AERIAL TRIANGULATION OF DIGITAL AERIAL IMAGERY USING HYBRID FEATURES

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ABSTRACT:

Exterior Orientation Parameters (EOPs) of imaging sensors are demanded in different mapping tasks such as orthophoto and DEM generation, 3D extraction and object reconstruction. Bundle adjustment is one of the useful methods to determine the EOPs of all the images in a block with relatively low number of control points. As finding the corresponding points in is difficult especially in automatic matching procedures, and depending on the ground topography, some points might be hidden or be in occluded areas in images, in recent years, lots of investigations in the field of using straight line segments and other feature primitives in aerial triangulation are provided by different researchers. In this paper, the standard point-based collinearity equations together with the modified line-based collinearity equations proposed by Schenk are implemented and evaluated on a small block of six overlapped (60% side overlap and 25% strip overlap) digital aerial images of DiMac sensor. In this method, the optimal parametric representations of object straight lines are used to model the relationship between image space and object space. Parametric representation of features in object space allows the specification of any point on the feature. The main advantage of block adjustment using linear features is its high reliability and its capability to cope with the problem of occluded areas and is more reliability for automation. The results of block adjustment using points and lines, confirm the capabilities of the utilized method.

1. INTRODUCTION

Connection of an aerial image and its corresponding object space is performed by the exterior orientation parameters of that image. These parameters establish the physical geometry of imaging sensor with respect to ground and describe the position and orientation of that sensor at the time of imaging. These parameters are used in different mapping tasks such as DEM and orthophoto generation, 3D extraction and object reconstruction.

Using aerial resection, at least 3 full control points for the calculation of 6 exterior orientation parameters of each image are required. As the process of mapping of wide areas, depending on scale, needs lots of images in different strips on a block, the number of required control points extensively increases. Bundle adjustment is one of the useful methods to determine the EOPs of all the images in a block with relatively low number of control points. In this method, time and cost of mapping considerably reduces and connectivity of the resulting maps is also guaranteed by the aid of using tie points between the overlapped areas (Kubik, 1991). As finding the corresponding points in is difficult especially in automatic matching procedures, and depending on the ground topography, some points might be hidden or be in occluded areas on images, in recent years, lots of investigations in the field of using straight line segments and other feature primitives in aerial triangulation are provided by different researchers.

Two main reasons of attitude to features rather than points are (Kubik, 1991):

1. The features can be used in all photogrammetric tasks such as space intersection, resection and triangulation. The use of features is especially applicable in mapping of constructed areas. Since man-made objects include lot of linear curves and other feature primitives especially straight lines.
2. Although the feature based matching algorithms are more complex than point matching, features are more reliable in automation especially in automatic matching procedures. This increases the robustness of automatic aerial triangulation.

2. MATHEMATICAL MODELS OF FEATURE-BASED EOP DETERMINATION METHODS

Models which are used in EOP determination are generally divided into line-based collinearity and coplanarity equations. The mathematical concept of line-based collinearity and coplanarity methods are illustrated in Figure 1.

The analytical idea of coplanarity method is to ensure that a vector defining the object space line, the vector from the perspective center to a point on object line on the object line and the vector from the perspective center to the image point

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are all coplanar. Here, a condition is considered to force the projection planes in the image and object spaces to become identical. The projection plane defined by the projection center and the line in image space or object space is also called interpretation plane. In line-based collinearity approach, a point on the line feature in image space is taken and the projection ray is forced to intersect the control line by minimizing the residuals of the observed image point. This method requires a parametric representation of the object space lines.

