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Precise calibration of a rotation photogrammetric system

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Rotation photogrammetric systems are widely used for 3D information acquisition, where high-precision calibration is one of the critical steps. This study first shows how to derive the rotation model and deviation model in the object space coordinate system according to the basic structure of the system and the geometric relationship of the related coordinate systems. Then, overall adjustment of multi-images from a surveying station is employed to calibrate the rotation matrix and the deviation matrix of the system. The exterior orientation parameters of images captured by other surveying stations can be automatically calculated for 3D reconstruction. Finally, real measured data from Wumen wall of the Forbidden City is employed to verify the performance of the proposed calibration method. Experimental results show that this method is accurate and reliable and that a millimetre level precision can be obtained in practice.

Keywords: rotation photogrammetric system; calibration; deviation matrix; overall adjustment

1. Introduction

The calibration of camera system parameters is a necessary step for 3D information extraction from 2D images (*1*). As one of the commonly used 3D vision systems in the fields of close range photogrammetry and computer vision, a rotation photogrammetric system is composed of a digital camera fixed on a horizontal and vertical rotation platform. The vertical and horizontal rotation angles of the camera are automatically recorded by the system. By high-precision calibration, the relationship between the angles and the exterior orientation parameters of images can be established. Therefore, the calibration method of the camera system needs to be investigated.

Camera calibration in the context of 3D machine vision is the process of determining the internal camera geometric and optical characteristics (intrinsic parameters) and/or the 3D position and orientation of the camera frame relative to a certain world coordinate system (extrinsic parameters) (*2*). The commonly used calibration methods are divided into traditional calibration and self-calibration methods. The traditional approaches take advantage of a calibration pattern with precisely known structure. The parameters of the camera model are determined by conjugate points in the image space and the object space (*3–5*). The self-calibration method utilizes correspondences between small numbers of points in two or more views of a moving camera (*6*). Research has been done, based on the assumption that rotational motions of the camera is only considered and the rotation centre is its optical centre (*7*, *8*). Since the location of the optical centre is difficult to be exactly known, the translational offset was considered in self-calibration (*9*). However, this method requires strict constraint of the camera movements.

The main task of the calibration method proposed in this study is to determine the fixed rotation matrix and deviation matrix in the object space coordinates system. It is similar to hand-eye calibration of a robotic camera (*10–12*), the orientation and position of the object in relation to the camera needs to be translated to those in relation to the platform, and homogeneous matrix equation of the form AX = XB needs to be solved.

The basic structure of the system is illustrated and the rotation and deviation models of the system are presented in Section 1. Section 2 derives the methods to solve the rotation matrix and deviation matrix by overall adjustment, and Section 3 calculates the exterior orientation parameters of images for 3D reconstruction. Experiments are carried out in Section 4 to measure the performance of the proposed method. Finally, conclusions and future work are discussed.

2. Basic structure and mathematical models

2.1. Basic structure of the system

The rotation photogrammetric system is mainly composed of a digital camera and a horizontal and vertical rotation platform. As shown in Figure 1, the camera is fixed on the upper part of the platform, with the axis of lens perpendicular to the cylinder A_U. In the rotation coordinate system $P_C - XYZ$, P_C is the central point of intersection of the horizontal rotation cylinder A_H and

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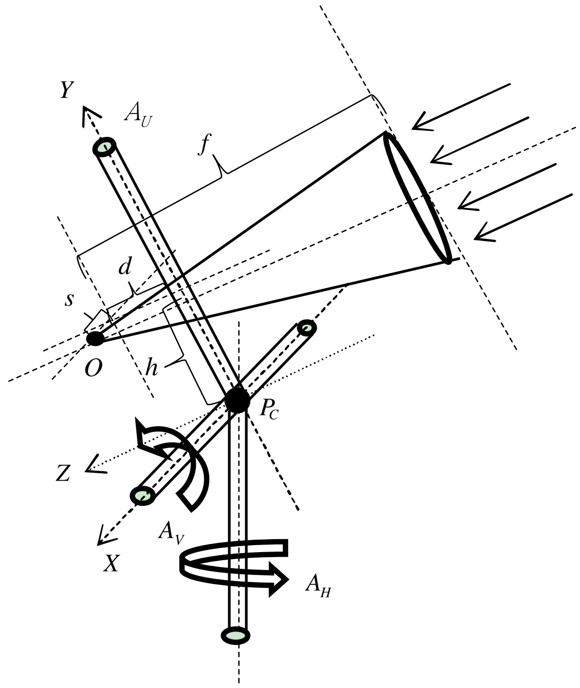

