# Binocular Initial Location and Extrinsic Parameters Real-time Calculation for Bionic Eye System

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***Abstract*—A simple binocular visual equipment is designed in this paper, which is mainly composed by two CCD cameras and four stepping motors. Firstly, the two cameras' initial location is determined based on rough location by moving to the limiting position, and precise location by driving the image center aligning with fitted ellipse center. Then, the transformation matrix between coordinate systems of motion module end and the camera is calibrated with eye-in-hand calibration method, which adopts multi frame images and a method based on Levenberg-Marquardt iterative algorithm to improve its precision and robustness. Finally, the updating equations of transformation matrix between two camera's coordinate systems are deduced with high precision and real-time property to guarantee the binocular visual system's depth perception. The performance of the above methods is confirmed by comparative experiments.**

**Keywords—bionic eye; ellipse fitting; stereo vision; calibration; Levenberg-Marquardt method; Eye-in-Hand system.**

## I. INTRODUCTION

It is well known that eye is the most important organ to acquire external information for human. The human visual system is highly-developed after the long time evolution. It forms complete movement and imagery mechanism and ability to adapt the internal and external environment changes. It is a hot topic to equip the robot with bionic intelligent eyes to acquire the environment message, then identify and track the target fast and precisely. At present, the research of bionic eye has got many achievements, especially in the eye movement control theory [1-3] and imagery theory research. A lot of bionic eye research reported that the eye movement can be controlled regularly with the artificial muscle or other equipment [4-5], and there are some achievements of acquiring image based on bionic eye theory and processing image [6-7]. On the whole, most of bionic eyes are with complicated structure and large volume, so it is not fitted to the small robots.

This paper uses two CCD cameras and four stepping motors to build a simple bionic eye platform, used to study intelligent sensing technology and bionic motion control of bionic eye. According to the structure characteristics of the platform, initial location process and method with a high precision are designed. The transformation matrix between the motion module end and the camera is calibrated with the eye-in-hand calibration method. The transformation matrix between two camera's coordinate systems is deduced with high precision and real-time property. The platform's difference with the binocular visual system in [8] is that the camera has two independent degrees of freedom: pitch and yaw.

## II. THE DEVICE AND COORDINATE SYSTEM

The physical map of bionic eye system is shown in Fig.1, which consists of visual system and motion system. The visual system is composed of two CCD cameras, a visual positioning plate and a double circuit video capture card. The motion system is composed of four stepping motors, four limit switches, two motion modules and a programmable control main board which controls the stepping motors. One CCD camera is fixed on the motion module end, and its position is stationary relative to the motion module end. Each motion module includes two stepper motors to control the yaw and pitch of the motion module. Two limit switches on the pedestal limit the yaw angle; the other two limit switches on the motion module limit the pitch angle of the two motion modules. The visual positioning plate has a solid circle. It is on the fixed position of pedestal.

Fig.2 shows the bionic eye system mechanical structure and coordinate systems definition. $O_{cl}X_{cl}Y_{cl}Z_{cl}$ is the coordinate system of left camera, whose origin Ocl lies on the camera optic center. $Z_{cl}$ is parallel to the camera optical axis

