

A New Efficient Calibration Method for Binocular Camera

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Abstract

In the vision 3-D measurement field, camera calibration results directly affect the accuracy of measurement. So camera calibration method is hot spot in this field. This paper proposes a new efficient calibration method with binocular camera. First, the method uses an accurate extraction algorithm to extract the ellipse center of calibration target image. Second, the paper presents a automatic matching algorithm based RANSAC (RANSAC SAMPLE CONSENSUS), the automatic matching algorithm is simple, fast, and can complete space calibration feature points matching its image point at once. At the beginning of matching, sort calibration points in the target according to a certain sequence. The sequence of feature points extracted in the calibration image does not correspond with one of the feature points in calibration target, because of the camera distortion. But obtain the correct matching points by the RANSAC algorithm. According to the camera calibration model, use the correct matching points and obtain correct intrinsic and extrinsic parameters of each camera and the relative parameters of two cameras. Finally, through experimental verification, the results show that the calibration method is fast and robust, and has higher calibration accuracy.

Keywords: Camera calibration; RANSAC algorithm; Calibration point correspondence

1. Introduction

In the visual field of 3D measurement, camera calibration is a critical step, is the determination of intrinsic and extrinsic parameter of camera. Performance of the whole measurement system depends on accuracy of camera calibration. Many calibration methods [1] are used to shoot calibration target, extract calibration target feature points in the image, match space calibration feature points, compute intrinsic and extrinsic parameter of camera by calibration model [2]. Point matching is the correspondence of the calibration target feature points in the world coordinate system and the image points in the camera. Camera calibration accuracy usually depends on camera model, extraction accuracy of feature points and matching rate of feature points. Once determining the camera model, camera calibration accuracy depends mainly on the last two factors. So correct extraction and matching of feature points is a critical step in camera calibration.

Calibration references of camera have two-dimensional and three-dimensional references. Due to manufacturing three-dimensional reference is difficult, cost is expensive, two dimensional references are widely used [3]. Calibration feature points are generally used to maintain the consistency of points to translation, scaling, rotation transform in the image, for example, the crossing point of lines, the center of a circle, the corner of the chessboard box, etc [4, 5]. Different feature points have different extraction algorithms, such as, centroid method, gray focus method, edge location method, fitting

method, phase analysis method and template relative matching method [6, 7]. Matching calibration feature points is also a lot of methods [8, 9], for example, one method is setting encoding image in the 2D calibration target, matching calibration feature points through the identification of code image, the other is marking special symbols on the special position of a calibration target, matching through the identification of special symbols. Those matching methods are complexity and large amount of computation, leads to extra work for camera calibration. So it is very important to choose calibration points. In research, we know that circle has strong anti noise ability, and feature point extraction algorithm is simple and high accuracy. So the paper chooses planar calibration plate based 2D solid circular array. Owing to a circle in the camera imaging is an ellipse, selecting the ellipse center as calibration feature points. High accuracy ellipse fitting method is used to extract ellipse center. In matching feature points, to avoid complex recognition, this paper presents a matching feature points method based RANSAC algorithm. This method is to sort calibration points by certain sequence, obtain the correct matching points by the RANSAC algorithm. According to the camera calibration model, use the correct matching points and obtain correct intrinsic and extrinsic parameters of each camera, also, determine the relative position and attitude between two cameras.

2. Calibration Feature Points Extraction

Select the solid circular array calibration plate of German BASLER Company as camera calibration target. The size of the calibration plate is 350mm * 280mm, the number of marking dot is 11*9, the diameter of great circle is 15mm, the diameter of small circle is 7.5mm, the distance is 3.5mm between centers of two adjacent circles. The BASLER A102f CCD camera has 1400000 pixels, resolution of 1392*1040 pixels. Acquired calibration image is shown in Figure 1 by the camera.

Select center of circle as calibration feature points. During the actual process, it is difficult to guarantee the camera optical axis perpendicular to the calibration plate, so shooting circle is ellipse at fact. Extraction calibration feature points are center of ellipse. The method of extraction center is from document [10], the extraction result is shown in the Figure 2.

