Research on Camera Calibration Method for Visual Inspection of Excavator Working Object

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Abstract. In order to realize the identification and positioning of the working object when the excavator works independently, it is necessary to calibrate the binocular camera to determine that the binocular is the internal and external parameters of the camera. This paper focuses on the calibration of binocular camera, and determines the transformation relationship among world coordinate system, camera coordinate system and image coordinate system based on binocular stereo vision ranging principle. The checkerboard images that meet the calibration requirements are selected by using the visual toolbox of MATLAB. The camera calibration process is carried out to determine the camera parameters to be determined. The calibration parameters are analyzed and compared to preliminarily verify the accuracy of the calibration parameters. Finally, the error source is analyzed in QT 5.14.2 programming environment combined with OpenCV 3.4.10, the calibration method meets the application requirements.

1. Introduction

Computer vision technology is widely used in production and life at present, the field of automatic construction of engineering vehicles is one of them. In order to realize the automatic construction of excavators, it is an important way that computer vision technology is applied to the identification and positioning of working objects [1]. The calibration of the camera is one of the key steps to improve the recognition and positioning accuracy of the work object. The basic principle of binocular stereo vision is used to complete the transformation between world coordinate system, camera coordinate system and image coordinate system. The visual toolbox of MATLAB is used to screen out the calibration images that meet the requirements. The internal and external parameters of the camera are determined by the hand eye calibration method with high precision, and the matching and correction are completed with the help of the correlation function of OpenCV. Through the range experiment, it is verified that the accuracy of the data obtained by the calibration process is high, and it can be used to identify and locate the working object of excavator.

2. Basic principle of binocular stereo vision ranging

In the real three-dimensional world, the geometric characteristics of the measured object can not be described from a fixed angle only, and it can not adapt to the complex and diverse three-dimensional environment. Binocular stereo vision can compensate for this defect in principle. The basic principle of binocular stereo vision ranging is to observe the object in the same scene through two parallel optical axis cameras placed at different positions on the left and right, and collect images from different angles. The parallax depth value of the measured object in the scene can be obtained by using the parallax principle and relevant geometric principles, that is the three-dimensional coordinate value of the measured object [2].
Figure 1. Schematic diagram of binocular distance measurement

The principle of binocular stereo vision ranging is shown in Figure 1, \( O_l \) and \( O_r \) are two parallel axis cameras, point \( P \) is the target point to be observed, the imaging points of point \( P \) in the left and right cameras are \( P_l \) and \( P_r \) respectively, the corresponding coordinates are \((x_l, y_l)\) and \((x_r, y_r)\). For the convenience of analysis, the origin of left camera coordinate is set as the origin of camera coordinate system:

\[
\begin{align*}
    x_l &= f \frac{X_c}{Z_c} \\
    x_r &= f \frac{(X_c - B)}{Z_c} \\
    y &= f \frac{Y_c}{Z_c} \\
    \frac{T - (x_l - x_r)}{Z - f} &= \frac{T}{Z} \Rightarrow Z = \frac{fB}{x_l - x_r}
\end{align*}
\]

Among them, \( f \) is the focal length of the camera, \( B \) is the distance between the two parallel optical axes, \( x_l \) and \( x_r \) are the pixel coordinates of the X-axis of the left and right camera images, the parallax is \( D = x_l - x_r \), and the coordinates of object \( P \) relative to the camera are as follows:

\[
\begin{align*}
    X_c &= \frac{Bx_l}{D} \\
    Y_c &= \frac{By}{D} \\
    Z_c &= \frac{Bf}{D}
\end{align*}
\]

The projection points of the same point in different images in the scene are conjugate pairs, and the points in the imaging plane of the left and right cameras are one-to-one corresponding. According to the geometric properties of the triangle, the coordinates of the measured object in the camera coordinate system can be determined, and finally the three-dimensional coordinate value of the measured object can be determined.
3. Camera calibration

3.1. Camera calibration principle

The process of solving the internal and external parameters of the camera is the camera calibration. The internal parameters mainly include the focal length of the camera, image coordinates, lens distortion, etc., and the external parameters are composed of rotation matrix and translation matrix. Camera calibration involves three coordinate systems, namely world coordinate system, camera coordinate system and image coordinate system. Image coordinate system includes image physical coordinate system and image pixel coordinate system. Camera calibration mainly determines the projection matrix from world coordinate to camera coordinate and then to image coordinate system [3].

