DETERMINATION OF GEOMETRIC CHARACTERISTICS OF A DIGITAL CAMERA BY SELF-CALIBRATION

H.El-Habrouk, X.P.Li, W.Faig
Department of Geodesy and Geomatics Engineering
University of New Brunswick
Fredericton, New Brunswick
Canada, E3B 5A3

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ABSTRACT

Digital cameras are being used in a wide range of industrial and engineering applications. To achieve highly accurate and precise results, the digital cameras have to be calibrated for both their geometric and radiometric characteristics. Generally, the geometric calibration is conducted with the aid of some special digital image processing software. Often however, the available software is cumbersome or unsuitable for certain industrial applications.
This paper illustrates the use of a well-established self-calibration procedure for the determination of the geometric characteristics of a Fujix DS-100 digital camera.
Based on the results of this study, a self-calibrating bundle adjustment in conjunction with basic digital image processing provides an excellent solution to the geometric calibration of digital cameras.

KURZFASSUNG

Zahlreiche Anwendungen der Industrie-und Ingenieurphotogrammetrie benützen digitale Kameras, welche für höhere Genauigkeitsansprüche radiometrisch und geometrisch kalibriert werden müssen.
Es gibt spezielle Bildverarbeitungsprogramme für die geometrische Kalibrierung, jedoch sind diese oft umständlich und ungeeignet für bestimmte Projekte.
In diesem Artikel wird die Anwendung eines bekannten Selbstkalibrierungsverfahren für die Bestimmung der geometrischen Parameter der Fujix DS-100 beschrieben.
Die Ergebnisse zeigen, dass einfache digitale Bildverarbeitung mit selbstkalibrierender Bündelausgleichung für die geometrische Kalibrierung digitaler Kameras gut geeignet ist.

I. INTRODUCTION

Photogrammetry is at present in the process of a radical transition from hard copy imagery to digital imagery. Digital imagery possesses many advantages over their traditional analogue counterpart and thus is gradually being utilized in numerous applications.

High accuracy and precision are often demanded for certain industrial applications. This requires high geometric and radiometric fidelity of the digital imagery, which in turn demands solid construction and calibration of the imaging equipment, i.e., the digital camera. Once the appropriate type of digital camera according to the requirements and preference has been selected by the users, the calibration task becomes prominent when trying to obtain accurate results for the applications.

The objective of digital camera calibration is to exploit the high accuracy potential of digital photogrammetry by modelling and compensating for the systematic errors due to the lens, solid state sensors, etc. It usually includes two aspects, namely, geometric calibration and radiometric calibration. For some of the digital cameras, the geometric characteristics have been thought as the main factors which have a negative influence upon the quality of the digital imagery. Generally, the geometric calibration of the digital camera is implemented based on special sophisticated digital image processing software and relevant hardware, which are not always available for certain organizations or applications.

Self-calibration methods have demonstrated their important role in analytical photogrammetry during the past several decades. This type of method can efficiently model most systematic errors of the imaging system.

This paper describes a research project conducted at the Department of Geodesy and Geomatics Engineering at the University of New Brunswick (Canada). Its goal was to investigate the feasibility and the performance of a well established self-calibration procedure for the determination of the geometric characteristics of an off-the-shelf digital camera. Two simple test models were prepared for this project.

2. SELF-CALIBRATION

2.1 Theoretical Background

Self-calibration means that the interior geometric quantities of a camera (e.g., calibrated principal distance, principal point, lens distortion parameters, etc.) can be determined based on the relationship of two or more overlapping photographs without additional control requirements. It has found wide applications in aerotriangulation and industrial close-range photogrammetry. Usually, certain additional parameters (APs) are included to model the systematic errors of the imaging system in a self-calibrating bundle adjustment in order to achieve high accuracy. Extended collinearity equations are used as the functional model in self-calibrating bundle adjustments.

$$x+\Delta x-x_0=-c\frac{m_{11}(X-X_0)+m_{12}(Y-Y_0)+m_{13}(Z-Z_0)}{m_{31}(X-X_0)+m_{32}(Y-Y_0)+m_{33}(Z-Z_0)}$$

$$y+\Delta y-y_0=-c\frac{m_{21}(X-X_0)+m_{22}(Y-Y_0)+m_{23}(Z-Z_0)}{m_{31}(X-X_0)+m_{32}(Y-Y_0)+m_{33}(Z-Z_0)} \quad (1)$$

where, x, y are the image coordinates of the image points; X, Y, and Z denote the object coordinates of the corresponding object points, and x_0, y_0 and c represent the basic interior orientation parameters, i.e., the location of the principal point and the calibrated principal distance; Δx and Δy stand for the correction terms applied to the image coordinate measurements, which are the functions of the selected APs; m_{ij} (i,j=1, 3) are the elements of the rotation matrix between image space and object space based on three independent orientation angles, and X_0, Y_0, Z_0 are the object coordinates of the projection centre.