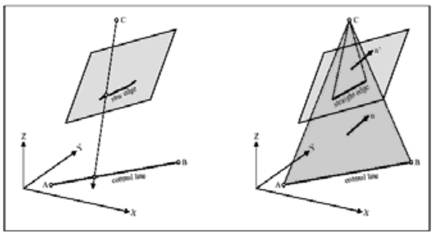

Figure 1. Establishing the relationship between corresponding image and object space lines by (a) coplanarity and (b) and collinearity approach (Schenk, 2003)

In the last years many researches about using linear features in photogrammetric procedures are presented by different authors. (Habib and Kelly, 2001; Habib et al., 2000) provided methods for the computation of exterior orientation parameters of a single image by linear features. (Zalmanson, 2000; Mulawa and Mikhail, 1998) pursued the use on non-linear features for image orientation. In line-based coplanarity equations proposed by (Habib, 1999; Heuvel, 1997), it is assumed that the image of a straight line in object space will be a straight line if the distortions are negligible. Using this constraint, the normal vectors to the interpretation planes are used to formulate the relation of image and object spaces. However, as considering the tie lines in more than two images is not possible in coplanarity equations, these models are not suitable for block adjustment and therefore the bundle adjustment are often based and developed on collinearity equations. In this paper, the line-based collinearity equations proposed by (Schenk, 2003) are implemented and evaluated.

2.1 Collinearity Approach Proposed by Schenk

In this model, the standard collinearity model is extended such that the projection ray from the perspective center through an edge point on the image intersects its corresponding control line in object space. Here, the parametric representations of object straight lines are used to model the relationship between image space and object space (Schenk, 2003). The relationship between image and object space by parametric representation of lines is illustrated in Figure 2.

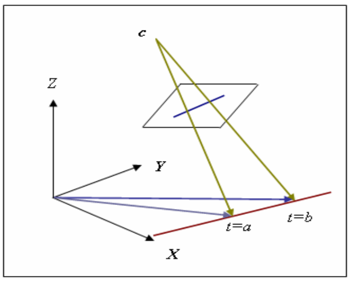

Figure 2. Relationship between image and object space using parametric representation of line

In parametric representation, a line in object space is pressed by a point A=(X_A, Y_A, Z_A) on it and its direction vector d=(a, b, c). Any point on the line is defined by Equation 1:

$$\begin{aligned} X(t) &= X_A + t.a \\ Y(t) &= Y_A + t.b \\ Z(t) &= Z_A + t.c \end{aligned} \tag{1}$$

where t = line parameter

The standard collinearity equations are then modified to Equation (2) by substituting the object space coordinates:

$$\begin{cases} x = -f\,\dfrac{m_{11}(X(t)-X_C)+m_{12}(Y(t)-Y_C)+m_{13}(Z(t)-Z_C)}{m_{31}(X(t)-X_c)+m_{32}(Y(t)-Y_C)+m_{33}(Z(t)-Z_C)} \\ y = -f\,\dfrac{m_{21}(X(t)-X_C)+m_{22}(Y(t)-Y_C)+m_{23}(Z(t)-Z_C)}{m_{31}(X(t)-X_c)+m_{32}(Y(t)-Y_C)+m_{33}(Z(t)-Z_C)} \end{cases} \tag{2}$$

where (x, y) = image space coordinates of edge point
f = focal length
m_{ij} = elements of the rotation matrix
(X_C,Y_C,Z_C) = coordinates of the perspective center

In Equations 2, the unknowns are six exterior orientation parameters and also the line parameter "t". So to determine the orientation parameters of each image, three non-collinear control lines are needed and using more than two points on an image line does not increase the degree of freedom (Schenk, 2003).

3. DIFFERENT REPRESENTATIONS OF LINES

Parametric representation of lines can be used in either image or object spaces of collinearity equations, but, as in Schenk model the parametric line equations are utilized in object space, the usual representation and optimal solution of parametric line representations in object space are introduced in this section.

