Measurement and Precision Analysis of Exterior Orientation Element Based on Landmark Point Auxiliary Orientation

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ABSTRACT: Obtaining the interior and exterior orientation elements and distortion parameters of camera is critical in the applications of photogrammetric survey and computer vision on recovering object position and angular orientation. While being used outside as supervision devices monitoring objects in the air, cameras are generally installed in non-calibration designated regions with high erection and elevation postures within their view distance over the sky. Therefore, it is really hard to obtain the exterior orientation element of camera. In order to solve this problem, this paper proposed a method to obtain the exterior orientation element of camera outdoors by applying landmark point auxiliary orientation and to obtain the interior and exterior orientation elements and distortion coefficient of camera by using self-check bundle adjustment in indoor three-dimensional control field. Thus, the transformational relations between the landmark points of different positions could be calculated according to the method of landmark point auxiliary orientation. The exterior orientation elements of camera could be recovered through transformational relations, and the position and posture of recovered camera in outdoor non-calibration designated field could be simulated accordingly. The experiential results show that the exterior orientation elements of camera can be effectively recovered through the method of landmark point auxiliary orientation while certain high intersection precision can be maintained.

Keywords: exterior orientation elements; bundle adjustment; landmark point auxiliary orientation

1 INTRODUCTION

In three-dimensional measurement, camera is commonly used as measuring equipment. Two or more cameras are usually used to obtain the three-dimensional information of targets. While using cameras for measurement, the interior and exterior orientation elements and distortion parameters of each camera can be obtained by camera calibration. And we use feature extraction to obtain the homonymy points in images and take the method of forward intersection to get the spatial positions of targets. At present, two or more cameras fixed through geometrical relationship are commonly applied in three-dimensional reconstruction and engineering measurement [1, 2].

The precondition of recovering the accurate beam shape during photographing is to obtain the exact positions, postures and distortion parameters of cameras. Since camera was used in computer vision, relevant scholars have proposed different camera models and calibration methods. Space resection method, Tsai’s two-stage method [3], three-dimensional DLT method [4, 5], Zhengyou Zhang calibration method [6], two-dimensional DLT demarcating method [7, 8], camera self-calibration method based on vanishing point [9, 10], and bundle adjustment based on collinearity equation. Part parameters and different models can be selected for calibration according to objectives and accuracy needs to be reached. Among photographing measuring methods, the demarcating method of bundle adjustment model based on collinearity equation is the strictest one. However, as it is a nonlinear demarcating method which needs linearization, original values of parameters need to be provided for ensuring iteration convergence.

When cameras are installed outdoors in non-calibration field with high erection and elevation, it is impracticable to establish special demarcating facilities for each camera in order to obtain high-precision camera parameters. This paper added auxiliary landmark points on camera shell and conducted camera calibration in indoor three-dimensional control field to obtain the interior and exterior parameters and distortion parameters of camera. The exterior orientation
elements of camera in outdoor non-calibration field were simulated and recovered by calculating the transformational relations between the auxiliary landmark points of cameras in different positions within the control field. Camera parameters were calculated through the transformational relations of auxiliary landmark points while homologous image points were obtained by extracting the point coordinates of the three-dimensional points in the control field. Thus, the three-dimensional coordinates of the control points were obtained from the exterior orientation element intersection calculated through the transformational relations. In the end, the three-dimensional coordinates were compared with the truth-values of the control points for precision analysis.

2 RESEARCH METHOD

Six landmark points were set on camera shell in indoor three-dimensional calibration field as shown in Figure (1). In the control field, camera was in angle of elevation. The camera took photos of the three-dimensional calibration field in three different positions and used total station to measure the locations of the landmark points on camera shell in the three photographing positions. Camera calibration was conducted by applying the homologous image points and the coordinates of corresponding control points in accordance with three-dimensional DLT-bundle adjustment to obtain the camera parameters on Position 1. Use whole station to measure the landmark points and obtain the point coordinate.

2.1 Camera calibration and measurement of landmark points on camera shell

Apply feature extraction method to extract the image point coordinates of the control point on the image. As the three-dimensional field has been calibrated, the extracted image point coordinates can be numbered. The points sharing the same numbers in different
photos are thus called homologous image points.