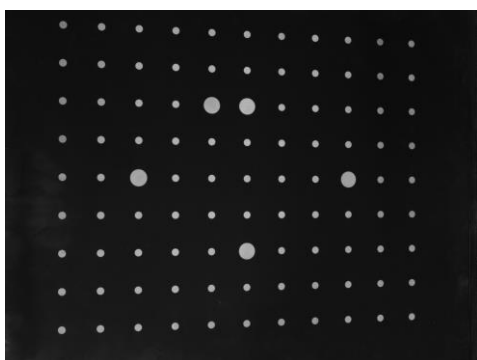


Figure 1. Calibration Target Image

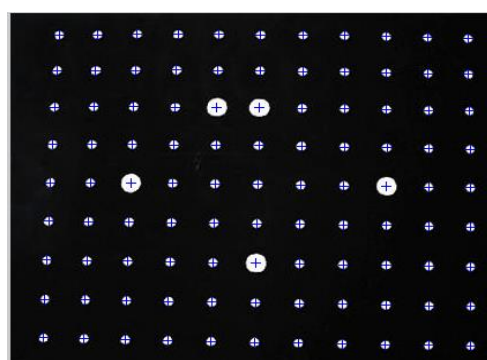


Figure 2. Extraction Result of Center of Ellipse

3. Calibration Feature Points Correspondence

3.1. Spatial Calibration Points Sorted

Usually the calibration plate plane is in the world coordinate system of $Z=0$ plane. Select the lower left corner of calibration plate as the origin of world coordinate system. The length and width directions of calibration plate are X and Y axis directions of the

world coordinate system respectively.

The serial number of points of calibration plate is from 1 to 99, from bottom to top, from left to right. The result sorted is shown in Figure 3.

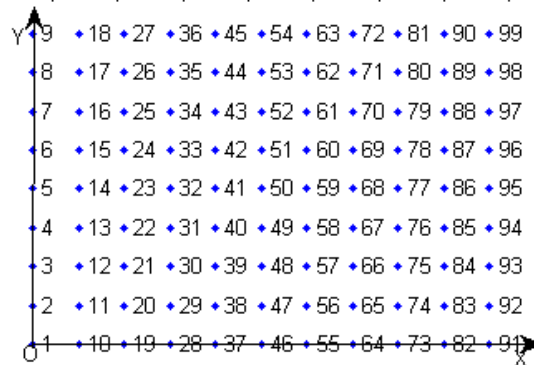


Figure 3. Spatial calibration points sorted

3.2. Image Calibration Points Sorted

The two factors lead to that sequence of image calibration point does not correspond to the sequence of spatial calibration target. The first factor is the distortion of camera lens, the second factor is very difficult to guarantee the camera optical axis perpendicular to the calibration plate in the experiments. Sequence of calibration points in the image is shown in Figure 4. From Figure 4, the points in the image are rung up by red circles. Its sequence in the image does not correspond to sequence of the spatial calibration points.

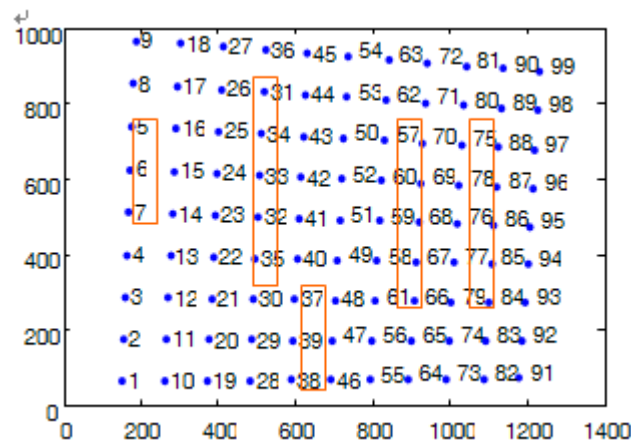


Figure 4. Order of Feature Points in the Image

3.3. Feature Points Matching

Matching feature points correctly is a prerequisite for camera calibration. A lot of documents provide a variety of methods for feature points matching [11, 14], but those algorithms are complex. This paper applies RANSAC algorithm to matching feature points, the correct rate of matching feature points is 100%.

3.3.1. Monocular Camera Model: $M = [X_M, Y_M, 1]^T$ is spatial points, $m = [u, v, 1]^T$ is image points. The coordinate system is shown in Figure 5. According to the imaging principle of camera, obtain the corresponding relationship of spatial calibration points and image points, this is shown in formula (1).