3.1 Parametric Cartesian Representation of Line

In this model, the parametric representation of straight lines is defined by Equation 3:

$$\begin{bmatrix} X(t) \\ Y(t) \\ Z(t) \end{bmatrix} = \begin{bmatrix} X_{SP} \\ Y_{SP} \\ Z_{SP} \end{bmatrix} + t \begin{bmatrix} X_{EP} - X_{SP} \\ Y_{EP} - Y_{SP} \\ Z_{EP} - Z_{SP} \end{bmatrix} \tag{3}$$

where (X_{SP},Y_{SP},Z_{SP}) = coordinate of start point of the line
(X_{EP},Y_{EP},Z_{EP}) = coordinate of end point of the line
t = variable parameter

This is not a unique solution because there are an infinite number of points that can be chosen, and the direction vector can be multiplied by any scale factor. To effectively solve the orientation parameters with straight lines, an optimal representation of line in Euclidean 3D space should meet these requirements (Schenk, 2003):

1. number of parameters should be equal to the degrees of freedom of a 3D line
2. the representation should be unique and free of singularities

3. there should be a one-to-one correspondence between the representation and the definition of the line
4. representation should be suitable for parametric expression.

3.2 Optimal Representation of Line

Consider that L is a line given in a Cartesian coordinate system $O-XYZ$. $O-X'Y'Z'$ is a coordinate system with the same origin but rotated such that the Z' -axis becomes parallel to L. The rotation between the two coordinate systems is defined by the two angles that specify the line direction. The third angle, (rotation about the line itself), is irrelevant and can be fixed, for example zero. Spherical coordinate system is used to define the rotation between these two coordinate systems. For this reason, ϕ is defined as azimuth and θ as zenith. For vertical lines to the XY-plane, the azimuth is set to zero. Line L intersects the $X'Y'$ plane in point (x_0, y_0) . Then, the four parameters (ϕ, θ, x_0, y_0) define the optimal representation of line in object space (Schenk, 2003). This concept is illustrated in Figure 3.

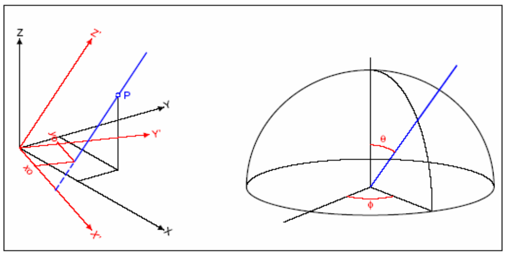

Figure 3. concept of the four-parameter representation (Schenk, 2003)

This representation is simple, and has a unique one to one mapping. It also gives equal importance to angles and positions.

3.3 Determination of the Line Parameters

The four parameters of optimally represented line (ϕ, θ, x_0, y_0) are determined using two points on it. Let the coordinates of two end points of line L are known. The four parameters of this line are defined in the following way:
The direction vector is converted to spherical coordinates (ρ, ϕ, θ). With the two angles, the rotation matrix is formed (Schenk, 2003).

$$R = \begin{bmatrix} \cos\theta\cos\phi & \cos\theta\sin\phi & -\sin\theta \\ -\sin\phi & \cos\phi & 0 \\ \sin\theta\cos\phi & \sin\theta\sin\phi & \cos\theta \end{bmatrix} \tag{4}$$

Let P be a point on line L in $O-XYZ$ coordinate system with coordinates $[X, Y, Z]^T$. R rotates point P into P' in $O-X'Y'Z'$ coordinate system whose z-axis is parallel to the straight line. Then the new point P' is expressed by:

$$P' = R \times P \tag{5}$$

In fact, any point $P_i = (X_i, Y_i, Z_i)$ on the line L in $O-X'Y'Z'$ coordinate system will have the same planimetric coordinates (x_0, y_0) but a different z-coordinate (z_i).

$$P_i' = \begin{bmatrix} x_0 \\ y_0 \\ z_i \end{bmatrix} \tag{6}$$

To map any point in the four-parameter representation in $O-X'Y'Z'$ to a unique point in $O-XYZ$ of line L, below equation is used:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_0\cos\phi\cos\theta - y_0\sin\phi + z\sin\theta\cos\phi \\ x_0\sin\phi\cos\theta + y_0\cos\phi + z\sin\theta\sin\phi \\ -x_0\sin\theta + z\cos\theta \end{bmatrix} \tag{7}$$

z can be viewed as the parameter in the parametric form of the line representation (Schenk, 2003).

