AUTOMATIC SELF-CALIBRATION OF DIGITAL CAMERAS FOR CLOSE-RANGE PHOTOGRAMMETRY

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ABSTRACT

Digital cameras are getting widely used due to their operation conveniences and real-time processing capabilities. Although digital cameras have been considered suitable to photogrammetric tasks, their metric characteristics are not clear and stable as traditional metric cameras. A real-time on-the-job calibration is, therefore, required before a digital camera can be applied for a photogrammetric task. The technique of self-calibration is considered an effective means for digital camera calibration, but a large amount of image measurements are required. To solve this problem, we designed a new text-coded target and proposed an automatic process to detect, position, and identify the targets. Automatic camera calibration can be achieved by integrating this automatic measuring process and bundle adjustment computation. The experimental results are encouraging and optimally show the feasibility of the proposed method.

1 INTRODUCTION

Digital cameras are getting widely used due to their operation conveniences and real-time processing capabilities. The rapid development of large-format CCD arrays pushes the industry to produce high resolution digital cameras, for example Kodak DCS 460 has a 3060*2036 pixel CCD array, which may attain triangulation accuracy for 1:100,000 [Peipe, 1995]. In addition, the digital camera can be used flexibly and capable to obtain results real-time, which are distinct advantages to make it a preferred tool for a close-range photogrammetric task. Especially for mobile mapping systems [Klemm *et al.*, 1997], motion measurements [Oda *et al.*, 1997], industry measurements [Schäfer *et al.*, 1989][Fraser, 1997], and robotic systems [Beyer *et al.*, 1989], digital cameras have shown their potential for real-time and high-quality photogrammetric tasks.

Although digital cameras have been considered suitable to photogrammetric tasks, their metric characteristics are not clear and stable as traditional metric cameras. For example, the focus of digital cameras is usually changeable and there are no fiducial marks to provide the photograph coordinate system. Furthermore, the principle point location is prone to move during the normal handling of the camera due to the mounting mechanism of the CCD array [Shortis *et al.*, 1998]. Therefore, digital cameras need to be calibrated on the job instead of in a laboratory.

On-the-job calibration is referred as a technology that determines object coordinates and calibration parameters simultaneously with a pre-defined control frame [Fryer, 1996]. Usually, to be measured objects are pictured together with the pre-coordinated control frame. The control frame serves not only for datum determination but also for calibration. Reasonable accuracy of measurement can be achieved with only two or three overlapped images. However, its applications are frequently restricted by the difficulties of building a well-defined control frame or fitting the objects to be measured into the frame.

Self-calibration is an extension of the concept embodied in on-the-job calibration. Instead of using a control frame, a large number of overlapped images, usually more than 6, are taken to reinforce the measurement geometry, so that both of object coordinates and calibration parameters can be solved accurately. This solution does not need substantial control points but a minimum constraint for datum determination. However, a large number of image measurements are needed to carry out a self-calibration task. It would be impractical, if images were measured manually. It is, therefore, becoming the motivation of this research project to develop an automatic target measurement system for camera calibration.

2 CONCEPT OF AUTOMATIC CAMERA CALIBRATION

The implementation of an automatic camera calibration system should consist of two stages: (1) image processing: detecting targets, positioning target centers, and identify target numbers; (2) computation of self-calibration: initial value estimation and bundle adjustment.

More than 50 artificial targets are generally needed for a camera calibration task. Due to their similarity, targets tend to be mismatched or misidentified among a set of images. For automatic target identification and for users being able to verify the results, coded targets are preferable to the implementation of automatic camera calibration. As Ahn *et al.* [1997] suggested, a coded target should meet the requirements below:

- Independence of location, rotation and scale
- Robust to defective decoding, possibly with error detection and error correction
- Precise and accurate center point determination
- Detection and localization in any patterned image without initial values
- Short processing time
- Compact target size
- Provision of a sufficient number of identification codes
- A low rate of manufacturing costs

Based on the suggestion, the adopted target design consists of five circular symbols and a three-digit number. Circular symbols are independent to rotation and scale, and easy to detect and locate automatically using algorithms, such as template matching, gray value gravity method, Hough transform, Förstner interest operator, or our circular-symbol detector. The three-digit number can provide up to 999 options of targets, which can satisfy most close-range photogrammetry tasks, and can be identified both by human eyes and computer programs automatically.