Many versions of self-calibrating bundle adjustment algorithms exist. One of the main differences is the selection of the APs and the composition of Δx and Δy. Due to the non-linearity of eq.(1), linearization and iterations are necessary for its solution.

2.2 Digital Camera and Its Calibration

A digital camera is very much like a non-metric camera in many aspects, except for the substitution of the film with solid state sensors. Therefore, the images captured by a digital camera are also suffering from certain distortions due to systematic errors during imaging, which leads to inaccurate results. In order to exploit the potential of the photogrammetric techniques, camera calibration is necessary to determine the quality of the images and the imaging system and thus to be able to efficiently compensate for the systematic influences, which should lead to improved final accuracy.

On the other hand, the interior geometric structure of a digital camera is also instable, which means that its geometric characteristics may alter to a certain extent over time. This suggests that the calibration has to be carried out simultaneously with the data reduction rather than as separate laboratory calibration with subsequent data evaluation. Consequently, self-calibration seems to be an ideal tool to combine the two steps.

2.3 UNBASC2 Self-Calibration Method

A self-calibrating bundle block adjustment program (UNBASC2) was developed for aerotriangulation and close-range photogrammetric applications (Moniwa, 1977), which can be successfully applied to a non-metric camera (Faig et al,1990). Compared to other methods, UNBASC2 possesses two advantages:

- It is a photo-variant procedure with no limitation on the number of photos, the type of camera used, e.g. metric camera, non-metric camera or even digital camera.
- No approximate initial values are needed for the adjustment, although linearization and iteration have to be dealt with. This is convenient for applications, where the approximations are difficult to obtain.

In UNBASC2, the error model comprises of the following three independent functions which model systematic distortions of the camera system.

2.3.1 Radial Lens Distortion. Odd power polynomials are used to describe radial symmetric lens distortion:

$$dr=k_1 r^3+k_2 r^5+k_3 r^7+\ldots \quad (2)$$

which leads to its components in the photo coordinate system:

$$dr_x=(x-x_0)(k_1 r^2+k_2 r^4+k_3 r^6+\ldots)$$

$$dr_y=(y-y_0)(k_1 r^2+k_2 r^4+k_3 r^6+\ldots) \quad (3)$$

where dr is the radial distortion and dr_x, dr_y represent the components in x and y directions, respectively. r refers to the radial distance between principal point and image point; k_i are the coefficients of radial distortion functions.

2.3.2 Decentering Lens Distortion. The decentering lens distortion is defined by Conrady-Brown's model (Brown, 1966) in UNBASC2:

$$dp_x=(1+p_3r^2+p_4r^4+\ldots)$$
$$\cdot[p_1\{r^2+2(x-x_0)^2\}+2p_2(x-x_0)(y-y_0)]$$
$$dp_y=(1+p_3r^2+p_4r^4+\ldots)$$
$$\cdot[p_2\{r^2+2(y-y_0)^2\}+2p_1(x-x_0)(y-y_0)] \quad (4)$$

where p_i are decentering distortion parameters.

Usually, k_1, k_2, k_3 and p_1, p_2 are sufficient to define the radial and decentering lens distortion for most commercial non-metric cameras (Faig, 1973). If not, higher order terms could be included.

2.3.3 Film Deformation. Originally, an affine transformation is employed to model the film deformation,

$$dq_x=A(y-y_0)$$

$$dq_y=B(y-y_0) \quad (5)$$

where A and B are parameters defining scale change and non-perpendicularity of coordinate axes. Due to the fact that most digital cameras use CCD sensors for capturing the image instead of the emulsion material, film deformation will not be present in digital cameras. Nevertheless, there still may exist a certain deformation for the CCD sensor plane. On the other hand, the image coordinate determination process is not error free. The above affinity parameters A and B, are therefore kept in the calibration procedure in order to investigate these effects.

Thus, seven parameters, i.e., k_1, k_2, k_3, p_1, p_2 , A and B are included to model the image distortion, which together with the basic interior and exterior orientation parameters forms the functional model of the UNBASC2 self-calibrating bundle adjustment.

3. CALIBRATION EXPERIMENT WITH THE FUJIX DS-100 DIGITAL CAMERA

3.1 The Fujix DS-100 Digital Camera

The Fujix DS-100 Digital Camera is an all purpose, portable, compact digital camera manufactured by Fuji Photo Film with a slide-in memory card to store images. Its relevant technical data are as follows:

Table 1. Technical Data for the Fujix DS -100 Digital Camera

CCD array size	720 x 488
Pixel size	9.7 µm x 8.5 µm
Lens type	Autofocus, zoom f=8--24mm
Aperture setting	f/2--f/11
Minimum focus distance	30 mm
Shutter speed	1/4--1/750 second

The image data is resampled internally to an array of 640 x 488 pixels of 9.7 µm x 9.7 µm square size for storage on the slide-in memory card. The captured images can then be transferred to a computer for further processing by using a DP-100 Card Processor available as an option.