Figure 1. Basic structure of the system.

the vertically rotation cylinder A_V, the X-axis and Y-axis lie on the central lines of A_H and A_U, respectively, and the Z-axis is parallel to the axis of lens. s, d and h are the deviations of the principal point of image O with respect to the X-axis, the Y-axis and the Z-axis, respectively. f is the focal length.

When the platform is rotating around the rotation cylinders A_H andA_V, the exterior orientation parameters of the image captured by the camera are changing. The geometric relationship of the related coordinate systems is shown in Figure 2. $P - X_0Y_0Z_0$ is the standard position coordinate system where the camera is directly facing the target, with the Y_0-axis pointing to the zenith, the Z_0-axis perpendicular to the target and the X_0-axis perpendicular to the former two. If the camera is being rotated around A_H and A_V with the angles θ_V then, θ_H, $P_C - X_0Y_0Z_0$ will be coincident with $P_C - XYZ$. $S - X_GY_GZ_G$ is the object space coordinate system.

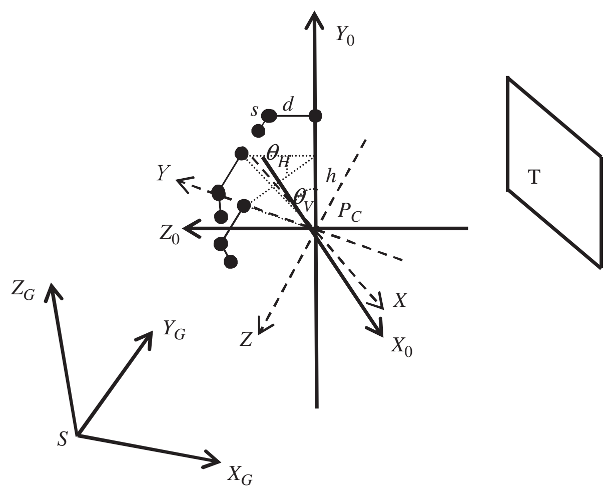

Figure 2. Geometric relationship of the related coordinate systems.

2.2. Rotation model of the system

According to the basic structure of the rotation photogrammetric system and the geometric relationship of the related coordinate systems, the rotation model of the system in relation to the object space coordinate system can be written as:

$$R = R_{SC}R_{HV}R_I \tag{1}$$

Where R is the rotation matrix of the exterior orientation parameters in the object space coordinate system. The standard approach of constructing R is to use three angular elements ϕ, ω and κ (*13*), then R can be expressed as follows:

$$\begin{aligned} R &= R_\phi R_\omega R_\kappa \\ &= \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega & -\sin\omega \\ 0 & \sin\omega & \cos\omega \end{bmatrix} \\ &\quad \times \begin{bmatrix} \cos\kappa & -\sin\kappa & 0 \\ \sin\kappa & \cos\kappa & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{2}$$

Where R_{SC} is the rotation matrix between the object space coordinate system and the standard position coordinate system. With regard to the images captured by a fixed survey station, the value of R_{SC} is invariant. The approach of constructing R_{SC} is similar to that of R, which can be expressed by three sequential rotations ϕ_{SC}, ω_{SC} and κ_{SC} as follows:

$$\begin{aligned} R_{SC} &= R_{\phi_{SC}} R_{\omega_{SC}} R_{\kappa_{SC}} \\ &= \begin{bmatrix} \cos\phi_{SC} & 0 & -\sin\phi_{SC} \\ 0 & 1 & 0 \\ \sin\phi_{SC} & 0 & \cos\phi_{SC} \end{bmatrix} \\ &\quad \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega_{SC} & -\sin\omega_{SC} \\ 0 & \sin\omega_{SC} & \cos\omega_{SC} \end{bmatrix} \\ &\quad \times \begin{bmatrix} \cos\kappa_{SC} & -\sin\kappa_{SC} & 0 \\ \sin\kappa_{SC} & \cos\kappa_{SC} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{3}$$