Self-calibration is an extension of the bundle adjustment. It simultaneously solves the calibration parameters and points coordinates in object space with the measurements of a sufficient number of well-distributed points. Thus, the major problem of automatic self-calibration is how to estimate the initial value. Some research use additional equipments, such as the Inertial System (INS), to provide the position and the attitude of a camera [Koizumi *et al.*, 1997]. Some others use 3 object space control points and the closed-form space resection to estimate the initial values of orientation parameters [Rampal, 1979]. In this paper, the initial coordinates of targets are derived from the previous photogrammetric task, or simply measured by meters.

3 AUTOMATIC TARGETS IDENTIFICATION

3.1 Target Design

Figure 1 shows the design pattern of text-coded targets. The base unit is the radius of small circular symbols, so that the target size can be scaled to meet actual needs. Setting target background to black can make the foreground sharper.

The whole target consists of two parts: five circular symbols and three digits. The circular symbols are independent of location, rotation and scale, and their centers can be determined precisely and accurately. In addition, detecting solid circles is easier than detecting other kind of symbols. The bigger circular symbol is used to secure the detection when the image scale is small. The five symbols will provide enough information to rectify the deformation of the targets, so that the target number can be matched with the patterns.

The design allows both of human eyes and computers to recognize the number of the targets, which provides a possibility of automatic identification and visually verifying the results. The font of the digits is a special design that possesses low similarities between any two different digits.

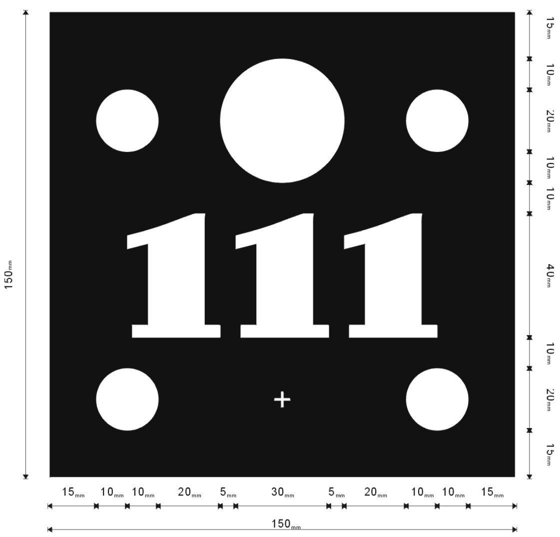

Figure 1. The proposed pattern of text-coded target

The automatic identification process for text-coded targets can be accomplished in three steps: detecting circular symbols, positioning the centers of circular symbols, and identifying the target number.

3.2 Detection of Circular Symbols

An *ad hoc* circular-symbol detector is designed to detect circular symbols in an image. The detector uses a matched filter to test the existence of edges along 8 directions in a search window (figure 2). When the center 9 pixels are tested to be a homogeneous white area, the detector starts to perform the matched filter along 8 directions. This matching process will result in 8 distances, which represent 8 directional radii of a circle. The 8 directional radii are then checked to determine whether they belong to a circle or not. The algorithm is illustrated in figure 2.

