A NEW CALIBRATION METHOD FOR STEREO CAMERA

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ABSTRACT: Using stereo cameras for three-dimensional reconstruction is highly applied, because relative orientation parameters are stable during the imaging. Also the accuracy of the reconstructed object with this method is homogenous in different directions. True calibration of the stereo cameras which are used in environmental modeling has a great effect on the final accuracy of results.

In this research, in respect to common methods, to calibrate stereo camera 3D Fuji, the exterior and interior orientation parameters for each camera lenses were determined by solving bundle adjustment. After that, the relative orientation parameters of the two lenses were calculated by using the relationships between the two lenses.

In our method, to calibrate stereo cameras using constrained bundle adjustment, relative orientation parameters were determined directly. The unknown exterior and interior orientation parameters are decreased by applying the constraint of the two lenses in each imaging stations. The degree of freedom increases, also the stability of the equations is improved by decreasing the number of the unknowns. In this way, the relative orientation parameters between the two lenses would be calculated more accurately than the other methods.

Finally, by comparison of the results accuracy, two mentioned methods were evaluated and analyzed.

1. Introduction

Today, non-metric cameras are used in different applications of close range photogrammetry, because of the appropriate price, low maintenance cost, and diversity. Meanwhile, using stereo cameras to reconstruct the three-dimensional is highly noted, for their relative orientation parameters are constant during the imaging.

Of all the usages of the stereo cameras in production of the three-dimensional model, we can mention the completion of the existing maps, providing the urban models, controlling and robotic, providing the virtual three-dimensional models, video games, navigation, and intelligent systems which are capable of understanding the environment and decision making (D. Gledhill, 2009).

Vision inspection has been widely used in industrial measurement and scientific research, owing to its non contact manner. Three dimensional measurements for industrial products inspection Requires high accuracy and flexibility. Camera calibration is a key issue that affects the accuracy of stereo vision system.
Camera calibration is the process of determining the interior and exterior parameters of camera via capturing external Reference objects .The single camera calibration has been studied extensively (TsaiRY,1987), (ZhangZ,2000),(HonkavaaraE et al.2006).
Camera calibration is a necessary step in 3D computer vision in order to extract metric information from 2D images. Being different from with single camera calibration, binocular stereo vision systems not only need to ascertain intrinsic parameters, but also the relative position relation of two cameras (Yongjie Yan et al.2006)
Traditionally, the two cameras in the stereo camera are calibrated individually (Hanqi ZhuangA, 1995)

The exterior and interior orientation parameters were determined during the calibration level. But today, in order to reach a greater accuracy, in addition to the exterior and interior orientation parameters, the relative orientation parameters are also determined. And these parameters are used as stable amounts in the next levels. This becomes very important when it comes to the rotational cameras and multi camera systems. In these systems, image stitching and the extraction of the geometric information, is up to the correct calibration of the whole system and the determination of the interior and relative orientation parameters. In other words, determining the relative orientation parameters between the cameras in multi-camera systems can be a great help in the image stitching.

In this research, a new method to calibrate the stereo cameras in order to determine the relative orientation parameters of the two cameras are provided based on the bundle adjustment method. In this method, in addition to the determination of exterior orientation parameters of the left lens of the stereo camera, the relative orientation parameters between the two lenses are estimated simultaneously. The presented method was evaluated in the real calibration of a stereo camera, using a test field.

2. Stereo Cameras

In recent years, extensive researches have been performed about the combination of the cameras to three-dimensional reconstruction of the environment. Using stereo cameras is one of the perfect tool for three-dimensional reconstruction, because its relative orientation parameters are stable during the imaging and the accuracy of the geometric reconstruction is homogenous in different directions to the other methods.

Stereo cameras have been around since 1839, when they were invented (http://www.stereoscopy.com/). These cameras, unlike the single camera, have two lenses which capture separate pictures. In this situation, stereoscopy becomes possible with the two pictures which have been captured from one area. These cameras are usually placed in an integrated framework and their imaging is done simultaneously. The accurate calibration of the cameras, especially stereo cameras, is one of the important levels to the photogrammetry and computer science, and without doing the correct and accurate calibration of the camera; the geometric information extracted from the images can be vulnerable to errors. The calibration of a stereo camera contains determining the interior orientation parameters of each camera and determining the relative orientation parameters of the two cameras. Of course, it should be noted that if there is correlation between the parameters, this correlation will produce a systematic error in the information extracted from the images.

