Acquisition of Directional Parameters in Aerial Images Based on DEM Data

LI Pingxiang  YU Jie  BIAN Fuling

ABSTRACT This paper develops a method which can be used to assist aerial navigation by determining the spatial position and posture of the aerial photographic plane. After the method, aerial images match known DEM to capture the spatial position and posture. Some aerial images and terrain data are used to testify our method. Compared with those of analytic and stereo mappers, the results by our method are correspondent to real measurements well.

KEY WORDS aerial navigation; aerial images; DEM data

1 Extraction of the steep curve map

The steep curve is defined as connection line from zero cross points which are produced from the convolution of Laplace (LOG) filtration to DEM. Firstly, the elevation data from DEM are processed with LOG convolution and zero cross. The sampling formula is

$$\nabla^2 G(i,j) = \frac{1}{2\pi \sigma^4} (r^2 - 2\sigma^2) e^{-r^2/2\sigma^2}$$

where \(-M \leq i \leq M, -M \leq j \leq M, r^2 = i^2 + j^2\), \(M\) is the filtration radius, nearly equaling to 5. \(1\sigma\); prediction error \(\sigma\) is set to 4. Suppose that \(e[i,j]\) is a small area in DEM, in which we are interested, and \(c[i,j]\) is a predicted steep curve, we can get DEM from Eq. (2):

$$V[i,j] = \sum_{n=-M}^{M} \sum_{m=-M}^{M} \nabla^2 G[m,n] e[i-m,j-n]$$

where \(0 \leq i \leq N_x, 0 \leq j \leq N_y\), and \(N_x, N_y\) are the line and column number, respectively. The position zero cross is:

$$c[i,j] = \begin{cases} 1, & \text{when } V[i,j] > 0 \text{ and } (V(i,j - 1) < 0, \text{ or } V(i,j + 1) < 0) \\ 0, & \text{others} \end{cases}$$

The steep curve from zero cross calculation is shown in Fig. 1.

2 Inspection of the feature points

The feature points are composed of the end points and turning points in the steep curve. Firstly, a straight-line equation is established by two end points in the steep curve (A and B in Fig. 2).

$$A_0x + A_1y + A_2 = 0$$

where \(A_0 = \frac{1}{x_B - x_A}, A_1 = \frac{-1}{y_B - y_A}, A_2 = \frac{y_B x_B - x_B y_B}{(y_B - y_A)(x_B - x_A)}\). Then compute the difference between each point in the curve AB and the
Fig. 2 End points of steep curve

straight line $AB$:

$$d_i = \frac{|A_i x_i + A_j y_i + A_k|}{\sqrt{A_i^2 + A_j^2}}$$

(4)

When $d_{\text{max}} > \varepsilon$, these points that are correspondent to $d_{\text{max}}$ are turning points in the curve. Similarly, the new turning point may be inspected from two neighbor turning points or end points. When $d_{\text{max}} \leq \varepsilon$, then the next pair of neighbor turning points or end points is inspected. All turning points and end points are shown in Fig. 3.

Fig. 3 Results of turning and end points

3 Calculation of aspect of slope and grade model

Traditionally, the lightness change is used for digital image matching. But in this paper, we use the slope grade as criterion for DEM matching.

For matching convenience, the surface accident is classified into aspect of slope and slope grade which are calculated by a simulation plane. Each grid of DEM is used as a calculation element in order to build a coordinate system (Fig. 4). The 3D coordinates of the 4 corner points in each element can be used to simulate a plane. The angle between the plane normal vector and vertical line can be used to calculate average slope grade of

one element. The simulation equation is:

$$z = Ax + By + C$$

(5)

Using the least square method, we can obtain:

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} (z_2 - z_1 + z_3 - z_4)/2\Delta x \\ (z_4 - z_1 + z_2 - z_3)/2\Delta y \\ (3z_1 + z_2 - z_3 - z_4)/4 \end{bmatrix}$$

(6)

The normal vector of the simulation plane is as follows:

$$\mathbf{n} = [A, B, -1]^T = \begin{bmatrix} z_2 - z_1 + z_3 - z_4 \\ 2\Delta x \\ z_4 - z_1 + z_2 - z_3 \\ 2\Delta y \\ -1 \end{bmatrix}$$

(7)

The average slope grade of one element is given by:

$$\tan \alpha = \frac{|\mathbf{n} \cdot \mathbf{\rho}|}{|\mathbf{n}|} - 1 = \sqrt{\left(\frac{z_2 - z_1 + z_3 - z_4}{2\Delta x}\right)^2 + \left(\frac{z_4 - z_1 + z_2 - z_3}{2\Delta y}\right)^2}$$

(8)

where $\mathbf{\rho}$ is a unit vector in vertical direction.

