Laboratory geometric calibration of areal digital aerial camera

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Abstract. Digital aerial camera is non-metric camera. Geometric calibration, including the determination of interior orientation elements and distortion parameters, is the base of high precision photogrammetry. In this paper, a laboratory geometric calibration system of areal digital aerial cameras is developed. This system uses a collimator and a star tester as the target generator. After measurement of the coordinates of targets on the CCD plane and corresponding angles of parallel lights, the geometric calibration of digital aerial camera can be realized according to the geometric calibration model of this paper. Geometric calibration experiments are taken out based on this system using two kinds of mainstream digital aerial cameras, Canon EOS 5D Mark II and Hasselblad H3D. Experiment results show that this system can satisfy the calibration requirements of aerial photogrammetric application and prove the correctness and the reliability of this calibration method.

1. Introduction

Compared with traditional photogrammetry, digital photogrammetry has many advantages, such as short mapping period, high precision, low costs and so on. With the development of computer, CCD and many other techniques, mature large areal digital cameras with high resolution have appeared in the international market. Digital cameras are replacing traditional film cameras gradually and become important devices of data acquiring in photogrammetry. But digital cameras are not designed or manufactured for photogrammetry specially. They have no interior orientation elements determined precisely, and usually have distortions and other defects. Therefore, they need to be geometrically calibrated precisely before performing photogrammetric work, and this is one of the most important works of digital aerial photogrammetry.

Geometric calibration methods of aerial cameras mainly include test field calibration method, self-calibration method, laboratory calibration method and so on [1-3].

For test filed calibration method, after using the camera that is to be calibrated to image the test filed, interior orientation elements and other factors that affect the shape of bundles are solved according to space resection or bundle adjustment. Usually, test filed is composed of marked points with known spatial coordinates. It can be three-dimensional control field indoor, control field outdoor, or even artificial buildings chosen for camera calibration specially.

For self-calibration method, a variety of systematic errors of cameras are thought as undetermined parameters and solved in aerotriangulation with high precision control points. These additional unknown parameters can reflect interior orientation elements, distortions, film deformation (or
deformation within the CCD) or parts of them, and sometimes simple polynomial designed specially is used.

Special equipments are used in laboratory calibration method. It uses multiple collimators or a moving collimator as the basic equipments. Axis of the camera is fixed, pointing horizontal or vertical and the collimator telescope is moving around the entrance node of the camera. The precisely known grid crosses from the illuminated master grid mounted in the focal plane of the camera are projected through the lens. These grid points are observed from the collimator telescope and each corresponding angle in object space is measured and recorded. Based on known coordinates of grid points and corresponding angles, interior orientation elements and distortion parameters can be solved [4-6].

The process of laboratory calibration method is carried out indoor, free from the influences of weather and other environmental factors and specialized equipments are used in calibration, so the calibration process is relatively standard. Based on the characteristics of digital aerial cameras, a laboratory geometric calibration system of areal digital aerial camera is developed in this paper. This system can achieve precise geometric calibration of areal digital aerial cameras. Two typical digital aerial cameras are tested, and the correctness and accuracy of this system are verified.

2. Contents of geometric calibration

The contents of geometric calibration of digital aerial camera are to determine its interior orientation elements, distortion parameters, deformation coefficients of CCD and so on.

2.1. Interior orientation elements

The interior orientation elements of a camera are parameters that describe the correlated position between the projection centre and the image plane, including the principal distance and the position of principle point. The principal distance \( f \) is the vertical distance from back node to the image plane, and the perpendicular foot is the principle point \( o \).

2.2. Optical distortion

Optical distortion is the description of deviation from an image point to its ideal location caused by the design, manufacture and assembly, including the radial distortion and the eccentric distortion.

2.2.1. Radial distortion

Radial distortion is relative to the incidence angles of object points. Radial distortions are equal where they have equal incidence angles. According to the principle of geometrical optics, the radial distortion can be expressed as following polynomial:

\[
\Delta x_r = x(k_0 + k_1r^2 + k_2r^4 + k_3r^6 + L) \\
\Delta y_r = y(k_0 + k_1r^2 + k_2r^4 + k_3r^6 + L)
\]

In equation (1), \( k_i \) is a radial distortion coefficient, \( r \) is the radial distance, and \( r^2 = x^2 + y^2 \).

