Proceedings of the 2016 IEEE
International Conference on Robotics and Biomimetics
Qingdao, China, December 3-7, 2016

A Novel Kinematic Calibration Method for a Handling Robot Based on Optimal Trajectory Planning

Lei Ding, En Li, Zize Liang, Min Tan

Abstract—**Kinematic calibration is of great significance to the application of handling robot in the field of stamping industry. In this paper, a novel kinematic calibration method of a 5-DOF handling robot is proposed based on optimal trajectory planning. In order to illustrate our independently developed mechanical structure composed of three rotary joints and two translational joints, the forward kinematic model is constructed using the MDH method. And then, we establish the error model according to the difference between the theoretical position and actual position of robot end effector. Furthermore, a low cost vision measurement system is designed with single camera and self-designed target, while the optimal trajectory for kinematic calibration consisted of calibration points is obtained by Genetic Algorithm (GA). Finally, two simulation experiments are executed to verify the effectiveness and efficiency of our kinematic calibration method.**

I. Introduction

In the stamping industry, traditional manual methods are gradually replaced by automatic methods. Handling robot which is used as automatic feeding and unloading for punching press is widely used. Like other industrial robots, the repetitive positioning precision of handling robot is pretty high, while the absolute positioning precision is quite low [1]. The development and application of handling robot for stamping industry is seriously restricted by its low absolute positioning precision. So the research of improving the absolute positioning precision is of great importance. At present, main ways to improve the absolute positioning precision can be divided into two types:

- Error prevention method, the method is realized by improving the mechanical design, advancing the manufacturing and assembling process to improve the precision of robot components. The realization of this method needs high precision processing technology. Usually the cost of this method is very high.
- Error compensation method, which is the kinematic calibration method. The kinematic calibration is needed because the position of robot is based on a precise description of the kinematic parameters [2]. The kinematic calibration uses advanced measurement method and appropriate parameter identification method to identify the accurate parameters of the forward kinematic model, so as to improve the absolute positioning precision. Low cost is the advantage of this method and it is currently the most frequently used method to improve the absolute positioning precision of robot. The steps of kinematic calibration are modeling, pose measurement, parameter identification and error compensation. The first three steps are discussed in this paper.

*This work is supported by National Science and Technology Support Program of China (2015BAK06B01) and National Natural Science Foundation (NNSF) of China (61403372).

L. Ding is with the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China and the University of Chinese Academy of Sciences, Beijing 100049, China. E-mail: dinglei2014@ia.ac.cn.

E. Li, Z. Liang, and M. Tan are with the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China. E-mail: {en.li, zize.liang, min.tan}@ia.ac.cn.

At present, the commonly used pose measuring systems for robot calibration are the theodolite, the three coordinate measuring instruments and the laser tracker [3-5]. The common disadvantages of these measuring devices are high cost and complex measuring procedures. With the development of machine vision, visual measurement is gradually used to implement kinematic calibration. P. Renaud et al. [6] used monocular vision system to perform kinematic calibration for parallel robot, and the correctness of the method was verified by H4 robot calibration experiment. G. Campion et al. [7] made use of 3D analyzer and movable monocular vision system to perform kinematic calibration for surgical robot and achieved high accuracy. Z. Xie et al. [8] used a single camera that was installed on the end effector of robot and fixed plane target to complete the calibration of kinematic parameters. The method simplified the calibration process and reached the mean error of 0.366791 mm. Z. Ying et al. [9] performed kinematic calibration for industrial robot based on binocular tracking technique. The complex calculation of model was not required in calibration and the positioning error was reduced. Y. Ding et al. [10] proposed an identification method based on monocular camera and 3D target. The method established the relationship between the spatial pose and its 2D image mapping using four spatial feature points with parallelogram constraints. The kinematic calibration was carried out in the Delta robot platform.

The above kinematic calibration systems both use vision as measuring means without taking into account that the trajectory consisted of calibration points may influence camera measurement and final calibration precision. In other words, the trajectory of robot is not optimized. Besides, the above robots are both composed of rotary joints, while the robot structures that are composed of rotary joints and translational joints are rarely involved.

In order to solve these problems, kinematic and error model are established for the independently developed 5-DOF handling robot that is formed by the combination of three rotary joints and two translational joints. A new monocular vision measurement system is designed in this paper. In kinematic calibration, Genetic Algorithm (GA for short) is firstly used to obtain the optimal trajectory. Levenberg-Marquardt algorithm is used to identify kinematic parameters. At last, two simulation experiments are carried out in handling robot to validate the correctness of our kinematic calibration method.

Next, the modeling is described in Section II. Section III and Section IV provides the detailed design of the pose measurement system and the optimal trajectory for kinematic calibration. Simulation experiment and the results are given in Section V. Finally, conclusions are provided in Section VI.