The aspect of slope represents a slant direction of the slope. The projection of the aspect of slope to level surface can be divided into 10 situations that are shown in Fig. 5. When the slope grade is $0^\circ$, the aspect of slope $T$ is set to 0; when the slope grade is $90^\circ$, the aspect of slope $T$ is set to 9; when the aspect of slope is slant to $-x$ coordinate with $\pm 22.5^\circ$, $T$ is set to 1, and so forth.
4 DEM feature point matching based on slope grade

4.1 Selection of match points

All matching points REM are selected from BEM feature points according to the aspect of slope. Suppose that in the REM, one feature point \( P \) has the aspect of slope \( T_o \), then the aspect of slope of the matching points should satisfy:

\[
T \in \{0, 9, T_o, T_o \pm 1, \ldots, 9\}, \quad \text{when} \quad T_o = 0 \text{ or } 9
\]

4.2 The second matching

The second matching is to select unique correct matching point among many matching points in REM by using the slope grades. In Fig. 6, \( P \) is an object point on which a \( 3 \times 3 \) object area is centered. Suppose that there are four matching points, which are \( a, b, c \) and \( d \) around point \( P \), then a \( 5 \times 5 \) neighbor area around point \( P \) is regarded as the search area for matching.

Consequently, we calculate a slope grade difference between the searching area and object area:

\[
\rho(i,j) = \sum_{m=0}^{2} \sum_{n=0}^{2} (S_{mn} - a_{mn})^2
\]

When \( \rho(i,j) = \min \), \( \rho_{\text{min}} \) is a matching point of \( P \) in the BEM. In Eq. (10), \( i, j \) are the line number and row number, respectively, of the center point in the computing matrix that matches Point \( P \); \( \rho(i,j) \) is the matching measurement of point \( (i,j) \); \( S_{mn} \) is the \( 3 \times 3 \) slope grade element of the object area; \( a_{mn} \) is the \( 3 \times 3 \) slope grade element of the neighbor area of point \( (i,j) \) in the searching area.

4.3 Final selection of matching points

First, four pairs of matching points with smaller values of \( \rho \) are selected, and the average \( \Delta x, \Delta y \) of their correspondent \( x, y \) coordinate differences are:

\[
\Delta x = \frac{1}{4} \sum_{i=1}^{4} (x_{ib} - x_{ia}), \quad \Delta y = \frac{1}{4} \sum_{i=1}^{4} (y_{ib} - y_{ia})
\]

(11)

where \( x_{ib}, y_{ib} \) are the coordinates \( x, y \) of feature point \( i \) in the REM, respectively; \( x_{ia}, y_{ia} \) are the coordinate \( x, y \) of matching points in the BEM, respectively.

Secondly, \( \Delta x_i, \Delta y_i \) of the four pairs of points are calculated and compared with \( \Delta x, \Delta y \):

\[
\Delta x_i = x_{ib} - x_{ia}, \quad \Delta y_i = y_{ib} - y_{ia}, \quad i = 1, 2, 3, 4
\]

\[
|\Delta x_i - \Delta x| \leq \epsilon, \quad |\Delta y_i - \Delta y| \leq \epsilon
\]

(12)

(13)

For the two DEM data, due to similar transformation, the displacement for any pair of points should be stable in theory and satisfies Eq. (13). Otherwise, the pair of points should be cancelled and another new pair of points with second minimum \( \rho \) value is selected for calculation in Eqs. (12) and (13) until the new pair satisfies Eq. (13). In Eq. (13), \( \epsilon \) is a pre-set threshold and dependent of the surface relief and sampling interval.

Finally, all matching points are calculated in Eq. (12) to get \( \Delta x, \Delta y \). Then, their values are assessed by Eq. (13). All matching points which satisfy Eq. (13) are kept as correct matching pairs of points, otherwise cancelled. Fig. 7 is a matching map between results of matching points and steep curve.

4.4 Matching between REM and BEM

After we get the correct matching pairs of points between REM and BEM, the similar transformation parameters between REM and BEM can be solved. The transformation equa-
tion is

\[
\begin{bmatrix}
    x \\
    y \\
    z
\end{bmatrix}
= \lambda \cdot R
\begin{bmatrix}
    x \\
    y \\
    z
\end{bmatrix}
+ \begin{bmatrix}
    \Delta x_0 \\
    \Delta y_0 \\
    \Delta z_0
\end{bmatrix}
\]

(14)

where \([x, y, z]_R\) is the coordinate of REM feature point; \([x, y, z]_B\) is the coordinate of BEM feature point matching the REM feature point; \([\Delta x_0, \Delta y_0, \Delta z_0]\) is the REM translation value relative to BEM in \(x, y, z\) direction; \(\lambda\) is a scale parameter between the two models; \(R\) is a directional cosine matrix involving between the two models with three involving angels \((\Phi, \Omega, K)\).

For the matching between REM and BEM, the seven similar transformation parameters \(\lambda, \Phi, \Omega, K, \Delta x_0, \Delta y_0, \Delta z_0\) must be calculated. For example, we may use one pair of matching points \((x, y, z)_R\) and \((x, y, z)_B\) given in Fig. 7 to calculate the above seven parameters through the least squares adjustment in order to realize a matching between REM and BEM.

