CAMERA CALIBRATION BASED ON LIQUID CRYSTAL DISPLAY (LCD)

ZHAN Zongqian [a]

[a] School of Geodesy and Geomatics, Wuhan University, 129 Luoyu Road, Wuhan 430079, China, - zqzhan@sgg.whu.edu.cn

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ABSTRACT:

This paper presents a novel calibration method based on Liquid Crystal Display (LCD). As a planar pattern, 2D Direct Linear Transformation (2D-DLT) and Self-calibration Bundle Adjustment are used for camera interior parameters solution. Moreover, four key problems were also detailedly analyzed. They are calibration grid, images shooting method, Non-planarity analysis of LCD and accuracy in real surveying. Lots of experiments have been done and, fortunately, good results were obtained.

1. INTRODUCTION

Camera Calibration is an important step in computer vision and photogrammetry to obtain a 3D model from 2D images [1, 2]. With the rapid development of computer and information technology, ordinary and cheap digital cameras are becoming more and more popular for surveying and vision. So, convenience, flexibility, robustness and high precision are critical factors for camera calibration [2, 3]. Currently, self-calibration without special calibration object has become the best approach for some on-line works that don't need much high precision. However, in more case, it's still necessary to obtain good interior parameters based on some calibration objects. This paper presents a novel but common object — Liquid Crystal Display (LCD) for calibration in contrast with some other 3D high precision control fields or special planar pattern which are difficult and time-consuming to be created [3, 4]. As a popular peripheral for the ordinary computer, a successful camera calibration method based on LCD will be more convenience and practical.

Calibration based on planar pattern and computer vision method was early presented by Zhang [3]. Afterward, another Zhang presents a similar method based on 2D-DLT and self-calibration bundle adjustment of photogrammetry [4]. As a completed flat display, LCD-based calibration is also a plane-based method. Therefore, both of their methods can be used for the solution. Here, we use the later.

In order to confirm such novel method, four problems should be analyzed and solved firstly. First one is to make a precise calibration grid on LCD. Second one is to present a corresponding and efficient images shooting method. Third one is to analyze the non-planarity of LCD by doing some preliminary experiments, which is very important for understanding the characteristic of LCD and further improving the accuracy of calibration. The final and most important one is the accuracy in real surveying with camera interior parameters from LCD-based calibration.

Therefore, this paper is summarized in seven sections. Section 1 is introduction. And preliminary knowledge of distortion model and self-calibration bundle adjustment is tersely described in section 2. Calibration grid is presented in section 3. Section 4 summarizes the Images shooting method. We present preliminary experiments and non-planarity of LCD in section 5 and accuracy in surveying with real data is in section 6. Finally, conclusions are summarized in section 7.

2. DISTORTION MODEL AND SELF-CALIBRATION BUNDLE ADJUSTMENT

Distortion model is the most important parts of the camera interior parameters and has been detailedly described in [2]. In our method, we use the popular model (formula 1) that includes radial and decentering lens distortions.

$$\begin{aligned}\Delta x &= (x - x_0)(K_1 \cdot r^2 + K_2 \cdot r^4) + P_1\left(r^2 + 2\cdot(x - x_0)^2\right) + 2\cdot P_2 (x - x_0)\cdot(y - y_0) \\ \Delta y &= (y - y_0)(K_1 \cdot r^2 + K_2 \cdot r^4) + P_2\left(r^2 + 2\cdot(y - y_0)^2\right) + 2\cdot P_1 (x - x_0)\cdot(y - y_0)\end{aligned} \quad (1)$$

Where, $r^2 = (x - x_0)^2 + (y - y_0)^2$, (x_0, y_0) are the image coordinates of principle point, K_1 and K_2 are the radial lens distortion parameters, and P_1 and P_2 are the decentering lens distortion parameters, (x, y) are coordinates of current image point and $(\Delta x, \Delta y)$ are distortion correction value of current image point (x, y).

In photogrammetry, the collinearity equations (Formula 2) are used in self-calibration bundle adjustment to solve for: Object coordinates of tie points, Exterior orientation parameters (position and attitude) of the involved imagery, Interior parameters of the involved camera(s).

$$\left.\begin{aligned} & x - x_0 - \Delta x = \\ & - f\,\frac{a_1(X - X_S) + b_1(Y - Y_S) + c_1(Z - Z_S)}{a_3(X - X_S) + b_3(Y - Y_S) + c_3(Z - Z_S)} \\ & y - y_0 - \Delta y = \\ & - f\,\frac{a_2(X - X_S) + b_2(Y - Y_S) + c_2(Z - Z_S)}{a_3(X - X_S) + b_3(Y - Y_S) + c_3(Z - Z_S)} \end{aligned}\right\} \quad (2)$$

Where, f is principle distance, (X_S, Y_S, Z_S) are the object coordinates of the perspective center, (X, Y, Z) are the coordinates of the corresponding object point, $R = \{a_i, b_i, c_i, i = 1,2,3\}$ are the elements of the rotation matrix that depend on the rotation angles φ, ω, κ .