II. Modeling

A. Kinematic Modeling

The research objective of this paper is improving the absolute positioning precision of the independently developed 5-DOF handling robot [11] to 0.2 mm, as shown in Fig.1. The handling robot consists of following components: 1. base, 2. waist joint, 3, 4. translational joint, 5. elbow joint, and 6. wrist joint. Five degrees of freedom are respectively rotational motion of the main arm, vertical motion of the main arm, parallel motion of the forearm, torsion motion of the forearm and rotational motion of the end execution. The kinematic model of robot is established by DH method. The link coordinate systems of handling robot are shown in Fig. 2.

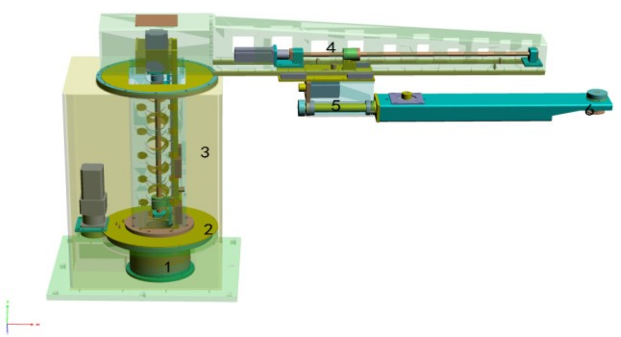

Figure 1. Mechanical structure of handling robot.

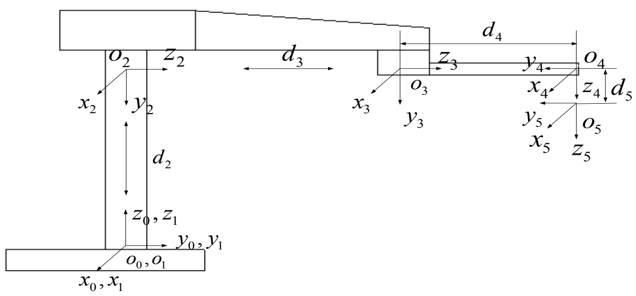

Figure 2. Link coordinate system of handling robot.

TABLE I. Nominal Kinematic Parameters of MDH Model

Link	θ_i /°	α_i /°	a_i /mm	d_i /mm	β_i /°
1	θ_1	0	×	×	0
2	×	-90°	×	d_2	×
3	×	0	×	d_3	0
4	θ_4	-90°	0	d_4=300	×
5	θ_5	0	0	d_5=25	×

The × in Table I means that transformation matrix does not contain this parameter. The joint angle of each joint is θ_i, the torsion angle is α_i, the length of the link is a_i, and the connecting link displacement is d_i, the rotation angle of the Y axis β_i.

When adjacent joints are parallel or approximately parallel with each other, small changes in the link parameters will have a significant impact on link coordinate system parameters [12]. So a modified DH model (MDH model) [13] is used to describe the kinematic. With regard to the handling robot, rotary joint 1 is parallel with translational joint 2, while translational joint 3 is parallel with rotary joint 4. So the nominal kinematic parameters of MDH model are shown in Table I.

According to the nominal kinematic parameters of MDH model from Table I, translation matrix of each link can be obtained. The foreword kinematic model of handling robot can be obtained by the MATLAB symbolic [14] computing.

B. Error Modeling

According to the nominal kinematic model of handling robot obtained in Section A, the theoretical position of robot end effector p can be described as follows:

$$\boldsymbol{p} = \boldsymbol{f}(\boldsymbol{\theta}, \boldsymbol{\alpha}, \boldsymbol{a}, \boldsymbol{d}, \boldsymbol{\beta}). \tag{1}$$

After manufacturing and assembling, mechanical structure of robot will change. It inevitably leads to the difference between the actual kinematic parameters and nominal values of robot [15]. So the theoretical position of robot end effector p and the actual position p_a will be different. The actual position p_a can be expressed as follows:

$$\boldsymbol{p}_a = \boldsymbol{f}(\boldsymbol{\theta} + \boldsymbol{\Delta\theta}, \boldsymbol{\alpha} + \boldsymbol{\Delta\alpha}, \boldsymbol{a} + \boldsymbol{\Delta a}, \boldsymbol{d} + \boldsymbol{\Delta d}, \boldsymbol{\beta} + \boldsymbol{\Delta\beta}). \tag{2}$$

where $\Delta\theta$, $\Delta\alpha$, Δa, Δd, $\Delta\beta$ are error parameters.

