RESEARCH ON CLOSE-RANGE PHOTOGRAMMETRY WITH BIG ROTATION ANGLE

Lu Jue[a]

[a]The Department of Surveying and Geo-informatics Engineering, Tongji University, Shanghai, 200092. - lujue1985@126.com

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ABSTRACT:

This paper studies the influence of big rotation angles on the classical solution of analytical process. Close-range photogrammetry differs from traditional aerial photogrammetry, for the former usually adopts oblique photography or convergent photography, while the latter is similar to take vertical photos wherein the orientation elements are very small. In this paper, an exploration of the algorithm in every step of the analytical process from dependent relative orientation to absolute orientation is described. In order to emphasize the differences, contrasts will be made between the solution of the classical aerial photography and the algorithm of the close-range photogrammetry. A practical close-range photogrammetry experiment is presented to demonstrate this new algorithm. Through the example, it is pointed that with this new algorithm, the coordinates of the ground points and the exterior orientation can be accurately calculated. The results indicate that the algorithm deduced in this paper is applicable in the close-range photogrammetry with big rotation angle.

1. INTRODUCTION

Close-range photogrammetry determines the shape, size, and geometric position of close targets with photogrammetric technology [1]. Close-range photogrammetry differs from traditional aerial photogrammetry in several ways. For example, the former usually takes oblique or convergent photographs, so the rotation angles in the exterior orientation elements are often very big and the discrepancies between the adjacent camera stations' three-dimensional coordinates will also be quite large, while the latter is similar to taking vertical photos wherein the orientation elements are very small. So in the field of close-range photogrammetry, performance of every step of the analytical process, such as dependent relative orientation, space intersection, strip formation process, absolute orientation and space resection, etc, a simplified model with small angles or a simple mathematical model can not be continued to use to calculate the parameters or coordinates that we need.

In this paper, an exploration of the algorithm in every step of the analytical process in close-range photogrammetry is described. Special emphasis is placed on the contrasts between the solution of the classic aerial photography and the close-range photogrammetry. And corresponding examples will be presented to explain and verify the algorithm.

2. BASIC PRINCIPLE OF SPACE RESECTION AND TLS

Collinearity condition equations are essential in analytical photogrammetry. The fundamental theory of the collinearity equations is that the perspective center, the image point, and the corresponding object point all lie on a line. Based on these equations, image and object coordinate systems will be related by three position parameters and three orientation parameters, called exterior orientations [2]. No matter what format of the three orientation parameters are present, they will be implicitly expressed in the nine elements of a 3×3 orthogonal rotation matrix R. So the collinearity equations can be expressed as follow:

$$x - x_0 = -f\,\frac{a_1(X - X_s) + b_1(Y - Y_s) + c_1(Z - Z_s)}{a_3(X - X_s) + b_3(Y - Y_s) + c_3(Z - Z_s)} \qquad (1)$$

$$y - y_0 = -f\,\frac{a_2(X - X_s) + b_2(Y - Y_s) + c_2(Z - Z_s)}{a_3(X - X_s) + b_3(Y - Y_s) + c_3(Z - Z_s)}$$

$$R = \begin{bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{bmatrix} \qquad (2)$$

Where (x_0, y_0, f) are the interior orientations. (X, Y, Z) and (X_s, Y_s, Z_s) are the object space coordinates of the ground points and the perspective centres. a_1、a_2、a_3、b_1、b_2、b_3、c_1、c_2、c_3 are the 9 elements of the rotation matrix. In resection, once the interior parameters are known, the collinearity equations can be employed to determine 6 exterior orientation parameters. With more than 3 control points, to estimate better results, we linearize the collinearity equations and introduce the Least Square method [3]. However, good initial values are required for the LS estimation process to converge to appropriate values [2].

In traditional aerial photogrammetry, the initial values of three orientation parameters can be set at zeros, for its vertical manner [4]. But in close-range photogrammetry with big rotation angles, if they are still zeros, the process may not converge to proper results. So we need to determine the exterior orientations without the knowledge of their approximate values.