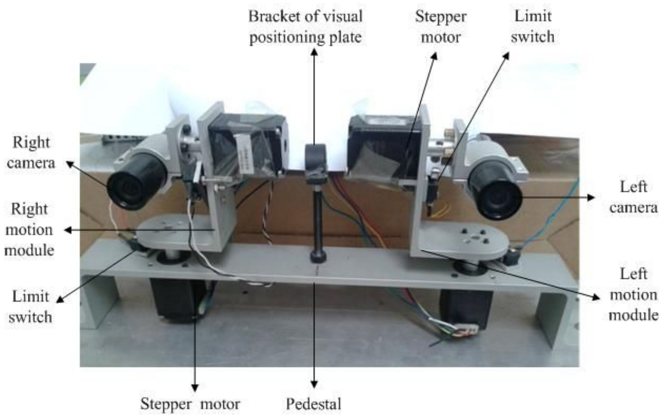



Fig. 1. The bionic eye system

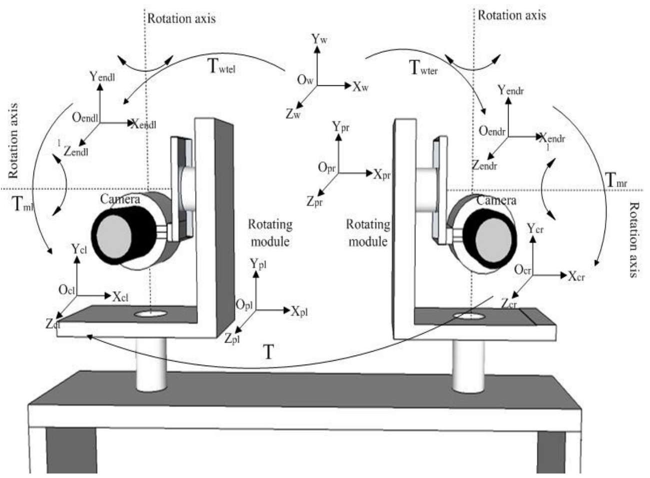



Fig. 2. The bionic eye system mechanical structure and coordinate system

points to scene. $X_{cl}$ points to the left horizontally along to the image plane. $Y_{cl}$ points to the down vertically along to the image plane. $O_{pl}X_{pl}Y_{pl}Z_{pl}$ is the left movement module base coordinate system, whose origin $O_{pl}$ is set on the point of intersection of two orthogonal rotation axes. $Z_{pl}$ is vertical to two rotation axis pointing to scene. $X_{pl}$ is the pitch axis, whose direction is parallel to $X_{cl}$ in the initial state. $Y_{pl}$ is the yaw axis, whose direction is parallel to the $Y_{cl}$ in the initial state. Definitions of right camera's coordinate systems $O_{cr}X_{cr}Y_{cr}Z_{cr}$ and $O_{pr}X_{pr}Y_{pr}Z_{pr}$ are similar to those of left camera. $O_wX_wY_wZ_w$ is the world coordinate system, whose origin $O_w$ coincides with $O_{pr}$, and its $X_w$, $Y_w$, $Z_w$ are parallel to $X_{pr}$, $Y_{pr}$, $Z_{pr}$ respectively. In the initial position, the motion module end coordinate systems $O_{endl}X_{endl}Y_{endl}Z_{endl}$ and $O_{endr}X_{endr}Y_{endr}Z_{endr}$ coincide with their motion module base coordinate systems $O_{pl}X_{pl}Y_{pl}Z_{pl}$ and $O_{pr}X_{pr}Y_{pr}Z_{pr}$, respectively. $T$ is the transformation matrix from $O_{cr}X_{cr}Y_{cr}Z_{cr}$ to $O_{cl}X_{cl}Y_{cl}Z_{cl}$. $T_{ml}$ is the transformation matrix from the left motion module end coordinate system $O_{endl}X_{endl}Y_{endl}Z_{endl}$ to $O_{cl}X_{cl}Y_{cl}Z_{cl}$. $T_{mr}$ is the transformation matrix from the right motion module end coordinate system $O_{endr}X_{endr}Y_{endr}Z_{endr}$ to $O_{cr}X_{cr}Y_{cr}Z_{cr}$. $T_{wtpl}$ is the transformation matrix from $O_wX_wY_wZ_w$ to $O_{pl}X_{pl}Y_{pl}Z_{pl}$. $T_{wtpr}$ is the transformation matrix from $O_wX_wY_wZ_w$ to $O_{pr}X_{pr}Y_{pr}Z_{pr}$.

