STUDY OF DIGITAL CAMERA CALIBRATION ON A FLAT TEST OBJECT

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ABSTRACT:

The paper presents a method for calibration of digital cameras based on the use of a flat test object. The main distinctive feature of this method is that the camera is fixed and does not change its position in space. A series of images of a flat test object (for example, a chessboard) is taken at various distances and inclination of the test object. One should tilt the test object relative to the image plane in order to avoid ambiguity in solving the problem. All these images are measured separately, and processing is performed together, counting them as one image with common exterior orientation elements. Experimental studies have shown sufficient efficiency of such calibration, which is easily implemented and gives positive results in comparison with the classical calibration of the camera on a spatial test object. The results of experimental studies on real images have shown that proposed calibration method gives the comparable with conventional method accuracy. Thus, it is possible to use simple and cheap flat calibration test object instead of spatial one. To achieve the maximum result in camera calibration accuracy, use this method to tilt the chessboard at angles in the range of 30-40 degrees to the optical axis of the camera being calibrated.

1. INTRODUCTION

Although the calibration of digital cameras has been well studied and developed, research in this area continues and will continue because numerous results of calibrations of various cameras show the need to improve the accuracy of calibration. In the works (Thomas Luhman, et al. 2019, Mikhailov A. P., Chibunichev A. G. 2016, Barazzetti, L., et al. 2011, Chibunichev, A. G., et al., 2019, Knyaz, V. A. 2006, Knyaz, V. A. and Moshkantsev, P. V. 2019), you can find a description of the main methods of calibration of digital cameras used today. These methods are based on the application of both spatial and flat test objects, using various mathematical models of sensors (Luhmann T., et al., 2016, Remondino, F. and Fraser, C. S., 2006, Hannemose M., et al., 2019), including neural networks (Fakhri, S. A. and Fakhri, S. A., 2019). Recently, many researchers want to use a flat test object for camera calibration, since it is cheaper than a spatial object and more accessible (Choinowski, A., et al., 2019, Geiger A., et al., 2012, Grammatikopoulos, L., et al., 2019, Tan L., et al., 2017, Wohlfeil, J., et al., 2019). Basically, a chessboard is used as a flat test object in these works. This is natural, because it can be easily manufactured and there are quite a few methods for accurate automatic measurement of the coordinates of the chessboard nodes in the images. All these calibration methods are based mainly on repeatedly imaging the chessboard from different angles and then processing all the images together at the same time. As a result, not only the camera calibration parameters (focal length, principal point coordinates, and lens distortion) are determined, but also the external orientation elements of all images. In this paper, we propose a different approach for calibrating the camera by a flat test object.

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2. METHOD DESCRIPTION

The essence of the method is as follows. The camera is mounted on a tripod and a series of images of a flat test object (for example, a chessboard) is taken at different distances and inclination angles of the test object (Fig.1).

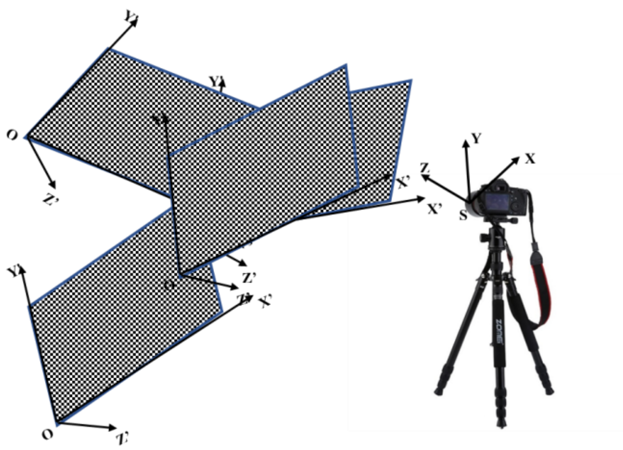


Figure 1. Imaging principle for calibrating the camera (the camera is stationary, but the chessboard moves and tilts)

Then all images are processed together, considering them as one image with fixed exterior orientation elements. In other words, exterior orientation elements of images are not defined, but set. The solution is based on the known collinearity equations, considering the exterior orientation elements of images as constant values and equal to zero: **$Xs=Ys=Zs=\omega=\alpha=\aleph=0$**

$$\left.\begin{array}{l} x_0 - f\dfrac{X}{Z} - x + d_x = 0 \\ y_0 - f\dfrac{Y}{Z} - y + d_y = 0 \end{array}\right\} \quad (1)$$