The error parameters above are usually quite small. By using the Taylor formula, ignoring the derivative terms of the two degrees or above, the deviation between p_a and p can be described as:

$$\boldsymbol{\Delta p} = \boldsymbol{p}_a - \boldsymbol{p} = \frac{\partial f}{\partial \boldsymbol{\theta}}\boldsymbol{\Delta\theta} + \frac{\partial f}{\partial \boldsymbol{\alpha}}\boldsymbol{\Delta\alpha} + \frac{\partial f}{\partial \boldsymbol{a}}\boldsymbol{\Delta a} + \frac{\partial f}{\partial \boldsymbol{d}}\boldsymbol{\Delta d} + \frac{\partial f}{\partial \boldsymbol{\beta}}\boldsymbol{\Delta\beta} = \boldsymbol{J\Delta\delta}. \tag{3}$$

where fifteen dimension kinematic error parameters is:

$$\boldsymbol{\Delta\delta} = \left[\Delta\theta_1 \ \ \Delta\theta_4 \ \ \Delta\theta_5 \ \ \Delta\alpha_1 \ \ \Delta\alpha_2 \ \ \Delta\alpha_3 \ \ \Delta\alpha_4 \ \ \Delta a_4 \ \ \Delta a_5 \ \ \Delta d_2 \ \ \Delta d_3 \ \ \Delta d_4 \ \ \Delta d_5 \ \ \Delta\beta_1 \ \ \Delta\beta_3\right]$$

Error coefficient matrix J is:

$$\boldsymbol{J} = \left[\frac{\partial f}{\partial \boldsymbol{\theta}} \ \ \frac{\partial f}{\partial \boldsymbol{\alpha}} \ \ \frac{\partial f}{\partial \boldsymbol{a}} \ \ \frac{\partial f}{\partial \boldsymbol{d}} \ \ \frac{\partial f}{\partial \boldsymbol{\beta}}\right]. \tag{4}$$

$$\frac{\partial f}{\partial \boldsymbol{\theta}} = \left[\frac{\partial f}{\partial \theta_1} \ \ \frac{\partial f}{\partial \theta_4} \ \ \frac{\partial f}{\partial \theta_5}\right], \frac{\partial f}{\partial \boldsymbol{\alpha}} = \left[\frac{\partial f}{\partial \alpha_1} \ \ \frac{\partial f}{\partial \alpha_2} \ \ \frac{\partial f}{\partial \alpha_3} \ \ \frac{\partial f}{\partial \alpha_4}\right]$$

$$\frac{\partial f}{\partial \boldsymbol{a}} = \left[\frac{\partial f}{\partial a_4} \ \ \frac{\partial f}{\partial a_5}\right], \frac{\partial f}{\partial \boldsymbol{d}} = \left[\frac{\partial f}{\partial d_2} \ \ \frac{\partial f}{\partial d_3} \ \ \frac{\partial f}{\partial d_4} \ \ \frac{\partial f}{\partial d_5}\right], \frac{\partial f}{\partial \boldsymbol{\beta}} = \left[\frac{\partial f}{\partial \beta_1} \ \ \frac{\partial f}{\partial \beta_3}\right]$$

$$\boldsymbol{f} = \left[f_x \ \ f_y \ \ f_z\right]^T$$

In (3), the error model is nonlinear equations about kinematic error parameters. In order to solve the equations, we need to generate position information of at least five points considering that Δp is a three dimension vector. Next we will introduce the vision measurement system and search for the optimal trajectory to serve as data set for the error model.

III. Pose Measurement

The most commonly used measurement methods based on vision can be divided into monocular, binocular and multi vision. The binocular and multi vision mainly depend on the depth information of measuring point. When the distance between the vision system and the target is far, measurement error is large. It is difficult to meet the requirements of absolute positioning accuracy [16]. Besides, with the increase of the number of camera, cost of measurement system increases, and the coordinate transformations between cameras bring extra error. Therefore, we propose a new type of monocular vision measurement system, as shown in Fig. 3.

The system is composed of a camera and target. A camera, which is installed on a tripod, is placed out of the workspace of handling robot. The target, which is installed on the end effector, is composed of a base, three cylindrical supporting frames and triangular measuring plane. Three endpoints of triangular measuring plane are measuring points. They form an equilateral triangle relationship and distances between measuring points are known.

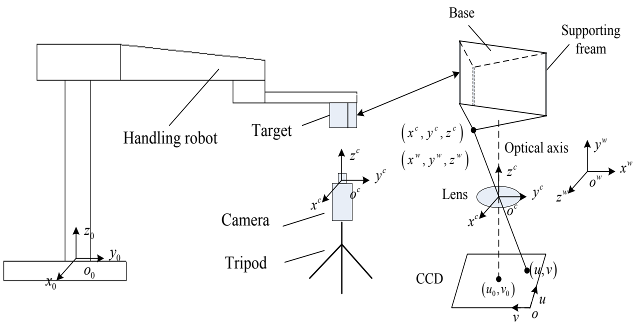

Figure 3. Monocular vision measurement system.