According to the structure of the bionic eye system, it is necessary to solve the following three questions to ensure the realization of bionic eye stereo perception and motion control function. (1) The two camera's initial locations when device is powered on must be determined precisely so that the initial relationship between the coordinate systems $O_{cr}X_{cr}Y_{cr}Z_{cr}$ and $O_{cl}X_{cl}Y_{cl}Z_{cl}$ is definite and repeatable. (2) Calibration the extrinsic parameters between the motion module end coordinate system and the camera coordinate system. (3) Real-time re-calculation of transformation matrix between two eye's coordinate systems when the binocular posture changes.

## III. System Initial Location

The left and right motion modules should be initially located individually because they are independent of each other. The initial location method is proposed as follows.

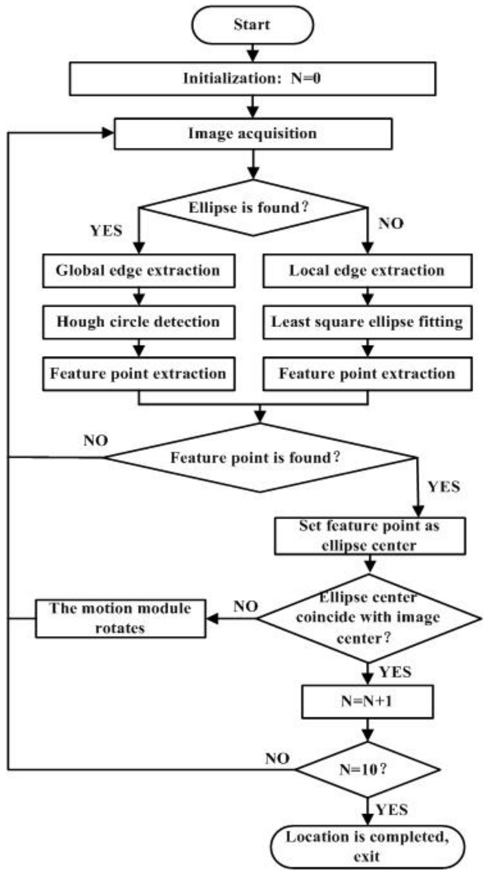



Fig. 3. Precise location algorithm process based on ellipse center fitting

*a) Rough location based on the limit position:* The two cameras are yawed and pitched towards the preset directions until they arrive at the limit positions. It is not fitted for precise location due to the big trigger errors of limit switches.

*b) precise location based on elliptic fitting as shown in Fig. 3:* Select The two motion modules are separately rotated specified angles in order to capture the whole image of the plate located in the middle position of the system as shown in Fig. 1. Then the plate's images are captured by the two cameras and are processed to extract the ellipse center position on the images. Each motion module rotates according to the deviation between the ellipse center and the image center, until they are overlapped with each other. The edge extraction is implemented in whole image by Prewitt operator. When the ellipse is found and fitted out, the search area is reduced to a small rectangle around the ellipse center with predefined size.

*c) Return start position:* The motion modules are rotated to a fixed position precisely by driven the stepper motor running predefined steps, which guarantee the two cameras have a normal relationship similar to human beings.

## IV. Camera Parameters Calibration

Two groups of parameters shown as follow in the bionic eye system should be calibrated in order to measure the object in three-dimensional space with the images acquired by two cameras.

- Binocular parameters calibration, including intrinsic parameters and distortion parameters of the two cameras, and extrinsic parameters between the two cameras at the initial position.
- The transformation matrix of each camera relative to its motion module end.

Then the transformation matrix between two cameras is calculated at the new position according to the rotation angles of the motion modules.

### *A. Binocular Parameters Calibration*

The intrinsic parameter matrices of the left and right cameras could be calibrated using Zhang's calibration method [9].

$$M_{inl} = \begin{pmatrix} f_{xl} & c_l & u_{0l} \\ 0 & f_{yl} & v_{0l} \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

$$M_{inr} = \begin{pmatrix} f_{xr} & c_l & u_{0r} \\ 0 & f_{yr} & v_{0r} \\ 0 & 0 & 1 \end{pmatrix} \quad (2)$$

Where ($f_{xl}$, $f_{yl}$) and ($f_{xr}$, $f_{rl}$) are magnification factors, $c_l$ and $c_r$ are coupling factors, ($u_{0l}$, $v_{0l}$) and ($u_{0r}$, $v_{0r}$) are image coordinates of the primary points of the left and right cameras.

