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An External Parameter Optimize Method for 3D Optical Measurement System

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Abstract

A simple and effective external parameter calibration and optimize method based on epipolar geometry for improving the accuracy and stabilization of 3D optical measurement system are present. First, the internal parameters of two cameras are calibrated using the planar calibration method. Then using the parameters as initial value calibrates the external parameter of the 3D optical measurement system in every view. Optimization result is computed through minimizing epipolar line error of the same pair of points in every view. Experimental results show that the measurement precision is high and stable in the measurement volume.

Keywords*: optical measurement system, external parameter, calibration, epipolar geometry*

1. Introduction

In recent years, with the rapid development of computer and digital image processing technique, the structured light measurement system is widely used in these fields, such as reverse engineering, product testing and so on, for its advantage of non-contacted, high-speed, low cost, high accuracy, simple structure easily to implement and so on[1-2]. The calibration accuracy of binocular measurement system directly affects the final measurement accuracy of the parts. The high accuracy measurement could be got only in the case that the relative position of the camera relationship transform matrix is calibrated very accurately[3].

The camera calibration is the process to compute intrinsic and external parameter of cameras. Firstly, cameras are used to obtain set images of the calibration object which has specific geometric features such as checkerboard or dots in different location in the scene. Then the corresponding relationship between the two-dimensional image coordinate and three-dimensional world coordinate of feature points of calibration object is established according to the camera model. Finally, the back-projection error is minimized to calculate the intrinsic and external parameter[4].The different images in different locations emerged in the process of the calibration are used to get the intrinsic parameter of the camera and an external parameter in each location. The accuracy of external parameters are different in each view angle by the impact of ambient light, image clarity, electronic noise and so on. Therefor, which set of external parameter to choose is an key problem in the process of the three-dimensional points calculation in the binocular optical measurement system[5]. Usually, the first set external parameter which get form the first set images as binocular measurement system parameter is used to calculate the points. The other way is to calculate the back-projection error using different external parameters matrix in the different views. And then use the external parameter which has the minimum back-projection error as the external parameter of the binocular measurement system to calculate three-dimensional points. However the problem is that the back-projection error is only ensure the highest accuracy

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in this view angle. In the other view angle of the whole measurement space the accuracy is great difference which is a fatal problem to the precision measurement. A bundle adjustment method was proposed to optimize intrinsic and external parameter of optical binocular vision system in the reference [6]. The method is simultaneous optimize the back-projection errors of the feature points under the multi-view and the intrinsic and external parameter of the camera to obtain the optimal solution. However, the disadvantage of the optimization method is that it will failure when the common calibration feature points at multi-view are insufficient [7]. A novel calibration method for optical binocular system based on matching the synthetic images of concentric circles was proposed in the reference [8]. The synthetic images are calculated through the model of camera and the known position of concentric circles in the target plane. By matching the synthetic images and observed images, the coordinate of the centre circles in image plane is located with optimization. Then, based on the image coordinate of the concentric circles in two cameras and the constraint of binocular vision, the parameters of binocular vision sensor arc optimized by Levenberg-Marquart method. The method can improve the measurement accuracy to some extent. However, the large number of the goal functions and optimal parameters defined by this method is easy to cause the instability of the calculation process.

To solve the problem that the external parameter of binocular vision system is imprecise, a simple and effective optimization algorithm is proposed. Optimization result is computed through minimizing epipolar line error of the same pair of points in every view. This ensures the binocular measurement system having high and stable accurate in the whole measurement space.

2. The Modal of Binocular Measurement System

The binocular measurement system described in the passage consists of two cameras and a projected device. The objects in the scene should be observed at the same time. The system imaging structural model is shown in Fig.1. There is only a rotation and translation of the rigid transformation between the two devices.

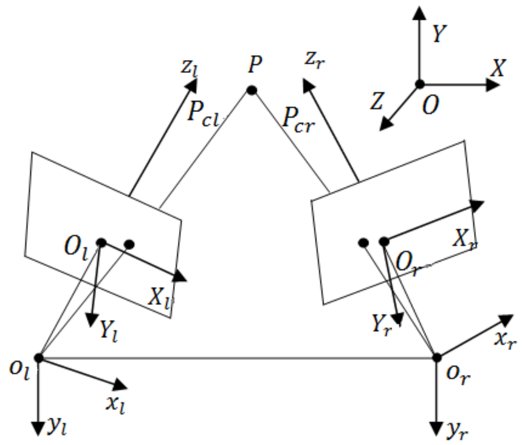

Figure 1. Binocular Stereo Imaging Modal

In the binocular measurement system, we not only need calibrate intrinsic parameters of the camera but also determine the relative position and attitude of the cameras. In the model, using R_{rtl}, t_{rtl} represent the rotation matrix and translation vector respectively which produced from the left coordinate of the camera to the right. The transform formula is shown as follow:

$$P_{cr} = R_{rtl}P_{cl} + t_{rtl} \quad (1)$$

The P_{cr}, P_{cl} in the formula respectively represent the coordinate of the space point P in the right and the left camera coordinate system, R_{rtl} and t_{rtl} are called external parameter in the binocular measurement system.