Where

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_{0i} \\ Y_{0i} \\ Z_{0i} \end{pmatrix} + A_i \begin{pmatrix} X' \\ Y' \\ 0 \end{pmatrix}$$

$$d_x = k_1(x - x_0)((x - x_0)^2 + (y - y_0)^2) + k_2(x - x_0)((x - x_0)^2 + (y - y_0)^2)^2$$
$$d_y = k_1(y - y_0)((x - x_0)^2 + (y - y_0)^2) + k_2(y - y_0)((x - x_0)^2 + (y - y_0)^2)^2$$

Here x, y = image coordinates
X'Y' = coordinates of the flat test object (board) points in its OX'Y'Z' coordinate system
f, x_o, y_o, k_1, k_2 = the unknowns. Interior orientation parameters of the camera (focal length, coordinates of the principal point, lens distortion coefficients)
X_{oi},Y_{oi},Z_{oi},ω_i,α_i,$\aleph_i$ = the orientation elements of the i-th flat test object (boards, i = 2, ... n, where n is the number of boards) in the SXYZ coordinate system.

Since the test object has a flat structure, to avoid the uncertainty of determining the focal length at least 2 images of tilted boards should be used.

Equation (1) is none-linear and a linear approximation should be used to solve for unknowns. An experimental software was written in MATLAB system and consists of two parts. First one is doing preliminary operations. It reads photographs, performs measurements and prepare the data. Second one fulfils the calibration itself.
To start an iterative process a good approximation should be set for all unknowns. The initial value of the focal length of a camera lens is taken from EXIF data usually. First approximation for orientations of chessboards are determined by proposed method with interior parameters are set to approximation values. During this step the interior orientation parameters are not subject to change.

3. RESULTS

3.1 Synthetic data

Studies of the proposed calibration method were carried out using the simulated images. For this purpose, a chessboard was modeled with the size of 5 x 5 cells, in the coordinates of the nodes of which errors were introduced with an RMSE equal to 0.08 mm. The camera was set with the following parameters: focal length 100mm, coordinates of the principal point x_o=y_o=0, no distortion. The error-free image coordinates were affected by errors with RMSE equal to 0.001 mm. Chessboards were given different angles of inclination ranging from 5 to 75 degrees relative to the image plane. For each angle value, 4 boards were modeled with different angles of ±α and ±ω. The results of the camera calibration are shown in table 1 and fig. 2. Here are the values RMSE camera calibration parameters obtained by deviations from the true values of the camera parameters. Each value in this table is determined as RMS from 100 trials.

	RMSE f (mm)	***RMSE x_o (mm)***	***RMSE y_o (mm)***	***RMSE k_1***	***RMSE k_2***
5°	*1.178*	*0.080*	*0.089*	*5.85E-09*	*4.63E-13*
15°	*0.152*	*0.040*	*0.039*	*1.15E-08*	*5.80E-13*
25°	*0.057*	*0.029*	*0.029*	*1.60E-08*	*6.01E-13*
35°	*0.032*	*0.024*	*0.029*	*1.79E-08*	*5.41E-13*
45°	*0.025*	*0.025*	*0.033*	*1.89E-08*	*4.77E-13*
55°	*0.024*	*0.027*	*0.040*	*1.98E-08*	*3.89E-13*
65°	*0.022*	*0.027*	*0.043*	*2.17E-08*	*3.78E-13*
75°	*0.544*	*0.054*	*0.461*	*7.01E-08*	*1.00E-12*

Table 1 Estimation of the accuracy of determining the camera calibration parameters depending on the angle of inclination of the chessboard

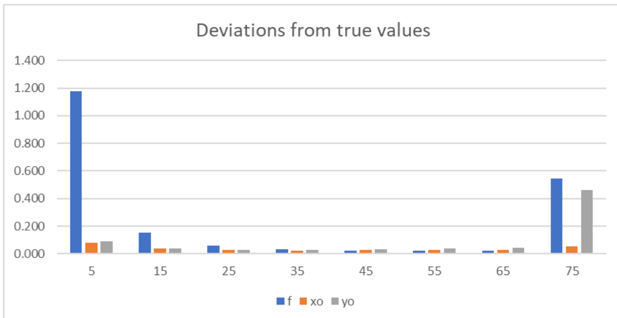


Figure 2. Evaluation of the accuracy of determining the camera calibration parameters depending on the angle of the chessboard

The results of experimental studies on synthetic data have shown that this calibration method has the right to exist. It is easily implemented, and gives positive results. To achieve the maximum result in camera calibration accuracy using this method the tilt the chessboards should be in the range of 30-40 degrees to the optical axis of the camera being calibrated.