As we know, the nonlinear collinearity equations should be linearized and solved by iterative method. So it is necessary to obtain initial values of all unknown parameters in the equations. Zhang presented a good method that using 2D-DLT and planar control points. More detailed description was presented in [4].

3. CALIBRATION GRID

In order to calibrate based on LCD, we should make a program to draw grid points on the LCD. Grid points are black circle pattern and background is white (Fig.1). The radius of circle and interval between two circle-centers are variable so as to satisfy kinds of cameras. Above all things, Calibration Grid should be shown with the standard resolution of LCD so that the display size is the exact size set by the user. For example, standard resolution of Dell E173FP LCD (Fig.1) we used is 1280×1024.

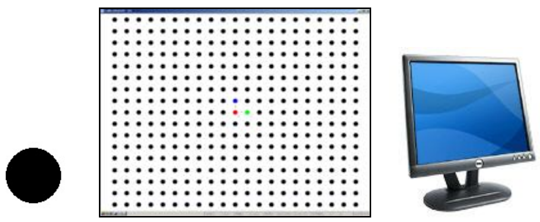

Figure. 1. Circle Pattern (Left), Calibration Grid combined with circle pattern (Middle), Dell E173FP LCD (Right)

Figure.2. Kodak DC290 (Left) and Kodak DCS Pro SLR/n (Right)

Figure. 3. Calibration Images shot at four positions, each position includes 9 photos

4. IMAGES SHOOTING METHOD

Method for shooting calibration images had once been detailedly presented by experts [3, 4, 5]. However, for the reason of the field depth limitation, camera can not be too close to LCD. So, images of LCD are usually very small with the size limitation of LCD. Especially, it often presents in large frame and Single-Lens Reflex (SLR) camera. As Figure 2 shows, Kodak DC290 is for preliminary experiments and Kodak DCS Pro SLR/n is for accuracy testing in surveying. Their principle distances are about 7.8*mm* and 50*mm*. their resolutions are 2240 ×1500 and 4500×3000.

Then our new presented shooting method is detailedly described as:

- It may be four or five shooting positions in front of the LCD: top-left of front, top-right of front, bottom-left of front, bottom-right of front and right ahead (inessential).
- Distances between camera and LCD should be as much as close on the condition that camera can capture clear images of the calibration grid.
- Because of small imagery of LCD, camera at each position should be yawed and pitched so that imageries can evenly local at the different regions of imagery frame.
- In order to decrease parametric relativities, camera at each shooting position should be rolled around the optic axis with 90 degree to shoot more photos too.

According to the presented method, calibration images are shot at four positions with the camera of Kodak DC290 (Fig.3). Each position includes 9 photos.

5. PRELIMINARY EXPERIMENTS AND NON-PLANARITY OF LCD

5.1 Real Data Experiments

Calibration grid includes 357 circle points (17×21). In order to prove the effectivity of LCD-based calibration, 277 of them are used for control points in self-calibration bundle adjustment and 80 of them are used for checkpoints. Two groups of calibration images are shot with Kodak DC290. All circle Centers can be exactly extracted by the special image processing technology [6]. Then 2D-DLT and self-calibration bundle adjustment can be carried out to obtain camera interior parameters.

Table 1 shows the accuracies of checkpoints with the LCD-based calibration. Where *A* and *B* are two real data. m_0 is the mean square error of unit weight of image points. Its unit is *pixel*. D_X, D_Y and D_Z are mean square errors of plane and height. Their units are both *mm*. R_{XY} is relative accuracy of planar error, which is obtained from dividing the mean depth between perspective centers and grid points by $\sqrt{(D_X)^2 + (D_Y)^2}$. R_Z is relative accuracy of height error, which is obtained from dividing *D* by D_Z .

	m_0	D_X/D_Y	R_{XY}	D_Z	R_Z
A	0.109	**0.0076/0.0077**	**90265**	**0.0580**	**16740**
B	0.106	**0.0073/0.0082**	**94771**	**0.0642**	**16212**

Table 1. Accuracies of LCD-based calibration with real data

Obviously, accuracy of LCD-based calibration is very high, especially in plane. However, although the θ are great, accuracies of height are much less than those of plane, which may imply that there are some big errors still present in the bundle data.

