have little effect on the reliability of the position error and the reliability of the position error increased from 82.57% to 83.09%, 82.64%, 82.13% respectively. This is in line with the actual situation and verifies that the first three joints mainly affect the rationality of the position of the robot end effector.

5. Conclusion
(1) This work established the static pose error model of the serial robot based on the improved D-H model.
(2) The reliability evaluation index of the robot’s static pose error accuracy was established, the influence of joint parameters was analysed, and got the most influential factor is the joint rotation angle. When the error standard deviation of joint rotation angle was reduced by 5 times, the static pose error and accuracy reliability of the robot end were improved.
(3) The sensitivity of the joint rotation angle was analysed, and the joint that greatest influenced the accuracy of the static pose error of the robot end was joint 3. In the subsequent design, installation and use, it is necessary to focus on minimizing the rotation angle error of each joint of the robot and controlling the rotation angle error of the joint 3.
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