In this paper, the collinearity solution based on the orthogonal matrix is applied. In this method, the nine elements of the matrix are used instead of the three angles, with three position parameters to take the roles of the unknown. The linear observation equations can then be made along with six additional condition equations based on the orthogonal conditions of the rotation matrix ($RR^T=R^TR=I$) [5], the 6 orthogonal conditions are :

$$\begin{cases} a_1^2+a_2^2+a_3^2=1 \\ b_1^2+b_2^2+b_3^2=1 \\ c_1^2+c_2^2+c_3^2=1 \\ a_1\times a_2+b_1\times b_2+c_1\times c_2=0 \\ a_1\times a_3+b_1\times b_3+c_1\times c_3=0 \\ a_2\times a_3+b_2\times b_3+c_2\times c_3=0 \end{cases} \tag{3}$$

Then the adjustment with conditions is applied. The expressions of the error equations are:

$$v = Ax - l$$

$$v = \begin{bmatrix} v_x \\ v_y \end{bmatrix}, l = \begin{bmatrix} l_x \\ l_y \end{bmatrix} = \begin{bmatrix} x-(x) \\ y-(y) \end{bmatrix}$$

$$x^T = \begin{bmatrix} dX_s & dY_s & dZ_s & da_1 & da_2 & da_3 & db_1 & db_2 & db_3 & dc_1 & dc_2 & dc_3 \end{bmatrix}$$

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} & a_{18} & a_{19} & a_{20} & a_{21} & a_{22} \\ b_{11} & b_{12} & b_{13} & b_{14} & b_{15} & b_{16} & b_{17} & b_{18} & b_{19} & b_{20} & b_{21} & b_{22} \end{bmatrix}$$

$$= \begin{bmatrix} \frac{\partial x}{\partial X_s} & \frac{\partial x}{\partial Y_s} & \frac{\partial x}{\partial Z_s} & \frac{\partial x}{\partial a_1} & \frac{\partial x}{\partial a_2} & \frac{\partial x}{\partial a_3} & \frac{\partial x}{\partial b_1} & \frac{\partial x}{\partial b_2} & \frac{\partial x}{\partial b_3} & \frac{\partial x}{\partial c_1} & \frac{\partial x}{\partial c_2} & \frac{\partial x}{\partial c_3} \\ \frac{\partial y}{\partial X_s} & \frac{\partial y}{\partial Y_s} & \frac{\partial y}{\partial Z_s} & \frac{\partial y}{\partial a_1} & \frac{\partial y}{\partial a_2} & \frac{\partial y}{\partial a_3} & \frac{\partial y}{\partial b_1} & \frac{\partial y}{\partial b_2} & \frac{\partial y}{\partial b_3} & \frac{\partial y}{\partial c_1} & \frac{\partial y}{\partial c_2} & \frac{\partial y}{\partial c_3} \end{bmatrix} \tag{4}$$

If $\overline{Z} = (a_3 \times (X - X_S) + b_3 \times (Y - Y_S) + c_3 \times (Z - Z_S))$, then the elements in the coefficient matrix A are:

$$\begin{array}{ll} a_{11} = (a_1 \times f + a_3 \times (x - x_0)) / \overline{Z}, & b_{11} = (a_2 \times f + a_3 \times (y - y_0)) / \overline{Z} \\ a_{12} = (b_1 \times f + b_3 \times (x - x_0)) / \overline{Z}, & b_{12} = (b_2 \times f + b_3 \times (y - y_0)) / \overline{Z} \\ a_{13} = (c_1 \times f + c_3 \times (x - x_0)) / \overline{Z}, & b_{13} = (c_2 \times f + c_3 \times (y - y_0)) / \overline{Z} \\ a_{14} = -f \times (X - X_S) / \overline{Z}, & b_{14} = 0 \\ a_{15} = 0, & b_{15} = -f \times (X - X_S) / \overline{Z} \\ a_{16} = -(x - x_0) \times (X - X_S) / \overline{Z}, & b_{16} = -(y - y_0) \times (X - X_S) / \overline{Z} \\ a_{17} = -f \times (Y - Y_S) / \overline{Z}, & b_{17} = 0 \\ a_{18} = 0, & b_{18} = -f \times (Y - Y_S) / \overline{Z} \\ a_{19} = -(x - x_0) \times (Y - Y_S) / \overline{Z}, & b_{19} = -(y - y_0) \times (Y - Y_S) / \overline{Z} \\ a_{20} = -f \times (Z - Z_S) / \overline{Z}, & b_{20} = 0 \\ a_{21} = 0, & b_{21} = -f \times (Z - Z_S) / \overline{Z} \\ a_{22} = -(x - x_0) \times (Z - Z_S) / \overline{Z}, & b_{22} = -(y - y_0) \times (Z - Z_S) / \overline{Z} \end{array} \tag{5}$$