Where R_{HV} is the rotation matrix between the standard position coordinate system and the rotation coordinate system. R_{HV} is constructed by θ_H and θ_V, and its value varies according to the imaging attitude among different images. The basic form of R_{HV} is:

$$R_{HV} = \begin{bmatrix} \cos\theta_H & 0 & -\sin\theta_H \\ 0 & 1 & 0 \\ \sin\theta_H & 0 & \cos\theta_H \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_V & -\sin\theta_V \\ 0 & \sin\theta_V & \cos\theta_V \end{bmatrix} \quad (4)$$

Where R_I is the rotation matrix between the rotation coordinate system and the image space coordinate system. With regard to all the images captured by different survey stations, the value of R_I is invariant, so R_I is the intrinsic rotation parameter of the system which needs to be calibrated. The approach of constructing R_I is also similar to that of R, which can be expressed by three sequential rotations ϕ_I, ω_I and κ_I as follows:

$$\begin{aligned} R_I &= R_{\phi_I} R_{\omega_I} R_{\kappa_I} \\ &= \begin{bmatrix} \cos\phi_I & 0 & -\sin\phi_I \\ 0 & 1 & 0 \\ \sin\phi_I & 0 & \cos\phi_I \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega_I & -\sin\omega_I \\ 0 & \sin\omega_I & \cos\omega_I \end{bmatrix} \times \begin{bmatrix} \cos\kappa_I & -\sin\kappa_I & 0 \\ \sin\kappa_I & \cos\kappa_I & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned} \quad (5)$$

2.3. *Deviation model of the system*

The deviation model of the rotation photogrammetric system in relation to the object space coordinate system is:

$$P = R_{SC} R_{HV} T_I + P_C \quad (6)$$

Where $P = (X_s, Y_s, Z_s)^T$ is the coordinate matrix of linear elements X_s, Y_s and Z_s of the exterior orientation parameters, $T_I = (s, h, d)^T$ is the coordinate matrix of the original point O of the image space coordinate system in the rotation coordinate system. With regard to all the images captured by different survey stations, the value of T_I is invariant, so T_I is the intrinsic deviation parameter of the system which needs to be calibrated. $P_C = (X_C, Y_C, Z_C)^T$ is the coordinate matrix of P_C in the object space coordinate system. With regard to images captured by a fixed survey station, the value of P_C is invariant. Hence, R_I and T_I are the parameters of the rotation photogrammetric system that need to be calibrated.

3. Calibration method

3.1. *Calibration of the rotation matrix*

If $N(N \geq 3)$ images are captured by the first survey station, the exterior orientation parameters of the images are recorded as $(\phi_{1j}, \omega_{1j}, \kappa_{1j}, X_{S1j}, Y_{S1j}, Z_{S1j})$, the vertical rotation angle and horizontal rotation angle are recorded as θ_{H1j} and θ_{V1j}, respectively; where, the subscript 1 and j $(j = 1, 2, \ldots, N)$ identifies the station number and the image number.

According to Equation (2), the rotation matrix of the exterior orientation parameters R_{1j} are constructed by the angular elements $\phi_{1j}, \omega_{1j}, \kappa_{1j}$ $(j = 1, 2, \ldots, N)$. The coordinate matrix of the exterior orientation parameters P_{1j} are constructed by the liner elements X_{S1j}, Y_{S1j}, Z_{S1j} $(j = 1, 2, ...N)$.