3. External Parameters Optimization Algorithm

In the system calibration process, we can obtain a set of intrinsic parameter of both left and right camera and multiple sets of external parameters. For example, if we use seven sets of images to calibrate the binocular system, there will be produce seven sets of the corresponding external parameters under different view angle. Generally, the intrinsic parameter is sufficiently accurate since many images are involved in the process of calibration calculation, which has been proved by the practice. However, the external parameter accuracy is not like this. Because of the images feature points exacted accuracy under different view angle are affected by factors such as electronic noise, ambient light and so on. The external parameter transformation matrix accuracy under some locations is higher than the others which will bring a thorny problem to the three-dimensional reconstruction.

Usually, formula (2) is used to calculate of the left and right camera respectively. And then choose a set external parameter which has minimum back-projection error about to reconstruct 3D points.

$$e_{rep}[i] = \frac{1}{n}\sum_{j=1}^{n} ||P_i\left(X_j\right) - x_j||. \quad (2)$$

In the formula, $P_i = A \cdot [R_i|t_i]$ represents the projection matrix in the i view angle of any camera. x_j is the image points coordinates detected in the view angle. X_j is the corresponding model points coordinates of the calibration object. The small back-projection error means the accurate of projection matrix in this position is high, so the back-projection error is widely used to evaluate the accuracy of the camera calibration [9-10].However, this algorithm could not be used to assess the accuracy of the external parameter of binocular measurement system. As shown in figure 4, when the calibration points are under the perspective of single camera, we can calculate the current perspective back-projection error to assess the accuracy of external parameters by formula (2). But we are not able to contact together the viewing angle i_1, i_2 ....

In the binocular measurement system, if the calibrated points D could be shot by both left and right cameras in multiple viewing angles such as i_1 and i_2, we can get the solution from polar geometry that one point in the left image must be in the polar in the right image. The polar formulas of left and right images according to polar geometry definition are shown as follows:

$$l_r = Fd_l \quad (3)$$

$$l_l = F^T d_r \quad (4)$$

In the formula, d_l and d_r represents homogeneous coordinates of three-dimensional point D in both left and right images respectively. F is the basic matrix defined by intrinsic parameter A_l、A_r and external parameter, and it could be represented as follows[11].

$$F = A_r^{-T} S R A_l^{-1} \quad (5)$$

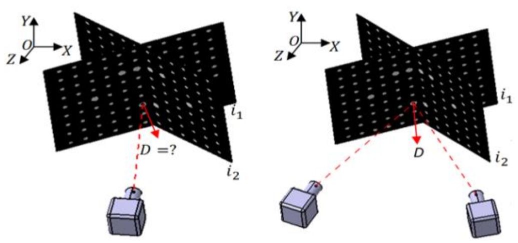

Figure 2. Schematic Diagram of Multi-View Calibration

In the formula (5), S is the anti-symmetric matrix and defined by translation vector as follows:

$$S = [t]_\times = \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix}$$

When known the camera intrinsic parameters A_l and A_r, we could normalize the image coordinate of corresponding feature points. $\hat{d}_l$ and $\hat{d}_r$ are coordinates after d_l and d_r normalized respectively, so

$$\hat{d}_r{}^T E \hat{d}_l = 0 \tag{6}$$

Here, $E = [t]_\times R$ is the essential matrix. It is only related to the structural parameters of the optical measurement system.