And the condition equations can be written as:

$$Cx + W = 0$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 2a_1 & 2a_2 & 2a_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 2b_1 & 2b_2 & 2b_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2c_1 & 2c_2 & 2c_3 \\ 0 & 0 & 0 & a_2 & a_1 & 0 & b_2 & b_1 & 0 & c_2 & c_1 & 0 \\ 0 & 0 & 0 & a_3 & 0 & a_1 & b_3 & 0 & b_1 & c_3 & 0 & c_1 \\ 0 & 0 & 0 & 0 & a_3 & a_2 & 0 & b_3 & b_2 & 0 & c_3 & c_2 \end{bmatrix}$$

$$W = \begin{bmatrix} a_1^2 + a_2^2 + a_3^2 - 1 \\ b_1^2 + b_2^2 + b_3^2 - 1 \\ c_1^2 + c_2^2 + c_3^2 - 1 \\ a_1 a_2 + b_1 b_2 + c_1 c_2 \\ a_1 a_3 + b_1 b_3 + c_1 c_3 \\ a_2 a_3 + b_2 b_3 + c_2 c_3 \end{bmatrix} \tag{6}$$

This process has eliminated the need for differentiating the nonlinear observation equations and it can be used for any angle regardless of the format of the three ratios and what size they are.

3. ALGORITHM OF THE ANALYTICAL PROCESS WITH BIG ROTATION ANGLES

3.1 Dependent Relative Orientation

The model coordinate system in dependent relative orientation is parallel to the first image's coordinate system, leaving two position parameters and the three orientation parameters of the second image with respect to the model coordinate system to be determined. In one image pair, if the left and the right images' space coordinates are S_1-$X_1Y_1Z_1$ and S_2-$X_2Y_2Z_2$, the coordinates of the image points A_1, A_2 in these two coordinate systems are (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2), and the coordinates of the perspective centre S_2 in coordinate system S_1-$X_1Y_1Z_1$ are (B_x, B_y, B_z), then the coplanarity condition equations can be expressed as follow:

$$F = \begin{vmatrix} B_x & B_y & B_z \\ X_1 & Y_1 & Z_1 \\ X_1 + B_x & Y_1 + B_y & Z_1 + B_z \end{vmatrix} = \begin{vmatrix} B_x & B_y & B_z \\ X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \end{vmatrix} = 0 \tag{7}$$

In aerial photogrammety, since the perspective centres lie in nearly a straight line, the usual procedure is to extract the component of the base line B_x, and then B_y, B_z can be expressed by minute angles, like μ and ν. With the other three rotation angles, the five relative orientation parameters μ, ν, φ, ω, κ are formed. Then the coplanarity condition equations are simplified as:

$$F = B_x \begin{vmatrix} 1 & \mathrm{tg}\mu & \frac{\mathrm{tg}\nu}{\cos\mu} \\ X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \end{vmatrix} \approx B_x \begin{vmatrix} 1 & \mu & \nu \\ X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \end{vmatrix} \tag{8}$$

Where $(X_2, Y_2, Z_2)^T = R \times (X_1, Y_1, Z_1)^T$, and R is the rotation matrix from right image to left one, like equation (2). This method is available in the classic aerial photography, but in wide-angle photogrammetry, these five angles (five relative orientation parameters) are not small any more, so two problems may be arised.

First, since the values of the relative orientation parameters φ, ω, κ are very big, if the initial values are not appropriate enough, the LS estimation process of the nonlinear observation equations may not converge to right values. So the relative orientation solution based on the orthogonal matrix is employed.