3. Common method to determine the relative Orientation Parameters of the Stereo Camera

By solving the bundle adjustment of the images resulted from the two stereo cameras, in addition to the determination of the interior orientation parameters, the exterior orientation parameters of each imaging stations are also achieved. Normally, we can obtain the relative orientation parameters between left and right lenses using exterior orientation parameters achieved in each imaging stations. Equation 1 shows the transformation from an image coordinate system to a object coordinate system, and it can be written for the images of left and right lenses of the stereo cameras.

$$R_m \cdot \begin{bmatrix} x_i \\ y_i \\ C_i \end{bmatrix} + T_m = \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} \qquad (1)$$

In the equation above, T is the transformation matrix, R is the rotation matrix, X, Y, and Z are the ground coordinates, C is the camera's focal length, and x,y are the image coordinates of points.

Due to the equality of the targets' ground coordinates for the images of the left and right lenses of the stereo camera, equation (1) can be written for the left and right lenses like this.

$$R_{left} \cdot \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}_{left} + T_{left} = R_{right} \cdot \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}_{right} + T_{right} = \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} \qquad (2)$$

Finally, we can determine the relative orientation parameters like the equation (3).

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}_{left} = \underbrace{R^t_{left} \times R_{right}}_{R'} \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}_{right} \underbrace{+ R^t_{left} \times (T_{right} - T_{left})}_{T'} \tag{3}$$

In equation (3), R' represents the rotation matrix between the left and right lenses and T' represents the transformation matrix between the lenses.

Table 1, the result of estimated average relative orientation of 18 stations

parameters	average	std	Max.error
ΔΩ (degree)	0.1172	0.0186	0.0255
ΔΦ (degree)	3.0157	0.0172	0.0305
ΔΚ (degree)	-0.4789	0.0103	0.0110
BX (mm)	76.8180	0.3292	0.5691
BY (mm)	-0.0042	0.4072	0.8123
BZ (mm)	-0.7626	0.4019	0.7712
Base-Line	76.8239	0.3339	0.5826

4. New method to determine the relative Orientation Parameters of the Stereo Camera

As it was mentioned before, the relative orientation parameters between the left and right lenses in stereo cameras are stable. As a result, we can decrease the unknown parameters in bundle adjustment by applying the constancy constraint of the relative orientation of the two lenses in each imaging stations. In order that by the reduction of the total of the unknowns, with the total of equations being stable, the degree of freedom becomes higher and the strength of the equations will increase. According to this concept, a new method in determining the relative orientation of the two cameras in a system will be presented. The relative orientation parameters of the two lenses will be considered stable in each station, so that the unknowns in the adjustment will decrease from $12 \times n + 3 \times m + p$ to $6 \times n + 6 + 3 \times m + p$, **P** represents the total of interior orientation parameters, **n** represents the total of the imaging stations, and **m** represents the total of targets. In fact, according to this idea, exterior orientation parameters of the whole stations of the right lens, with the three rotation parameters and three shift parameters will become dependent to the exterior orientation parameters of the station of the left lens.

$$\begin{aligned} F_x &= F_{x0} + \frac{\partial F_x}{\partial Xo}\Delta Xo + \frac{\partial F_x}{\partial Yo}\Delta Yo + \frac{\partial F_x}{\partial Zo}\Delta Zo + \frac{\partial F_x}{\partial \omega}\Delta\omega + \frac{\partial F_x}{\partial \varphi}\Delta\varphi + \frac{\partial F_x}{\partial \kappa}\Delta\kappa + \frac{\partial F_x}{\partial X_A}\Delta X_A + \frac{\partial F_x}{\partial Y_A}\Delta Y_A + \frac{\partial F_x}{\partial Z_A}\Delta Z_A = 0 \\ F_y &= F_{y0} + \frac{\partial F_y}{\partial Xo}\Delta Xo + \frac{\partial F_y}{\partial Yo}\Delta Yo + \frac{\partial F_y}{\partial Zo}\Delta Zo + \frac{\partial F_y}{\partial \omega}\Delta\omega + \frac{\partial F_y}{\partial \varphi}\Delta\varphi + \frac{\partial F_y}{\partial \kappa}\Delta\kappa + \frac{\partial F_y}{\partial X_A}\Delta X_A + \frac{\partial F_y}{\partial Y_A}\Delta Y_A + \frac{\partial F_y}{\partial Z_A}\Delta Z_A = 0 \end{aligned} \tag{4}$$