If the calibration is accurate enough, the corresponding point of the left image must be in the polar line in the right image. Based on the theory, according to the point to the straight line distance formula, we can define the polar error as follows:

$$e_r[i] = \frac{1}{N}\sum_{j=1}^{N}\left(\frac{1}{M_j}\sum_{k=1}^{M_j}\left|\frac{\hat{d}_r{}^T E_i \hat{d}_l}{\sqrt{\left(E_i\hat{d}_l[1]\right)^2 + \left(E_i\hat{d}_l[2]\right)^2}}\right|\right) \tag{7}$$

In the formula, E_i is the essential matrix obtained from the calibration under the i viewing angle in the calibration process. N is the quantity of sequence image in the procedure of calibration. M_j is the quantity of calibration points which detected by left and right camera at the same time in the jviewing angle. Assuming that the algebraic of the polar equation shows $ax + by + c = 0$. Here $E_i\hat{d}_l[1]$is the parameter a and $E_i\hat{d}_l[2]$is the parameterb. According to the theory of the polar geometry, we can get $e_r \approx e_l$. The procedure of external parameters optimization is the procedure of minimizing the formula (7) under the viewing angle S of sequence image. The objective function is:

$$min_{i\in S}\sum_{c\in\{l,r\}}(e_c[i]) \tag{8}$$

We optimize the essential matrix with the formula (8) to obtain the external parameter, and get the structural parameters of the binocular vision system.

4. Experiment

4.1. The Calibration Experiment of the System

Binocular experimental system is shown in figure 3. The hardware of the system includes: two Basler A102f cameras that the sensor technology is CCD (Charge-coupled Device) , the sensor size is 2/3 inch, the physical size of each pixel is $6.45\mu m \times 6.45\mu m$ and the resolution is1392×1040pixel .Two Japan's Computar megapixels optical lens whose nominal focal length is 16mm. And a calibration board which has 357 circular signalized points 21 lines and 17 columns with different size. The calibration board is shown in figure 4.The accurate distances between two big circles located in horizontal and vertical direction in the calibration board measured by image measuring instrument are 144.007 mm and 120.005mm.

In the calibration experiment, we apply the procedure of binocular measurement system mentioned in 2.1 to calibrate, use the external parameter of binocular system calculated by traditional method and the algorithm mentioned in this paper respectively, then to calculate the 3D points of feature points of calibration board at any position in the measurement space. The results are shown in table 1 and table 2. The traditional method mentioned above is that using one set of parameter to calculate the structure parameter of binocular stereo-vision system.

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Figure 5. Binocular Measurement System

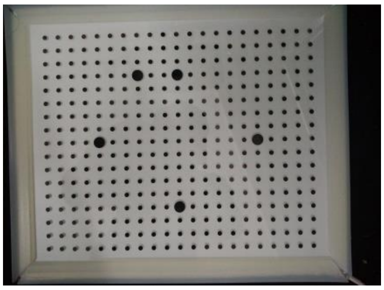

Figure 6. Calibration Board

Table 1. The Error Comparison of 3D Reconstruction between the Big Points' Distance in Every Calibration Position (mm)

	Position	1	2	3	4	5	6	7
Traditional	Horizontal	144.008	144.016	144.000	144.024	144.020	144.015	144.017
	Error	0.001	0.009	-0.007	0.017	-0.015	0.008	0.01
	Vertical	120.007	120.000	119.999	119.992	120.013	120.016	120.010
	Error	0.002	-0.005	-0.006	-0.013	0.008	0.011	0.005
This paper	Horizontal	144.010	144.012	144.003	144.016	144.011	144.009	144.010
	Error	0.003	0.005	-0.004	0.009	0.004	0.002	0.003
	Vertical	120.009	120.002	120.004	120.002	120.011	120.008	120.003
	Error	0.004	-0.003	-0.001	-0.003	0.006	0.003	-0.002

The data is shown in table 1 is the points of calibration board reconstruction result in every calibrated position. Through analysis the data we can know that the reconstruction result is very high in the first view angle which is to calculation the external parameter using the traditional method. However, the results which are optimized by this paper are higher and distributed uniformly in every view angle.

Table 2. The Error Comparison of 3D Reconstruction between the Big Points' Distance in the any Position of Measurement Volume (mm)

	位置	1	2	3	4	5	6	7
Back-projection	Horizontal	144.021	143.998	143.984	144.015	144.017	144.016	144.011
	Error	0.014	-0.009	-0.023	0.008	-0.010	0.009	0.004
	Vertical	120.015	119.999	120.021	119.980	120.011	120.014	120.018
	Error	0.010	-0.006	0.016	-0.015	0.006	0.009	-0.013
This paper	Horizontal	144.016	144.003	144.02	144.012	144.010	144.07	144.012
	Error	0.009	-0.004	-0.005	0.005	0.003	0.010	0.007
	Vertical	120.010	120.002	120.014	120.003	120.012	120.005	120.000
	Error	0.005	-0.003	0.009	-0.002	0.007	0.000	-0.005

According to the data was shown in table 2, we can see that the reconstructing error is larger in the any position of measurement volume based on the traditional method. However, the accuracy in these positions is high and stable obtained by the algorithm mentioned in the paper.