The initial value of T_I and R_{SC1} (i.e. the rotation matrix between the object space coordinate system and the standard position coordinate system of the first survey station) can be calculated by the rotation models (refer to Equation (1)) of the first three images $R_{1j} = R_{SC1} R_{HV1j} R_I$ $(j = 1, 2, 3)$. If R_I is eliminated from the three equations, for example, these equations can be written as:

$$\begin{aligned} (R_{11} R_{12}^{-1}) R_{SC1} &= R_{SC1} (R_{HV11} R_{HV12}^{-1}) \\ (R_{12} R_{13}^{-1}) R_{SC1} &= R_{SC1} (R_{HV12} R_{HV13}^{-1}) \end{aligned} \quad (7)$$

Setting the parameter at the lower right corner of the matrix R_{SC1} to be 1, the other eights to be unknowns, Equation (7) is expanded into eighteen equations about the eight unknowns. Since the initial value of R_{SC1} need not be calculated precisely, the correlations of the nine parameters of R_{SC1} are not considered in this step. The normal equations are constructed and calculated on the basis of least squares adjustment (*14*).

$$X = (A^{\mathrm{T}} A)^{-1} A^{\mathrm{T}} L \quad (8)$$

Where X is the unknown matrix, A is the coefficient matrix and L is the constant matrix.

The initial value of R_{SC1} is constructed and normalized by the unknowns and the initial value of R_I can be calculated based on the rotation model (refer to Equation (1)). R_{SC1} and R_I can be decomposed to be the rotation angles of ϕ_{SC1}, ω_{SC1}, κ_{SC1} and ϕ_I, ω_I, κ_I, respectively (*13*).

Then, the rotation models (refer to Equation (1)) of all the images captured by the first survey station are converted into error equations and linearized using the Taylor series expansion as follows:

$$\begin{aligned} V = {} & \frac{\partial F}{\partial \phi_{SC1}} d\phi_{SC1} + \frac{\partial F}{\partial \omega_{SC1}} d\omega_{SC1} + \frac{\partial F}{\partial \kappa_{SC1}} d\kappa_{SC1} \\ & + \frac{\partial F}{\partial \phi_{I1}} d\phi_{I1} + \frac{\partial F}{\partial \omega_I} d\omega_I + \frac{\partial F}{\partial \kappa_I} d\kappa_I + V_0 \end{aligned} \quad (9)$$

Where V is the correction terms of the observations, $d\phi_{SC1}$, $d\omega_{SC1}$, $d\kappa_{SC1}$, $d\phi_{I1}$, $d\omega_I$ and $d\kappa_I$ are the correction terms of ϕ_{SC1}, ω_{SC1}, κ_{SC1}, ϕ_I, ω_I and κ_I, $\frac{\partial F}{\partial \phi_{SC1}}, \frac{\partial F}{\partial \omega_{SC1}}, \frac{\partial F}{\partial \kappa_{SC1}}, \frac{\partial F}{\partial \phi_{I1}}, \frac{\partial F}{\partial \omega_I}$ and $\frac{\partial F}{\partial \kappa_I}$ are the first-order partial derivatives of $F = R_{1j} - R_{SC1} R_{HV1j} R_I$ $(j = 1, 2, \ldots, N)$

in accordance with the unknowns, V_0 is the constant matrix calculated by the approximate values of the unknowns.

The matrices in Equation (9) are in three columns and rows. Therefore, the corresponding items of all the matrices are extracted to compose nine error equations for convenience of calculation. Taking the initial values of ϕ_{SC1}, ω_{SC1}, κ_{SC1}, ϕ_I, ω_I and κ_I as iterated initial values of unknowns, the normal equations are constructed and calculated by overall adjustment as Equation (8). The precise value of R_{SC1} and T_I are constructed by the final iterated results.

3.2. Calibration of the deviation matrix

To calculate the deviation matrix P_{C1}, the deviation models (refer to Equation (6)) of images captured by the first station can be rewritten as follows:

$$P_{1j} = \begin{pmatrix} R_{SC1}R_{HV1j} & E \end{pmatrix}\begin{pmatrix} T_I \\ P_{C1} \end{pmatrix}(j = 1, 2, \ldots, N) \quad (10)$$

Where E is the identity matrix, P_{C1} is the coordinate matrix of P_C in the object space coordinate system of the first survey station.

Taking $X = (T_I, P_{C1})^T$ as unknowns, the normal equations are constructed and calculated by overall adjustment as Equation (8). Then, the precise value of T_I is acquired. The flow chart of calibrating the rotation matrix and deviation matrix is shown in Figure 3.

