Accuracy analysis and errors compensation of 4-DOF reconfigurable punching robot

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Abstract. The aims of this paper were to enhance the accuracy of the 4-DOF reconfigurable punching robot when it was working, as well as to reduce the error made by robots when they were loading and unloading materials. For these ends, by elucidating the composition and function of 4-DOF serial re-configurable punching robot, the static pose error model and the dynamic pose error model of the robot actuator were built in the present paper. Besides, MATLAB was employed to plot the actuator pose error curve. Subsequently, the pose error of the robot actuator under was delved into based on both static and dynamic factors. Afterwards, the comprehensive pose error model of the actuator was developed to plot the comprehensive pose error curve of the actuator. The perturbation compensation method was used to compensate the robot actuators. The results showed that the positioning accuracy of the robot was effectively improved. These the mentioned efforts, a solid basis was laid for manufacturing the 4-DOF reconfigurable punching robot, as well as enhancing its accuracy.

1. Introduction

With the development of industrial robots, in order to reduce labor costs and improve work rhythm and production efficiency [1], it is the first choice to replace the manual loading and unloading with punching robots. At present, most of the punching robots in the enterprise production line are "one machine for one job only". If the working conditions are changed, they cannot work normally. When a major change in production method occurs, the existing robot should be replaced, which leads to increased production costs. Reconfigurable punching robots can be converted into different architectures and degrees of freedom to adapt to different production methods of different production lines in the enterprise, effectively solving the problem that most of the punching robots currently used in enterprises are tailored to the working conditions. [2]

What’s more, working accuracy is one of the important indicators for evaluating the working performance of robots. In actual working conditions, robots may have errors such as manufacturing errors, transmission errors, and assembly errors, which directly affect the positioning accuracy of the robot. Huang Zhen [3-5] and others used the vector method to analyze the accuracy of the robot's actuator and obtained the position error. But when using the vector method to solve, there were a large number of partial derivatives in the final expression, which was tedious to calculate. Yan Hua [6-7] and others gave a method to solve the pose accuracy of the robot. This method used the model of information entropy to analyze the probability distribution of errors caused by various error factors and the impact of accidental measurement on the position and posture error of the end effector, but the calculation process was very complicated and should to be generalized. In order to improve the
accuracy of the four-degree-of-freedom reconfigurable punching robot, the author chose the matrix
differential method to analyze the accuracy of the robot actuator. The matrix differential method is a
basic method for establishing a static error model of an industrial robot. [8] The pose error model of the
robot actuator is obtained through the error transmission between adjacent rods. In the process,
calculations between matrices are mainly used. The physical meaning of the method is clear, intuitive
and easy to understand, and the form is simple. Based on the comprehensive errors of the robot [9],
this paper studies the error compensation of the robot [10], which provides an important basis for the
manufacturing and accuracy improvement of a four-degree-of-freedom reconfigurable punching robot.

2. Composition and pose description of 4-DOF reconfigurable punching robots

2.1. Composition of 4-DOF reconfigurable punching robots

The 4-DOF reconfigurable punching robot is a tandem robot composed of a rotating mechanism, a
driving mechanism, an auxiliary mechanism (link and base), and an end effector connected in series
[10]. It is fixed and positioned by means of screw connection and key connection. The schematic
diagram of each module of the robot shown in Figure 1-4 below. A represents a rotating mechanism,
and B represents a driving mechanism. Through reassembly and assembly, 16 types of robots suitable
for different working conditions can be obtained. As shown in Figure 5 below, ABBA robots are
cylindrical coordinate type robots. This paper takes the ABBA robot as an example for error analysis
and error compensation. The following Table 1 shows the size parameters of each module.

![Figure 1. Robot driving mechanism.](image)
![Figure 2. Robot rotating mechanism.](image)
![Figure 3. Robot end effector.](image)

![Figure 4. Robot auxiliary mechanism.](image)

![Figure 5. ABBA type robot.](image)
Table 1. Size parameters of each module. (unit: mm).

|                      | Rotating mechanism module | Corner connecting bar module | Driving mechanism module | Corner two shore module |
|----------------------|---------------------------|----------------------------|--------------------------|-------------------------|
| \( h_1 \) = 100     | \( l_{31} = 200 \)       | \( L_1 = 150 \)            | \( l_{22} = 200 \)      |
| \( h_2 \) = 100     | \( l_{31} = 200 \)       | \( L_2 = 150 \)            |                          |

- \( h_i \) - The height of the ith rotating mechanism module.
- \( L_i \) - The length of the ith driving mechanism module.
- \( l_{ij} \) - The vertical distance between the two interfaces of the ith corner connection bars.
- \( l_{hi} \) - The horizontal distance between the two interfaces of the ith corner connection bars.