3.2 Calibration Experiment

The objective of the designed experiment was to evaluate the geometric quality of the Fujix DS-100 digital camera using the existing self-calibration program UNBASC2. Two simple models were prepared for the calibration purpose. The image coordinates were determined with the help of a Digital Video Plotter (DVP) from Leica.

3.2.1 Model Preparation. Two models were prepared for the experiment. Model I is a metal grid plate with dimensions of 17 cm x 17 cm, containing 36 intersections engraved on the plate surface and 25 bolts with different heights (ranging from 12 mm to 37 mm) fixed perpendicularly to the plate (see Fig. 1). Model II is a roof model measuring 95 cm x 63 cm x 25 cm. There are 21 targeted points distributed uniformly throughout the three-dimensional model space. 17 and 11 fine metal strings are stretched across the model from the four sides of the model, respectively (see Fig. 2). Thus, 17 x 11 intersections are formed by these strings. This model is also used as a hanging and standing roof structure for digital industrial photogrammetry research (Faig et al, 1996). The three dimensional coordinates of all the targeted points in both models were determined by an Electronic Coordinate Determination System (ECDS) (Wilkins et al, 1988). The resulting accuracies are 0.03 mm, 0.04 mm and 0.03 mm in X, Y and Z directions, respectively.

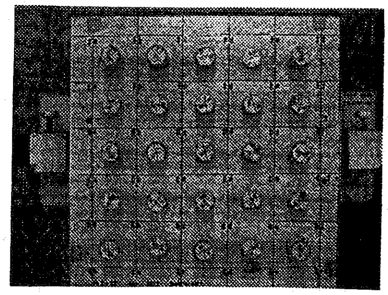

Fig. 1 Model I for the Calibration Test

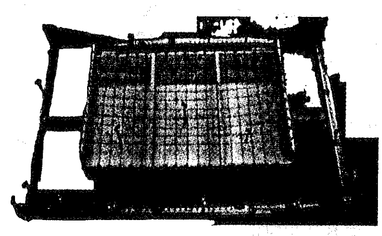

Fig. 2 Model II for the Calibration Test

3.2.2 Digital Image Acquisition. For each model, digital images were taken directly from three different camera stations, which form a multi-station convergent imaging configuration. For the model I case, the digital camera was fixed at the support frame, while the plate was rotated along its central axis into three orientations, i.e., backwards, level and forwards, which is equivalent to the situation that the model is kept still and the camera is placed at three corresponding locations providing convergent coverage. For model II, three camera stations were distributed uniformly around the model while the model was left untouched during the imaging process.

As the Fujix DS-100 digital camera is equipped with an automatic zoom lens, the interior orientation will alter with the focussing process (Faig et al, 1990). It seems therefore necessary to investigate the performance of the digital camera for different object distances. Thus, two distinct distances 0.4 m and 2 m were adopted for models I and II, respectively.

Several sets of digital images were captured under different imaging conditions from each camera station to assess the image appearance. The best one was selected from each set for the subsequent evaluation. It is well known that the illumination has an important influence upon the digital image's quality. However, it is worth to note here that no special illumination was adopted during the image taking, only the normal indoor illumination with ceiling fluorescent light was applied. To avoid shadows on the image, the flash of the digital camera was disabled when the images were captured.

3.2.3 Image Coordinate Measurements. The image coordinates are the basic input for the self-calibration bundle adjustment and their accuracy directly influences the final results. Thus, accurate determination of the image point location is necessary for better evaluation. Although many automatic techniques were developed for this purpose (Chen and Schenk, 1992; Edmundson et al, 1991; Heipke et al, 1992; Paquette et al, 1990; Stefanidis et al, 1990; Vosselman and Förstner, 1988), this research is based on existing readily available and low-cost software and hardware. Thus, the following solution was adopted: Firstly, due to the lack of fiducial marks of the digital camera and the poor definition of the corners and edges of the obtained images, the pixel location of each image point relative to the top left corner of the sensor plane was determined. Then, with known pixel size, the image coordinates of the image points can be easily obtained by a simple multiplying operation. An assumption is made here that all elements of the CCD sensor have uniform size and are evenly distributed.