Usually, linearization of co-linear equations in order in use in bundle adjustment, it is derivate from 9 parameters including exterior orientation parameters and ground coordinates of the point shown in equation (5):

$$\begin{aligned} F_x &= F_{x0} + \frac{\partial F_x}{\partial Xo}\Delta Xo + \frac{\partial F_x}{\partial Yo}\Delta Yo + \frac{\partial F_x}{\partial Zo}\Delta Zo + \frac{\partial F_x}{\partial \omega}\Delta\omega + \frac{\partial F_x}{\partial \varphi}\Delta\varphi + \frac{\partial F_x}{\partial \kappa}\Delta\kappa + \boxed{\frac{\partial F_x}{\partial BX}\Delta BX + \frac{\partial F_x}{\partial BY}\Delta BY + \frac{\partial F_x}{\partial BZ}\Delta BZ + \frac{\partial F_x}{\partial \omega'}\Delta\omega' + \frac{\partial F_x}{\partial \varphi'}\Delta\varphi' + \frac{\partial F_x}{\partial \kappa'}\Delta\kappa'} + \\ &\quad \frac{\partial F_x}{\partial X_A}\Delta X_A + \frac{\partial F_x}{\partial Y_A}\Delta Y_A + \frac{\partial F_x}{\partial Z_A}\Delta Z_A + = 0 \\ F_y &= F_{y0} + \frac{\partial F_y}{\partial Xo}\Delta Xo + \frac{\partial F_y}{\partial Yo}\Delta Yo + \frac{\partial F_y}{\partial Zo}\Delta Zo + \frac{\partial Fy}{\partial \omega}\Delta\omega + \frac{\partial F_y}{\partial \varphi}\Delta\varphi + \frac{\partial F_y}{\partial \kappa}\Delta\kappa + \boxed{\frac{\partial F_y}{\partial BX}\Delta BX + \frac{\partial F_y}{\partial BY}\Delta BY + \frac{\partial F_y}{\partial BZ}\Delta BZ + \frac{\partial F_y}{\partial \omega'}\Delta\omega' + \frac{\partial F_y}{\partial \varphi'}\Delta\varphi' + \frac{\partial F_y}{\partial \kappa'}\Delta\kappa'} + \\ &\quad \frac{\partial F_y}{\partial X_A}\Delta X_A + \frac{\partial F_y}{\partial Y_A}\Delta Y_A + \frac{\partial F_y}{\partial Z_A}\Delta Z_A = 0 \end{aligned} \tag{5}$$

In the proposed method, mentioned equations are used for image points of the left lens. But for the right lens, according to this fact that the rotation and the shift matrixes of the right lens is the function of rotation and shift parameters of the left lens and relative orientation between two lenses, for linearization of the co-linear equations of image points of the right lens, deviation is done from 15 parameters including 9 mentioned parameters plus 3 shift parameters and 3 rotation parameters between the two lenses. Consequently, derivation of the bundle adjustment equation for image points of the left lens is as distinctive parts in equation (5).

Finally, the observations' matrix for all the imaging stations will become like figure 1. In this figure, the green color is the derivative towards the exterior orientation parameters of the left lens, and the red color is the derivative towards the relative orientation parameters between the two lenses, and **n** represents the total of the existing points in each image (station).

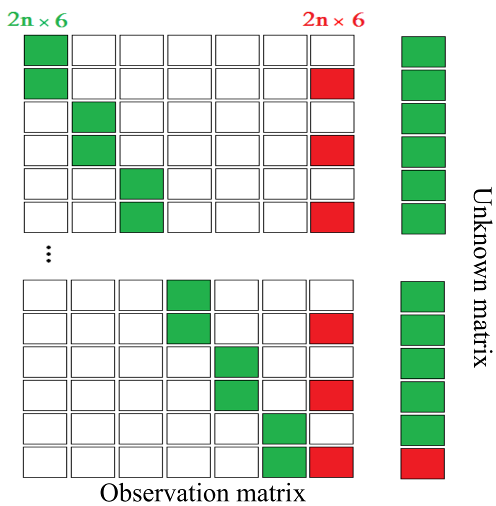

Figure 1, the observations' matrix for all the stations

The results of the estimation of the relative orientation parameters using the proposed method with the accuracy of the calculation are shown Table2.

Table 2, the relative orientation parameters with constraint

parameters	Estimated values	std
ΔΩ (degree)	0.0510	0.0165
ΔΦ (degree)	2.2058	0.0139
ΔK (degree)	-0.4360	0.0079
BX (mm)	76.4771	0.2232
BY (mm)	-0.9904	0.3060
BZ (mm)	-0.0993	0.3543
Base-Line	76.4836	---

According to the reduction of the unknowns and the increase in the freedom degree in using this method, the relative orientation parameters are achieved with a proper accuracy equal to 0.01 degrees for the rotation parameters and 0.3 millimeters for the transfer parameters.