The distortion parameter matrices of the left and right cameras could be calibrated using Brown's calibration method [10].

$$K_{dl} = (k_{1l}, k_{2l}, p_{1l}, p_{2l}, k_{3l}) \quad (3)$$

$$K_{dr} = (k_{1r}, k_{2r}, p_{1r}, p_{2r}, k_{3r}) \quad (4)$$

Where ($k_{1l}$, $k_{2l}$, $k_{3l}$) and ($k_{1r}$, $k_{2r}$, $k_{3r}$) are radial distortion parameters, ($p_{1l}$, $p_{2l}$) and ($p_{1r}$, $p_{2r}$) are tangential distortion parameters.

The binocular extrinsic parameters could be calibrated using Zhang's stereo calibration method [9], $R$ is 3×3 rotation matrix. And $p$ is 3×1 translation vectors.

$$R = \begin{pmatrix} n_x & o_x & a_x \\ n_y & o_y & a_y \\ n_z & o_z & a_z \end{pmatrix} \qquad p = \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} \quad (5)$$

### *B. Extrinsic Parameters Calibration between the Camera and Its Motion module End*

In the bionic eye system, the motion module end can be regarded as a robot end. So, eye-in-hand calibration method can be used to calibrate the extrinsic parameters between the camera and its motion module end.

Commonly, in the eye-in-hand calibration process, the robot end is moved two times. The parameters between the three positions of the camera and the target are calibrated. Finally, the relationship between the camera and robot end can be calculated out according to the extrinsic parameters between the camera and the target, the position and pose of the robot end.

In this paper, the method of eye-in-hand calibration is described as follows. Three positions P1, P2, P3 are set. Three images of calibration board are acquired at these three positions formed by moving the camera with fixed motor steps. Then the board's pose is changed and the other three images are acquired again. The above operations are repeated until 48 frames image are obtained.

On the above operations, P1, P2, P3 can be regard as three different viewpoints. Define $R_{Ri}$ and $p_{Ri}$ as the extrinsic parameters of the camera from position $i$-1 (P1, or P2) to position $i$ (P2, or P3). Then, through equation (6) and (7), many groups' estimation values of $R_{Ri}$ and $p_{Ri}$ can be calculated. Its median value is taken as the initial value and Levenberg-Marquardt iterative algorithm [11] is employed to optimize the extrinsic parameters. The minimum projection error of chessboard corner in the two positions' camera view can be searched out, and the optimized $R_{Ri}$ and $p_{Ri}$ are obtained. In equation (6) and (7), $R_{ci}$ and $p_{ci}$ is rotation matrix and translation vector between camera and target in the position $i$ respectively.

$$R_{Ri} = R_{c(i-1)} R_{ci}^{-1} \quad (6)$$

$$p_{Ri} = p_{c(i-1)} - R_{c(i-1)} R_{ci}^{-1} p_{ci} \quad (7)$$

Define $R_{wtei}$ and $p_{wtei}$ as extrinsic parameters between the motion module base coordinate system and the motion module end coordinate system in the position $i$. For the motion module of the bionic eye system can only yaw and pitch, the translation vector $p_{wtei}$ =0. $R_{Li}$ and $p_{Li}$ are the extrinsic parameters that describes the motion module end's relationship between position $i$ and position $i$-1. $R_{Li}$ and $p_{Li}$ can be obtained by equation (8) and (9).

$$R_{Li} = R_{wte(i-1)}^{-1} R_{wtei} \quad (8)$$

$$p_{Li} = p_{wte(i-1)} - R_{wte(i-1)} R_{wtei}^{-1} p_{wtei} = 0 \quad (9)$$

Submitting the equation (8) and (9) into the equation (10), then extrinsic parameters $R_m$ and $p_m$ between the camera and the motion module end can be deduced out.