4. Calculation of exterior orientation parameters

Once the rotation matrix and deviation matrix are calibrated by the data of images of the first survey station, the exterior orientation parameters of the images of other survey stations can be automatically calculated taking advantages of the vertical and horizontal rotation angles. The angles are recorded as θ_{Hij} and $\theta_V ij$, respectively; where, the subscript i and $j\,(i,j = 1, 2, \ldots, N)$ identifies the station number and the image number. The exterior orientation parameters of the first image of each other station is recorded as $(\phi_{i1}, \omega_{i1}, \kappa_{i1}, X_{Si1}, Y_{Si1}, Z_{Si1})$ $(i = 1, 2, \ldots, N)$. The rotation matrix of the exterior orientation parameters R_{i1} and the coordinate matrix of the exterior orientation parameters P_{i1} are constructed according to Equation (2). The rotation matrix between the standard position coordinate system and the rotation coordinate system R_{HVij} is constructed according to Equation (4).

The rotation matrix between the object space coordinate system and the standard position coordinate system of the i survey station $R_{SCi}\,(i = 1, 2, \ldots, N)$ is calculated as follows:

$$R_{SCi} = R_{i1}R_I^{-1}R_{HVi1}^{-1} \quad (11)$$

The coordinate matrix of P_C in the object space coordinate system of the i survey station $P_{Ci}\,(i = 1, 2, \ldots, N)$ is calculated as follows:

$$P_{Ci} = P_{i1} - R_{SCi}R_{HVi1}T_I \quad (12)$$

The rotation matrix $R_{ij}\,(i = 1, 2, \ldots N)$ and the coordinate matrix $P_{ij}\,(i = 1, 2, \ldots, N)$ of the exterior orientation parameters of other images of the i survey station are calculated according to Equations (1) and (6). They are decomposed to be the six exterior orientation parameters, finally. The flow chart of calculating the exterior orientation parameters is shown in Figure 4.

5. Experiments and results

To verify the performance of the calibration method proposed in this study, survey data from Wumen wall of the Forbidden City were used for experiments. A Cannon digital camera with a focal length of 50 mm is mounted on the platform of the rotation photogrammetric system. Eight survey stations were set up along the wall at a distance of about 25 m. Four to eight images were captured by the system at each survey station from different directions. The horizontal and vertical rotation angles of each image were automatically recorded. The

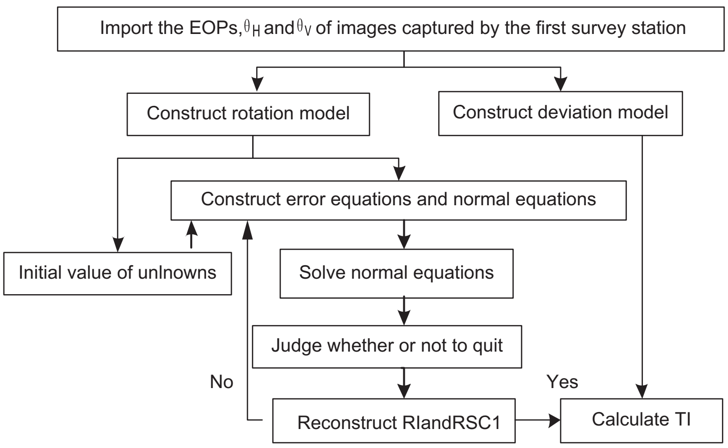

Figure 3. Flow chart of calibrating the rotation matrix and deviation matrix.

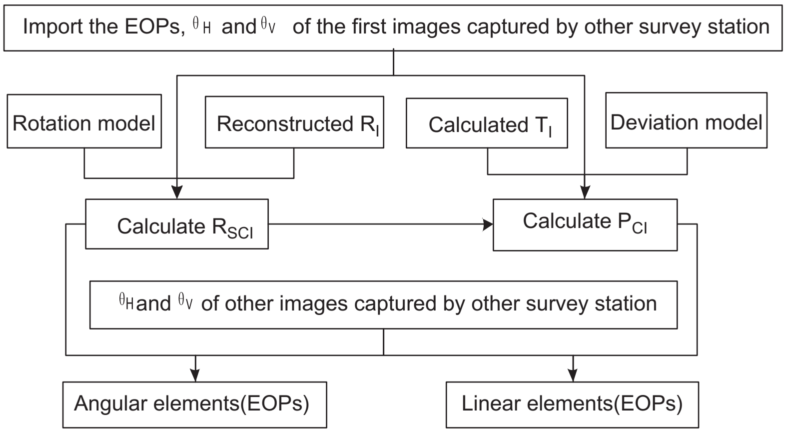

Figure 4. Flow chart of calculating the exterior orientation parameters.