As the interior parameters of camera are unknown and contain radial distortion, tangential distortion and affine distortion, it is necessary to do camera calibration and calculate the interior orientation elements, the exterior orientation elements and the distortion parameters of camera in order to ensure the imaging effect and precision. Camera calibration is to establish model according to the known object space points and their corresponding image points. Calculate geometric parameters and optical parameters of camera so as to recover the right beam shape during photographing. In photographing measurement, the bundle adjustment model based on collinearity equation is a nonlinear calibration method which needs linearization. Therefore, the original values of the parameters shall be provided to ensure iteration convergence. As a result, exterior orientation elements can be used as the original values of bundle adjustment and can be obtained by applying three-dimensional DLT method. Then bring the exterior orientation elements in bundle adjustment to calculate the parameters.

The process of camera calibration is as follows:

1. Use the camera to take more than 3 images in the control field.
2. Precisely extract the image point coordinates of the control point imaging of each image.
3. Use three-dimensional DLT method to obtain the interior and exterior orientation elements of camera as the original values of bundle adjustment.
4. Use bundle adjustment to obtain calibration parameters.

Figure 3. The workflow of camera calibration.

See the model of three-dimensional DLT below:

\[
\begin{align*}
  x + l_1X + l_2Y + l_3Z + l_4 &= 0 \\
  y + l_1X + l_2Y + l_3Z + l_4 &= 0
\end{align*}
\] (1)

Unfold the equations to obtain the equations of unknown numbers:

\[
\begin{align*}
  l_1X + l_2X + l_3X + l_4X + 0 + 0 + 0 + + \\
  x_1l_1X + x_2l_2Y + x_3l_3X + x + 0 + 0 + \\
  0 + 0 + 0 + l_1X + l_2X + l_3X + l_4X + \\
  y_1l_1X + y_2l_2X + y_3l_3X + y + 0
\end{align*}
\] (2)

Constitute the equations and apply the least square method to obtain the matrixes of the unknown numbers. Then, calculate the exterior orientation elements:

\[
\begin{align*}
  l_1X + l_2Y + l_3Z = -l_4 \\
  l_4X + l_1X + l_2Y + l_3Z = -l_4
\end{align*}
\] (3)

The original values of the exterior orientation elements can be obtained. As no interior orientation element of camera is needed in three-dimensional DLT model, this model is significantly important for non-metric camera. To calculate the 11 parameters, at least 6 flat high points are required which shall not be placed on the same plane.

Take the exterior orientation elements obtained from three-dimensional DLT method as bundle adjustment to calculate the original values of the exterior orientation elements. After completing compensating computation through bundle adjustment, beam shape can be better recovered and the interior orientation elements of camera can be obtained. In general, there’s distortion in camera lens. Major distortion can impact on the calibration precision of the camera. Therefore, distortion correction parameters need to be included in adjustment model.

The beam model with the distortion correction parameters set in references [11, 12]:

\[
\begin{align*}
  x - x_0 - \Delta x &= -f \frac{X}{Z} \\
  y - y_0 - \Delta y &= -f \frac{Y}{Z}
\end{align*}
\] (4)

Among which there are focal distances of two directions belonging to interior orientation element.

Intersection-angle system is applied in rotation matrix

Among which:

\[
\begin{align*}
  a_1 &= \cos \phi \cos\omega - \sin \phi \sin \omega \sin k \\
  a_2 &= -\cos \phi \sin\omega - \sin \phi \cos \omega \\
  a_3 &= -\sin \phi \cos \omega \\
  b_1 &= \cos \phi \sin k \\
  b_2 &= \cos \phi \cos k \\
  b_3 &= -\sin \omega \\
  c_1 &= \sin \phi \cos k + \cos \phi \sin \omega \sin k \\
  c_2 &= -\sin \phi \sin k + \cos \phi \cos \omega \\
  c_3 &= \cos \phi \cos \omega
\end{align*}
\]

Distortion correction model is as follows:
\[ \Delta x = (x - x_0)(K_r^2 + K_v^2) + P_1(r^2 + 2(x - x_0)^2) + 2P_2(x - x_0)(y - y_0) \]
\[ \Delta y = (y - y_0)(K_r^2 + K_v^2) + P_1(r^2 + 2(x - x_0)^2) + 2P_2(x - x_0)(y - y_0) \]  \hfill (5)

Among which there are radial distortion parameters, tangential distortion parameters, pixel coordinates, and principal point coordinates.