$$\begin{cases} R_{Li} = R_m R_{Ri} R_m^T \\ -R_{Li} p_m + R_m p_{Ri} + p_m = p_{Li} \end{cases} \tag{10}$$

## V. BINOCULAR EXTRINSIC PARAMETERS CALCULATION

At the initial position, coordinate system $O_{endr}X_{endr}Y_{endr}Z_{endr}$ coincidents with coordinate system $O_{pr}X_{pr}Y_{pr}Z_{pr}$, coordinate system $O_{endl}X_{endl}Y_{endl}Z_{endl}$ coincidents with coordinate system $O_{pl}X_{pl}Y_{pl}Z_{pl}$. The transformation matrix of the coordinate system $O_{pl}X_{pl}Y_{pl}Z_{pl}$ to coordinate system $O_wX_wY_wZ_w$ can be determined as

$$T_{wtpl} = T_{mr} \times T \times T_{ml}^{-1} \tag{11}$$

Where:

$$T_{mr} = \begin{pmatrix} R_{mr} & p_{mr} \\ 0 & 1 \end{pmatrix} \quad T = \begin{pmatrix} R & p \\ 0 & 1 \end{pmatrix} \quad T_{ml} = \begin{pmatrix} R_{ml} & p_{ml} \\ 0 & 1 \end{pmatrix}$$

When the right motion module end is rotated a certain angle, define the rotation matrix of right motion module end in yaw direction relative to coordinate system $O_{pr}X_{pr}Y_{pr}Z_{pr}$ as $R_{iyawr}$, the corresponding rotation matrix in pitch direction as $R_{ipchr}$. The transformation matrix $T_{ir}$ of right motion module end relative to coordinate system $O_{pr}X_{pr}Y_{pr}Z_{pr}$ can be calculated out according to equation (12). Similarly, when the left motion module end rotates a certain angle, define the rotation matrix of left motion module end in yaw direction relative to coordinate system $O_{pl}X_{pl}Y_{pl}Z_{pl}$ as $R_{iyawl}$, the corresponding rotation matrix in pitch direction as $R_{ipchl}$, then the transformation matrix $T_{il}$ of left motion module end relative to coordinate system $O_{pl}X_{pl}Y_{pl}Z_{pl}$ can be calculated out according to equation (12).

$$\begin{cases} T_{ir} = \begin{pmatrix} R_{ir} & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} R_{iyawr} & 0 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} R_{irpchr} & 0 \\ 0 & 1 \end{pmatrix} \\ T_{il} = \begin{pmatrix} R_{il} & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} R_{iyawl} & 0 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} R_{irpchl} & 0 \\ 0 & 1 \end{pmatrix} \end{cases} \tag{12}$$

In the above case, define the transformation matrix from coordinate system $O_{cr}X_{cr}Y_{cr}Z_{cr}$ to the coordinate system $O_{cl}X_{cl}Y_{cl}Z_{cl}$ as $T_i$. The transformation matrix from the coordinate system $O_{pl}X_{pl}Y_{pl}Z_{pl}$ to coordinate system $O_wX_wY_wZ_w$ can be determined as

$$T_{wtpl} = T_{ir} \times T_{mr} \times T_i \times T_{mr}^{-1} \times T_{il}^{-1} \tag{13}$$

Submitting equation (13) into equation (11), then

$$T_{ir} \times T_{mr} \times T_i \times T_{mr}^{-1} \times T_{il}^{-1} = T_{mr} \times T \times T_{ml}^{-1} \tag{14}$$

Then $T_i$ can be calculated as

$$T_i = T_{mr}^{-1} \times T_{ir}^{-1} \times T_{mr} \times T \times T_{ml}^{-1} \times T_{ir} \times T_{ml} = \begin{pmatrix} R_i & p_i \\ 0 & 1 \end{pmatrix} \tag{15}$$