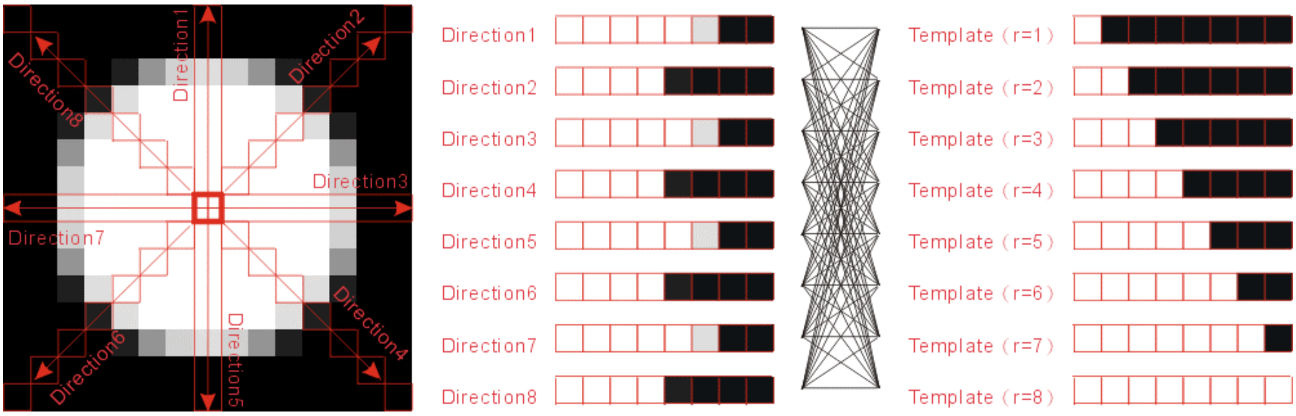

Figure 2. The circular-symbol detection algorithm

The matched filter is implemented by computing the normalized correlation coefficient (NCC) for each direction with all the templates (r=1,2…n, where n is the width of the searching window). The largest NCC represents the most possible radius in that direction. Notice that the pixel length in direction 2,4,6,8 is not equal to that in direction 1,3,5,7. There is a $\sqrt{2}$ scale factor difference due to the pixel length difference. For circle detection, a threshold is set to examine if the radii in opposite directions are about equal. When a circular symbol is found, the center of the searching window defines the circle center, and the average length of the 8 radii represents the circle radius.

The circular-symbol detector moves from the upper left corner to right and down all over the image. Therefore, all the possible circular symbols in the image may be detected and their centers coordinates and radii are determined. Having detected circular symbols, precise positioning can be performed next.

3.3 Accurate Positioning

Accurate positioning of circle symbols may be problem, especially when symbols are deformed in an image. Circular symbols may become ellipses after deformation. Using the gravity center is computationally simple, but the gravity center may differ from the real center when the gray value is not homogeneous. The Hough transform can give precise location of the center, but it is quite computation intensive. The least squares matching (LSM) ended up to be the adopted method for accurate positioning.

Considering the intensity changes in an image due to the lighting situation, the matching template is formed using local intensity. The gray value of the circle in the template is obtained by taking the average gray levels of the nine center pixels of the detected symbol, and the background intensity is derived from the four pixels in the four corners of the searching window

If the matching result is not convergent or the residuals are larger than a defined threshold, the detected symbol will be discard. Otherwise, the position corresponding to the template center is considered as the circle center. The standard deviation of the LSM not only represents the correspondence between the template and the symbol, but also is treated as an index of the precision of positioning. The LSM procedure can also be used to filter out wrongly detected circles.

3.4 Identifying Target Numbers

After detecting and positioning circle symbols, the grouping procedure is applied. Taking one symbol as a “seed” at one time, it searches the closest four symbols around the seed. If all distances among the symbols fit the target structure, the five symbols are grouped into a target. Symbols do not fit the target structure will be discard and replaced by other ungrouped symbols and the verification is repeated until all symbols are checked. At the end of the procedure, only those symbols that fit the target structure are maintained to form targets.

A target in an image is usually twisted or deformed, so that it is necessary to rectify the deformation before the number of the target can be identified. Since the topological relations among five symbols are fixed and the target consists of five known centers, the eight parameters of the projective transform can be solved. Then, the target can be rectified back to its original shape and the three digits can be extracted individually as shown in figure 3.

The proposed identification algorithm is based on the 2-D normalized correlation. Computing the NCC between each digit of the number and ten digit-templates (from 0 to 9), template with the biggest NCC is the most likely number of that digit. Then, the target is given a number by composing the three digits, so that it can be distinguished from each other in a set of images.

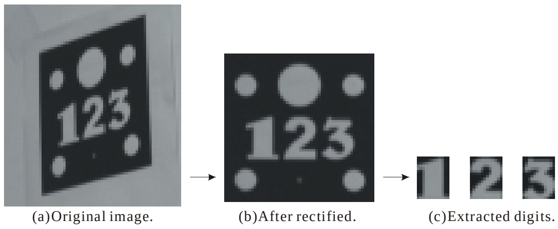

Figure 3. Rectify and extract the three digits

4 COMPUTATION OF SELF-CALIBRATION

Self-calibration technique does not require any object space control as a means of camera calibration. The observations of targets are used as the data required for both object points determination and for the determination of camera calibration parameters. The basic formulas of self-calibration are the colinearity equations with lens distortion and a series of additional parameters (APs), which can be written as: [Fryer, 1992]

$$
\begin{aligned}
x_{ij} - x_p + \frac{(x_{ij} - x_p)}{r}\delta_r + \Delta x &= f_i^x \frac{(X_j - X_i^o)m_{11} + (Y_j - Y_i^o)m_{12} + (Z_j - Z_i^o)m_{13}}{(X_j - X_i^o)m_{31} + (Y_j - Y_i^o)m_{32} + (Z_j - Z_i^o)m_{33}} + dx_{AP} \\
y_{ij} - y_p + \frac{(y_{ij} - y_p)}{r}\delta_r + \Delta y &= f_i^y \frac{(X_j - X_i^o)m_{21} + (Y_j - Y_i^o)m_{22} + (Z_j - Z_i^o)m_{23}}{(X_j - X_i^o)m_{31} + (Y_j - Y_i^o)m_{32} + (Z_j - Z_i^o)m_{33}} + dy_{AP}
\end{aligned} \tag{1}
$$

where the subscripts denote:

^{o} ：the perspective center　　　　p ：the principle point

i ：the ith photograph　　　　j ：the jth point

In equation (1), δ_r represents the radial distortion and $\triangle x$, $\triangle y$ represent the decentering distortions. On the right side of the equation, f_i^x, f_i^y are the principle distances form the image respect to x and y. These two factors are usually simplified as a common value f_i. The terms m_{11}, m_{12},…, m_{33} are elements of the rotation matrix, which consists of three rotation angle: ω, φ, κ .The last terms dx_{AP} and dy_{AP} are additional parameters modeled with polynomials.

The purpose of the camera calibration is to solve the interior orientation elements: x_p, y_p, f_i, lens distortion parameters δ_r, $\triangle x$, $\triangle y$; and the additional parameters dx_{AP}, dy_{AP}. In self-calibration, orientation parameters (m_{11}, m_{12}… m_{33}) and observed points ground coordinates (X_j, Y_j, Z_j) are solved simultaneously. However, the colinearity equations are nonlinear, so that the Newton-Raphson approach of least squares adjustment is used to solve the unknowns, which is an iteration approach.

The iteration approach requires good initial values of unknowns, otherwise the iteration may not convergent. The closed-form resection proposed by Zeng *et al.* [1992] is an analytical method to estimate exterior parameters without the need of initial values. The solution is based on the pyramid geometric relationship formed by three object space control points and the projective center. The computation of self-calibration becomes a totally automatic process by introducing a minimum number of ground control points. A full automatic camera calibration procedure is then possible by linking the process of automatic image measurement and self-calibration.

5 EXPERIMENTS

5.1 Test Field

The test field applied for the experiments as shown in figure 4 is a three dimensional control field. There are 29 targets fixed on the aluminum rods hung on the ceiling or on the walls. The object coordinates of the targets were measured using Wild P32 metric camera. Six photographs were taken to form a solid intersection block. The distribution of exposure stations is shown in figure 5. Station 1 and 4 are on the same position but in different heights, so do the station pairs of (2, 5) and (3, 6). The image coordinates of the targets were measured using an analytical plotter.

The BINGO-F program was used to solve the exterior orientation (EO) of the exposures and the object coordinates simultaneously. The average accuracy of the point coordinates is 0.001m in X and Y coordinates, 0.002m in Z coordinate. The solution of the object coordinates serve as the check data for the case study of the digital camera calibration.

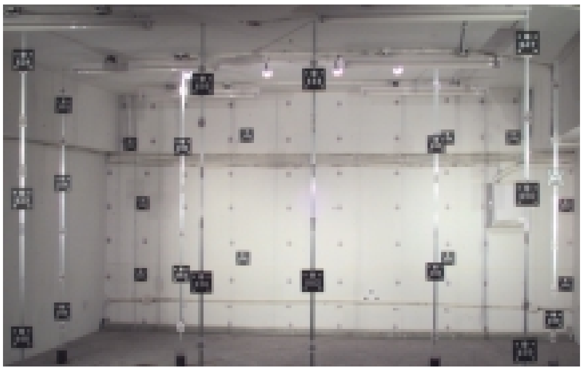

Figure 4. The test field.

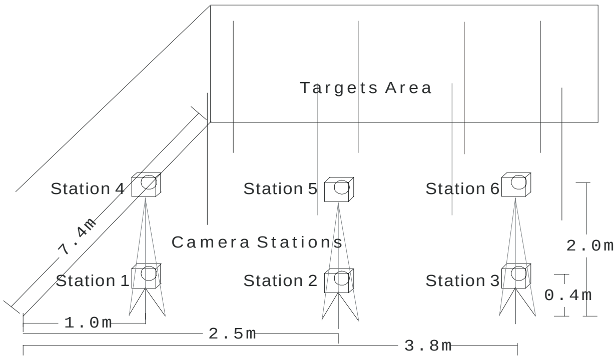

Figure 5. The distribution of exposure stations.