Conduct linearization to collinearity equation and obtain the error equation as follows:
\[
\begin{align*}
& v = \frac{\partial X}{\partial x} \Delta x + \frac{\partial X}{\partial y} \Delta y + \frac{\partial X}{\partial R} \Delta R + \frac{\partial X}{\partial \beta} \Delta \beta + \frac{\partial X}{\partial \gamma} \Delta \gamma - x_s + \Delta x \quad (6) \\
& v = \frac{\partial X}{\partial x} \Delta x + \frac{\partial X}{\partial y} \Delta y + \frac{\partial X}{\partial R} \Delta R + \frac{\partial X}{\partial \beta} \Delta \beta + \frac{\partial X}{\partial \gamma} \Delta \gamma + \Delta x \quad (6)
\end{align*}
\]

\[
\begin{align*}
l_1 &= (x - x_0 - \Delta x) + f \frac{x}{f} \\
l_2 &= (y - y_0 - \Delta y) + f \frac{y}{f}
\end{align*}
\]  \hfill (7)

Formula (6) can be written into an indirect adjustment model which can be calculated according to indirect adjustment method.

2.2 Obtaining exterior orientation elements of camera

After cameras are installed in outdoor places such as non-calibration field, auxiliary landmark points are applied for orientation as it is hard to install camera calibration equipment within the visible range of camera because of camera installation height and angle. The orientation model in accordance with references [11, 12] is as follows:
\[
\begin{align*}
X_x' &= \left[ a_1 \quad a_2 \quad a_3 \right] X_x + \Delta X \\
Y_y' &= \left[ b_1 \quad b_2 \quad b_3 \right] Y_y + \Delta Y \\
Z_z' &= \left[ c_1 \quad c_2 \quad c_3 \right] Z_z + \Delta Z
\end{align*}
\]  \hfill (8)

Among which, use whole station to measure the coordinates of the landmark points on camera shell in calibration field and use whole station to measure the coordinates of the landmark points on camera shell in non-calibration field. As the model is a rigid body transformation model, the zooming parameter of the transformation matrix is 1. And the direction cosines are the orientation elements which need to be solved. There shall be at least two horizontal & vertical control points with one vertical control point in the solving model. All the three control points cannot be on the same line.

Complete transformation for the exterior orientation elements of camera in calibration field by using the obtained rotation matrix and the translation matrix, so as to obtain the exterior orientation elements of camera in non-calibration field. Assume the exterior orientation elements of the same camera on the first position are respectively φ, ω, κ, X_s, Y_s and Z_s, and the exterior orientation elements of the same camera on the second position are respectively φ', ω', κ', X_s', Y_s' and Z_s', the transformation relation between them can be described as:
\[
\begin{align*}
X_s' &= \begin{bmatrix} a_1 & a_2 & a_3 \end{bmatrix} X_s + \Delta X \\
Y_s' &= \begin{bmatrix} b_1 & b_2 & b_3 \end{bmatrix} Y_s + \Delta Y \\
Z_s' &= \begin{bmatrix} c_1 & c_2 & c_3 \end{bmatrix} Z_s + \Delta Z \\
R(\varphi' \omega' \kappa') &= R(\varphi \omega \kappa) R(\varphi' \omega' \kappa')
\end{align*}
\]  \hfill (9)

2.3 Use homologous image points to do forward intersection and precision analysis

Use the homologous image points, the interior parameters of camera, the distortion parameters of camera and the exterior orientation elements recovered through Formula (9) to solve the coordinates of object space points. The applied model is in accordance with Formula (4) and Formula (5). And the unfolded formula is as follows:
\[
\begin{align*}
(x - x_0 - \Delta x) &= a_0(x - x_0) + b_0(y - y_0) + c_0(Z - z_0) \\
(y - y_0 - \Delta y) &= a_1(x - x_0) + b_1(y - y_0) + c_1(Z - z_0) \\
(Z - z_0) &= a_2(x - x_0) + b_2(y - y_0) + c_2(Z - z_0)
\end{align*}
\]  \hfill (10)

\[
\begin{align*}
l_1 X + l_1 Y + l_1 Z - l_1 &= 0 \\
l_2 X + l_2 Y + l_2 Z - l_2 &= 0
\end{align*}
\]  \hfill (11)

Among which:
\[
\begin{align*}
l_1 &= f a_1 + f(x - x_0 - \Delta x) a_1 + l_2 = f b_1 + f(x - x_0 - \Delta y) b_1 + l_3 = f c_1 + (x - x_0 - \Delta z) c_1, \\
l_4 &= f a_2 + f(x - x_0 - \Delta x) a_2 + l_5 = f b_2 + f(y - y_0 - \Delta y) b_2 + l_6 = f c_2 + (y - y_0 - \Delta z) c_2, \\
l_7 &= f a_3 + f(x - x_0 - \Delta x) a_3 + l_8 = f b_3 + f(y - y_0 - \Delta y) b_3 + l_9 = f c_3 + (y - y_0 - \Delta z) c_3,
\end{align*}
\]

For a pair of homologous points, there are four equations which can be listed to solve three unknown numbers. As the equation set is linear, no original value is required in the equations.