Before measuring, we need to calibrate the camera, and get the internal and external parameters matrix. The calibration is performed on Camera Calibration Toolbox for MATLAB [17]. According to the coordinate system shown in Fig. 3, after calibration, camera model can be described as:

$$z^c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \boldsymbol{M_1 M_2} \begin{bmatrix} x^w \\ y^w \\ z^w \\ 1 \end{bmatrix}. \tag{5}$$

where M_1 is the 3*4 internal parameter matrix, M_2 is the 4*4 external parameter matrix, we obtain them by camera calibration. (u, v) is the measuring point's coordinate in the image coordinate system. z^c is the measuring point's z coordinate in the camera coordinate system. (x^w, y^w, z^w) is the measuring point's coordinate in the camera world coordinate system.

When the robot's position is fixed, equations can be obtained using three measuring points' camera model and the constraints that three measuring points form an equilateral triangle and the distances between them are known. Three measuring points' coordinates in the camera world coordinate system can be obtained through solving the equations. Robot end effector position measurement is realized.

IV. Optimal Trajectory for Calibration

In kinematic calibration, the selection of calibration points directly affects kinematic calibration results. In order to achieve high precision results, the first thing needs to do is choosing calibration points and optimizing the trajectory of robot.

Firstly, we need to establish the relationship between vision measurement and the error model. In (5), when kinematic error parameters are not considered, camera model can be described in non-homogeneous form as:

$$z^c \begin{bmatrix} u \\ v \end{bmatrix} = \boldsymbol{M_{11}} \begin{bmatrix} x^c \\ y^c \\ z^c \end{bmatrix}. \tag{6}$$

where (x^c, y^c, z^c) is the measuring point's coordinate in the camera coordinate system. (u, v) is the measuring point's coordinate in the image coordinate system. M_{11} is the non-homogeneous form of internal parameter matrix M_1.

When kinematic error parameters are considered, camera model can be approximately described as:

$$z_a^c \begin{bmatrix} u_a \\ v_a \end{bmatrix} \approx z^c \begin{bmatrix} u_a \\ v_a \end{bmatrix} = \boldsymbol{M_{11}} \begin{bmatrix} x_a^c \\ y_a^c \\ z_a^c \end{bmatrix}. \tag{7}$$

where (x_a^c, y_a^c, z_a^c) is the measuring point's coordinate in the camera coordinate system when kinematic error parameters are considered. (u_a, v_a) is the measuring point's coordinate in the image coordinate system when kinematic error parameters are considered.

Considering that robot and camera are stationary, the following equation can be obtained:

$$\begin{bmatrix} x_a^c \\ y_a^c \\ z_a^c \end{bmatrix} = \boldsymbol{R} \begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix} + \boldsymbol{T} = \begin{bmatrix} x^c + \Delta p_x \\ y^c + \Delta p_y \\ z^c + \Delta p_z \end{bmatrix}. \tag{8}$$

where R is the 3*3 rotation matrix, T is the 3*1 translation matrix. R is identity matrix. (x_a, y_a, z_a) is the measuring point's coordinate in the robot base coordinate system when kinematic error parameters are considered. (Δp_x, Δp_y, Δp_z) is the deviation between p_a and p in (3).

The error of the measuring points' image coordinate can be described as follows by (7) - (6) and (8).

$$\begin{bmatrix} \Delta u \\ \Delta v \end{bmatrix} = \frac{1}{z_c} \boldsymbol{M_{11}} \begin{bmatrix} \Delta p_x \\ \Delta p_y \\ \Delta p_z \end{bmatrix} = \frac{1}{z_c} \boldsymbol{M_{11} J \Delta \delta}. \tag{9}$$

In some postures of handling robot, small changes in vision measurement may result in great changes of kinematic calibration results. If the trajectory of handling robot is not optimized, calibration results may be influenced greatly. In order to make all the error parameters well solved, one of the cost functions can be the condition number, which reflects the pathological degree of matrix, as in (10). Smaller condition number means that measurement error has smaller impact on the error parameter, which means the calibration accuracy is higher.

$$\begin{aligned} cond_1 &= \left\| \boldsymbol{JM_{11}} / z_{a1}^c \right\| * \left\| \left(\boldsymbol{JM_{11}} / z_{a1}^c \right)^{-1} \right\| \\ cond_2 &= \left\| \boldsymbol{JM_{11}} / z_{a2}^c \right\| * \left\| \left(\boldsymbol{JM_{11}} / z_{a2}^c \right)^{-1} \right\|. \\ cond_3 &= \left\| \boldsymbol{JM_{11}} / z_{a3}^c \right\| * \left\| \left(\boldsymbol{JM_{11}} / z_{a3}^c \right)^{-1} \right\| \end{aligned} \tag{10}$$

where J is the error coefficient matrix in (4). z_{a1}^c, z_{a2}^c, z_{a3}^c are respectively the target's three measuring points' z coordinates in the camera coordinate system when kinematic error parameters are considered.