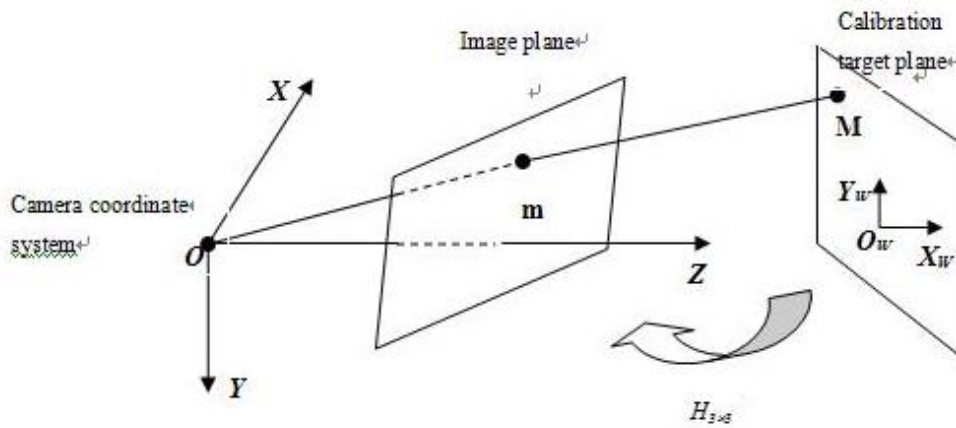


Figure 5. Coordinate System

$$sm = A \begin{bmatrix} r_1, r_2, r_3, t \end{bmatrix} \begin{bmatrix} X_M \\ Y_M \\ 0 \\ 1 \end{bmatrix} = A \begin{bmatrix} r_1, r_2, t \end{bmatrix} \begin{bmatrix} X_M \\ Y_M \\ 1 \end{bmatrix} = H \begin{bmatrix} X_M \\ Y_M \\ 1 \end{bmatrix} = HM \quad (1)$$

$$A = \begin{bmatrix} f_u & \lambda & u_0 \\ 0 & f_v & v_0 \\ 0 & 0 & 1 \end{bmatrix}$$

In the formula, s is the proportionality constant, \mathbf{R} is the rotation matrix, \mathbf{T} is the translation matrix.

If the coordinates of 4 pairs of corresponding points are known, obtain from the formula (1).

$$s_i m_i = H M_i \quad i = 1, 2, 3, 4 \quad (2)$$

According to formula (2), calculate the homography matrix \mathbf{H} .

3.3.2. RANSAC Algorithm: The RANSAC algorithm is better than the traditional robustness algorithm in dealing with the error matching points, than the least squares technique in the fitting technique. The least squares is estimated model with more data points as possible (including error points), and the RANSAC algorithm is estimated model with less data points as possible, it is higher accuracy. The idea of the RANSAC algorithm is to specify solving model according to the specific problem, then estimate the initial values of the parameters in the model with the random extracting minimum points set. Select repeatedly the optimal points set according to the initial values of the parameters, finally use the optimal point set to re estimate of the parameters in the model [15].

In the paper, use RANSAC algorithm to match spatial calibration feature points and its image points, the solving model is $\hat{m}_n = H M_n$, \hat{m} is image points, M is spatial points, H is homography matrix. Solving the homography matrix H requires at least 4 pairs of corresponding points, so $n = 4$. Suppose that N is needed to match the points, L is effective points, the proportion of L / N is ω .

Sampling times for:

$$k = \frac{1 + 3\sqrt{1 - \omega^n}}{\omega^n} \quad (3)$$

For the points set $D = \{\hat{m}_j \leftrightarrow M_j | 1 \leq j \leq 99\}$, from a sample J , calculate the corresponding homography H_J , the corresponding agreement set of H_J is:

$$S(H_J) = \{(\hat{m} \leftrightarrow M) \in D | d^2(\hat{m}, H_J M) < t^2\} \quad (4)$$

In the formula, $t = 0.001$ according to the experience, d is the point-to-point distance.

For all the calculated results H_J , take H_J of the largest consistent set as the optimal interior points, re estimate the homography matrix H .

Match spatial feature points and its image points by H . For spatial points M_i , its corresponding image point is HM_i . If the point \hat{m}_j is the nearest to HM_i , the point \hat{m}_j is matching the point M_i , is written in the following formula:

$$m_i = \min\{d(HM_i, \hat{m}_j)\} \quad (3)$$

3.3.3. Matching Results: Use the RANSAC algorithm to match the Figure 3 and its imaging Figure 4. The matching result is shown in Figure 6.

