LADYBUG3 CAMERA CALIBRATION

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KEY WORDS: Cyber-City, Camera Calibration, Mobile Mapping System

ABSTRACT: The applications of photogrammetry such as aerial triangulation, 3D modeling, and automatic texture mapping need precise camera internal geometry in order to obtain high precision results. Ladybug3 equipped with 6 short focal length fish-eye cameras, which can acquire 720 degrees panoramic image and is useful for augmented reality applications. The field of view (FOV) of each lens is about 95 degrees by 77 degrees. Thus, their lens distortion is serious and the way to calibrate their interior orientation parameters is critical for photogrammetry purposes. Therefore, this research proposes two types of indoor calibration field to solve these problems using single camera calibration and multiple camera calibration. A rotatable calibration field contains 112 pillars with Australis© coded target is designed. The basic idea of such calibration field is to acquire high convergent imaging geometry with lots of redundant image measurements by means of automatic code target recognition. The purpose of the second calibration field is to calibrate both the interior orientation parameters and relative orientation parameters between the six cameras. A 3D cube, with 4 meters in length, 3 meters in width and 2.5 meters in height is used, where 118 Australis coded targets are fixed and spread uniformly to the ceiling, the floor, and all four walls. Since the Australis is capable of self-calibrating multiple cameras at the same time, the interior and exterior orientation parameters can be solved. Based on the exterior orientation parameters, the relative orientation parameters can be estimated. The accuracy of relative rotation angles is around 0.02 degrees and the accuracy of perspective center offset which between the referenced camera to the others is less than 1 mm. It is expected that the accuracy is precise enough for direct georeferencing applications using a land vehicle mobile mapping system.

1. Introduction

Cyber-city is a way to simulate the real city. Users can surf the virtual 3D cyber-city which constructed by computer graphics technology, so that users could obtain the feelings like in the reality. There are two main components in the cyber-city: 3D geometric models and images of texture mapping. 3D geometric model describes the shapes of objects, images of texture mapping shows the object's true color, material and texture. Due to the extensive applications of cyber-city in recent years, these two components are the key points of this research, especially the part of texture mapping random texture mapping methods cannot satisfy users' requirement, the use of real photos to build realistic cyber-city has been the most common way to produce façade's texture (Zhu et al., 2011; Grenzdörffer, Guretzki, and Friedlander 2007).

A lot of photogrammetric procedures like aerial triangulation, 3D modeling or texture mapping, need to calibrate the camera's interior orientation parameters (i.e. principal point's location, focal length, and the lens distortion parameters) (Fraser 1997). These photogrammetric procedures could get better result if the precise interior orientation parameters are provided.

The calibration method used in this study called "self-calibration bundle adjustment with additional parameters" (Fraser 1998), and two calibration fields are built for this purpose. A round rotatable board is designed for calibrating camera's interior orientation parameters, whereas a cubic calibration field for calculating both the relative and interior orientation parameters. Every image after calibration has the exterior orientation parameters, the relative offset of camera's perspective center and the relative rotation angles of each Ladybug3 cameras can thus be estimated.

In the future, we will setup the Ladybug3 panoramic camera on a land-based mobile mapping system. The exterior orientation parameters will be derived by direct georeferencing and the estimated relative orientation parameters. These pictures can be used for generating the texture of the building models of the cyber-city. In order to reduce the effect of lens distortion when producing the texture, Ladybug3 camera should be calibrated precisely in advance.

2. Methodology

2.1 Introduction of the Ladybug3 camera

Ladybug3 is a so-called 720 degrees panoramic camera, it has 6 Sony ICX274 color CCD sensor, the resolution of each lens is about 2 million pixels, and they're fish-eye lenses with a short focal length of 3.3 mm. The wide field of view (FOV) is the characteristic of fish-eye lens. The FOV on the horizontal direction is about 77 degrees, and almost 95 degrees on the vertical direction. Fig. 1 is an example of Ladybug3 camera denoting its wide FOV. Therefore, the neighbor images have overlapping area that could be merged as a panoramic image. On the other hand, the lens distortion is extremely critical to the fish-eye lens. The condition of distorted features can be figured out by Fig. 2, e.g. the air conditioner, wall, ceiling, and the ground's structure lines are distorted into curve.