In the image coordinate system, small distances between measurement points are not expected. So area of the triangle that is formed by the reflection of measuring points in the image is used as another cost function, as in (11).

$$S = abs\left(u_1v_2 + u_2v_3 + u_3v_1 - u_1v_3 - u_2v_1 - u_3v_2\right). \quad (11)$$

where (u_1, v_1), (u_2, v_2), (u_3, v_3) are respectively the three measurement points' coordinates in the image coordinate.

We hope that measurement points are not far away from the z^c axis in the camera coordinate system, so the angles between the measurement points and the z^c axis in the camera coordinate system are the last cost function.

In this paper, GA is used in the robot's workspace to find the optimal trajectory for calibration. GA is a kind of efficient, parallel, global search method, and mainly used for the optimization of nonlinear, multiple model, multiple target and other complex system. The advantage is that it is not easy to fall into local optimum. It is realized by using the genetic algorithm toolbox [18].

In this thesis, joint variables are θ_1, d_2, d_3, θ_4, θ_5. Binary code is applied to these variables, and then GA is used for iterative search. Evolutionary generation is set to 200. Considering the mechanical limits of 5-DOF handling robot, the value ranges of the five parameters are shown in Table II.

TABLE II. VALUE RANGES OF JOINT VARIABLES

Variable	Value range
θ_1 /°	-165~165
d_2 /mm	850~1350
d_3 /mm	0~700
θ_4 /°	0~175
θ_5 /°	-175~175

We use the cost functions above to form fitness function for GA. The multi-objective optimization problem is transformed into single objective optimization problem by using the weight coefficient transform method. Fitness function can be described as follows:

$$\min\left[c_1 * \left(cond_1 + cond_2 + cond_3\right) + c_2 * \left(\theta_{c1} + \theta_{c2} + \theta_{c3}\right) + c_3 * S\right]. \quad (12)$$

where $cond_1$, $cond_2$, $cond_3$ are respectively the condition number of the three measuring points, as in (10). θ_{c1}, θ_{c2}, θ_{c3} are respectively the angle between three measuring points and the camera optical axis. S is the area of the triangle that is formed by the reflection of measuring points in the image, as in (11). c_1, c_2 and c_3 are weight ratio that can be adjusted according to the actual situation. The procedure of GA is shown in Fig. 4.

The main working area of handling robot focuses on the former half of the whole workspace. So we set the initial pose of handling robot as [pi/4, 1100, 0, pi/2, 0], as shown in Fig. 5. In the process of optimization, the positional relation of monocular camera and the robot is shown in Fig. 5. The green line is a simplified representation of handling robot, and the red dot represents the camera's position.

We search for forty interior points in Cartesian space so as to cover the main working area as much as possible, and then use linear motion to connect neighbor points to construct the optimal trajectory for calibration, as shown in Fig. 5, and the motion of each joint with time (point number) is shown in Fig. 6.

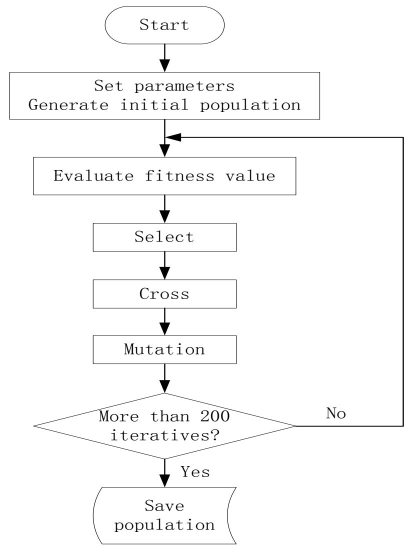

Figure 4. The procedure of GA.