5 Matching between an aerial image and BEM

When REM is constructed, the relative orientation elements are:

Left picture: \(X_S = Y_S = Z_S = 0, \varphi_1 = \omega_1 = \kappa_1 = 0\)

Right picture: \(X_S = B_X, Y_S = B_Y, Z_S = B_Z, \varphi_2 = \omega_2 = \omega_2 = \kappa_2 = \kappa_2\)

After the matching between REM and BEM, the seven similar transformation parameters \(\lambda, \Phi, \Omega, K, \Delta x_0, \Delta y_0, \Delta z_0\) are known, thus, the line elements of the picture relative to BEM are:

Left picture: \(X_S = \Delta X_0, Y_S = \Delta Y_0, Z_S = \Delta Z_0\)

Right picture: \(X_S = \Delta X_0 + \lambda \cdot B_X, Y_S = \Delta Y_0 + \lambda \cdot B_Y, Z_S = \Delta Z_0 + \lambda \cdot B_Z\)

(15)

Usually, because \(\varphi, \omega, \kappa, \Phi, \Omega, K\) are all small angles, those values more than the second orders are ignored in equation deduction, thus we have:

Left picture: \(\varphi_{\text{left}} = \Phi + \varphi_1 = \Phi, \omega_{\text{left}} = \Omega + \omega_1 = \Omega + \kappa_1 = \Omega + \kappa_1 = K\)

Right picture: \(\varphi_{\text{right}} = \Phi + \varphi_2, \omega_{\text{right}} = \Omega + \omega_2, \kappa_{\text{right}} = K + \kappa_2\)

(16)

The six exterior orientation elements for the left and right pictures are, respectively, formed by Eqs. (15) and (16).

6 Experimental results and conclusions

In order to testify the above models, we employ analogue mapper Topovart and analogue mapper C130 to read exterior orientation elements from an aerial image and make a matching calculation between the aerial image and BEM. The experimental data and results are shown in Table 1-Table 3.
Table 2. Absolute orientation and image matching results of the image pairs in Chongyang Area

| Method          | \( \phi \)  | \( \omega \)  | \( \kappa \)  | \( \lambda \) |
|-----------------|-------------|-------------|-------------|-------------|
| Our method      | 2°04'45"   | 1°47'10"   | 0°05'24"   | 0.996 0    |
| By topocar      | 2°00'00"   | 2°00'00"   | 0°00'00"   | 1.000 0    |
| By contrast     | 0°04'45"   | -0°12'50"  | 0°06'24"   | -0.004 0   |

Table 3. Results of exterior orientation elements from Lichuan area by use of C130 and our method

| Method          | \( X_s \)  | \( Y_s \)  | \( Z_s \)  | \( \phi \)  | \( \omega \)  | \( \kappa \) |
|-----------------|------------|------------|------------|-------------|-------------|-------------|
| Left picture    |            |            |            |             |             |             |
| Our method      | 611 819.886 | 375 343.449 | 5 429.156  | -1°38'11"  | 0°44'06"   | 0°10'21"   |
| C130            | 611 842.136 | 375 373.889 | 5 427.396  | -1°17'24"  | 0°29'44"   | 0°03'17"   |
| By contrast     | -22.250    | -30.440    | 1.760      | -0°14'22"  | 0°14'22"   | 0°07'04"   |
| Right picture   |            |            |            |             |             |             |
| Our method      | 613 790.249 | 375 303.360 | 5 426.088  | -1°26'19"  | -5°05'53"  | -0°57'19"  |
| C130            | 613 811.319 | 375 332.010 | 5 424.338  | -1°05'32"  | -2°20'19"  | -2°04'23"  |
| By contrast     | -21.070    | -28.650    | 1.750      | -0°20'47"  | 0°14'22"   | 0°07'04"   |

From Table 3, it is found that the results of the Z direction (elevation) are the best among the exterior line orientation elements, the difference between by our method and by C130 is only 1.8 m. The plane position difference is 25 m (equal to the width of one BEM pixel). The difference of the exterior orientation angle elements is from 10' to 20', which results from the elevation difference of sampling points in the DTM.

From the above discussion, the following conclusions are drawn.

1) Automatic matching between the aerial image and DEM by digital photogrammetry can be applied for airplane navigation.

2) Precision of the exterior orientation element calculation is mainly dependent on sampling interval of DEM and BEM. When topographic fluctuation is bigger, the sampling interval should be decreased.

3) Our method is applicable when REM and BEM have nearly the same coordinate system.

But for navigation, REM and BEM may have a big difference between their coordinate systems. However, if a better initial value of the three angle elements for REM spatial altitude is available by other method, our method is also applicable.

4) If the plane spatial position decided by GPS and REM spatial aid coordinate are all used as REM initial spatial position, the matching efficiency of REM and BEM will be increased.

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