The sequence of points in Figure 6. is consistent with the sequence of points in Figure 3. To validate the error of this algorithm RANSAC, in the same coordinate, display the points of m_i and \hat{m}_i , as shown in Figure 7.

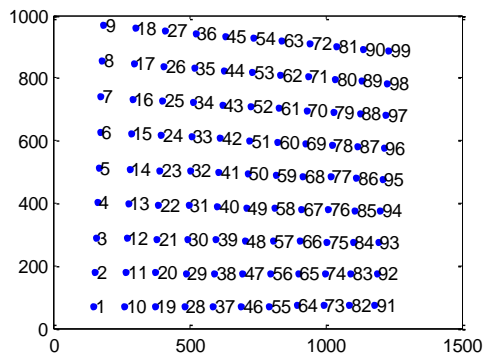


Figure 6. The Order of Image Points after Matching

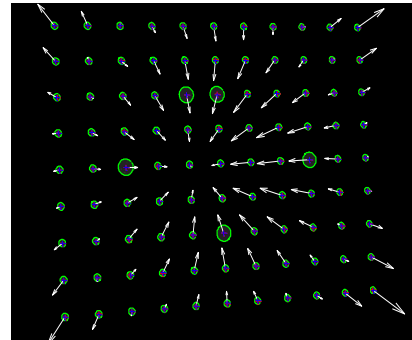


Figure 7. Error

In Figure 7, blue sign + is \hat{m}_i extracted, red sign + is m_i . The direction of the arrow indicates the direction of deviation, the size of arrow is the size of the error. From Figure 7, the maximum error is far less than the radius of the solid circle. Therefore, the proposed matching algorithm has higher accuracy than the original manual extraction feature points.

4. Camera Calibration

4.1. Monocular Camera Calibration

Apply the two steps calibration method of Zhang to monocular camera calibration [16, 18]. According to the formula (1), the first step is the following. Calculate the

homography matrix H by RANSAC algorithm, and obtain the intrinsic and extrinsic parameters matrix A , R and T .

The second step is the following. Compute distortion coefficients of the camera, (x, y) is expressed by image feature point in the ideal state, (x', y') is expressed image feature point by in the distortion state. Camera distortion model is the following:

$$\begin{cases} x' = x + k_1 x(x^2 + y^2) + k_2 x(x^2 + y^2)^2 + p_1(3x^2 + y^2) + 2p_2 xy \\ y' = y + k_1 y(x^2 + y^2) + k_2 y(x^2 + y^2)^2 + 2p_1 xy + p_2(3x^2 + y^2) \end{cases} \quad (6)$$

This model is nonlinear model, for camera calibration, nonlinear optimal algorithm is introduced. Adding too many nonlinear parameters to the model will lead to unreliable solution. So, in the paper, consider the radial distortion and tangential distortion. Use the least square method to calculate the distortion coefficient k_1 , k_2 , p_1 and p_2 . To obtain more accurate results of intrinsic parameters, make spatial points re projection to obtain image error, using Levenberg-Marquardt algorithm optimize the error.

4.2. Binocular Camera Calibration

Binocular camera calibration model is shown in Figure 8.

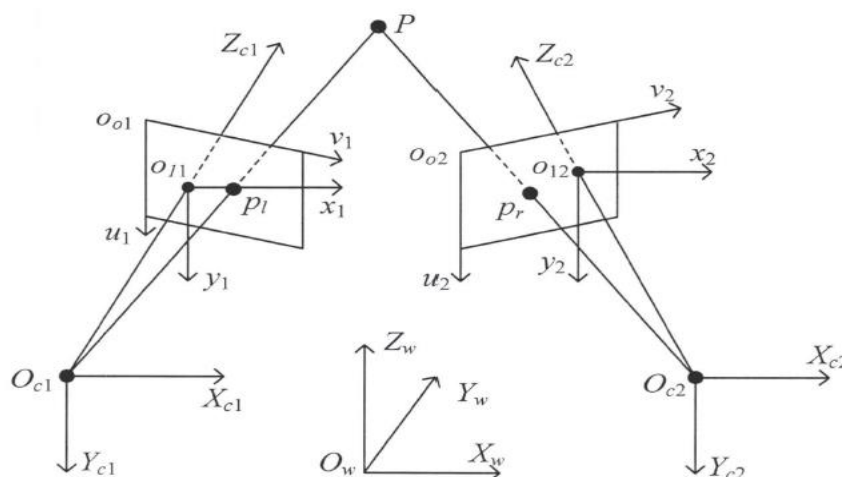


Figure 8. Binocular Camera Calibration Model

The coordinates of point P in the world coordinate system and the left camera coordinate system is $P_w = (X_w, Y_w, Z_w)^T$, $p_l = (x_l, y_l, z_l)^T$, $p_r = (x_r, y_r, z_r)^T$ respectively. R_l and T_l indicate the relative position left camera and world coordinate system, R_r and T_r indicate the relative position of the right camera and world coordinate system. thus:

$$\begin{aligned} p_l &= R_l P_w + T_l \\ p_r &= R_r P_w + T_r \end{aligned} \quad (7)$$