Second, in the aerial photography, μ、ν are adopted instead of tanμ、tanν/cosμ, for the values of the two angles are small. This step can avoid the need for differentiating the nonlinear function. But in close-range photogrammetry, μ、ν may be big angles, so the simplified formats are not still suitable. The development of the solution is to calculate the three components of the base line B_x, B_y and B_z directly, not using the two angles μ、ν. So we use twelve unknowns, three of which are components of the base line, while the others are the nine elements of the rotation matrix. Since relative orientation involves the determination of five degrees of freedom, seven condition equations will be added after the observation equations: one for the limitation of base line components and the others based on the orthogonal conditions of the rotation matrix. The error equations are:

$$
\begin{gathered}
v = Ax - l \\
x^T = \begin{bmatrix} dB_x & dB_y & dB_z & da_1 & da_2 & da_3 & db_1 & db_2 & db_3 & dc_1 & dc_2 & dc_3 \end{bmatrix} \\
l = -F_0 = X_2Y_1B_z + X_1Z_2B_y + Y_2Z_1B_x - Y_1Z_2B_x - X_1Y_2B_z - X_2Z_1B_y \\
A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} & a_{18} & a_{19} & a_{20} & a_{21} & a_{22} \end{bmatrix} \\
= \begin{bmatrix} \frac{\partial F}{\partial B_x} & \frac{\partial F}{\partial B_y} & \frac{\partial F}{\partial B_z} & \frac{\partial F}{\partial a_1} & \frac{\partial F}{\partial a_2} & \frac{\partial F}{\partial a_3} & \frac{\partial F}{\partial b_1} & \frac{\partial F}{\partial b_2} & \frac{\partial F}{\partial b_3} & \frac{\partial F}{\partial c_1} & \frac{\partial F}{\partial c_2} & \frac{\partial F}{\partial c_3} \end{bmatrix}
\end{gathered} \tag{9}
$$

And the coefficients of the data matrix A are:

$$
\begin{aligned}
& a_{11} = \frac{\partial F}{\partial B_x} = Y_1Z_2 - Y_2Z_1, && a_{12} = \frac{\partial F}{\partial B_y} = X_2Z_1 - X_1Z_2 \\
& a_{13} = \frac{\partial F}{\partial B_z} = X_1Y_2 - X_2Y_1, && a_{14} = \frac{\partial F}{\partial a_1} = (x_2 - x_0)\times(B_yZ_1 - B_zY_1) \\
& a_{15} = \frac{\partial F}{\partial a_2} = (y_2 - y_0)\times(B_yZ_1 - B_zY_1), && a_{16} = \frac{\partial F}{\partial a_3} = (-f)\times(B_yZ_1 - B_zY_1) \\
& a_{17} = \frac{\partial F}{\partial b_1} = (x_2 - x_0)\times(B_zX_1 - B_xZ_1), && a_{18} = \frac{\partial F}{\partial b2} = (y_2 - y_0)\times(B_zX_1 - B_xZ_1) \\
& a_{19} = \frac{\partial F}{\partial b_3} = (-f)\times(B_zX_1 - B_xZ_1), && a_{20} = \frac{\partial F}{\partial c_1} = (x_2 - x_0)\times(B_xY_1 - B_yX_1) \\
& a_{21} = \frac{\partial F}{\partial c_2} = (y_2 - y_0)\times(B_xY_1 - B_yX_1), && a_{22} = \frac{\partial F}{\partial c_3} = (-f)\times(B_xY_1 - B_yX_1)
\end{aligned} \tag{10}
$$

The conditions are:

$$
\begin{cases}
B_x^{\,2} + B_y^{\,2} + B_z^{\,2} = B^2 \\
a_1^2 + a_2^2 + a_3^2 = 1 \\
b_1^2 + b_2^2 + b_3^2 = 1 \\
c_1^2 + c_2^2 + c_3^2 = 1 \\
a_1 \times a_2 + b_1 \times b_2 + c_1 \times c_2 = 0 \\
a_1 \times a_3 + b_1 \times b_3 + c_1 \times c_3 = 0 \\
a_2 \times a_3 + b_2 \times b_3 + c_2 \times c_3 = 0
\end{cases} \tag{11}
$$