2.2.2. Eccentric distortion

Eccentric distortion is the description of deviation from an image point to its ideal location caused by axis deviation or skew when assembling. Normally, eccentric distortion is much smaller than radial distortion and can be expressed as following polynomial:

\[
\Delta x_e = p_1(r^2 + 2x^2) + 2p_2xy \\
\Delta y_e = p_2(r^2 + 2y^2) + 2p_1xy
\]

In equation (2), \( p_i \) is an eccentric distortion coefficient.

2.3. Deformation coefficients in CCD plane

Errors caused by CCD mainly include errors caused by the placement of CCD, unflat of CCD plane and deformation within CCD plane. Errors caused by the placement of CCD lead the coordinates of principle point of camera are not equal to 0 and experiments show that influence caused by unflat of
CCD array is small and can be neglected. Deformation within CCD plane is caused by irregular shapes of pixels, and usually can be expressed as following empirical formula:

\[
\Delta x_f = b_1 x + b_2 y \\
\Delta y_f = 0
\]

In equation (3), \(b_1\) is the scale parameter, and \(b_2\) is the trim parameter.

3. Principle of system and data processing

3.1. Principle of system and data acquiring

Laboratory geometric calibration system of digital aerial camera mainly includes a rotating arm with its controlling system and encoder, a camera bracket with its controlling system and encoder, a computer system, a collimator and so on. Its structural principle is shown in figure 1.

The encoder of rotating arm is inside of the rotating arm, and the computer communicated with the encoder through a serial port to control the rotation of the arm and acquire angles of the arm. The collimator is also inside of the rotating arm, and used to provide a target at infinity. Through the rotation of arm, it can provide a series of point targets at infinity with exact angles. In addition, computer communicates with the camera bracket to control the rotation of the camera and acquire the corresponding angles.

![Figure 1. Structural principle of system](image)

![Figure 2. Measurement principle of one dimensional calibration of a camera](image)

This system has many advantages, such as quick measuring speed, influenced by environmental change slightly, high precision and so on. Its technical characteristics are as follows:

- The camera lens faces down when measuring. That is consistent with the work state and the calibration results are credible.
- Rotating arm is driven by a motor, which with quick speed and high positioning accuracy.
- The rotating range of the rotating arm can be up to ±45°, and this can satisfy geometric calibration of large areal digital cameras with field angle up to 90°.
- Encoders used to measure angles are digitized with low error and its precision can be up to 1″.

When calibrating an areal digital aerial camera, first, the camera is fixed on the camera bracket with the entrance pupil through the centre of shaft of the rotating arm. Then, the camera scans the targets at infinity formed by a collimator through the rotation of the rotating arm. When the rotating arm rotates from one end to the other end, make the target images lie in the horizontal centre line of CCD by adjusting screws and the rotation of the camera bracket. Then make the target image locate in the central pixel of the horizontal centre line of CCD through the rotation of rotating arm, and set the corresponding angle of rotating arm to 0. According to width, focal length and other parameters of this camera, set the rotation range and interval. When rotating arm rotates to a target angle, make the camera image the target, and the software records the corresponding angle of rotating arm. After
measuring in horizontal centre line direction, rotate the camera 90°, measure the vertical centre line direction with the same process, and the data acquiring of geometric calibration is accomplished.

3.2. Data processing

3.2.1. Calculation of interior orientation elements

Calculation of interior orientation elements is to search for a method of calculating the principle point and principal distance based on the coordinates of image points and corresponding angles, so that the distortions of this aerial camera can meet certain constraint [7]. Different calculation methods can get different principle points, principal distances and distortions. The result principle point and principal distance calculated by the distortion least squares method is most favorable to mapping accurately, so this method is used in this paper.

The principle of the calculation of one-dimensional distortion and interior orientation elements of aerial camera is shown in figure 2. P is the principle point of image plane, and $\Delta W$ is the angle corresponding to the point P. In figure 2, H’ is the back node, O is the centre of the CCD, f is the principal distance, $S_i$ is a measured point, $L_i$ is the distance from $S_i$ to O, and $W_i$ is the angle corresponding to point $S_i$.