The digital images are originally stored in the slide-in memory card supplied with the digital camera. To measure the image coordinates, the images have to be transferred from the card to a DVP via a DP-100 Card Processor connected to the DVP. DVP is a low cost Digital Photogrammetric Workstation(DPW) based on a PC computer (Nolette, 1992). It can be employed to measure the location of image points in pixel units with its interior orientation function, which is essentially a manual screen digitization process. This technique seems like a step backwards, but is appropriate for certain cases where no other special image point determination tools are available and the number of image points is not large. Furthermore, to successfully apply existing software and equipment to arrive at a solution is useful as far as project cost is concerned. The resulting accuracy of repetition was 0.4 pixels, equivalent to 3.88 μm.

3.2.4 Evaluation of the Calibration Tests. After the image acquisition and image measurement, the self-calibration can proceed straightforward. To determine the geometric characteristics of the digital camera, the following tests with different APs were designed and carried out for both models:

Table 2. Calibration Tests

Test	Description
1	without any interior orientation parameters
2	with x_0, y_0 and c
3	with x_0, y_0, c, k_1, k_2, k_3
4	with x_0, y_0, c, k_1, k_2, k_3, p_1, p_2
5	with x_0, y_0, c, k_1, k_2, k_3, p_1, p_2, A, B

For model I, some of the coordinated points were used as control points, and the others were treated as check points. This was also true for model II; in addition, some of the unknown intersection points were included in the adjustment to improve the calibration results.

Due to the absence of the full variance-covariance matrix, statistical tests cannot be implemented to check the significance of the individual additional parameter. The evaluation of the effects of APs, therefore, is based on the root mean square errors(RMSE) of the image coordinates (σ_x and σ_y) and root mean square discrepancies (σ_X, σ_Y and σ_Z) for the check points between the resulting photogrammetric coordinates and the ECDS determined ones.

Since the number and distribution of the control points have a certain influence upon the final results, the control and check points in this project were kept fixed for all tests; thus a comparison can be made for different tests based on the same reference. The results of all tests from the two models are tabulated in Tables 3 and 4.

Table 3 RMSE of Image Coordinates After Self-Calibrating Bundle Adjustment

unit : μm (photo scale)

Test	Model I σ_x	Model I σ_y	Model II σ_x	Model II σ_y
1	78	61	61	49
2	11	11	4	4
3	10	10	2	3
4	4	3	2	3
5	1	2	2	1

Table 4 RMS Discrepancies for the Check Points

unit : mm (object scale)

Test	Model I (photo scale : 1 / 50) σ_X	σ_Y	σ_Z	Model II (photo scale : 1 / 300) σ_X	σ_Y	σ_Z
1	1.67	4.46	4.77	28.98	11.33	31.93
2	0.20	0.53	0.34	1.08	1.77	4.92
3	0.19	0.26	0.36	1.18	1.08	5.86
4	0.16	0.10	0.08	0.56	0.95	4.97
5	0.05	0.07	0.05	0.50	0.44	0.43

The above results show the following:

- With the self-calibration method, the final accuracy can be improved significantly. The larger the object distance, the bigger the improvement that can be achieved.
- The basic interior orientation parameters play the most important role in the data evaluation. Without them, the results are too inaccurate to meet industrial application requirements.
- The digital camera tested does not have a large radial lens distortion, which was verified by test 3 where the inclusion of k_1, k_2, k_3 does not show much improvement, with the accuracy gain in Y direction slightly better than for other two directions.
- The adoption of parameters p_1, p_2, A, B further improves the accuracy, which suggests that decentering lens distortion and certain imperfections related to the CCD senor plane and the DVP digitization process were successfully compensated by these parameters.

- The assumptions of uniform pixel size and distribution are rational, as evident by the final RMSE σ_x and σ_y of the image coordinates.

4. CONCLUSIONS

The studies described in this paper suggest that the geometric characteristics of a digital camera can be successfully evaluated by self-calibration. With an appropriate functional model, the systematic errors of the camera system can be effectively compensated, thus high accuracy can be achieved.

Due to the application of a zoom lens in the Fujix DS-100 digital camera, the camera displays different geometric properties at different object distances. The laboratory calibration, therefore, does not make much sense for subsequent applications. The self-calibration is thus imperative combining the calibration and evaluation in order to account for the changing inner orientation and the geometric structure. Therefore general purpose digital cameras of the Fujix DS-100 type can be applied to precise industrial measurement environments when used with a self-calibrating data reduction procedure.

A well-established self-calibrating bundle adjustment program, a Digital Video Plotter and simple auxiliary devices were involved in this research project. Although certain manual operations were needed during the processing, the combination of this software and hardware proved to provide an economic solution.

It is expected in the near future that a low cost fully automatic calibration procedure for precise applications using self-calibration will become standard practice in order to facilitate the evaluation of digital imagery and thus promote the performance of digital cameras.

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