2.2. Pose description of 4-DOF reconfigurable punching robots

Shown in Figure 6 below. Based on the base coordinate system, in the mechanism motion diagram:
Distance in direction \( Z \) : \( l_i \), \( h_i \), \( l_j \), \( l_k \);
Distance in direction \( Y \) : \( l_j \);
Distance in direction \( X \) : \( b_i \).

![Diagram on mechanism motion of 4-DOF punching robots.](image)

According to the D-H method, the homogeneous transformation matrix \( A \) of each adjacent member of the ABBA type robot was obtained as:

\[
A_i = \begin{bmatrix}
\cos \theta_i & -\sin \theta_i & 0 & 0 \\
\sin \theta_i & \cos \theta_i & 0 & 0 \\
0 & 0 & 1 & l_i \\
0 & 0 & 0 & 1
\end{bmatrix},
\]

\[
A_i = \begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1
\end{bmatrix},
\]

The robot end effector pose matrix was:

\[
T_i = \begin{bmatrix}
\cos(\theta_i + \theta_2) & -s_{12} & 0 & h_2 \cos \theta_i + l_i \sin \theta_i \\
\sin(\theta_i + \theta_2) & c_{12} & 0 & h_2 \sin \theta_i + l_i \cos \theta_i \\
0 & 0 & 1 & l_i + l_2 - l_4 + h_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

3. Error analysis of 4 DOF reconfigurable punching robot

In order to improve its working accuracy, we analyzed the robot error. On the basis of constructing the static and dynamic pose error model of the robot end effector, MATLAB was used to solve the position error curve and attitude error curve of the robot end effector, and the static and dynamic error.
factors were both combined to analyze posture error of robot end effector. Based on the comprehensive pose error model of the robot end effector, the comprehensive pose error curve of the robot end effector was solved, and then the comprehensive error analysis of the 4-DOF reconfigurable punching robot was performed.

3.1. Static error analysis of reconfigurable punching robot

Robot static pose error modelling methods mainly include matrix differential method, vector method and the information entropy-based analysis method [11-12]. The authors chose matrix differential method to analyze the error of 4-DOF reconfigurable punching robot end effector under the influence of static factors. The static pose error model of the robot end effector was constructed. Considering the influence of static pose errors, the homogeneous transformation matrix became \( \mathbf{A}_i + d\mathbf{A}_i \) (\( d\mathbf{A}_i \) is derived by fully differentiating \( \mathbf{A}_i \)). The actual transformation matrix of the robot changed from \( \mathbf{T}_n \) to \( \mathbf{T}_n + d\mathbf{T}_n \).

\[
d\mathbf{A}_i = \frac{\partial \mathbf{A}_i}{\partial \mathbf{\theta}_i} \Delta \mathbf{\theta}_i + \frac{\partial \mathbf{A}_i}{\partial \mathbf{l}_i} \Delta \mathbf{l}_i + \frac{\partial \mathbf{A}_i}{\partial \mathbf{b}_i} \Delta \mathbf{b}_i
\]

\[
\mathbf{T}_n + d\mathbf{T}_n = \prod_{i=1}^{N} \left( \mathbf{A}_i + d\mathbf{A}_i \right) = \mathbf{T}_n + \mathbf{T}_n \sum_{i=1}^{N} \left( \mathbf{U}_{i+1}^{-1} \Delta \mathbf{A}_i \mathbf{U}_i \right)
\]

The pose change expression of the robot end effector was:

\[
\Delta \mathbf{T}_n = \sum_{i=1}^{N} \left[ \begin{array}{cc} \Psi_i & \mathbf{D}_i \\
0 & 0 \end{array} \right]
\]

Position error \( \mathbf{D}_n \) was:

\[
\mathbf{D}_n = \left( \mathbf{R}_n^{(i)} \right)^\top \left[ \begin{array}{c} \delta_i \\
\mathbf{P}_n^{(i)} \end{array} \right] + \left( \mathbf{R}_n^{(i)} \right)^\top \mathbf{d}_i
\]