3.4 Implemented Block Adjustment Using Points and Lines

The point-based block bundle adjustment considers photogrammetric observations as a bundle of straight lines. Each straight line is defined by the condition of collinearity of perspective center and conjugate image and object spaces points. The mathematical formulation of bundle adjustment (Equation 8) is the standard collinearity equations which should be linearized to perform the least square adjustment to determine the exterior orientation parameters (EOPs) of the images involved and the coordinates of tie points.

$$\begin{cases} x = -f\dfrac{m_{11}(X-X_C)+m_{12}(Y-Y_C)+m_{13}(Z-Z_C)}{m_{31}(X-X_c)+m_{32}(Y-Y_C)+m_{33}(Z-Z_C)} \\ y = -f\dfrac{m_{21}(X-X_c)+m_{22}(Y-Y_C)+m_{23}(Z-Z_C)}{m_{31}(X-X_c)+m_{32}(Y-Y_C)+m_{33}(Z-Z_C)} \end{cases} \tag{8}$$

where (x,y) = coordinates of image points
(X,Y,Z) = object space coordinates of control or tie points
(X_C, Y_C, Z_C) = coordinates of the perspective center
f = focal length
m_{ij} = elements of the rotation matrix

In bundle adjustment using hybrid features (combination of points and lines), these point-based equations are adjusted together with line-based collinearity equations.

As was explained, the line based bundle adjustment considering the parametric representation of lines in object space is performed by substituting Equation 7 in standard collinearity equations. These modified collinearity equations are in the form of Equation 9 (Schenk, 2003):

$$x = -f\,\frac{u}{w} \quad , \quad y = -f\,\frac{v}{w} \tag{9}$$

where

$$u = (x_0 \cos\phi\cos\theta - y_0 \sin\phi + z\sin\theta\cos\phi - X_C)m_{11} + (x_0 \sin\phi\cos\theta + y_0 \cos\phi + z\sin\theta\sin\phi - Y_C)m_{12} + (-x_0 \sin\theta + z\cos\theta - Z_C)m_{13}$$

$$v = (x_0 \cos\phi\cos\theta - y_0 \sin\phi + z\sin\theta\cos\phi - X_C)m_{21} + (x_0 \sin\phi\cos\theta + y_0 \cos\phi + z\sin\theta\sin\phi - Y_C)m_{22} + (-x_0 \sin\theta + z\cos\theta - Z_C)m_{23}$$

and

$$w = (x_0 \cos\phi\cos\theta - y_0 \sin\phi + z\sin\theta\cos\phi - X_C)m_{31} + (x_0 \sin\phi\cos\theta + y_0 \cos\phi + z\sin\theta\sin\phi - Y_C)m_{32} + (-x_0 \sin\theta + z\cos\theta - Z_C)m_{33}$$

The modified collinearity equations contain the four line parameters (ϕ, θ, x_0, y_0), parameter z, and the exterior orientation parameters (perspective center X_C, Y_C, Z_C and attitude matrix with the elements $r_{11}, \ldots, r_{33}$)

4. EXPERIMENTAL RESULTS

To assess the capability of the proposed method (block adjustment using hybrid features), a toolbox in MATLAB is implemented in which it is possible to use points, lines and the combinations of points and lines for the adjustment of the block. In this paper, bundle adjustment using both points and lines are evaluated and quality assessment of this method is provided in the form of maximum residual errors and RMSEs in line and sample directions and error vectors on back projected image points. As was explained, the frequency of tie lines in the block should be at least three and frequency of tie points should be at least two.