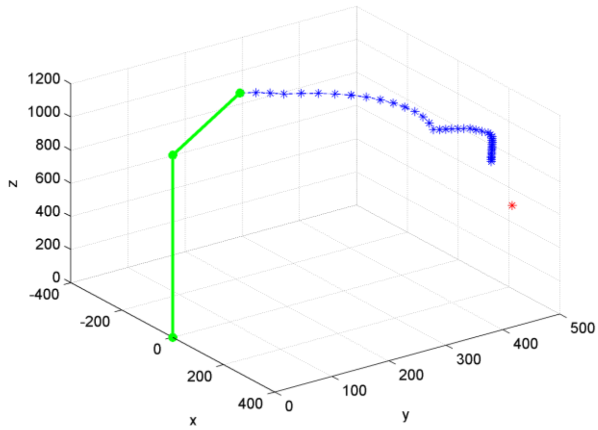

Figure 5. Optimal trajectory.

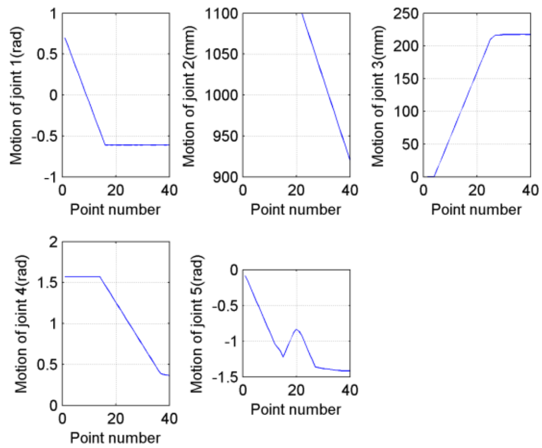

Figure 6. The motion of each joint.

V. Simulation and Results

In (3), the error model is nonlinear and over-determined equations about robot kinematic error parameters. In order to solve the equations, most commonly used algorithm is the least square method. But the least square method usually needs large calculation. Therefore, the Levenberg-Marquardt algorithm [19-20] is used to solve this problem. It has the advantages of fast convergence and strong robustness. We can obtain the solution of error parameters by using the following iterative equation:

$$\boldsymbol{\Delta\delta}_{k+1} = \left(\boldsymbol{J}_k^T\boldsymbol{J}_k + \lambda_k\boldsymbol{I}\right)^{-1}\boldsymbol{J}_k^T\boldsymbol{\Delta p}_k \,. \tag{13}$$

where λ_k is damping factor.

In order to validate the correctness and feasibility of the above kinematic calibration method, simulation experiments were designed.

A. Simulation Process

The process of simulation experiment was:

STEP1. The values of the error parameters were randomly set, as shown in Table III;

TABLE III. Set Values of The Error Parameters

Link	$\Delta\theta_i$ /rad	$\Delta\alpha_i$ /rad	Δa_i /mm	Δd_i /mm	$\Delta\beta_i$ /rad
1	0.002638	0.003693	×	×	0.00123
2	×	-0.005797	×	0.0184	×
3	×	0.005499	×	0.0240	0.006221
4	0.001455	0.001450	-0.0760	-0.0417	×
5	-0.001361	×	0.0240	0.0530	×

The × in Table III means that transformation matrix does not contain this parameter and there is no need to identify this parameter.

STEP2. The theoretical position of the end effector p was calculated according to the joint values from the calibration points of optimal trajectory. The actual position of the end effector p_a was calculated according to the actual kinematic parameters that was the combination of the nominal kinematic parameters and the set values of the error parameters. Δp_0 was obtained by the difference of p_a and p.

STEP3. The parameters for Levenberg-Marquardt algorithm were set. The initial values of the fifteen error parameters $\Delta\delta_0$ were all set as 0.01. The damping coefficient λ_0 was set as 1. Then the algorithm was used to identify the kinematic error parameters. The Levenberg-Marquardt algorithm terminated when the running times were more than 100 or the position error was less than 1.0×10^{-10}, and the identification was done.

B. Results of Simulation I

Simulation I was performed without considering the pose measuring error to validate the correctness of the error model, the optimal trajectory and the feasibility of the parameter identification algorithm. The changes of robot position error with iteration numbers in the identification process are shown in Fig. 7. Robot position error is less than the error setting value 1.0×10^{-10} after 24 iterative optimizations, and parameter identification is done. The identification results and the setting values of the error parameters are exactly the same when four digits are retained. So the correctness of the proposed kinematic calibration method is validated.

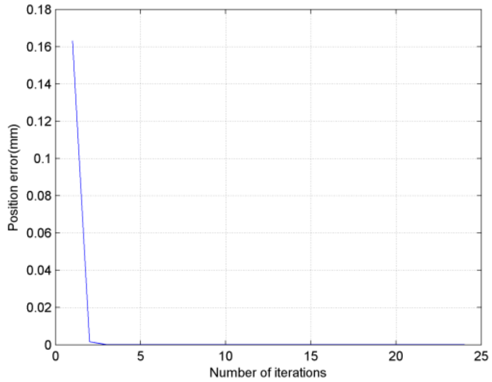

Figure 7. The changes of position error with iterations.