4.2 The Experiment Measurement of the Standard Ball Gauge

In order to further verify the calibration accuracy of optical binocular measurement system, the standard ball gauge is measured based on the phase structured light. As shown in figure 7, the distance between two standard ball gauge is$D = 160.007$mm, and the diameters of two ceramic balls are 80.001mm and 79.999mm respectively. We put the standard ball gauge in the viewing field of binocular measurement system. The sketch map of measuring position which is according to the German optical scanner inspection standards of VDI-VDE2634 is shown in figure 8. The results are shown in the table 3.

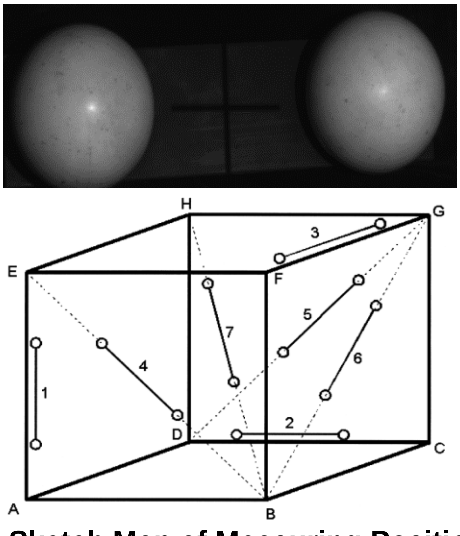

Figure 8. Sketch Map of Measuring Position

The standard ball gauge is measured six times at seven different positions in the measurement volum. All the point clouds of the standard ball gauge are fitted based on the least squares method to obtain the ball center. As shown in table 3, all the measurement errors of the distance between centers are less than 0.04mm and distribute uniformly in the whole measurement volum. The measurement accuracy of the standard ball gauge is lower than the three-dimensional reconstructing accuracy of the calibrated points. This is caused by the existence errors in the procedure of searching for corresponding points by the phase.

Table 3. The Measurement Result of Ceramic Standard Ball Gauge (mm)

Position	The number of measurement											
	1		2		3		4		5		6	
	测量值	误差	测量值	误差	测量值	误 差	测量值	误 差	测量值	误 差	测量值	误 差
1	160.040	0.033	160.045	0.038	160.043	0.036	160.039	0.032	160.044	0.037	160.042	0.035
2	160.041	0.034	160.044	0.037	160.043	0.036	160.042	0.035	160.042	0.035	160.040	0.033
3	160.042	0.035	160.044	0.037	160.045	0.038	160.040	0.033	160.045	0.038	160.046	0.039
4	160.038	0.031	160.040	0.033	160.043	0.036	160.038	0.031	160.042	0.035	160.040	0.033
5	160.036	0.029	160.039	0.032	160.046	0.039	160.042	0.035	160.043	0.036	160.046	0.039
6	160.038	0.031	160.038	0.031	160.044	0.037	160.042	0.035	160.040	0.033	160.041	0.034
7	160.039	0.032	160.042	0.035	160.044	0.037	160.040	0.033	160.045	0.038	160.042	0.035

A simple and effective external parameter calibration and optimize method based on epipolar geometry for improving the accuracy and stabilization of 3D optical measurement system are present. First, the internal parameters of two cameras are calibrated using the planar calibration method. Then using the parameters as initial value calibrates the external parameter of the 3D optical measurement system in every view. Optimization result is computed through minimizing epipolar line error of the same pair of points in every view. Experimental results show that the measurement precision is high and stable in the measurement volume.

4. Conclusions

A simple and effective external parameter calibration and optimize method based on epipolar geometry for improving the accuracy and stabilization of 3D optical measurement system are present in this paper. The left and right cameras are used to shoot the images respectively and calculate each intrinsic parameter. The external parameter of the system is calibrated by taking the above parameters as the intrinsic parameter of optical binocular system. The optimized objective functions under the multiple viewing angles are created according to the polar geometry constraint. The external parameter of the system is calculated using non-linear optimization. The advantage of this method is that the objective function is simple, the quantity of the optimize parameters is small and the calculation is stable. The experimental result shows that compared with the traditional method which external parameter calculated based on the back-projection error, the three-dimensional reconstructing accuracy of the calibrated board and standard ball gauge is high and stable in the whole measurement volume.

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