3.2 Real data

The DigiCAM HASSELBLAD H3DII-39 with 35 mm focal length lens was used for experiment on real data (figure 3). This camera has a resolution of 7212x5412 pix, and the size of the matrix 39x37 mm.

Figure 3. Digital camera HASSELBLAD H3DII-39

For comparison with the proposed calibration method, the conventional calibration program was used. The conventional calibration software as well as test object were designed at the Photogrammetry Chair of MIIGAiK and show more than 20 years of reliable calibration process results. The test object is shown at figure 4. There are 185 circular target points defined with 0.1 mm accuracy. The measurements of the image coordinates points are performed automatically calculating the geometric center of circular edge of the targets. The calibration software is based on collinearity equations extended by Brown polynomials for radial and tangential distortion definition. Typical number of images used for camera calibration is 4-6.
In our case, 4 images were taken with the camera rotated 180 degrees and a small offset in the plan. All 4 images participated in the calibration of the camera using conventional technology. The results are shown in table 2.

Figure 4. The calibration test object.

Figure 5 shows a chessboard survey to investigate the proposed camera calibration method. 10 images of the inclined chessboards have been used. The inclination varied from -40 up to +45 degrees in respect to the optical axis of the camera to be calibrated. The number of measured image points on each of chessboards was 96. In figure 5 the measured points are shown in red circles. All measurements of the coordinates of the chessboard image points were performed automatically using standard MATLAB libraries. However, among these measurements, sometimes there are blunders. To blunder detection and exclude them from the adjustment, we used robust method (Chibunichev et al. 1992), in which each equation of corrections from the collinearity equations (1) is multiplied by the weight, which is calculated using the following formula:

$$P_i = \begin{cases} 1, & if\ |v_i| \le 2\mu \\ e^{-0.1\left(\frac{|v_i|}{\mu}\right)^4}, & if\ |v_i| \le 2\mu\ \ and\ \ N \le 3 \\ e^{-0.1\left(\frac{|v_i|}{\mu}\right)^3}, & if\ |v_i| \le 2\mu\ \ and\ \ N \triangleright 3 \end{cases} \quad (2)$$

where v_i is the discrepancy in the i correction equation; μ is standard error calculated by v_i; N is the iteration number.
This approach has significantly improved the result of camera calibration.

Table 2 shows the results of camera calibration. We used only two radial distortion coefficients, since the other distortion coefficients do not improve accuracy for this camera. Here the root mean square error (RMSE) in determining the camera calibration parameters, obtained from an adjustment are shown in parentheses. As you can see from this table the accuracy of determining calibration parameters for the two methods is comparable.

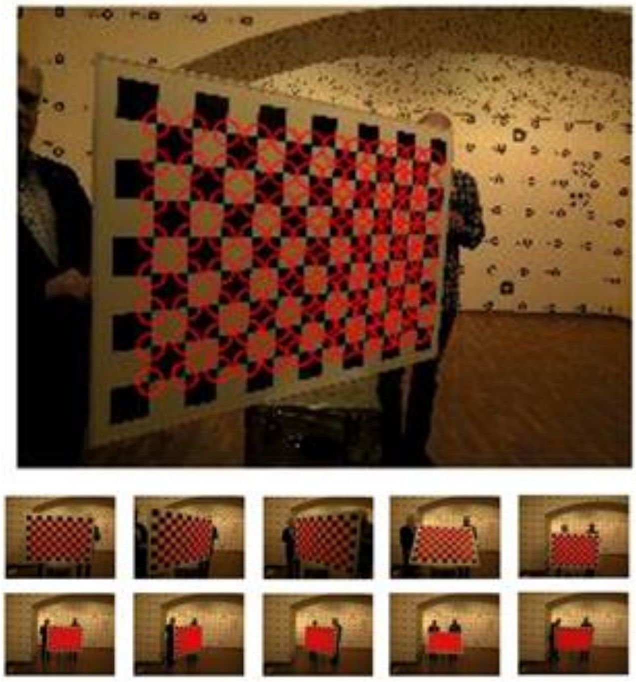
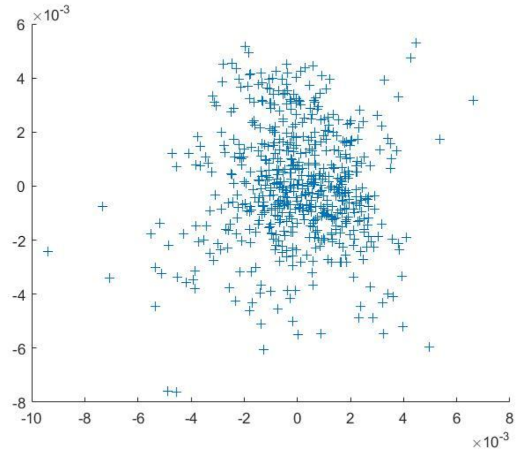