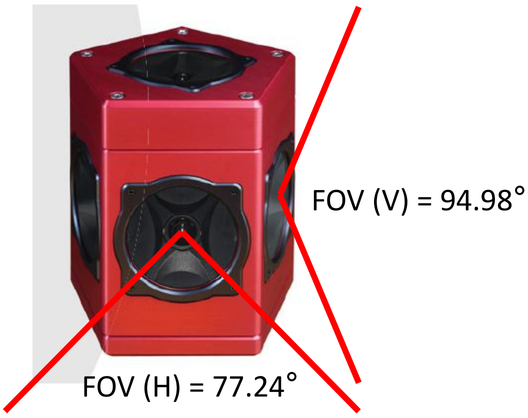

Fig. 1. Ladybug3 camera and its field of view (FOV) on the horizontal and vertical directions.

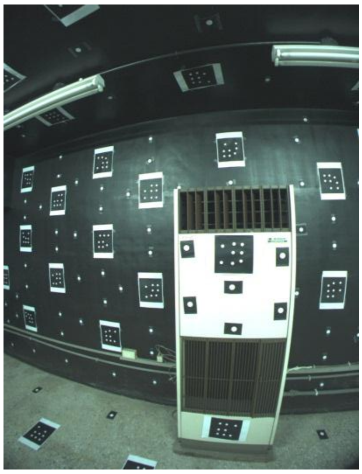

Fig. 2. The lens distortion is obvious.

2.2 Method of calibration

The adopted method for camera calibration in this research is the "self-calibration bundle adjustment with additional parameters". The used software is Photometric Australis© (Fraser and Edmundson 2000), its mathematical model is based on the collinearity equations, as shown in equations (1) and (2). The major observations are image coordinates of tie points. These observations are used to adjust the exterior / interior orientation parameters and additional parameters of the camera. The interior orientation parameters include principal point coordinates (x0, y0), focal length (c), radial lens distortion, decentric lens distortion, and CCD sensor's affine deformation, etc.

$$x_a = x_0 - c\frac{m_{11}(X_A-X_O)+m_{12}(Y_A-Y_O)+m_{13}(Z_A-Z_O)}{m_{31}(X_A-X_O)+m_{32}(Y_A-Y_O)+m_{33}(Z_A-Z_O)} - \Delta x \qquad (1)$$

$$y_a = y_0 - c\frac{m_{21}(X_A-X_O)+m_{22}(Y_A-Y_O)+m_{23}(Z_A-Z_O)}{m_{31}(X_A-X_O)+m_{32}(Y_A-Y_O)+m_{33}(Z_A-Z_O)} - \Delta y \qquad (2)$$

$$\Delta x = (r^2K_1 + r^4K_2 + r^6K_3)\overline{x} + P_1\left(2\overline{x}^2 + r^2\right) + 2P_2\overline{xy} + b_1\overline{x} + b_2\overline{y} \qquad (3)$$

$$\Delta y = (r^2K_1 + r^4K_2 + r^6K_3)\overline{y} + 2P_1\overline{xy} + P_2\left(2\overline{y}^2 + r^2\right) \qquad (4)$$

In which $\overline{x} = (x_a - x_p), \overline{y} = (y_a - y_p), r = \sqrt{\overline{x}^2 + \overline{y}^2}$, K_1, K_2, K_3 are radial lens distortion parameters, P_1, P_2 are decentric lens distortion parameters, and b_1, b_2 are CCD sensor's affine deformation.

For the purpose of determining meaningful additional parameters, this research uses the following significance test procedure. After bundle adjustment, an image coordinate measurement accuracy index, i.e. the a-posterior image coordinate standard error (Sigma0), can be obtained. At each round of self-calibration bundle adjustment, we add one additional parameter at each run. Then, we analyze the change of Sigma0. If the difference is larger than a-priori image measurement error, i.e. 0.05 pixels, the added parameter is considered “significant”. On the other hand, the added parameter will be ignored.