Where:

$$R_i = R_{mr}^T R_{ir}^T R_{mr} R R_{ml}^T R_{il} R_{ml} \tag{16}$$

$$\begin{aligned} p_i = & R_{mr}^T R_{ir}^T R_{mr} R R_{ml}^T R_{il} p_{ml} - R_{mr}^T R_{ir}^T R_{mr} R R_{ml}^T p_{ml} \\ & + R_{mr}^T R_{ir}^T R_{mr} T + R_{mr}^T R_{ir}^T p_{mr} - R_{mr}^T p_{mr} \end{aligned} \tag{17}$$

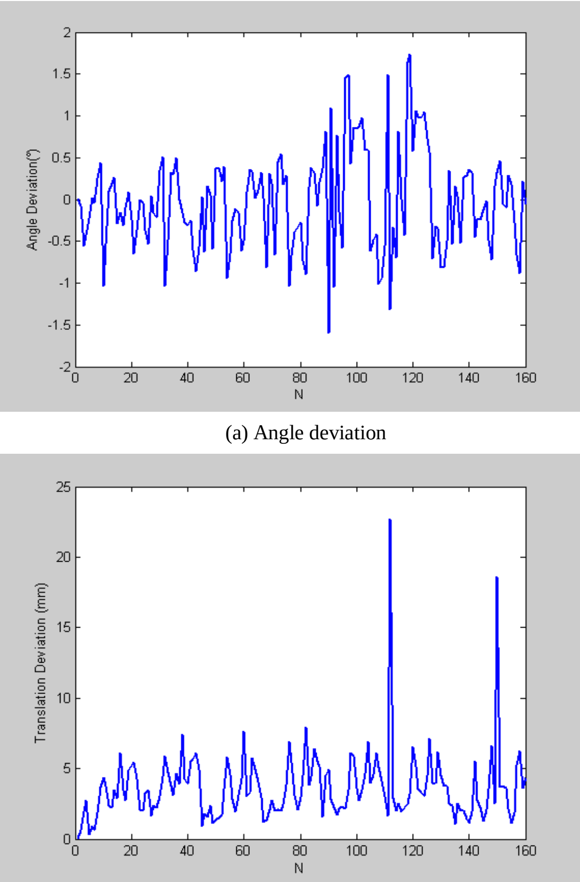
So, when left and right eye's poses are changed, the relationships between them can be recalculated and updated according to equation (15), (16) and (17) with high precision in real-time.

## VI. EXPERIMENTS

Experiments were carried out to verify performance of the bionic eye extrinsic parameters real-time calculation method proposed in this work. The left and right cameras were moved to the initial positions before experiments. The left and right cameras' positions and postures were changed by driving the yaw and pitch stepper motors. For each change, the rotation matrix and translation vector between two cameras were recalculated with the proposed method and recalibrated with the stereo vision calibration method simultaneously. The deviation between them was determined as our method's errors. In experiments, 160 groups of rotation matrix and translation vector were obtained. Table 1 shows 20 groups of parameters, where the angles were calculated out according to rotation matrix. The translation deviations were Euclidean distance between the translation vectors calibrated with stereo calibration method and those with the proposed method. As shown in Table 1, the extrinsic parameters calibrated with stereo calibration method are near to the parameters calibrated with the proposed method. Fig. 4(a) and Fig. 4(b) show the deviation's curves of angle and translation vector. It can be seen from Table 1 and Fig. 4 that our method has similar performance to the static stereo calibration method. However, the extrinsic parameters between the two cameras do not need to be calibrated after the two cameras are rotated in our method. Deviation is mainly caused by the low accuracy of the platform. With further optimization of device structure in future, the deviation will be reduced.