C. Results of Simulation II

As in Section IV, small changes in vision measurement may result in great changes of kinematic calibration results. In order to validate that kinematic calibration using optimal trajectory will reduce the changes, Simulation II was designed.

Simulation II was performed with pose measuring error. The random measuring error was set as [-0.1mm, 0.1mm] to meet the requirement of 0.2mm absolute positioning precision. The calibration points in optimal trajectory obtained in Section IV were used to identify the error parameters. Then the error parameters were used on test data, which were randomly obtained in the main working area, as shown in Fig. 8. Meanwhile a random trajectory was used as comparison.

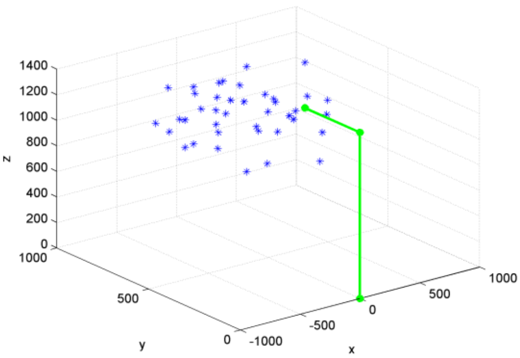

Figure 8. Test data.

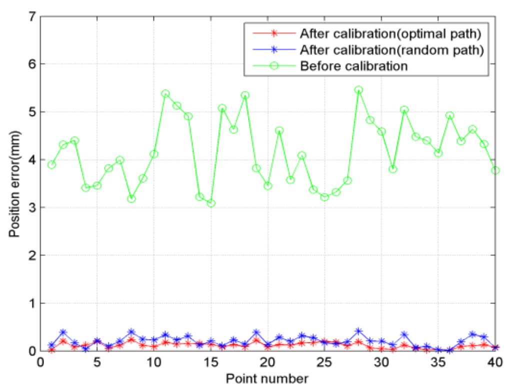

Figure 9. The position error on test data.

TABLE IV. POSITION ERROR BEFORE AND AFTER CALIBRATION ON TEST DATA

Path	Error	Before calibration /mm	After calibration /mm
Optimal trajectory	Maximum	5.4600	0.2359
	Mean	4.1723	0.1175
Random trajectory	Maximum	5.4600	0.4123
	Mean	4.1723	0.2066

As shown in Fig. 9, and Table IV, the maximum and mean position error on test data using optimal trajectory have reduced 95.68 and 97.18 percent. The maximum and mean position error on test data using random trajectory have reduced 92.45 and 95.05 percent. The maximum and mean position error on test data using optimal trajectory have reduced greatly and are smaller than the maximum and mean position error on test data using random trajectory. As shown in Table V and Table VI, because of the random measuring error, identification values are different from the set values. But the amplitude of variation of identification values with the random trajectory is bigger than identification results with the optimal trajectory. This proves that kinematic calibration using optimal trajectory will reduce the changes and all the error parameters are well solved.

TABLE V. IDENTIFICATION VALUES WITH THE OPTIMAL TRAJECTORY

Link	$\Delta\theta_i$ /rad	$\Delta\alpha_i$ /rad	Δa_i /mm	Δd_i /mm	$\Delta\beta_i$ /rad
1	0.0024	0.0039	×	×	0.0008
2	×	-0.0061	×	0.3117	×
3	×	0.0045	×	2.1625	0.0075
4	0.0212	-0.1709	0.3551	2.3338	×
5	-0.3719	×	0.0474	0.3835	×

TABLE VI. IDENTIFICATION VALUES WITH THE RANDOM TRAJECTORY

Link	$\Delta\theta_i$ /rad	$\Delta\alpha_i$ /rad	Δa_i /mm	Δd_i /mm	$\Delta\beta_i$ /rad
1	0.0025	0.0045	×	×	0.0011
2	×	-0.0071	×	2.1045	×
3	×	-0.0009	×	3.5538	0.0062
4	-0.1407	-0.2461	-3.6901	3.5716	×
5	0.4289	×	0.0852	0.4755	×

VI. CONCLUSION

In this paper, the kinematic calibration method of the 5-DOF handling robot is studied, and the following problems are solved:

1) Based on the independently developed mechanical structure that is composed of three rotary joints and two translational joints, the kinematic model is established using MDH method. Then the error model is built.
2) A low cost vision measurement system based on monocular vision is designed. The position measurement of the end effector is achieved by the coordination of camera and target.
3) The self-developed handling robot is not the mechanical structure that can reach all of the posture. The optimal trajectory for kinematic calibration is obtained using GA in the workspace of handling robot to ensure high precision kinematic calibration results.
4) Two simulation experiments are designed and the results verify the correctness of proposed method. The simulation experiments laid a solid foundation for subsequent research.