Attitude error \( \mathbf{\Psi}_n \) was:

\[
\mathbf{\Psi}_n = \left( \mathbf{R}_n^{(i)} \right)^\top \left[ \begin{array}{c} \delta_i \\
\mathbf{R}_n^{(i)} \end{array} \right]
\]

According to the above method, the pose transformation of the robot's end effector can be obtained (the solution process was omitted):

\[
\Delta \mathbf{T}_n = \left[ \begin{array}{cccc}
0 & -\left( \Delta \mathbf{\theta}_1 + \Delta \mathbf{\theta}_2 \right) & 0 & b_2 \sin \mathbf{\theta}_1 \Delta \mathbf{\theta}_1 + \cos \mathbf{\theta}_1 \left( \Delta \mathbf{b}_2 + \Delta \mathbf{l}_2 \right) + \sin \mathbf{\theta}_1 \mathbf{\Delta l}_2 \\
\Delta \mathbf{\theta}_1 + \Delta \mathbf{\theta}_2 & 0 & 0 & b_2 \cos \mathbf{\theta}_1 \Delta \mathbf{b}_1 + \sin \mathbf{\theta}_1 \left( \Delta \mathbf{\theta}_2 + \Delta \mathbf{\theta}_1 \right) + \cos \mathbf{\theta}_1 \mathbf{\Delta l}_1 \\
0 & 0 & 0 & \Delta \mathbf{\theta}_2 \\
0 & 0 & 0 & \Delta \mathbf{b}_1 + \Delta \mathbf{l}_1 - \Delta \mathbf{l}_2
\end{array} \right]
\]

D-H parameters and deviations between adjacent bars were showed in Table 2:

| Lever | \( l_i \) (mm) | \( \Delta l_i \) (mm) | \( b_i \) (mm) | \( \Delta b_i \) (mm) | \( \theta_i \) (°) | \( \theta_i \) (°) |
|-------|----------|----------|----------|----------|----------|----------|
| 0     | \( l_i \) | 0.03     | 0        | 0        | 0        | 0        |
| 1     | 0        | 0        | 0        | 0        | 0        | 0.01     |
| 2     | \( l_i \) | 0.03     | \( b_i \) | 0.05     | 0        | 0        |
| 3     | 0        | 0        | 0        | 0        | 0        | 0        |
| 4     | \( l_i \) | 0.03     | 0        | 0        | \( \theta_i \) | 0.01     |

The motion law of 4-DOF reconfigurable punching robots was illustrated in equation 9:

\[
\theta = \begin{cases}
\theta_{11} \left( \frac{2t}{T} - \sin \left( \frac{4\pi t}{T} \right)/2\pi \right) & 0 \leq t \leq \frac{T}{2} \\
\theta_{12} \left( 2 - \frac{2t}{T} + \sin \left( \frac{4\pi t}{T} \right)/2\pi \right) & \frac{T}{2} < t < T
\end{cases}
\]
where: \( T \) is Joint motion cycle, and take \( T \) as 5s; \( b \) is Move joints; \( \theta \) is Rotate joints.

MATLAB was used to solve the static pose error curve of 4-DOF punching robot end effector which was showed in Figure 7. The static position error peaks of the robot end effectors in the X, Y, and Z directions were 1.1 mm, 2 mm, and 0.05 mm respectively. The static attitude error of the robot end effector in the Z direction was 0.02°, and there was no attitude error in the X, Y direction.

\[
b = \frac{b}{2} \left[ 1 - \cos \left( \frac{2\pi t}{T} \right) \right]
\]  

(10)

![Static error curve](image)

Figure 7. Static position and attitude error curves of 4-DOF punching robot end effector.

3.2. Analysis on influencing factors of static error of reconfigurable punching robot

![Static error curve](image)

Figure 8. Static position and attitude error curve of the influence of the angle error of the rotating mechanism on the end effector of the robot.

In this work, the single variable principle was used to analyze the influence of static error factors on the accuracy of robot end effectors. When the displacement error of the robot's driving mechanism remains the same, the angular error of the rotating mechanism should be increased by 5 times (0.01° → 0.05°), and MATLAB would be used to solve the static posture error curve of the robot's end effector, as shown in Figure 8. The peak position error of the robot's end effector in the X, Y, and Z directions were approximately 5.5mm, 10mm, and 0.05mm. The peak value of the end effector's
attitude error in the Z direction was approximately 0.1°. Comparing and analysing Figure 7 and Figure 8, it can be seen that the peak values of position and attitude errors both increased by 5 times, except the position error of the robot end effector in the Z direction which was not changed, indicated that the angle error of the rotating mechanism had a significant impact on the positioning accuracy of the robot.