Table 1. Actual accuracy of the exterior orientation parameters of each station.

Items	ϕ (rad)	ω (rad)	κ (rad)	X_s (m)	Y_s (m)	Z_s (m)
No. 2 survey station (3 images)	0.000698	0.000469	0.000031	0.001988	0.003014	0.002933
No. 3 survey station (3 images)	0.000082	0.000173	0.000046	0.002873	0.005807	0.002756
No. 4 survey station (3 images)	0.000208	0.000510	0.000058	0.006016	0.005392	0.002580
No. 5 survey station (7 images)	0.000288	0.000441	0.000054	0.002808	0.003775	0.004351
No. 6 survey station (7 images)	0.000592	0.000487	0.000085	0.002432	0.004158	0.003261
No. 7 survey station (7 images)	0.000316	0.000648	0.000085	0.002161	0.004293	0.000810
No. 8 survey station (7 images)	0.000518	0.000496	0.000141	0.002489	0.006241	0.001183

physical pixel size of the camera is 0.0064 mm; thus, the ground sample distance is about 3.2 mm. The exterior orientation parameters of the images are precisely calculated by block adjustment. The unit weight root mean square (RMS) error of bundle adjustment is 0.0018 mm (equal to 0.28 pixels).

Four images of the first survey station were used for calibration. The horizontal and vertical rotation angles and the exterior orientation parameters of the first station are taken as known during calibration. The solutions to ϕ_I, ω_I and κ_I were 0.056692, -0.027153 and 0.000622 rad, respectively. The RMS error was 0.000123 rad and their theoretical accuracy was about 0.000349 rad. The solutions to s, h and d were 0.002695, 0.070068, and -0.050236 m, respectively. The RMS error is 0.002848 m and the theoretical accuracy was about 0.003696 m.

After precise calibration, the exterior orientation parameters of the first images of a certain survey stations are taken as known to predict the exterior orientation parameters of the rest images. Based on the calibration method proposed in this study, the actual accuracies of the exterior orientation parameters of other images of each station were calculated by the calibrated parameters and are shown in Table 1.

The actual accuracy of the angular elements ϕ, ω and κ reaches to a few ten thousandth of a radian, with the maximum and minimum errors to be 0.0011 and 0.000054 rad, 0.000936 and 0.000072 rad, 0.000258 and 0.000035 rad, respectively. The actual accuracy of the linear elements X_S, Y_S and Z_S are at a millimetre level, with the maximum and minimum errors to be 0.008292 and 0.000075 m, 0.008982 and 0.000082 m, 0.005932 and 0.000203 m, respectively. The exterior orientation parameters of other images are calculated precisely based on the calibration method proposed in this study. Hence, this method is meaningful for high-precision 3D reconstruction in practice.

6. Conclusions and future work

According to the detailed analysis of the structure of the rotation photogrammetric system, this study promotes a novel calibration method utilizing the exterior orientation parameters, horizontal and vertical rotation angles of images captured by one survey station. High precision orientation and positioning of the system are realized by overall adjustment with multi-images. Supposing that the exterior orientation parameters of the first image of a certain survey station are known, the exterior orientation parameters of the other images can be automatically calculated making use of the calibration result.

The real data experiments of the Wumen wall of the Forbidden City verify the excellent performance of the proposed method. The study is meaningful for high-precision calibration and 3D reconstruction by the rotation photogrammetric system. Furthermore, the relative orientation and position between the survey stations can be measured during the layout of the survey network. The exterior orientation parameters of the first image of other survey stations are no longer needed, which makes the 3D reconstruction work more practical and convenient. Thus, the modified calibration method and error propagation regulation need to be further investigated in the future.

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