Where B is the arbitrary constant, so the condition equations can be expressed as:

$$
\begin{gathered}
Cx + W = 0 \\
C = \begin{bmatrix}
2Bx & 2By & 2Bz & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 2a_1 & 2a_2 & 2a_3 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 2b_1 & 2b_2 & 2b_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2c_1 & 2c_2 & 2c_3 \\
0 & 0 & 0 & a_2 & a_1 & 0 & b_2 & b_1 & 0 & c_2 & c_1 & 0 \\
0 & 0 & 0 & a_3 & 0 & a_1 & b_3 & 0 & b_1 & c_3 & 0 & c_1 \\
0 & 0 & 0 & 0 & a_3 & a_2 & 0 & b_3 & b_2 & 0 & c_3 & c_2
\end{bmatrix} \\
W = \begin{bmatrix}
Bx^2 + By^2 + Bz^2 - B^2 \\
a_1^2 + a_2^2 + a_3^2 - 1 \\
b_1^2 + b_2^2 + b_3^2 - 1 \\
c_1^2 + c_2^2 + c_3^2 - 1 \\
a_1a_2 + b_1b_2 + c_1c_2 \\
a_1a_3 + b_1b_3 + c_1c_3 \\
a_2a_3 + b_2b_3 + c_2c_3
\end{bmatrix}
\end{gathered} \tag{12}
$$

By this means, the nonlinear function can be changed into linear one as to eliminate the process of differentiating and it can converge to the correct result quickly without the knowledge of the approximate values of the parameters. The process of the deduction is not complicated, and the construction of the coefficient of the adjustment equations is clear and concise.

3.2 Intersection

Intersection refers to the determination of a point's position in object space by intersecting the image rays from two or more images. Here the standard method will be used that is the application of the collinearity equations, with two equations for each image of the point. With this method, more than two images can be performed to calculate the coordinates of the model points, making it a strict solution and not bounded by the number of photos [6].

$$
\begin{aligned}
v_x &= \frac{\partial x}{\partial X} dX + \frac{\partial x}{\partial Y} dY + \frac{\partial x}{\partial Z} dZ - (x - (x)) \\
v_y &= \frac{\partial y}{\partial X} dX + \frac{\partial y}{\partial Y} dY + \frac{\partial y}{\partial Z} dZ - (y - (y))
\end{aligned} \tag{13}
$$

3.3 Bridging of Models

The essence of model link is to calculate the scale between the two adjoining modles [6]. In aerial photogrammetry, the connective condition is based on the equation of the depths of the common points [7].

In contrast to the traditional method, in close-range photogrammetry, parallax is not only appeared along the X axis, but also existed along the Z axis. So the two adjoining stereo pairs of photographs are incongruous both in scale and orientation. If the connective condition is only the depths of the common points, it is obviously not strict enough. So the three-dimensional coordinates of the common points will be employed to bridge the successive model, for they should have the same coordinates in the same system. With following equations, the scale parameter k_i can be calculated:

$$\begin{bmatrix} X_i^m \\ Y_i^m \\ Z_i^m \end{bmatrix} = \begin{bmatrix} Bx_i \\ By_i \\ Bz_i \end{bmatrix} + k_{i+1} \times R(\varphi_{i+1}, \omega_{i+1}, \kappa_{i+1}) \times \begin{bmatrix} X_{i+1}^m \\ Y_{i+1}^m \\ Z_{i+1}^m \end{bmatrix} \tag{14}$$

Here (X_i^m, Y_i^m, Z_i^m) are the coordinates of the m model point in the i stereo pair of photographs. These values suit for the image coordinate system of the left image. (Bx_i, By_i, Bz_i), $(\varphi_i, \omega_i, \kappa_i)$ are the relative orientation parameters between the left image of the (i+1) stereo pair and the left image of the i stereo pair. So the unknown parameter is only the scale k_i.

3.4 Building the Integrated Successive Model

In close-angle photogrammetry, there are two inconsistencies between the two adjacent models. One is the scale, the other is the orientation. If R and k is the rotation matrix and the scale of the right image to the left one, the R' and k' are the rotation matrix and the scale to the first image:

$$\begin{aligned} R'(1) &= R(1) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ R'(2) &= R(2)R(1) = R(2) = \begin{bmatrix} a_1(1) & a_2(1) & a_3(1) \\ b_1(1) & b_2(1) & b_3(1) \\ c_1(1) & c_2(1) & c_3(1) \end{bmatrix} \\ R'(j) &= R(j) \times R(j-1) \times \cdots \times R(2) \times R(1), \quad (j = 3, 4..., n) \end{aligned} \tag{15}$$

$$\begin{aligned} k'(1) &= k(1) = 1 \\ k'(2) &= k(2)k(1) = k(2) \\ k'(j) &= k(j) \times k(j-1) \cdots k(2) \times k(1), \quad (j = 3, 4, ..., n) \end{aligned} \tag{16}$$