When the rotation joint angle error remained same and the displacement error of the driving mechanism was increased by 5 times (0.05mm → 0.25mm), MATLAB was adopted to solve the attitude error curve of the 4DOF reconfigurable punching robot end effector, as shown in Figure 9. The position errors of the robot's end effectors in the X, Y, and Z directions were 1.1 mm, 2 mm, and 0.25 mm. The peak position error of the end effector in the Z direction was approximately 0.02°. Comparing and analysing Figure 7 and Figure 9, we obtained that the position error of the robot end effector in the Z direction was increased by 5 times, which indicated that the error of the driving mechanism had a significant impact on the positioning accuracy of the robot.

![Figure 9](image_url)

(a) Static position error of the end effector of the robot when the error of the propulsion mechanism is increased by 5 times
(b) Static attitude error of the end effector of the robot when the error of the propulsion mechanism is increased by 5 times

**Figure 9.** Static position and attitude error curve of the influence of the angle error of the driving mechanism on the end effector of the robot.

### 3.3 Dynamic error analysis of reconfigurable punching robot

With the rapid development of the robot industry, the processing errors and assembly errors of robot component parts have reached their limitations. However, the flexible deformation caused by the robot operation will also deeply affect the positioning accuracy of the robot in real working conditions. Flexible deformation is a dynamic error affecting factor due to the force or moment of the rod. With the rapid development of lightweight robots and high-speed robots, the impact of flexible deformation on robot positioning accuracy has become increasingly apparent. The dynamic error factors caused by the flexible deformation then lead to a large deviation between the real positioning accuracy and the theoretical positioning accuracy of the robot. Therefore, it is necessary to analyse and study the dynamic error factors of the robot.

The dynamic position and attitude error of the robot end effector in working process is mainly caused by the flexible deformation between the various links of the robot. Therefore, the errors caused by the movement parameters and structural parameters of the robot rods can be associated with dynamic errors owing to the flexible deformation of the robot rods. Therefore, the differential method was used to find the dynamic position and attitude error of the robot's end effector, which are followed in equation 11 and 12:

$$D_n = \sum_{i=1}^{N} \frac{\partial R_n^{x}}{\partial \theta_i} \Delta \theta_i \Delta d_i' + \sum_{i=1}^{N} \frac{\partial R_n^{x}}{\partial \theta_i} \Delta d_i' + \sum_{i=1}^{N} \frac{\partial R_n^{x}}{\partial \theta_i} \Delta b_i \Delta d_i' + \sum_{i=1}^{N} \frac{\partial R_n^{x}}{\partial \theta_i} \Delta \alpha_i \Delta d_i'$$

(11)
\[ \Psi_x = \sum_{i=1}^{N} \left( \frac{\partial R^N}{\partial \theta_i} \Delta \theta_i \right) \delta_i + \sum_{i=1}^{N} \left( \frac{\partial R^N}{\partial \phi_i} \Delta \phi_i \right) \psi_i + \sum_{i=1}^{N} \left( \frac{\partial R^N}{\partial \psi_i} \Delta \psi_i \right) \theta_i \]

Where \( D_N \) is dynamic position error; \( \Psi_N \) is dynamic attitude error; \( k = i, i+1, \ldots, N \)

\[ D_N = \left[ D_{xN} \quad D_{yN} \quad D_{zN} \right] \]

\[ \Psi_N = \left[ \Psi_{xN} \quad \Psi_{yN} \quad \Psi_{zN} \right] \]

The dynamic position and attitude error of 4-DOF punching robot is:

\[ \Psi_x = \left( \frac{\partial R^N}{\partial \theta_i} + \frac{\partial R^N}{\partial \phi_i} \right) \Delta \theta_i \delta_i + \left( \frac{\partial R^N}{\partial \phi_i} \Delta \phi_i \right) \psi_i + \left( \frac{\partial R^N}{\partial \psi_i} \Delta \psi_i \right) \theta_i \]

Where: \( R^N = C_i C_i \cdots C_N \); \( C_i C_i \cdots C_N \) is Rotation matrix in transformation matrix.