The elimination of P_w :

$$p_r = R_r R_l^{-1} p_l + T_r - R_r R_l^{-1} T_l \quad (8)$$

If the left camera optical center is located at the origin of the world coordinate, the right camera relative to the left camera has the following geometric relationship between **R** and **T**:

$$R = R_r R_l^{-1}$$

$$T = T_r - R_r R_l^{-1} T_l$$

Therefore, **R** and **T** are the external parameters of binocular cameras. Two cameras collect calibration target images at the same time, calibrate left and right camera respectively using the two steps calibration method of Zhang. At last, calibrate the structural parameters of binocular cameras. Camera calibration process is shown in Figure 9.

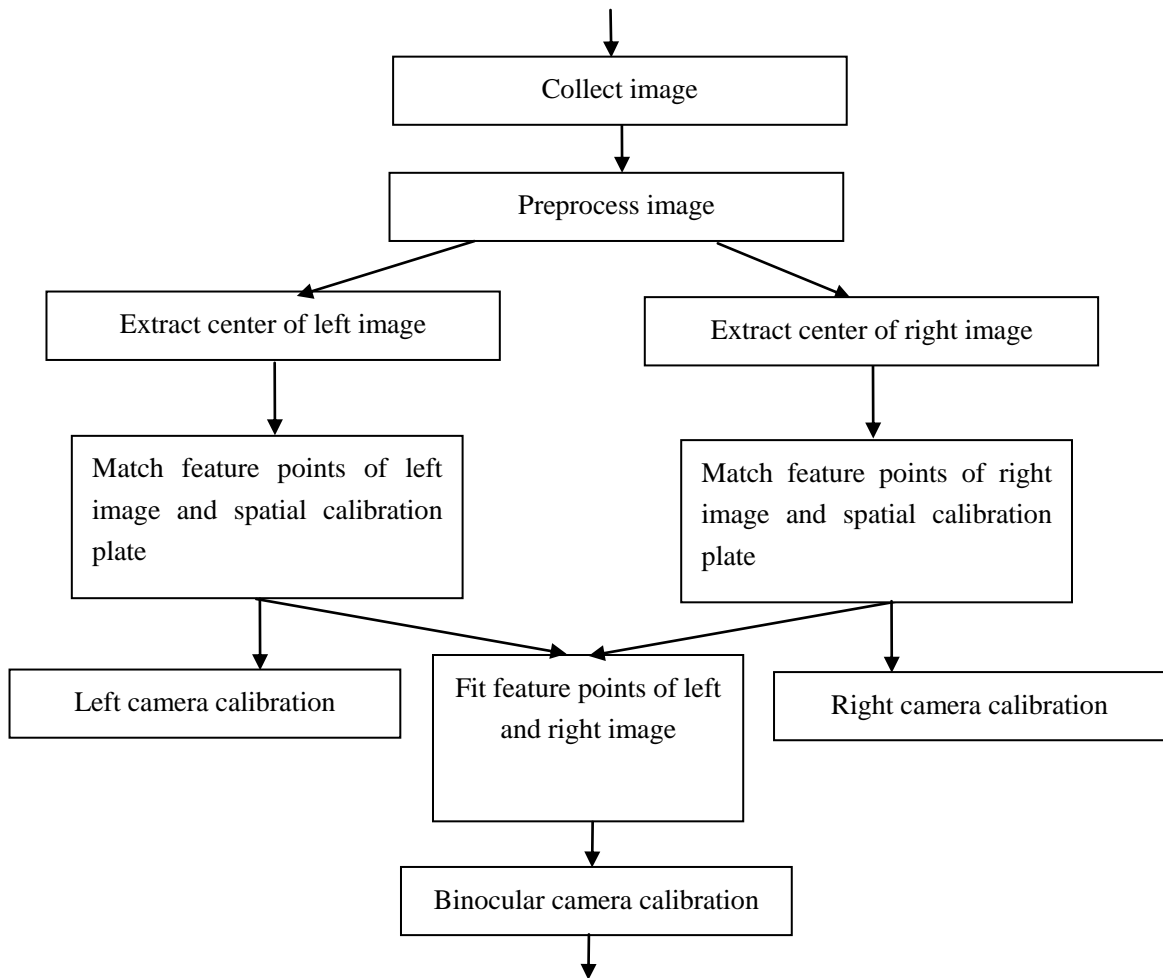


Figure 9. Camera Calibration Process

4.3. Experiments

Binocular measuring experiment device is shown in Figure 10.



Figure 10. Binocular Measuring Experiment Device

Two Basler A102f cameras, a resolution of 1392 pixel * 1040 pixel, the physical size of each pixel is 6.45 m * 6.45 m, the focus length is 16mm. The left and right cameras collect 6 images from different direction and height, extract feature points in the left and right image of calibration target, and then find out feature points in calibration target, and feature points in the left and right image matching feature points in calibration target, and matching feature points corresponding in the left and right image. According to matching points, calibrate and optimize left and right camera respectively. The calibration and optimization results are shown in Table 1, the lens distortion coefficients are shown in Table 2.

Table 1. Intrinsic Parameters of Left and Right Cameras

parameters		f_u	f_v	U_0	V_0	γ
Left camera	Ideal value	3428.03	3457.26	701.15	683.54	0.5237
	Optimal value	3439.05	3440.53	699.23	680.12	0.5201
Right camera	Ideal value	3425.78	3453.39	720.43	692.37	0.4465
	Optimal value	3437.33	3441.64	711.56	691.89	0.4568

Table 2. Distortion Coefficients of Left and Right Cameras

parameters		$K1$	$K2$	$P1$	$P2$
Left camera	Ideal value	0	0	0	0
	Optimal value	-2.15×10^{-6}	-1.13×10^{-11}	-1.11×10^{-6}	-1.05×10^{-6}
Right camera	Ideal value	0	0	0	0