On this basis, the coordinates of every perspective center in model coordinate system (XXs(j), YYs(j), ZZs(j)) can be deduced as:

$$\begin{pmatrix} \mathrm{XXs(j+1)} \\ \mathrm{YYs(j+1)} \\ \mathrm{ZZs(j+1)} \end{pmatrix} = \begin{pmatrix} \mathrm{XXs(j)} \\ \mathrm{YYs(j)} \\ \mathrm{ZZs(j)} \end{pmatrix} + \mathrm{k'(j)} \times \mathrm{R'(j)} \times \begin{pmatrix} B_x\mathrm{(j)} \\ B_y\mathrm{(j)} \\ B_z\mathrm{(j)} \end{pmatrix} \quad (\mathrm{j} = 2, 3, ..., \mathrm{n}) \tag{17}$$

After this process, every model coordinate system in the strip is parallel to the first image's coordinate system. So the model coordinates of all unknown points can be calculated with the application of the standard method of intersection using the collinearity equations.

3.5 Absolute Orientation

The final step is the absolute orientation. Analytical absolute orientation is based on the three-dimensional similarity transform. Seven parameters are involved: a uniform scale λ, three translations (X_0, Y_0, Z_0), and three rotations (Φ, Ω, K). In classic aerial photography, the simplified model with small angles is usually performed. But in wide-angle photogrammety, it can not be applied for the big rotation angles any longer.

The solution here is also based on the orthogonal rotation matrix. Instead of the calculation of the three rotations Φ, Ω, K directly, the nine elements of the matrix are used to establish the linear observation equations. So the adjustment with conditions will be applied [8].

In the process of calculation, the first step is to centralize the coordinates. The initial values of X_0^0, Y_0^0, Z_0^0 are the differences of the corresponding center of gravity coordinates in the two coordinate systems, $\lambda^0=1$, $R^0=I$. The error equations are:

$$\begin{aligned} v &= Ax - l \\ x^T &= [dX_0\ dY_0\ dZ_0\ d\lambda\ da_1\ da_2\ da_3\ db_1\ db_2\ db_3\ dc_1\ dc_2\ dc_3] \\ A &= \begin{bmatrix} 1 & 0 & 0 & a_1^0x(i)+a_2^0y(i)+a_3^0z(i) & \lambda^0x(i) & \lambda^0y(i) & \lambda^0z(i) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & b_1^0x(i)+b_2^0y(i)+b_3^0z(i) & 0 & 0 & 0 & \lambda^0x(i) & \lambda^0y(i) & \lambda^0z(i) & 0 & 0 & 0 \\ 0 & 0 & 0 & c_1^0x(i)+c_2^0y(i)+c_3^0z(i) & 0 & 0 & 0 & 0 & 0 & 0 & \lambda^0x(i) & \lambda^0y(i) & \lambda^0z(i) \end{bmatrix} \\ l &= \begin{bmatrix} X_0^0 \\ Y_0^0 \\ Z_0^0 \end{bmatrix} + \lambda^0 \begin{bmatrix} a_1^0 & a_2^0 & a_3^0 \\ b_1^0 & b_2^0 & b_3^0 \\ c_1^0 & c_2^0 & c_3^0 \end{bmatrix} \begin{bmatrix} x(i) \\ y(i) \\ z(i) \end{bmatrix} - \begin{bmatrix} X(i) \\ Y(i) \\ Z(i) \end{bmatrix} \end{aligned} \tag{18}$$

$(X(i), Y(i), Z(i))$ denotes the object space coordinates of the control points, $(x(i), y(i), z(i))$ the relative model space coordinates. This model of three-dimensional datum transformation can suit any angle.