5. Evaluation of the Accuracy of the Presented Method via common method to Estimate the relative Orientation Parameters

To evaluate the presented method, a Fuji 3DX camera was used as a sample stereo camera.

We can see the specification of camera in Table3.

Table3

Focal length	6mm
Base line	77mm
Pixel size	2 micron
Field of view	Horizontal 54 degree
	Vertical 44 degree
Dimension	120 mm

Figure 2, the index of this camera

In this investigation, a test field containing 100 targets has been used. Then the test field was imaged from 18 stations. To provide the proper strength of the network, and to prevent the correlation between the parameters, the test field was photographed with the rotation angle of 90 degrees. To reach the accuracy in the real scale, in this investigation three scale bar were used.

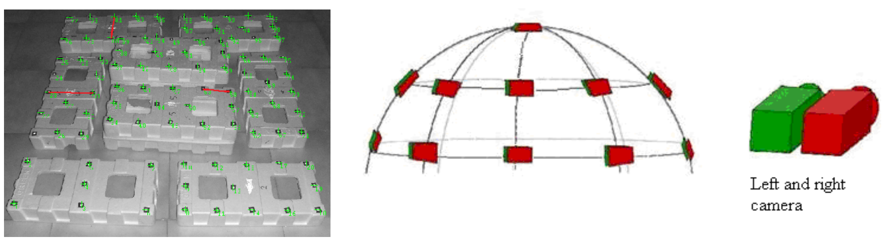

Figure 3 , the test field and the imaging network

By using the proposed method in bundle adjustment, in addition to the estimate of the interior orientation parameters and targets' ground coordinates, the exterior orientation parameters of the left lens and three shift parameters and three rotation parameters between the two cameras were estimated.

To evaluate the proposed method, the determination of the relative orientation parameters in two separate adjustments is done with the constancy constraint of the relative orientation of the proposed method and without the constancy constraint of common method. In this study, some check points were also used.

This evaluation was done using check points and co-planimetry, so that we can write these equations for the match points in stereo images.

$$\begin{bmatrix} x'_r \\ y'_r \\ z'_r \end{bmatrix} = R' \times \begin{bmatrix} x_r \\ y_r \\ -f_r \end{bmatrix} \qquad p = \begin{vmatrix} Bx & By & Bz \\ x_l & y_l & -f_l \\ x'_r & y'_r & z'_r \end{vmatrix} = 0 \quad (!)$$

in equation(8), x_r !!! y_r are the image coordinates of the right lens, R is the rotation matrix, and Bx, By, and Bz are the shift parameters between the left and right lenses. Ideally, in this equation, the determinant equals zero.

Equation 8 can be used to evaluate the relative orientation parameters of the two methods.

To perform this evaluation, determinant (p) was calculated for the match points in the stereo images. Finally, their RMSE was calculated in each imaging stations using equation 9.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} {p_i}^2}{n}} \tag{9}$$

Table 4, the precision of the presented method with constraint via common method without constraint in 5 stations.

station	Bundle adjustment without constrain RMSE(mm) The distance from zero	Bundle adjustment with constrain RMSE(mm) The distance from zero	The difference between the two values in each station
1	9.4355	2.4225	7.0129
2	8.3917	1.4353	6.9564
3	8.4777	1.8382	6.6394
4	8.6487	1.7645	6.8842
5	8.5405	1.3481	7.1923

The results of the Table 4, show that the accuracy resulted from determining the relative orientation parameters using the proposed constraint on the check points is better than the accuracy resulted from the common method (without considering the constraints).

Table 5, shows the RMSE (distance from zero) of the match points in the stereo images of 18 imaging stations. As seen in the table, using the proposed method, the average determinant is 7 millimeters closer to zero.

6. Conclusion

Using stereo cameras to utilize in geometric reconstruction of the objects and environment is highly noted. According to the proper stability and consistency of the relative orientation parameters of the two cameras in a stereo camera, these parameters can be used as stable values in the next calculation levels like image automatic stitching and geometric information extraction. In conclusion, the accurate determination of the relative orientation parameters of the two cameras is very important.

In this article, a new method for determination of the relative orientation parameters is provided based on bundle adjustment method. According to this method, in simultaneous adjustment, in addition to the determination of exterior orientation parameters of the left lens of the stereo camera, the relative orientation parameters between the two lenses are estimated simultaneously.

The provided method was evaluated in the real calibration of a stereo camera using a test field. In this study, the relative orientation, rotation parameters were obtained with the accuracy of 0.01 degrees and the shift parameters with the accuracy of 0.3 millimeters. The proposed method will decrease the unknowns and increase the freedom degree in proration, and the evaluation results shows the proper accuracy of the provided method.

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