According to the geometric relationship in figure 2:

$$L_i - p = f \times \tan(W_i - \Delta W)$$  \hspace{1cm} (4)

According to the definition of distortion of camera, $D_i$ is the distortion corresponding to point $S_i$:

$$D_i = f \times \tan(W_i - \Delta W) - L_i + p$$  \hspace{1cm} (5)

$\Delta W$ is the angle between the principle point and the centre of image plane, and the offset of principle point is usually small, so:

$$\Delta W = \frac{p}{f}$$  \hspace{1cm} (6)

Therefore, the item $\tan(W_i - \Delta W)$ can be approximated by Taylor’s formula:

$$\tan(W_i - \Delta W) = \tan W_i - \sec^2 W_i \times \frac{p}{f}$$  \hspace{1cm} (7)

And one-dimensional universal distortion expression can be expressed as:

$$D_i = f \times \tan(W_i) - p \times \tan^2 W_i - L_i$$  \hspace{1cm} (8)

In equation (8), $L_i$ and $W_i$ are obtained by measuring, while $f$, $p$, and $D_i$ are three unknowns to be solved. In order to solve these unknowns, a series of points in the image plane are measured, and the principal distance $f$ and coordinates of principle point $p$ can be solved by the least squares. So there should be:

$$\frac{\partial \sum D_i^2}{\partial f} = 0$$
$$\frac{\partial \sum D_i^2}{\partial p} = 0$$  \hspace{1cm} (9)

At last, the principal distance and the principle point can be expressed as:

$$f = \frac{\sum L_i \tan W_i \times \sum \tan^4 W_i) - \sum L_i \tan^2 W_i \times \sum \tan^3 W_i)}{\left(\sum \tan^2 W_i \times \sum \tan^4 W_i) - \left(\sum \tan^3 W_i\right)^2}\right)$$
$$p = \frac{\sum L_i \tan W_i \times \sum \tan^3 W_i) - \sum L_i \tan^2 W_i \times \sum \tan^2 W_i)}{\left(\sum \tan^2 W_i \times \sum \tan^4 W_i) - \left(\sum \tan^3 W_i\right)^2\right)}$$  \hspace{1cm} (10)

According to the formula (10) as well as data measured in the X and Y directions, principal distance $f$, and the principle point $p$, in the X-direction and the principal distance $f$, and the principle
point \( p_y \) in Y-direction can be solved respectively. Considering the digital camera usually has different size of the visual field in X and Y direction, principal distance in the direction with larger field angle should be used as the final principal distance.

3.2.2. Calculation of distortion parameters

After interior orientation elements are calculated in section 2, distortion of each measured point \( D_i \) can be calculated by the equation (11):

\[
D_i = f\times\tan(W_i - L_i) - (L_i - p)
\]

To achieve the purpose of distortion correction, using distortion model to fit distortions. According to previous analysis, the distortion model of this paper is:

\[
\begin{align*}
\Delta x &= (x - x_0)(k_0 + k_1r^2 + k_2r^4 + k_3r^6) + p_1[r^2 + 2(x - x_0)^2] + 2p_2(x - x_0)(y - y_0) \\
&+ b_1(x - x_0) + b_2(y - y_0)
\end{align*}
\]

\[
\begin{align*}
\Delta y &= (y - y_0)(k_0 + k_1r^2 + k_2r^4 + k_3r^6) + 2p_1(x - x_0)(y - y_0) + p_2[r^2 + 2(y - y_0)^2]
\end{align*}
\]

Based on the distortions of a series of measuring points, the distortion parameters \( k_0, k_1, k_2, k_3, p_1, p_2, b_1, \) and \( b_2 \) can be obtained from this over determined equation.

4. Experiments and analysis

Laboratory geometric calibration software of digital aerial camera is developed based on vc++ 6.0 in this paper. Its functions include hardware control, high-precision location of target images, and calculation of interior orientation elements and distortion parameters. In order to verify the correctness of the proposed method, two mainstream digital aerial cameras, Canon EOS 5D Mark II and Hasselblad H3D, are used to take experiments and the results are analyzed.