5.2 A Case Study

The Kodak DCS 460 is a widely used digital camera in the field of close-range photogrammetry, because its 18.4*27.6 mm CCD array can provide high-resolution images up to 3060*2036 pixels. The other benefit of using it is that, images can be transferred to the computer immediately via the SCSI port, which makes the real-time automatic processing system possible. However, the inner orientation is not stable due to the mounting mechanism of its CCD array. Therefore, self-calibration is necessary while applying DCS 460 to close-range photogrammetry tasks.

Our project is to calibrate DCS 460 automatically. Six images were taken in the stations distributed similar to that in figure 5. The experiment consists of two main stages: (1) targets identification and (2) self-calibration computation. In the first stage, image coordinates of targets are measured automatically from circular-symbol detector, LSM, and target number identification.

The number of detected circular symbols may change subject to the given thresholds of roundness and whiteness. Since unqualified symbols can be filtered out with LSM, it is better to loose the thresholds of circular-symbol detector to decrease the omission errors. Table 1 summarizes the results of the whole procedures. Most of the circular symbols were successfully detected. There were only few symbols omitted due to serious deformations or bad illuminations. After LSM positioning, the commission and omission errors decreased due to the filtering process. In the process of target number identification, although there were some misidentifications between the digits of ‘3’ and ‘8’, most of the digits were identified correctly.

Exposure Station	Number of Targets	Number of Circular Symbols	Circular-Symbol Detector			LSM Positioning			Target No. Identification				
			Correct	Commission	Omission	Correct	Commission	Omission	All Correct	1 Digit Error	2 Digits Error	All Error	Omission
1	27	135	135	32	0	134	11	1	13	10	3	0	1
2	26	130	130	28	0	130	0	0	9	11	3	0	3
3	18	90	90	24	0	88	3	2	7	9	1	0	1
4	26	138	137	35	1	132	4	6	8	12	3	0	5
5	26	130	130	30	0	127	4	3	9	12	2	2	1
6	20	100	100	25	0	97	3	3	12	5	1	1	1
Total	143	723	722	174	1	708	25	15	58	60	13	3	11

Table 1. Targets identification results.

After correcting misidentified target numbers, the computation of self-calibration can be carried out. Two computation cases were tried. In the first case, all circular symbols are treated as known positions, which were determined with P32. Figure 6 shows the residuals of points and the confidence ellipses. In the second case, the object coordinates were treated as unknowns, and rough coordinates were used as their initial values. The points residuals and confidence ellipses are shown in figure 7. The average coordinate differences between the two cases are 0.027m in X coordinate, 0.014m in Y coordinate, and 0.074m in Z coordinate. The camera parameters derived from two cases are summarized in table 2.

	f	σ_f	x_p	σ_{xp}	y_p	σ_{yp}
Object coordinates were treated as known	28.4137 m	0.0680 m	0.3546 m	0.0733 m	-0.3203 m	0.0947 m
Object coordinates were treated as unknowns	28.2228 m	0.2900 m	0.6617 m	0.2885 m	-1.0256 m	0.3672 m

Table 2. Camera parameters after self-calibration.