2.3 Single camera calibration

This research designs a rotatable round calibration board to calibrate single camera. The diagram is shown in Fig 3. On top of the board, 112 retro-reflex coded targets were fixed which could be auto-detected and recognized by the Australis software. Besides, a lot of white points are fixed on the board, too. They can be used as tie points as well in case approximate exterior orientation parameters were estimated, so that a lot of redundant observations may increase.

In order to reinforce the strength of space intersection geometry, makes adjustment results more reliable, and improves the positioning accuracy, a convergent imaging geometry is suggested. Hence, we fix the camera location and pointing to the center of the calibration board with 30~40 degrees of tilted angle. Every time we take two pictures (one portrait, one landscape) and rotate the calibration board with 45 degrees. The change of camera from portrait to landscape is to reduce the correlation among the adjusted unknown parameters. At last, we face the front of the calibration board and take another two pictures, so that there are totally 18 pictures. The image frame should fulfill with the coded target as much as possible to provide the observation along the image’s edge in order to describe the characteristics of lens distortion appropriately.

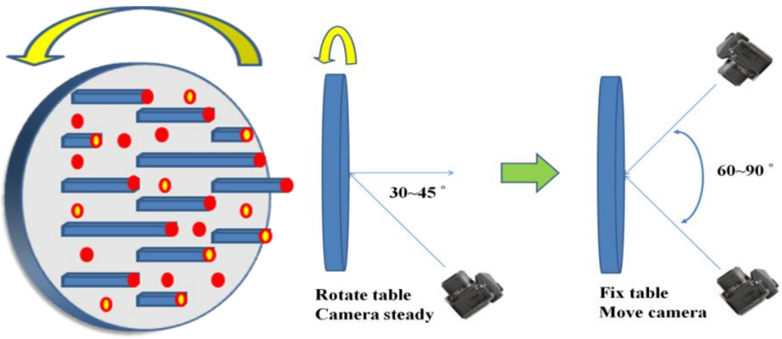

Fig. 3. The round board calibration field and its calibration method.

2.4 Multi camera calibration

For Ladybug3 multi-camera calibration, we design another cubic-shape calibration field which is about 4 meters long, 3 meters wide and 2.5 meters tall. Since the Ladybug3 is a low-resolution wide FOV camera, this research enlarges the Australis’s retro-reflex coded targets three times and fixes them on the walls, ceiling, and on the floor to pre-reserve the ability of automatic tie-point measurement. Meanwhile, lots of white circular points were setup to increase redundant observations. In total, there are 118 coded targets used. Fig. 4 is a panoramic image of the calibration field taken by Ladybug3 where we could see the distribution of coded targets and white circular points for redundant tie-point measurement.

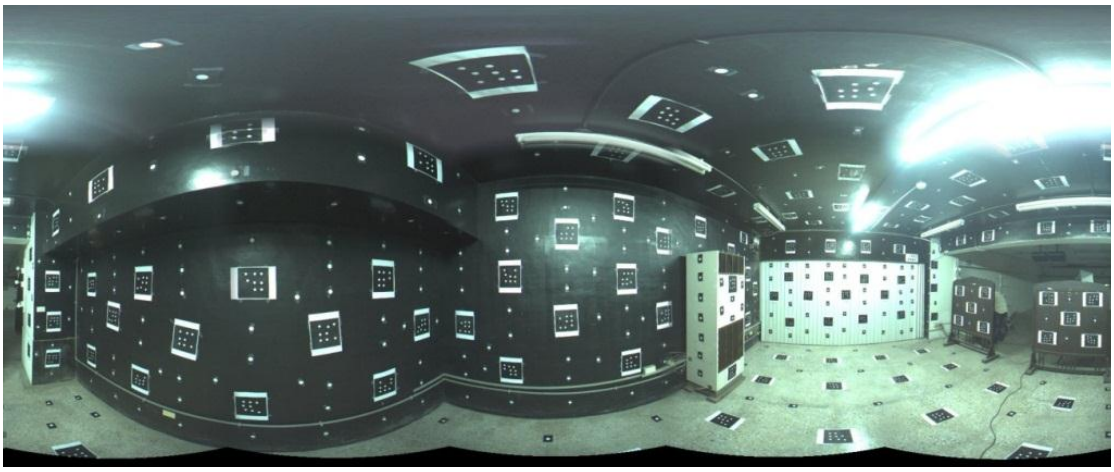

Fig. 4.The panoramic view of calibration field taken by Ladybug3.