How to accurately identify the error parameters and improve the efficiency of parameter identification algorithm is a worthy problem in the further study.

REFERENCES

[1] J. Santolaria and M. Ginés, “Uncertainty estimation in robot kinematic calibration,” Robotics and Computer-Integrated Manufacturing, vol. 29, no. 2, pp. 370-384, Apr. 2013.

[2] I. W. Park, B. J. Lee, S. H. Cho, Y. D. Hong and J. H. Kim, “Laser-Based Kinematic Calibration of Robot Manipulator Using Differential Kinematic, ” *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 6, pp. 1059-1067, Dec. 2012.

[3] A. Nubiola and I. A. Bonev, “Absolute calibration of an ABB IRB 1600 robot using a laser tracker,” Robotics and Computer-Integrated Manufacturing, vol. 29, no. 1, pp. 236-245, Feb. 2013.

[4] T. Sun, Y. Zhai, Y. Song and J. Zhang, “Kinematic calibration of a 3-DoF rotational parallel manipulator using laser tracker,” Robotics and Computer-Integrated Manufacturing, vol. 41, pp. 78-91, Oct. 2016.

[5] W. Tian, F. Yin, H. Liu, J. Li, Q. Li, T. Huang and D. G. Chetwynd, “Kinematic calibration of a 3-DOF spindle head using a double ball bar,” Mechanism and Machine Theory, vol. 102, pp. 167-178, Aug. 2016.

[6] P. Renaud, N. Andreff, J. M. Lavest and M. Dhome, “Simplifying the kinematic calibration of parallel mechanisms using vision-based metrology, ” *IEEE Transactions on Robotics*, vol. 22, no. 1, pp. 12-22, Feb. 2006.

[7] G. Campion, P. Fiorini and S. Martelli, “Robot calibration using mobile camera,” *IEEE International Conference on Robotics and Automation,* vol. 1, pp. 141-146, *2002*.

[8] Z. Xie, S. Xin, X. Li and S. Xu, “Method of robot calibration based on monocular vision,” Journal of mechanical engineering, vol. 47, no. 5, pp. 35-39, Mar. 2011.

[9] Z. Ying, Z. Li, X. Ping, Y. Jiang and K. Liu, “Robot calibration based on binocular vision dynamic tracking,” Application Research of Computers, vol. 31, no. 5, pp. 1424-1427, May 2014.

[10] Y. Ding, J. Mei, W. Zhang and X. Liu, “Position and Orientation Measurement of Parallel Robot Based on Monocular Vision,” Journal of mechanical engineering, vol. 50, no. 21, pp. 174-179, Nov. 2014.

[11] L. Ding, E. Li, M. Tan and Y. Wang, “System design and kinematic analysis of a 5-DOF handling robot,” J. Huazhong Univ. of Sci. & Tech. (Natural Science Edition), vol. 43, sup. I, pp. 19-22, Oct. 2015.

[12] H. Fang and X. Liu, “Parameter determination in robot kinematic model,” JOURNAL OF MACHINE DESIGN, vol. 28, no. 2, pp. 46-49, Feb. 2011.

[13] S. Hayti and M. Mirmirani, “Improving the absolute positioning accuracy of robot manipulators,” Journal of Robotic Systems, vol. 2, no. 4, pp. 397-413, Feb. 1985.

[14] MathWorks, Inc., http://cn.mathworks.com/products/symbolic/.

[15] R. He, Y. Zhao, S. Yang and S. Yang, “Kinematic-Parameter Identification for Serial-Robot Calibration Based on POE Formula,” *IEEE Transactions on Robotics*, vol. 26, no. 3, pp. 411-423, June 2010.

[16] Z. Xiao, W. Zhang, L. Geng, F. Zhang and J. Wu, “Accuracy Analysis of Binocular Vision System,” Opto-Eledtronic Engineering, vol. 41, no. 2, pp. 6-11, Feb. 2014.

[17] Camera Calibration Toolbox for MATLAB., http://www.vision.caltech.edu/bouguetj/calib_doc/index.html.

[18] Complex Optimization and Decision Making Laboratory (CODeM)., http://codem.group.shef.ac.uk/index.php/ga-toolbox.

[19] K. Levenberg. “A method for the solution of certain non-linear problems in least squares,” Quarterly of applied mathematics, vol. 2, pp. 164-168, 1944.

[20] D. W. Marquardt. “An algorithm for least-squares estimation of nonlinear parameters,” Journal of the Society for Industrial and Applied Mathematics, vol. 11, no. 2, pp. 431-441, June 1963.