	Optimal value	-1.06×10^{-6}	-1.21×10^{-11}	-1.36×10^{-6}	-1.08×10^{-6}

In order to evaluate the precision of single camera calibration, the calibration feature points on the target are re projected to the image coordinates. For different positions, every calibration graph corresponds to extrinsic parameters matrix \mathbf{R}_i and \mathbf{T}_i . During re projection of each image, calculate the maximum error and the root mean square error in

X and Y direction respectively. These error values are shown in table 3. From Table 3, camera calibration accuracy is very high. Compute binocular camera corresponding relation by using error minimum an image of the left camera from re projection. Binocular camera extrinsic parameters are shown in Table 4.

Table 3. Reprojection Error

parameters		Max error	Average values
Left camera	X	0.146	0.062
	Y	0.149	0.065
Right camera	X	0.151	0.065
	Y	0.153	0.067

Table 4. Binocular Camera Extrinsic Parameters

parameters	R	T
Values	$\begin{bmatrix} 0.1868 & 0.9633 & 0.1926 \\ 0.9796 & 0.168 & -0.1102 \\ -0.0738 & 0.2093 & -0.9751 \end{bmatrix}$	$\begin{bmatrix} -520.3371 \\ 87.7064 \\ 67.5923 \end{bmatrix}$

In order to evaluate the extrinsic parameters accuracy of binocular camera, measure the distance between the centers of the two pairs of great circles in 6 pieces of calibration target pairs. The horizontal and vertical distance is 210.007mm and 140.005mm between the centers of the two pairs of great circles through image measuring instrument. Rebuild the two great circles by using the calibration parameters, the distance between the centers of the two great circles is shown in Table 5.

Table 5. Values and Errors of the Distance between Great Circles

Parameters	Horizontal direction		Vertical direction	
	Values	error	Values	error
1	210.009	0.002	140.006	0.001
2	210.011	0.004	140.009	0.004
3	210.009	0.002	140.008	0.003
4	210.004	-0.003	140.003	-0.002
5	210.012	0.005	140.007	0.002
6	210.010	0.003	140.004	-0.001

From the Table 5, accuracy of binocular camera calibration is very high. The results can be applied to the measurement of industrial products, and be ready for the next step of 3D reconstruction.