Considering the strength of imaging geometry, the baseline between cameras is important. Thus, in this research 16 stations located at different positions and altitudes were chosen to take pictures. For two neighboring stations the horizontal and vertical baseline is around 80 cm. The Ladybug3 was rotated with 90 degrees clockwise for two consecutive stations. One more round of image acquisition is applied by changing the initial viewing direction with 45 degrees. In total, it results in 32 sets of images, i.e. 192 images, for camera calibration.

2.5 Relative orientation calibration

The basic idea of relative orientation calibration is to perform multiple cameras calibration at first, thus we could get the exterior orientation parameters including the positions and attitudes of all six Ladybug3 cameras acquired at the same station. The cameras' positions are described by $r_{C_0}^M, r_{C_1}^M, r_{C_2}^M, r_{C_3}^M, r_{C_4}^M, r_{C_5}^M$ and the attitudes are indicated by the rotation matrices, i.e. $R_{C_0}^M, R_{C_1}^M, R_{C_2}^M, R_{C_3}^M, R_{C_4}^M, R_{C_5}^M$. If camera-0 is used as the reference camera, the rotation matrix for camera-5 relative to the camera-0 can be described by equation (5), and the relative position of the camera's perspective center can be formulate as equation (6).

$$R_{C_0}^{C_5} = R_M^{C_5} \times R_{C_0}^M, \text{where } R_M^{C_5} = \left(R_{C_5}^M\right)^T \tag{5}$$

$$r_{C_0}^{C_5} = R_{C_5}^M \times \left(r_{C_5}^M - r_{C_0}^M\right) \tag{6}$$

3. The experiment results

3.1 The calibration results of the interior orientation parameters

The calibration result of interior orientation parameters of each Ladybug3's camera are shown in Table 1, some blanks have no value means the additional parameters were ignored during the significant test, in other words, the parameters can be set as 0. The Sigma0 values of all six cameras are between 0.17 to 0.22 pixels and the relative accuracies are all more than 1:20,000. It demonstrates that the measurement accuracy of close-range photogrammetric applications might be high. For example, a target with size around 2 m, the measurement accuracy can reach 0.1 mm (=2,000/20,000).

Table 1. The calibration result of interior orientation of Ladybug3 panoramic camera

	c mm)	xp mm)	yp(mm)	K1	K2	K3	P1	Relative accuracy	σ_0 (pixels)
Camera 0	3.3028	0.0119	-0.0947	2.57E-02	4.40E-04	1.79E-05	-1.69E-04	1:25400	0.17
Camera 1	3.2895	-0.0127	-0.0082	2.37E-02	7.76E-04			1:21200	0.22
Camera 2	3.2890	-0.0460	-0.0880	2.56E-02	5.37E-04	1.60E-05		1:28000	0.17
Camera 3	3.2924	-0.0064	-0.0925	2.56E-02	5.25E-04	1.47E-05		1:29200	0.17
Camera 4	3.2903	0.0057	-0.1029	2.58E-02	4.49E-04	2.06E-05	-5.25E-04	1:21600	0.22
Camera 5	3.2954	0.0258	-0.0524	2.35E-02	7.79E-04			1:27200	0.17