TABLE 1

| No. | Stereo calibration method | | | | Proposed method | | | | Angle deviation (°) | Translation deviation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| | angle(°) | X (mm) | Y (mm) | Z (mm) | Angle (°) | X (mm) | Y (mm) | Z (mm) | | |
| 1 | 5.21 | 200.8 | -2.2 | 0.8 | 5.19 | 200.5 | -3.0 | 1.3 | 0.02 | 1.0 |
| 2 | 10.09 | 193.2 | -2.1 | 83.6 | 9.83 | 191.1 | 0.0 | 85.5 | 0.26 | 3.5 |
| 3 | 29.47 | 185.6 | -2.6 | -7.3 | 29.83 | 185.7 | -3.1 | -3.1 | -0.36 | 4.2 |
| 4 | 1.23 | 197.4 | 1.9 | 50.7 | 0.88 | 196.8 | 3.2 | 53.3 | 0.35 | 3.0 |
| 5 | 9.87 | 173.4 | -10.6 | -117.1 | 10.03 | 174.2 | -16.8 | -113.1 | -0.16 | 7.4 |
| 6 | 4.57 | 205.7 | -6.5 | -14.8 | 5.19 | 206.1 | -8.1 | -14.3 | -0.62 | 1.7 |
| 7 | 0.79 | 177.7 | -26.5 | -95.4 | 1.73 | 177.0 | -31.9 | -93.4 | -0.94 | 5.8 |
| 8 | 10.25 | 194.2 | -11.9 | -34.2 | 9.89 | 193.9 | -13.2 | -31.2 | 0.36 | 3.3 |
| 9 | 14.83 | 186.0 | 18.3 | 46.6 | 14.64 | 186.9 | 19.8 | 48.7 | 0.19 | 2.7 |
| 10 | 9.80 | 208.4 | -10.5 | -15.6 | 10.19 | 209.3 | -11.1 | -12.8 | -0.39 | 3.0 |
| 11 | 9.62 | 161.0 | 43.6 | 103.4 | 9.69 | 161.1 | 48.6 | 105.7 | -0.07 | 5.5 |
| 12 | 5.10 | 200.4 | -1.0 | -0.1 | 5.26 | 200.7 | -2.9 | 1.0 | -0.16 | 2.2 |
| 13 | 10.74 | 192.9 | -9.1 | 82.9 | 9.76 | 190.9 | -7.2 | 85.1 | 0.98 | 3.5 |
| 14 | 29.35 | 186.9 | -0.7 | -5.5 | 29.90 | 186.4 | -2.6 | -3.3 | -0.55 | 2.9 |
| 15 | 2.59 | 197.5 | -13.4 | 48.6 | 0.95 | 196.8 | -14.2 | 50.9 | 1.65 | 2.5 |
| 16 | 10.32 | 172.5 | 30.2 | -113.5 | 9.75 | 173.5 | 23.3 | -112.5 | 0.57 | 7.0 |
| 17 | 4.11 | 204.2 | 5.4 | -14.7 | 4.65 | 205.4 | 4.6 | -16.6 | -0.54 | 2.4 |
| 18 | 1.36 | 178.3 | 41.5 | -90.1 | 1.81 | 177.5 | 36.7 | -92.9 | -0.45 | 5.6 |
| 19 | 10.78 | 191.2 | 20.4 | -48.2 | 10.45 | 196.2 | 11.4 | -32.8 | 0.33 | 18.5 |
| 20 | 28.86 | 179.7 | 0.8 | 42.9 | 29.74 | 178.3 | 2.6 | 48.7 | -0.88 | 6.2 |




(a) Angle deviation

(b) Translation vector deviation

Fig. 4. The deviations of the angle and translation vector

## VII. CONCLUSIONS

Three problems such as initial location, binocular parameters calibration and extrinsic parameters estimation in real-time are solved for the bionic eye system. The proposed bionic eye initial location method is simple, fast and accurate. According to the principle of the robot's eye-in-hand calibration method, the transformation matrix between motion module end coordinate system to the camera coordinate system can be calibrated by using multi images, which is accurate, and feasible. The recalculations equations of extrinsic parameters between two cameras have been deduced according to the camera's yawed and pitch angles. The experiment results have confirmed our method's precision and real-time property, which can guarantee the binocular bionic eye's depth perception ability.

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