The transformation relationship between the image physical coordinate system and the image pixel coordinate system is as follows:

\[
\begin{bmatrix}
  u \\
  v \\
  1
\end{bmatrix} = \begin{bmatrix}
  1 \\
  0 \\
  0
\end{bmatrix} \frac{dx}{dx} \begin{bmatrix}
  0 \\
  1 \\
  0
\end{bmatrix} \frac{dy}{dy} \begin{bmatrix}
  u_0 \\
  v_0 \\
  1
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix}
\]

(4)

Among them, \((x, y)\) is the physical coordinates of the image, usually in millimeters; \((u, v)\) is the pixel coordinates of the image, with the unit of pixels; \((u_0, v_0)\) is the origin of the physical coordinate system under the image pixel coordinate system; \(dx\) and \(dy\) are the pixel sizes.

The transformation relationship between the world coordinate system and the camera coordinate system is as follows:

\[
\begin{bmatrix}
  X_c \\
  Y_c \\
  Z_c \\
  1
\end{bmatrix} = \begin{bmatrix}
  R_{3 \times 3} \\
  T_{3 \times 1}
\end{bmatrix}
\begin{bmatrix}
  X_w \\
  Y_w \\
  Z_w \\
  1
\end{bmatrix}
\]

(5)

Among them, \((X_c, Y_c, Z_c)\) and \((X_w, Y_w, Z_w)\) are the coordinates of space point \(P\) in camera coordinate system and world coordinate system respectively. \(R\) is the orthogonal rotation matrix of \(3 \times 3\). \(T\) is a three-dimensional translation matrix of \(3 \times 1\).

The conversion relationship between the camera coordinate system and the image physical coordinate system:

\[
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix} = \begin{bmatrix}
  f & 0 & 0 & 0 \\
  0 & f & 0 & 0 \\
  0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
  X_c \\
  Y_c \\
  Z_c \\
  1
\end{bmatrix}
\]

(6)

Simultaneous formula (4) ~ (6):

\[
\begin{bmatrix}
  u \\
  v \\
  1
\end{bmatrix} = \begin{bmatrix}
  f & 0 & 0 & 0 \\
  0 & f & 0 & 0 \\
  0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
  R_{3 \times 3} \\
  T_{3 \times 1}
\end{bmatrix}
\begin{bmatrix}
  X_w \\
  Y_w \\
  Z_w \\
  1
\end{bmatrix}
\]

(7)
3.2. Camera calibration
Considering that the data accuracy of calibration by MATLAB calibration toolbox is better than that of self calibration method under opencv, in order to improve the accuracy of camera calibration parameters as much as possible, this paper solves the calibration parameters based on MATLAB calibration toolbox, and finally imports the calibration results into OpenCV to complete the subsequent image correction and stereo matching[4]. The specific implementation steps are as follows:

1. Build the platform, Install matlab development software, load calib calibration toolbox, set up camera calibration environment; In the experiment, CAM5031-V5 binocular camera as shown in Figure 2 was used to collect pictures; GP290−12×9 high precision (±0.01mm) grid series film calibration board is selected as shown in Figure 3, with checkerboard specification 20mm×20mm and angle point number is 12×9.

Load images. Call matlab calibration toolbox, input calib_ gui, load the checkerboard pictures taken by the camera. The size of the picture is 640×480. Calibrate the left and right cameras respectively. The calibration images of the left and right cameras after loading are shown in Figure 4 and Figure 5.

(3) Extract corners. After the image is loaded successfully, click extract grid corners to extract the corners of the loaded image in turn, as shown in Figure 6.
(4) Monocular calibration. After extracting the corners of all loaded images, click calibration to solve the calibration parameters, and the files of left and right camera calibration results will be saved in mat format.