Figure 5. Examples of chessboards imaging

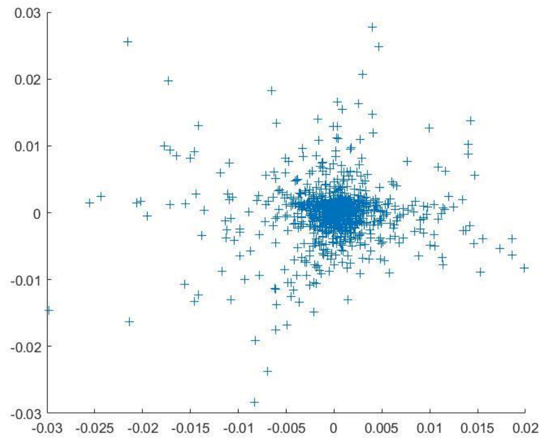
Parameters	***Conventional method***	***Proposed method***
Sigma0 mm	*0.002*	*0.002*
f (RMSE), mm	*35.730 (0.001)*	*35.788 (0.001)*
x_o (RMSE), mm	*0.009 (0.001)*	*0.081 (0.001)*
y_o (RMSE), mm	*0.277 (0.001)*	*0.272 (0.002)*
k_1 (RMSE)	*-7.3718e-05 (1.0448e-07)*	*-7.5239e-05(1.8257e-07)*
k_2 (RMSE)	*5.3571e-08 (1.1376e-10)*	*5.9419e-08 (5.6991e-11)*

Table 2. The calibration results for real images.

Figure 6 shows discrepancies between detected corner points and the re-projected ones with the estimated calibration parameters. From this figure, you can see that the main errors in re-projecting points to images after camera calibration are in the range of -0.005mm to +0.005 mm for the two camera calibration methods. Moreover, the root mean square error for both methods are the same and equal to 0.002 mm (table 2). However, for the proposed calibration method, there are points that lie outside this interval. In the future, these points can be rejected, which should lead to an increase in the accuracy of camera calibration by the proposed method.



a)



b)

Figure 6. Re-projection errors. a) for conventional method, b) for proposed method

The next experiment was to compare results of the definition of coordinates of points by photogrammetric processing of the stereopair using two sets of calibration parameters. To do this, a stereo pair of images of the spatial test object was obtained by the camera HASSELBLAD H3DII-39. Total measured in the stereopair points were 73. 52 target points were used as check points. The software is bundle adjustment procedure. Results are shown in the Table 3.

RMSE, mm	***Conventional method calibration used***	***Proposed method calibration used***
X	*0.9*	*0.3*
Y	*0.4*	*0.4*
Z	*1.5*	*1.9*
Planimetric	*1.0*	*0.5*
Full vector	*1.8*	*1.9*

Table 3. RMSE of discrepancies at the check points

The results of experimental studies on real images have shown that proposed calibration method gives the comparable with conventional method accuracy. Thus, it is possible to use simple and cheap flat calibration test object instead of the spatial one.

CONCLUSION

Method for calibration of digital cameras based on the use of a flat test object is proposed. The main idea of the method is that a flat test object is shooting several times with a fixed camera while positions and orientations of the test object are changed. Then all images are processed together, considering them as one image with fixed exterior orientation elements. Experimental studies have shown sufficient efficiency of such calibration, which is easily implemented and gives positive results in comparison with the classical calibration of the camera using a spatial test object. To achieve the maximum result in camera calibration accuracy, use this method to tilt the chessboard at angles in the range of 30-40 degrees to the optical axis of the camera being calibrated.
In the future, we should continue experimental studies of the digital camera calibration method. Special attention should be paid to the number and location of the chessboards in space relative to the camera. In addition, the possibility of applying the method to calibrate different types of cameras should be explored.

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