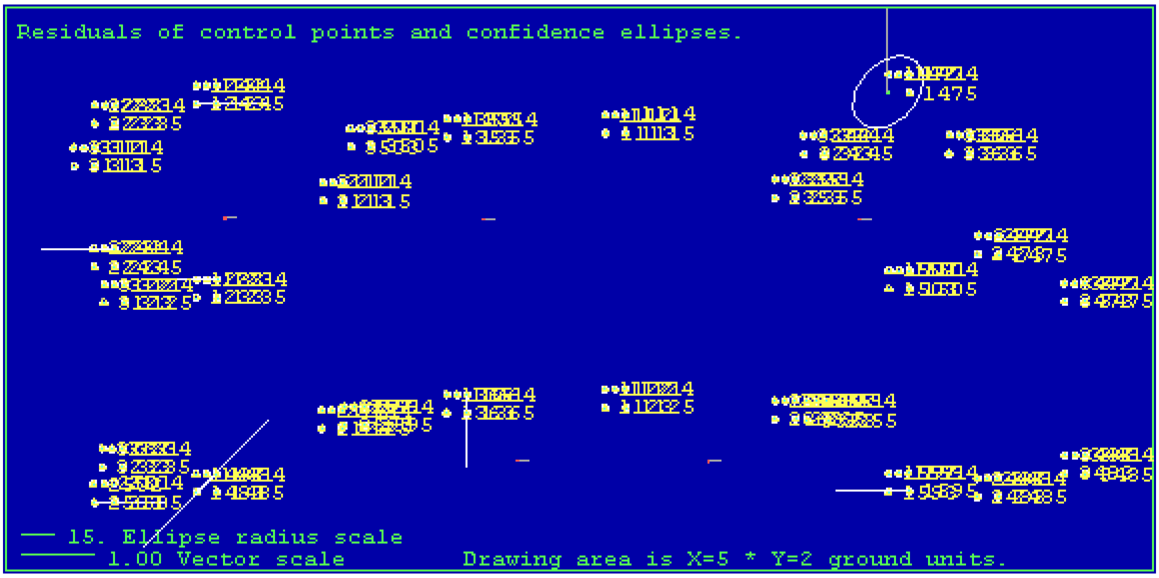

Figure 6. Residuals of points and confidence ellipses when object coordinates were treated as known.

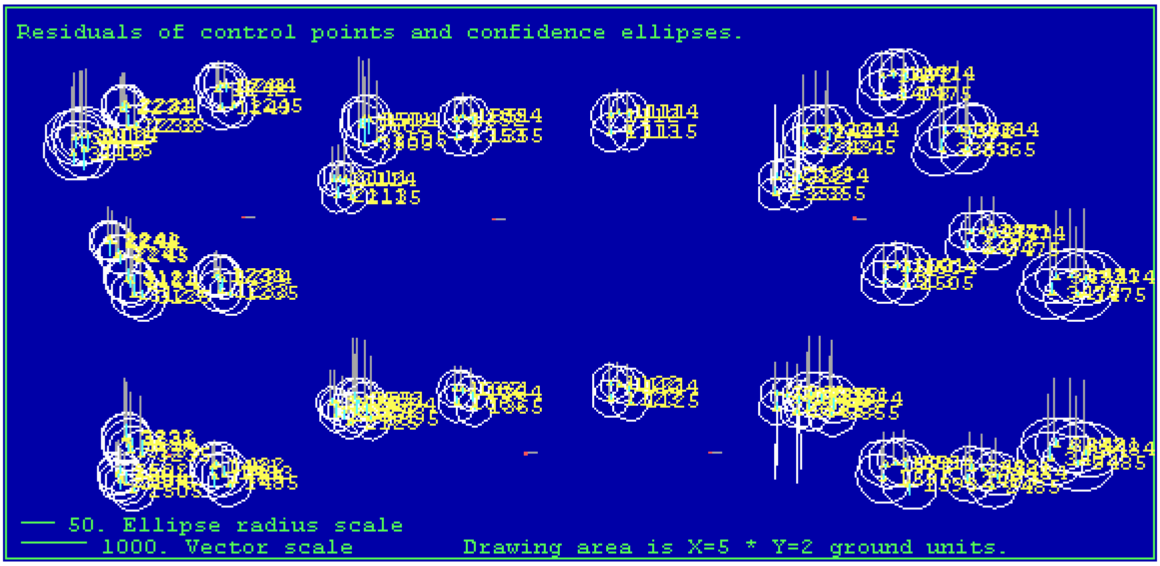

Figure 7. Residuals of points and confidence ellipses when object coordinates were treated as unknowns.

6 CONCLUSIONS

A real-time on-the-job camera calibration procedure is needed for the applications of digital cameras to a close-range photogrammetric task. A full automatic camera calibration procedure is proposed in this paper. This procedure is implemented in two stages: image measurement and self-calibration computation. For automatic image measurement, an *ad hoc* circular-symbol detector is developed to detect circular symbols in the specially designed targets, and followed by using LSM and template matching. Point positioning and target number identification can be accurately determined. The experimental results are encouraging and show the feasibility of the proposed method.

Mis-detection of symbols and mis-identification of targets in the experiment reveal that a robust self-check algorithm is needed for practical cases. This checking procedure should be able to filter out all possible commission errors to ensure the bundle adjustment can be preceded. The target detecting and identification algorithm should also be polished to adopt different lighting conditions of photography. For example, instead of using static threshold values and constant searching window size, dynamically adjusting threshold values and window size subject to the image condition would make the program more practical.

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