5.2 Analog Data Experiments

To confirm the possibility of the existent big errors, analog experiments should be done. In favor of the accuracy comparison between real and analog data with uniform conditions, most of the analog values except the coordinates of image points are directly taken from the results of real data. They are exterior parameters, interior parameters and object coordinates of grid points. Then, the analog image coordinates of grid points in each photos can be obtained from the collinear equation. According to the m_0 of results (Table 1), independent gauss random errors with zero-mean and standard deviation of 0.1 *pixel* are added into the coordinates of image points.

Therefore, if there are no other errors in the bundle data, the accuracies of calibration with analog data may be close to those of real data (Table 1).

Table 2 shows the accuracies of the checkpoints of analog data.

	m_0	D_X/D_Y	R_{XY}	D_Z	R_Z
A	0.099	**0.0069/0.0069**	**99671**	**0.0145**	**67148**
B	0.099	**0.0067/0.0057**	**118126**	**0.0145**	**71569**

Table 2. Accuracies of LCD-based calibration with analog data

Comparing with the accuracies of analog and real data, we can find that the accuracies of plane are very close and, however, accuracies of height are very different. So we can conclude that some big errors must still present in the bundle data besides the random error of image points.

5.3 Error Analysis

Because the accuracies of plane are very close between analog and real data, we only analyze the height error.

For visual analysis, the height error of all control points of real data *A* can be shown in 3D form (Fig.4). Where cross points denote as the positions of control points and lines denote as the direction and size of height error. Directions of lines are all parallel to the Z axis of the coordinate system.

Obviously, it can be read from the Figure 4 that the height error may be systemic.

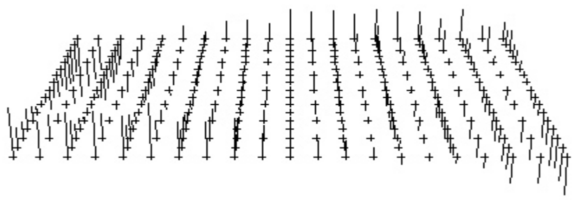

Fig. 4. 3D vision of height error of all control points

According to the theory of polybasic stepwise regression analysis [7], if the height error is systemic, a remarkable regression equation may be obtained. As formula 3 shows, initial equation of stepwise regression analysis may be normal polynomial.

$$dz = b_0 x + b_1 y + b_2 x^2 + b_3 xy + b_4 y^2 + b_5 x^3 + b_6 x^2 y + b_7 xy^2 + b_8 y^3 + b_9 \quad (3)$$

Where $b_i (i = 0 \sim 9)$ are 10 regression coefficients, $x, y, x^2, xy, y^2, x^3, x^2 y, xy^2, y^3$ are the corresponding independent variables, dz is random variable and also height error of each control points, (x, y) are object coordinates of each control points.

	A	*B*
b_0	0	-0.130049
b_1	0.058429	0.112941
b_2	-0.002512	-0.002459
b_3	0.007307	0.006541
b_4	0.006057	0.008924
b_5	0	0.000013
b_6	0	0
b_7	0	-0.000015
b_8	0	0
b_9	-12.0823	-22.5801
c	0.94	0.94

Table 3. Resulted coefficients of stepwise regression equation

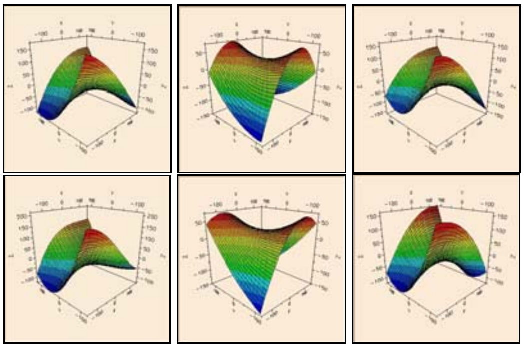

Figure. 5. 3D vision of kinds of regression equations

Table 3 shows the regression results of height errors of two real data, in which height errors are firstly magnified with enlargement factor of 1000. *c* is multi-correlation coefficient of regression analysis. It is the evaluation criterion that whether result of regression analysis is remarkable. Because the values of *c* are both close to 1, results of regression analysis are both remarkable. That is to say that the height errors are remarkably systemic. Two left figures in Figure 5 show the 3D vision of the regression analysis results. Obviously, they are very similar.

Then what causes such systemic height errors? According to the knowledge of photogrammetry[1, 8], it may be camera interior parameters error, systemic image coordinates error or object height coordinates error of control points (non-planarity of LCD). However, according to the knowledge of error processing and reliability theory [8], it is yet difficult to find out the acting error.