Use the coordinates of the control points obtained from intersection and those of the actual control points to solve the mean square error in the model.

3 TESTING AND ANALYSIS

German Basler cameras with 5mm lens were used on the spot. Six reflect-light membranes were attached to the periphery of the cameras for whole station obser-
vation. Simulation was conducted in the calibration field for the experiment. At first, the cameras were placed on 3 positions and calibration was made in accordance with bundle adjustment to obtain the camera parameters on the 3 positions. And then, Position 2 and Position 3 were made to simulate the positions in non-calibration field. Auxiliary landmark point orientation was used to recover camera parameters.

During the experiment, the same camera was used to take photos of the control field on 3 different positions. Whole station was used to measure the 6 reflect-light membranes attached to the camera shell on each position. Photos of the calibration field were taken on Position 1, Position 2 and Position 3. On Position 2 and Position 3, control points were extracted on images and 128 homologous points were obtained. Three-dimensional DLT-bundle adjustment method was applied to solve the interior orientation elements, the exterior orientation elements and the distortion coefficient of the camera. Through forward intersection, the coordinates of the control points were obtained. The difference value between the obtained coordinates and the coordinates of the known control points is shown in Figure 4. The mean square error was 2.1038mm. Data from whole station measurement was processed to obtain the positions of the six points on camera shell as shown in Figure 1. And the transformation parameters of the 6 points on Position 1 and

![Figure 4. The distribution of the difference between the control point coordinate and the result of the method of front section with the exterior orientation elements calculated by bundle adjustment: (a) is plane error distribution; (b) is the error distribution of depth direction error distribution; (c) is the point error distribution.](image)

![Figure 5. The distribution of the difference between the control point coordinate and the result of the method of front section with the the exterior orientation elements calculated by the auxiliary landmarks: (d) is plane error distribution; (e) is the Error distribution; of depth direction Error distribution; (f) is the point error distribution.](image)

<table>
<thead>
<tr>
<th>Number of landmark point</th>
<th>Position 1(X, Y, Z) (mm)</th>
<th>Position 2(X, Y, Z) (mm)</th>
<th>Position 3(X, Y, Z) (mm)</th>
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<td>1</td>
<td>2738.77, −2735.58, 16.21</td>
<td>4129.41, −2729.56, 17.28</td>
<td>1304.29, −2749.75, 14.95</td>
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<td>2701.69, −2703.23, 118.96</td>
<td>4083.37, −2707.98, 119.17</td>
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<td>2607.46, −2702.29, 119.13</td>
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<td>5</td>
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<th>Position</th>
<th>Xs (mm)</th>
<th>Ys (mm)</th>
<th>Zs (mm)</th>
<th>(Radian measure)</th>
<th>(Radian measure)</th>
<th>(Radian measure)</th>
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<tr>
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<td>42.6276</td>
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<td>Position 2</td>
<td>4049.898</td>
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<td>−0.08812</td>
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<td></td>
<td>Position 3</td>
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<td>44.1632</td>
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<td>Through relation transformation of landmark point</td>
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<td></td>
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<td>−0.03480</td>
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<th>fx(Pixel)</th>
<th>fy(Pixel)</th>
<th>x0(Pixel)</th>
<th>y0(Pixel)</th>
<th>K1</th>
<th>K2</th>
<th>P1</th>
<th>P2</th>
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<tbody>
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</table>
the 6 points on Position 2 were solved. The transformation parameters of the 6 points on Position 1 and the 6 points on Position 3 were solved. Formula (9) was used to solve the sum of the exterior orientation elements of Position 2 and Position 3. Coordinates of object space point was got from forward intersection. Comparison was made between the obtained coordinates and the known values of the control points. See Figure 5 for the involved different values. The mean square error in this method was $20.5813 \text{mm}$. The experiment has shown that when the base-height ratio is 1:3, the point precision obtained from auxiliary landmark point orientation will be around 20mm. This method can better recover the posture of camera in non-calibration field.

4 CONCLUSION

This paper studied how to recover camera parameters in non-calibration fields such as outdoor area. As a result, camera calibration method based on auxiliary landmark point can effectively solve the problem of completing camera calibration in the wild. Compared with camera calibration indoors, the method proposed in this paper is simple, easy and convenient for construction with high precision. By analyzing the experimental results, it has been proved that the method of auxiliary landmark point orientation can still obtain good exterior orientation elements of camera and intersection precision in outdoor non-calibration field. And this method can be applied in non-calibration field by using camera in tracking, detection, orientation and model establishment.

REFERENCES