The dynamic position and attitude error curve of the end effector of 4DOF reconfigurable punching robot under dynamic error factors was solved based on MATLAB, as shown in Figure 10. The dynamic position error curve of the robot end effector indicated that the peak value of the dynamic position error of the robot end effector in the X and Y directions was 0.16 mm, and the dynamic position error in the Z direction was 0. The dynamic attitude error curve of the robot end effector illustrated that under the influence of flexible deformation, the peak value of the dynamic attitude error of the robot end effector in the X and Y directions was 0.21 °, and the peak value of the dynamic attitude error in the Z direction was about 0.09 °. Compared with Figure 10 and Figure 7, it can be known that the static error factor is the main factor of the position error of the robot end effector, while the dynamic error factor mainly affected the attitude error of the robot end effector. Under the influence of the flexible deformation of the rod, the attitude error appeared simultaneously in the X and Y directions of the end effector of the robot.

(a) Dynamic position error of robot end effector (b) Dynamic attitude error of robot end effector

Figure 10. Dynamic position and attitude error curves of robot end effectors under the influence of flexible deformation.

3.4. Comprehensive error analysis of reconfigurable punching robot

According to the analysis of the influence of the static error factor and the dynamic error factor on the positioning accuracy of the robot end effector, it can be known that the deviation between the ideal position and attitude of the 4DOF reconfigurable punching robot end effector and the actual position and attitude was caused by the interaction of static errors of the robot itself and dynamic errors caused by flexible deformation between the various links of the robot. Therefore, the comprehensive error of
the robot should be analysed and researched. The components of the 4-DOF reconfigurable punching robot have high level of rigidity. The D-H parameter matrix transfers the static error factor of the robot and dynamic error caused by flexible deformation to the end effector of the robot, thereby the positioning accuracy was affected. Therefore, the static and dynamic factors are linearly superimposed, and the comprehensive position error $D_N'$ and comprehensive attitude error $\Psi_N'$ of the robot end effector can be obtained in equation 16 and 17:

\[
D_N' = D_N + D_N \tag{16}
\]
\[
\Psi_N' = \Psi_N + \Psi_N \tag{17}
\]

Figure 11 shows the comprehensive pose error curve of the robot's end effector based on MATLAB. With the influence of the comprehensive error, the peak value of the comprehensive position error of the robot end effector in the X, Y, and Z directions were 1.05mm, 2mm, and 0.05mm separately; the peak value of the comprehensive attitude error of the robot end effector in the X, Y, and Z directions were 0.21°, 0.21°, and 0.11°. By comparing and analyzing Figure 7, Figure 10 and Figure 11, it can be seen that the static position error graph was similar to the comprehensive position error graph, and the dynamic attitude error graph was close to the comprehensive attitude error graph. Hence, it is obvious that the static error factors mainly affected the position error of the robot end effector, while the dynamic error factors mainly affected the attitude error of the robot end effector.

![Figure 11](image)

(a) Comprehensive position error of robot end effector  
(b) Comprehensive attitude error of robot end effector

**Figure 11.** Comprehensive position and attitude error curve of the robot end effector.

4. Compensation for position errors of 4DOF reconfigurable robot

According to the comprehensive pose error analysis of the end effector of the robot, it was obvious that the working accuracy of the robot was low. In actual working conditions, the comprehensive posture error seriously affected the reliability and efficiency of the robot. In order to improve the positioning accuracy of the 4DOF reconfigurable punching robot, it is necessary to perform error compensation on the integrated attitude error of the robot end effector.

4.1. Robot error compensation principle

There are two commonly used error compensation methods: hardware compensation method and intrinsic software compensation method.[13] The hardware compensation method uses an error compensator to quickly and efficiently eliminate errors, but hardware compensation may cause additional manufacturing costs and increase costs for the robot. The intrinsic software compensation method makes the robot end effector reach the ideal position by adjusting the posture parameters [14]. There are two commonly used software compensation methods: parameter correction method and perturbation compensation method. Veitschegger [15] and others first solved the parameter error of each mechanism, and finally used the iterative method to compensate. Because the partial differential...
matrix equation and the least square method were used, the calculation was more complicated. Jiao Guotai [12] used the perturbation compensation method to add some motion variables to the robot in advance, which caused the robot actuator to generate a small additional motion. By using this motion to reduce or eliminate the error of the robot actuator, the effect is good.