Through analog analysis by adding some other distortions (for example high order radial distortion, Prism Distortion, etc.) into the coordinates of image points or considering non-square of CCD unit and still solving self-calibration bundle adjustment with the formula 1 and 2, results of the regression analysis show great different to those of the real data. So, it is improbable that camera interior parameter error causes the systemic height error in real data.

If the systemic height error is caused by the systemic image coordinate error, which is mainly caused by circle extraction algorithm, then another results based on different LCD may demonstrate the same error very likely. Unfortunately, two middle figures in Figure 5 show great different to the left figures. So, it is also improbable that systemic image coordinate error causes the systemic height error in real data.

Although analysis shows that the first two kinds of errors are both improbable to be the acting error, it is still necessary to prove the non-planarity of LCD. Two right figures in Figure 5 are 3D visions of regression analysis resulted from another analog data, in which analog coordinates of image points are calculated by object coordinates of control points added non-planarity error with the regression equation of real data *A* (Table 3) and, however, height coordinates of control points in bundle adjustment are still equal to zero. Obviously, this is the exact situation of real calibration when LCD is not flat. Fortunately, the 3D visions are so similar to those of real data. So we can confirm that the non-planarity of LCD causes the systemic height error now.

Because we had been obtained the non-planarity of LCD, we can firstly correct the object coordinates error of control points with the regression equation before bundle adjustment, so as to further improve the accuracy of the LCD-based calibration. Table 4 shows the better results of the two real data above, in which non-planarity of control points on the LCD have been corrected with the regression equation of real data *A* before there are used for self-calibration bundle adjustment.

	m_0	D_X/D_Y	R_{XY}	D_Z	R_Z
A	0.085	0.0071/0.0074	94953	0.0179	54450
B	0.08	0.0054/0.0065	123256	0.0215	48317

Table 4. Accuracies of LCD-based calibration with real data after correcting non-planarity.

6. ACCURACY IN SURVEYING

A good calibration method should be further proved in real surveying, especially in the surveying that accuracy can be checked by highprecision control points.

Surveying scene is a cofferdam of 250 meters width and 120 meters height. There are 20 control points with highprecision object coordinates. Eleven of them are used for accuracy checking and nine of them are used for controlling in bundle adjustment.

Used camera is Kodak DCS Pro SLR. It was calibrated twice based on LCD with about 140 images and resulted parameters (*P1* and *P2*) are both used for real surveying.

In order to demonstrate the accuracies of the LCD-based calibration, camera interior parameters (*P3*) obtained from the calibration based on 3D indoor highprecision control field is also used for comparison. Moreover, on-line self-calibration bundle adjustment with 9 control points and about 1300 tie points of real surveying data is also carried out (*P4*). Table 5 shows the interior parameters. Table 6 shows their corresponding accuracies in which units are same as those of Table 1.

Results show that accuracies of LCD-based calibration in real surveying are close to those of 3D-control-field-based calibration and on-line self-calibration.

	x_0	y_0	f	k_1	k_2	p_1	p_2
P1	0.217	0.076	51.75	-4.86 e-5	2.60 e-8	4.37 e-6	-9.84 e-6
P2	0.224	0.080	51.72	-4.85 e-5	2.58 e-8	6.22 e-6	-9.17 e-6
P3	0.144	0.130	51.57	-4.58 e-5	2.53 e-8	8.49 e-6	-4.35 e-6
P4	0.168	0.130	51.63	-4.34 e-5	2.32 e-8	8.38 e-6	-7.39 e-6

Table 5. Interior parameters of kinds of calibration methods

	m_0	D_X/D_Y	R_{XY}	D_Z	R_Z
P1	0.2585	27.17/14.95	7419	30.80	7472
P2	0.2487	22.87/13.36	8683	24.21	9499
P3	0.1875	19.14/10.89	10416	19.02	12057
P4	0.1655	18.89/10.03	10739	22.72	10112

Table 6. Accuracies of LCD-based calibration and other methods

7. CONCLUSIONS

A novel calibration method based on LCD has been described. The method is belonged to the method based on planar pattern in which circle points are drawn on the completed flat liquid crystal display by special program. Being a novel calibration object, autologous precision of LCD should be firstly analyzed which is generally ignored in the methods based on other calibration objects. Non-planarity of LCD was found by the polybasic stepwise regression analysis after comparison of accuracies between real and analog data. Fortunately, final accuracies of LCD-based calibration after correcting the Non-planarity of LCD show that the presented method is very feasible and satisfying. Especially, accuracies in real surveying are close to those of 3D-control-field-based calibration and on-line self-calibration which is great significative for large engineering surveying and photogrammetry at low altitude with autoboat or unpiloted aeroplane.

On shortage is the time-consuming in calibration of large frame and Single-Lens Reflex camera, in which we have to shoot much more photos because of the small imagery of LCD.

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