5. Conclusion

Zhang Zhengyou proposed a camera calibration method based on 2D panel template, the camera calibration is widely used, which avoids the disadvantages of traditional calibration methods. The calibration method accuracy is higher than a self-calibration method. Adopts circle instead of square in the calibration plate. The distortion degree of the image center is smaller than the image the edge by external noise impact. So this paper uses an accurate ellipse center extraction algorithm for extracting accurate calibration feature points on the target image, and proposes a kind of calibration feature points matching method based on RANSAC algorithm. The experiments show that this matching method can accurately match the spatial calibration feature points and the corresponding feature points in image, matching correct ratio is up to 100%, and the speed is fast. The matching method is very important to improve camera calibration accuracy.

Acknowledgment

The authors would like to thank Sir Qiao Fu for the language improvement, and to appreciate the financial support from the Technological Innovation Funds for technology-based small and medium-sized enterprises of China Grant No.14c26212300819.

References

- [1] H. Bingwei, W. Gongjian and Z. Xing, "Accurate geometric camera calibration technique using multi-views of a non-metric planar grid", *Optics and Lasers in Engineering*, vol. 51, (2013), pp. 432-439.
- [2] W. Forstner and E. Gulch, "A fast operator for detection and precise location of distinct points, corners and centres of circular features", In *Proc. Intercommission Conf. on Fast Processing of Photogrammetric Data*, (1987), pp. 281-305.
- [3] F. Remondino and C. Fraser, "Digital camera calibration methods: considerations and comparisons[J]", *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 36, no. 5, (2006), pp. 266-272.
- [4] X. Meng and Z. Hu, "A new easy camera calibration technique based on circular points", *Pattern Recognition*, vol. 36, no. 5, (2003), pp. 1155-1164.
- [5] M. VO, Z. WANG, B. PAN, "Hyper-accurate flexible calibration technique for fringe projection based three dimensional imaging", *Optics Express*, vol. 20, no. 15, (2012), pp. 16926-16941.
- [6] [6]K. Sirisantisamrid, K. Tirasesth, and T. Matsuura, "A determination method of initial camera parameters for coplanar calibration," *International Journal of Control, Automation and Systems*, Vol. 7, No. 5, pp. 777-787, Oct. 2009.
- [7] [7]D Huang, Q Zhao, W Wang, et al. A calibration method of multi-camera pose based on monocular vision. The 1st International Conference on Industrial Application Engineering 2013 (ICIAE2013).
- [8] [8]BIAN HOU-QING SU JIAN-BO. Feature correspondence algorithm based on scene-independent constraint. *Journal of Image and Graphics*, 2006, 11(3): 342 - 348.
- [9] [9]Furukawa Y, Ponce J. Accurate camera calibration from multi-view stereo and bundle adjustment. *International Journal of Computer Vision* 2009; 3: 257-68.
- [10] [10] J.N. Ouellet, P. Hebert. A simple operator for very precise estimation of ellipses. *Computer and Robot Vision*, 2007 (CRV'07), 2007. 21-28.
- [11] [11]BIAN HOU-QING SU JIAN-BO. Feature correspondence algorithm based on scene-independent

- constraint [J]. Journal of Image and Graphics, 2006, 11(3): 342 — 348.
- [12] [12] O. Nibouche, J. Jiang. Palmprint matching using feature points and SVD factorisation. Digital Signal Processing 2013(113):1-10.
- [13] [13] S. Arbouche, Feature Point Correspondences: A Matching Constraints Survey, M.C.S. Thesis, University of Ottawa, 1999.
- [14] [14] A. Baumberg, Reliable Feature Matching Across Widely Separated Views, CVPR, 2000.
- [15] [15] Fishier M A, Boles R C. Random Sample Consensus: A Paradigm for Model Fitting with Applications to Image Analysis and Automated Cartography, Comm Assoc Comp Mach, 1981, 24(6):381-395.
- [16] [16] Zhengyou Zhang. Flexible Camera Calibration By View a Plane From Unknown Orientations. <http://research.microsoft.com/~zhang>
- [17] [17] J. Weng, P. Cohen, and M. Hermiou, "Camera calibration with distortion models and accuracy evaluation," IEEE Trans. Pattern Analysis and Machine Intelligence, Vol. 14, No. 10, pp. 965-980, Oct. 1992.
- [18] [18] Kim J, Kweon IS. Camera calibration based on arbitrary parallelograms. Computer Vision and Image Understanding 2009(113):1-10.

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