3.2 The results of relative orientation calibration

Fig. 5 shows some bundles of the whole network after multiple cameras bundle adjustment of Ladybug3, it illustrates that a strong imaging geometry was obtained by means of the cubic-shape calibration field and the arrangement of camera's locations. During relative orientation calibration camera-0 is used as the reference camera. The results are shown in Table 2. The standard deviation of rotation angles is particular large between camera-0 and camera-5, because the Phi angle may yield an unstable transform result when the angle is close to ±90 degrees during the transformation from rotation matrices to rotation angles. This situation is not critical during photogrammetric applications, because the rotation matrices can be used instead of rotation angles. Except for this case, the standard deviations of relative rotation angles are all smaller than 0.02 degrees. That means, if a target is located 20 meters far from the camera, the exterior orientation parameters will cause an error of about 0.7 cm by using these relative rotation angles. In the meanwhile, the standard deviations of perspective center's offsets are all less than 1 mm, which shows a very high internal accuracy of the relative orientation's calibration results. It is expected that the calibration results could obtain high relative accuracy's even the exterior orientation parameters were derived by direct georeferencing.

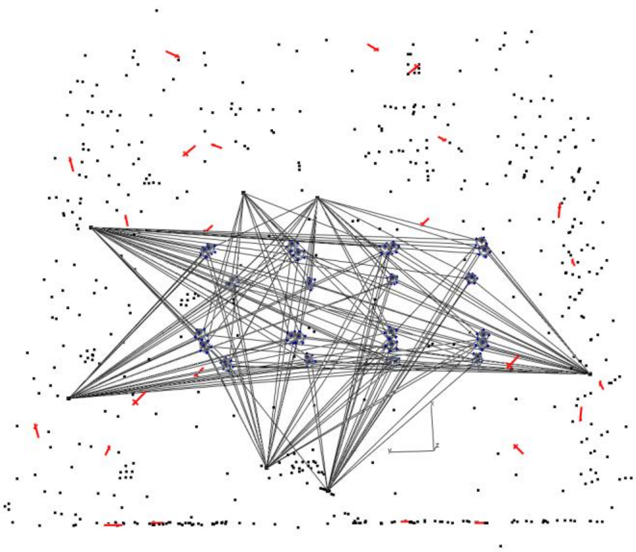

Fig. 5. The networks after Ladybug3 relative orientation calibration and adjustment

Table 2. The relative orientation calibration results for Ladybug3 panoramic camera (camera-0 is reference camera)

Relative rotation angle (degree)	**ω**	**φ**	**κ**	**ω std.**	**φ std.**	**κ std.**
Camera 1	72.1303	0.0195	0.2099	0.0131	0.0176	0.0136
Camera 2	143.9284	-179.8296	-0.0772	0.0172	0.0157	0.0123
Camera 3	-143.9365	-179.8952	-0.2055	0.0129	0.0159	0.0102
Camera 4	-72.1095	179.9350	-0.3598	0.0125	0.0146	0.0138
Camera 5	15.9035	-90.0488	-15.9412	39.7583	94.8767	39.7559
Relative perspective center offset (mm)	X	Y	Z	X std.	Y std.	Z std.
Camera 1	-0.4923	-40.1119	-29.4389	0.6327	0.3930	0.4923
Camera 2	-0.0223	-24.9758	-75.7383	0.5709	0.5266	0.4693
Camera 3	-0.1203	24.7746	-76.0601	0.7037	0.4227	0.6985
Camera 4	-0.1930	39.8666	-28.7468	0.6886	0.3980	0.3785
Camera 5	59.9513	0.1316	-42.3198	0.5620	0.4274	0.5176

4. Conclusions

This study designs two calibration fields for Ladybug3 camera calibration. A rotatable round board is used for calibrating the interior orientation parameters of single camera and the cubic-shape one dedicated for calibrating the interior and relative orientation parameters of a spherical camera. The radial lens distortion of each Ladybug3 camera lens is very serious, but the relative accuracy could reach to 1:20,000 after calibration, the relative orientation accuracies between 6 lenses are less than 0.02 degrees and 1 mm. It is expected that the relative accuracy after applying the results to a mobile mapping system for a target within 30 m could up to centimeters level.

Acknowledgement

This study is partially supported by the National Science Council (NSC), Taiwan (Project NSC 99-2221-E-006-179) and CECI Engineering Consultants, Inc. The authors are grateful for their support so this study can be accomplished successfully.

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