4.1. Experiments

Camera 1 is a Canon EOS 5D Mark II. The nominal focal length is 24 mm, pixel size is 0.0064 mm, and resolution is 5616×3744 pixels. Camera 2 is a Hasselblad H3D. The nominal focal length is 50 mm, pixel size is 0.0068 mm, and resolution is 7216×5412 pixels. According to parameters of these two cameras, the range of measuring angle of camera 1 is set to ±34° in horizontal direction and ±24° in vertical direction, and the step is set to 2°, while the range of measuring angle of camera 2 is set to ±22° in horizontal direction and ±17° in vertical direction, and the step is set to 1°. Data are collected according to the method of this paper, and interior orientation elements and distortion parameters of these two cameras are calculated and listed in table 1. Figure 3 and figure 4 are distortions of camera 1 before and after distortion fitting respectively, while figure 5 and figure 6 are distortions of camera 2 before and after distortion fitting respectively. Wherein, X direction is the horizontal direction, Y direction is the vertical direction, X axis is coordinates differences of points measured in X or Y direction, Y axis is distortions of points measured in X or Y direction, red dotted lines stand for distortions in X direction, and blue dotted lines stand for distortions in Y direction.

Standard deviation of results of distortion fitting according to the least squares method can be expressed as:

\[
\sigma = \left( \frac{\sum_{i=1}^{n} v_i^2}{n-t} \right)^{1/2}
\]

Where, \( v_i \) is the residual error after distortion fitting, \( t \) is the number of unknowns, \( n \) is the times of measuring independently with equal precisions. According to this formula, the standard deviation of camera 1 and camera 2 are 0.198 pixel and 0.166 pixel respectively.
Table 1. Results of interior orientation elements and distortion parameters

|                        | Canon EOS 5D Mark II | Hasselblad H3D |
|------------------------|----------------------|----------------|
| $f$                    | 23.846 mm            | 50.234 mm      |
| $x_0$                  | 14.997 pixels        | -35.530 pixels |
| $y_0$                  | -9.521 pixels        | -13.487 pixels |
| $k_0$                  | -0.0194216847        | -0.0002123679  |
| $k_1$                  | 0.0001796017         | 0.000022847    |
| $k_2$                  | -0.000052435         | -0.000000085   |
| $k_3$                  | -0.000000001         | 0.000000000    |
| $p_1$                  | -0.0001999953        | -0.0000009695  |
| $p_2$                  | 0.000035739          | -0.000000272   |
| $b_1$                  | 0.0000761476         | 0.0001797425   |
| $b_2$                  | 0.0312767829         | -0.0096822810  |

Figure 3. Distortions in X and Y direction after calculation of interior orientation elements of camera 1

Figure 4. Distortions in X and Y direction after distortion fitting of camera 1

Figure 5. Distortions in X and Y direction after calculation of interior orientation elements of camera 2

Figure 6. Distortions in X and Y direction after distortion fitting of camera 2
4.2. Results analysis
(1) Table 1 shows that, principal distances and principle points calculated by geometric calibration are different from their nominal focal lengths and principle points obviously. It shows the necessity of geometric calibration of digital aerial cameras.
(2) In figure 3, there are obvious distortions in two directions of camera 1. Distortions and distances from image point to the principle point in each direction have symmetry. And the laws of distortions in two directions are same. This is a kind of typical radial distortion. In figure 4, residual distortions in two directions are decreased obviously after distortion fitting. The standard deviation after distortion fitting is about 0.2 pixel, and this shows the correctness of distortion model of this paper.
(3) Figure 5 shows that the distortion of camera 2 is relatively small, and the maximum deviation is 0.8 pixel, with no obvious radial distortion. In figure 6, the residual distortions in two directions are decreased slightly after distortion fitting.
(4) From comparisons of the results of camera 1 and camera 2, the geometric image quality of camera 2 is superior to camera 1 significantly.

5. Conclusion
Geometric calibration of digital camera is the basis of its application in photogrammetry. Contents of geometric calibration are analyzed deeply, and a laboratory geometric calibration system of digital aerial camera is presented in this paper. The principle of this system and key techniques of data processing are introduced in detail. Two cameras are used to take experiments and the results are analyzed. Experiments results show that this system can satisfy accurate geometric calibration of multiple types of areal digital cameras and the calibration results are reliable.

With the development of science and technology, as well as advantages of multi-format digital aerial cameras, more and more multi-format digital cameras are applied to photogrammetry, such as DMC, UCD and SWDC. Besides calibration of normal cameras, geometric relationships between multiple formats also need to be calibrated. Next, geometric calibration of multi-format cameras will be studied, and this will provide technical supports for application of multi-format digital aerial cameras in photogrammetry.

Acknowledgments
The authors thank the anonymous reviewers for their insightful comments and suggestions. This research was funded by the Fundamental Research Funds for Chinese Academy of Surveying and Mapping under Grant 7771313.

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