When there are many comprehensive factors, the effect of the perturbation compensation method is more better. Analyzing the above errors, it can be known that the position and attitude errors of the four-degree-of-freedom reconfigurable punching robot end effector were affected by multiple factors, so the perturbation compensation method was selected for error compensation. Assuming that the precise position of a four-degree-of-freedom reconfigurable punching robot in an ideal working state is \( D_n \), the input variable of the rotary joint at this position is \( \theta_{in} \), and the input variable of the displacement joint is \( b_n \). Suppose \( \Delta D_n \) is the perturbation error of the reconfigurable punching robot end effector under the influence of comprehensive error factors. In order to compensate the perturbation error \( \Delta D_n \) of the robot end effector, a perturbation position \( \Delta^* D_n \) needs to be pre-added on the robot end effector. The corresponding rotation joint input variable is \( \Delta^* \theta_n \), and the displacement joint input motion variable is \( \Delta^* b_n \). The perturbation position \( \Delta^* D_n \) is used to offset the perturbation error \( \Delta D_n \) of the end effector of the robot to realize the position correction of robot end effector. The perturbation error expression based on the comprehensive error model of the robot’s end effector is:

\[
\Delta^* D_n = \sum_{i=1}^{n} \left( \frac{\partial D_n}{\partial \theta_i} \right) \Delta^* \theta_i + \sum_{i=1}^{n} \left( \frac{\partial D_n}{\partial b_i} \right) \Delta^* b_i
\]

(18)

4.2. Position error compensation of robot end effector

Based on the perturbation compensation method, the comprehensive pose error matrix of a four-degree-of-freedom reconfigurable punching robot end effector is:

\[
\Delta^* T_e = T_e \cdot \begin{bmatrix} 0 & -(\Psi_{st} + \Psi'_{st}) & \Psi_{st} + \Psi'_{st} & D_{st} + D'_{st} \\ -(\Psi_{st} + \Psi'_{st}) & 0 & -(\Psi_{st} + \Psi'_{st}) & D_{st} + D'_{st} \\ \Psi_{st} + \Psi'_{st} & -(\Psi_{st} + \Psi'_{st}) & 0 & D_{st} + D'_{st} \\ 0 & 0 & 0 & 0 \end{bmatrix}
\]

(19)

**Figure 12.** Comprehensive position error curve of robot end effector after perturbation compensation.

The comprehensive position error map of the end effector of the 4DOF reconfigurable punching robot after perturbation compensation was solved with MATLAB, which was shown in Figure 12. The peak position error of the robot end-effector in the X, Y, and Z directions were 0.12 mm, 0.1 mm, and 0 mm, respectively. By comparing and analyzing Figure 12 and Figure 11 (a), it can be known that the peak position error of the end effector of the robot after perturbation compensation was significantly reduced. This showed that the positioning accuracy of the robot can be improved, and it further
illustrated that the perturbation compensation method was effective for the position error of the end effector of the robot.

5. Conclusion
This work mainly focused on the positioning accuracy of the end effector of the 4-DOF reconfigurable punching robot. The kinematics equation of the robot was established by D-H matrix method. Based on the static pose error model of robot end effector, the static error model curve of robot end effector was solved by MATLAB. According to the principle of single variable, the influence of static factors on robot positioning accuracy was analysed. As the result of the dynamic error model of the robot end actuator, the error model curve of the robot under the dynamic error caused by the flexible deformation was solved with MATLAB. The static error and dynamic error were superposed linearly to get the comprehensive error curve of the robot end actuator. From the error analysis, we could learn that the position error of the robot end actuator is the result of the static error, whereas the dynamic error dominates the position error of the robot end actuator, and the static error factor and the dynamic error factor together affect the positioning accuracy of the robot. The perturbation compensation method were used to compensate the position error of the robot end actuator at the same time. The conclusions obtained in this work are as followed:

1. The angle error of the rotating actuator module noticeably impacted the pose error of the robot actuator. Given this, the accuracy of the rotating actuator module should be maximized during the designing and manufacturing phases of the actuator.

2. The displacement error of the propulsion actuator module primarily affected the pose error of the robot actuator in the Z direction. It is therefore speculated that the accuracy of the propulsion actuator module should be maximized as well when the actuator was being designed and manufactured.

3. The comprehensive attitude error curve complied with the dynamic attitude error curve. It is thus revealed that in terms of re-configurable punching robot, the static factors remarkably impacted the pose error of the actuator, and the dynamic factors attributed to the flexible deformation of the bar imposed an evident effect on the attitude error of the actuator.

4. The positioning accuracy of the robot was effectively improved by using the perturbation compensation method. The results showed that the error peak value of each direction was significantly lower than it before error compensation. It showed that the error compensation was practical and effective.

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