4.1 Test Areas and Data

For the analysis of proposed method, a small block of six overlapped (60% side overlap and 25% strip overlap) of color images (three in each strip) of DiMAC digital aerial camera are used. Its modular design allowing the combination of 1, 2, 3 or 4 camera modules together (true-color and IR) and producing 1, 2, 3 or 4 individual images simultaneously (DiMAC systems, 2006). The test block used in this experiment is taken from Charleroi region located in Belgium at Feb. 4, 2004. Each image has 5440×4080 pixels with a pixel size of 9 microns. This block has been flown at 1590 m above mean sea level (the average elevation of area is about 170 m) corresponding to the image scale 1:17700 and the ground pixel size is about 15 cm. For the extraction of object space points and lines, a 3D map of that region with 1:2000 scale is used. The IDs of six images of the sub-block are 38, 39 and 40 from the second run and 62, 63 and 64 from the third run. An overview of the utilized block is illustrated in Figure 4.

Tie lines should appear on more than two images to contribute toward the orientation of images, so, we have only selected tie lines in the 3-overlap areas of strips, and in the 4-overlap and 6-overlap areas between strips. Figure 5 shows the selected points and lines in the block.

Figure 4. Sub-block of Charleroi region with six overlapped images

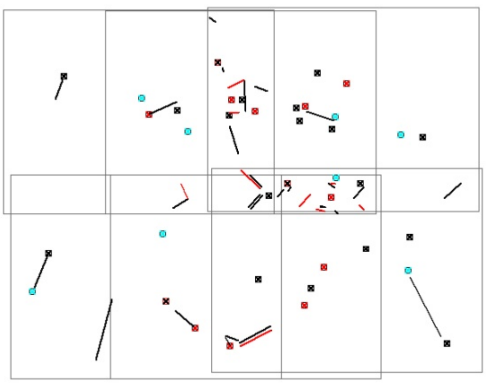

Figure 5. Selected points and lines in the block. Black: control, Blue: check and Red: tie

4.2 Results of Bundle Adjustment

The results of bundle adjustment using both points and lines are given in Table 6. In this table, the maximum residuals and RMSEs of on back projected image points are represented.

Image	Maximum Residual (x)	Maximum Residual (y)	RMSE (x)	RMSE (y)
39	0.06	0.20	0.04	0.08
40	0.13	0.10	0.04	0.04
41	0.34	0.18	0.09	0.06
63	0.15	0.14	0.11	0.07
64	0.22	0.17	0.07	0.06
65	0.15	0.19	0.06	0.08

Table 6. Maximum residuals and RMSEs of block bundle adjustment using points and lines on six images of the utilized block (unit: pix)

The error vectors of the implemented method on back projected points are also provided in Figure 7.

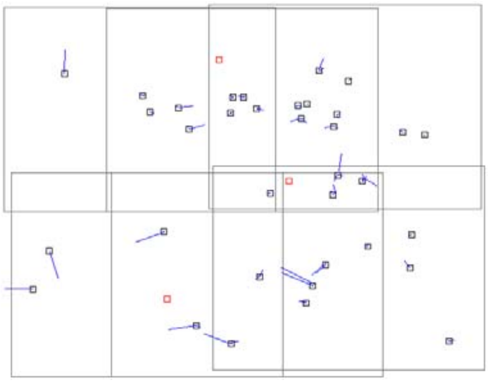

Figure 7. Error vectors of point-based aerial triangulation on back-projected image points (exaggeration: 1000)

5. CONCLUDING REMARKS

In this paper, the feature-based collinearity equations using points together with the parametric representation of straight lines (proposed by Schenk, 2003) were implemented and the results were represented and analyzed. The results show that the capability of the utilized method for the estimation of exterior orientation parameters of aerial images. Some advantages of using line-features in bundle adjustment can be introduced as:

1. in bundle adjustment using line features, correspondence between image and object space points is not required, in other words line-based collinearity equations does not require conjugate points.
2. in line-based triangulation, tie lines can connect images without any overlap and the overlap conditions of images are relaxed
3. as extraction and matching of linear features are easier and more reliable than that of point features, the line-based triangulation is more suitable for automation.

Line-based bundle adjustment can be extended to new applications. For example an interesting aspect of line-based bundle adjustment is the combination with surface reconstruction and DEM generation using LiDAR data. The tie lines can be used as breaklines. Tie lines can be also used in automatic matching procedures, especially for finding corresponding features in map and image data for map revision tasks.

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