4. CASE STUDY

In this section, the preceding approaches in close-range photogrammetry with big rotation angles will be studied. The target is a simple house, and 4 photos are taken, as expressed in Figure 1, where the red points are perspective centers, the blue points are known ground points, the green lines represent the main lines of the house, and the yellow lines are for the windows. The span of the house is from (0, 0, 0)m to (10, 10, 10)m, the coordinate of the top is (5, 5, 11)m. Randomly select No. 23, No. 24 and No. 25 points as ground control points, and the residual ones perform as check points. Interior orientations are $(x_0, y_0, f) = (0, 0, 50)mm$, and the exterior orientations are described in Table 1. The errors in image coordinates are about 0.1mm.

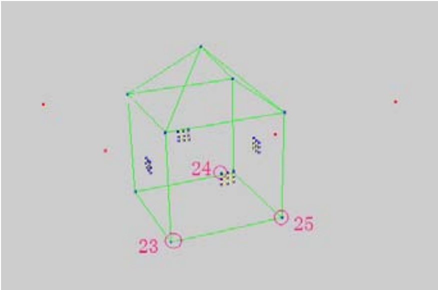

Figure 1. Image for experimental data

Image No.	Xs(m)	Ys(m)	Zs(m)	φ(°)	ω(°)	κ(°)
1	18	5	12	-30	0	0
2	16	16	12	-30	0	-20
3	5	18	12	0	-30	0
4	-6	16	12	30	0	20

Table 1. Given exterior orientations of every image

With the algorithms in the preceding section, the object space coordinates of the unknown points can be calculated. Two methods will be presented to evaluate the result.

Firstly, the accuracy is evaluated using check points whose world coordinates are known but not used as control in the solution. The root mean square of the differences between the computed coordinates and the known values provides a measure of the solution accuracy. The distribute of the errors of the check points is like Figure 2:

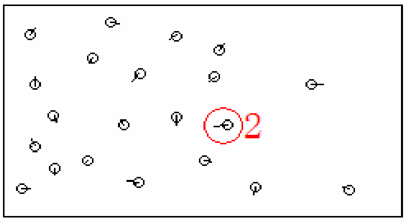

Figure 2. Plot of check point error

Figure 2 indicates that the orientations of the errors are random and the absolute values are small, and the maximal one is No.2, the values are $\max(dX, dY, dZ) = (0.891, 0.228, -0.662)mm$. If the number of check points is n_{check}, then the mean square errors are:

$$(\sigma_X, \sigma_Y, \sigma_Z) = \left(\sqrt{\sum \frac{dX^2}{n_{check}}}, \sqrt{\sum \frac{dY^2}{n_{check}}}, \sqrt{\sum \frac{dZ^2}{n_{check}}}\right) = (0.416, 0.101, 0.279)mm$$

Secondly, using the solution of space resection with big rotation angles (described in section 2) to calculate the exterior orientations of every image, and make a comparison between the computed values and the given ones. The result is expressed in Table 2.

Image No.	dXs (mm)	dYs (mm)	dZs (mm)	Dφ (″)	Dω (″)	Dκ (″)
1	0.1205	0.0946	0.0223	2.251	1.371	1.198
2	0.1142	0.0775	0.1076	2.549	1.354	1.250
3	0.0250	0.0461	0.0411	2.560	2.591	1.874
4	-0.0042	-0.0344	-0.0234	1.898	3.248	1.066

Table 2. Differences of the exterior orientations between the computed result and the known values

From Table 2, we can see the result is appropriate. More data have been analyzed outside this paper, and the outcome is also correct. So they verify the validity and robustness of the algorithms in close-range photogrammetry with big rotation angles in this paper.

5. CONCLUSION

The algorithms for close-range photogrammetry with big rotation angles have been developed in this paper to perform the analytical process, including dependent relative orientation, space intersection, strip formation process, absolute orientation and space resection, etc.

Using these algorithms, we have obtained high accuracy and robust results. So they verify the validity and robustness of the algorithms deduced in this research paper. Compared with the approaches of the analytical process in classic aerial photogrammetry, the algorithms in this paper have such advantages:

(1) They are applicable in close-range photogrammetry with big rotation angles and they differ from the methods used in classic photogrammetery because the algorithms in this paper are stricter, but not employ the simplified models.

(2) They continue to be suitable when the absolute values of the difference between the adjacent camera stations' three-dimensional coordinates are quite large.
With these algorithms, the images can be tied into a successive model like a strip, so fewer control points (more than 2) are needed to perform the absolute orientation. It reduces the amount of the field work.

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