(5) Stereo calibration. The steoreo_gui command in MATLAB calibration toolbox is used to calibrate the left and right camera parameters, and the rotation matrix and translation matrix of the position relationship between the two cameras can be obtained.

4. Correction and matching
The stereo correction of camera is to eliminate the error of camera placement. Because of the placement error, the images collected by the left and right cameras cannot be coplanar, and the line alignment cannot be well realized. The stereo rectification and initundistorrectifymap functions in OpenCV are used to complete the image correction by combining the internal and external parameters after camera calibration[5].

Camera stereo matching is a way to obtain the corresponding relationship of the object under test in the same scene by two cameras. In stereo matching, sgbm algorithm with good parallax accuracy and moderate computational complexity is selected to solve the disparity. The implementation steps of the whole algorithm mainly include image preprocessing, cost calculation, dynamic programming and parallax post-processing[6].

5. Experimental results and error analysis
The reprojection error of the collected calibration images is detected, and the qualified calibration images are selected to solve the internal and external parameters of the camera. The internal and external parameters of the left and right cameras obtained according to the above camera calibration experiments are shown in Table 1.

| Parameter             | Left camera                                  | Right camera                                 |
|-----------------------|----------------------------------------------|----------------------------------------------|
| Focal Length          | [674.25604 675.06004]                         | [668.02850 667.13195]                         |
| Principal point       | [290.56178  220.44567]                        | [298.03247  237.17465]                       |
| Distortion            | [0.02979  0.35039  0.00051]                   | [0.06761 -0.64246  0.00067]                  |
|                       | 0.00866  0.00000                              | -0.00507  0.00000                            |
| Translation matrix    | [-39.55890  0.52690 -1.48545]                 |                                              |
|                       | 0.9998  0.0029  0.0196                         |                                              |
|                       | -0.0028  1.0000  -0.0003                        |                                              |
|                       | -0.0196  0.0003  0.9998                        |                                              |

The calibration results show that the distance between the optical axes is 39.55890 mm, which is only 1.1% error with the actual distance of 40 mm, and the rotation matrix is similar to the identity
matrix, almost no rotation is produced. After analyzing the calibration data, the calibration results obtained by the above process basically conform to the binocular stereo vision model.

Import the internal and external parameters of the camera into the correlation function of OpenCV, and measure the spatial coordinates of the measured object in the QT programming environment, then the distance between the measured object and the camera can be obtained. The results of comparative analysis with the measured distance are shown in Table 2. Through the analysis of experimental data, it can be concluded that with the increase of distance, the distance error measured by binocular camera also has an increasing trend. Compared with the industrial camera, the camera used in this experiment has a certain gap in manufacturing technology, which directly affects the accuracy of camera calibration parameters. In addition, with the increase of distance, the image noise increases in the scene, which is also one of the sources of error.

| Number | Measurement distance (mm) | Actual distance (mm) | Error  |
|--------|--------------------------|----------------------|--------|
| 1      | 151.32                   | 150                  | 0.88%  |
| 2      | 201.92                   | 200                  | 0.96%  |
| 3      | 253.73                   | 250                  | 1.49%  |
| 4      | 305.25                   | 300                  | 1.75%  |
| 5      | 356.42                   | 350                  | 1.83%  |
| 6      | 409.15                   | 400                  | 2.29%  |
| 7      | 460.54                   | 450                  | 2.34%  |
| 8      | 514.42                   | 500                  | 2.88%  |

6. Conclusion
Based on the principle of binocular stereo vision ranging, the calibration experiment and parameter determination of binocular camera are completed by using the calibration toolbox in Matlab environment. The coordinate information of the measured object in three-dimensional space is obtained under the QT5.14.2 programming environment combined with OpenCV3.4.10, which verifies that the calibration scheme can meet the accuracy requirements of excavator positioning and recognition of working objects. The causes of the error are analyzed, which has important guiding significance for the follow-up research of excavator autonomous operation.

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