AN INVESTIGATION INTO IMAGE ORIENTATION USING LINEAR FEATURES

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ABSTRACT:

At present all commercially available digital photogrammetric software products are utilizing points to solve the problem of image orientation. Photogrammetry based on linear features is still at the research level. The challenge is to represent appropriate features to overcome the inherent singularities. This paper addresses the utilization of linear features in image orientation by using the 4-parametric representation of lines in object space proposed by Schenk (2004). The relationship of the lines in object space and in image space is established based on the perspective projection. The collinearity equations are modified accordingly. The algorithms are tested by using simulated data of aerial configurations for single image resection. Experiments revealed some geometric configurations of the object control lines for which the condition fit of the normal equation matrix indicated numerical instability with the mathematical model. But in general, the spatial resection for a single image has been performed with straight lines successfully by strengthening the geometrical stability. The accuracy of the estimated parameters is slightly higher than in the classical point based model.

1 INTRODUCTION

1.1 Background

Points play an important role in photogrammetry especially in image orientation and aerial triangulation. The ground control point information is collected by surveying methods or taken from existing maps. Point based measurement in photogrammetric images is well performed by the human operators with the knowledge of the object space. The transfer from analogue to digital photogrammetry has dramatically changed the equipment from specialised hardware to modern digital photogrammetric workstations. In addition, digital photogrammetry became highly influenced by other disciplines such as computer vision, image understanding and pattern recognition. These disciplines reinvented many well known photogrammetric procedures, in particular in the field of image orientation. But they also pushed algorithmic developments towards linear and direct solutions based on points. Beyond points, line features and areal features are of interest as well.

Most of the direct solutions lead towards non-redundant approaches without consideration of error propagation. Direct solutions as well as linear ones are of particular interest if the execution time is a crucial factor of an application. Linear non-redundant solutions can be extended into redundant models, but often at the price of replacing traditional objective functions, observations or orientation parameters.

The most remarkable breakthrough of digital photogrammetry is its potential for automation. Since extracting features from a digital image in the form of points, lines or regions is no longer a novel idea, extracted points replaced the manually selected and measured points in traditional practice. Matching techniques have been used for searching the corresponding points on the other images. Ambiguity in finding such corresponding points indicates the necessity of utilizing of higher features which are geometrically more unique and stable than points to carry out tasks in image orientation and aerial triangulation. Habib et al. (2002) point out some advantages of utilizing lines over the representation of points as,

- points are not as useful as linear features when it comes to tasks like object recognition.
- it is more efficient to extract linear features automatically than points (Kubik, 1988).
- linear features are often available in man made environments.

Schenk (2003a, 2004) discussed automatic orientation with linear features in detail and strongly recommended to move from points to features.

The concept of using features in photogrammetry has a relatively long history. For example, straight lines were employed by Tommaselli and Lugnani (1988) while Mulawa and Mikhail (1988) used conic sections. Mikhail and Sayed (1990) explored the use of linear (straight and circular) features in the photogrammetric restitution process. Zielinski (1993) used a similar model to define a point on the 3D line. Habib et al. (2000a) discussed issues in line photogrammetry and extended the concept from frame imagery to linear array scanners. These concepts were improved further towards robust parameter estimation in Habib and Kelly (2001), Habib et al. (2000b) and Habib et al. (2002).

A detailed review on the progress in automatic aerial triangulation is given by Schenk (2003a). Schenk (2004) proposed a new approach, which is based on unique 4-parameter line representation. The parameters of the lines appear in block adjustment like the tie points do. This paper addresses characteristics of the 4-parametric model within the adjustment. Results are analysed for single photo resection of different line configurations.

2 THEORETICAL BACKGROUND

Linear features are quite common in man-made environments. They can often be extracted as straight lines. A straight line is a fundamental primitive of feature-based photogrammetry.
The theoretical background of the 4-parameter line concept is briefly outlined in this section. For more details of the mathematical and stochastic model the reader is referred to Schenk (2004).

2.1 Linear Feature Representation

Schenk (2004) states that for solving orientation and reconstruction an optimal line representation in Euclidean 3D space should fulfill the following requirements

- the line representation should be suitable for parametric expression,
- the representation should be unique and free of singularities,
- number of parameters should be equal to the minimum number of parameters necessary to specify a 3D line,
- there should be a one to one correspondence between the representation and the definition of the line,
- the parameters should allow a meaningful stochastic interpretation.

2.2 Approaches for Using Linear Features in Orientation

Basically, there are two different ways to establish a relationship between a line in image and in object space. One way relies in the coplanarity condition which requires that the lines are lying in the same plane in 3D space. These approaches employ some straight line fitting through the respective image pixels to get an image line. The relationship between the image line and the object line can be established based on the coplanarity model.

The second type of approaches is based on the collinearity model. It deals with an arbitrary point on the line representation of the image feature and a corresponding representation of the feature in object space. To establish the image-object relationship through the collinearity model is more complex than the coplanarity model. In return, the collinearity equations allow working with lower level primitives (e.g. edge pixels). The collinearity equations are used in this research and the way the original equations are extended along with the defined parametric model is discussed in the following section.

2.2.1 The Collinearity Approach

Calculating the exterior orientation parameters using points is well understood and straight forward in photogrammetric practice. The collinearity condition requires that the vector from the perspective centre to a distinct point on the image is a scaled version of the vector from the perspective centre to the corresponding object point. To extend the approach to object lines, instead of individual object control points a set of control points are defined along the selected control line. Through this trick the parametric representation of the control line connects well to the collinearity model. Let the line be represented by point A = (X_A, Y_A, Z_A) and the direction vector **d** = (a, b, c). Then any point on the line is defined (Equation 1) by introducing a real variable t denoted as the line parameter.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} + t \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (1)$$

The collinearity equations for point P with object coordinates (X_P, Y_P, Z_P) read as

$$x_p = -f \cdot \frac{U}{W} \quad (2)$$

$$y_p = -f \cdot \frac{V}{W} \quad (3)$$

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = R^T \cdot \begin{bmatrix} X_P - X_0 \\ Y_P - Y_0 \\ Z_P - Z_0 \end{bmatrix} \quad (4)$$

where

x_p, y_p	measured image coordinates
R	the rotation matrix
X_0, Y_0, Z_0	the object space coordinates of the perspective centre
f	focal length

The superscript T denotes the transpose of the matrix.

Now U, V, and W can be modified with the line parameter representation

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = R^T \left(\left(\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} + t \begin{bmatrix} a \\ b \\ c \end{bmatrix} \right) - \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \right) \quad (5)$$

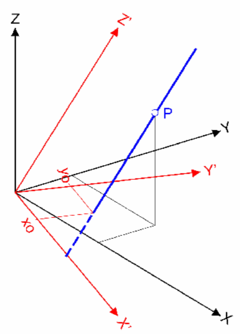
and the standard collinearity equations (2) and (3) are modified accordingly.

This is the basic mathematical model to incorporate line features into the collinearity constraints. Moreover, this does not give a unique solution because there are infinite number of points that can be selected and many ways to define the direction. Two constraints are added to fix that ambiguity. One is for fixing the point and the second constraint is for defining the direction. The most acute problem which is faced is the appropriate parametric representation. Schenk (2004) proposes a 4-parameter representation which simplifies the unnecessary complication that appears in the general approach. The proposed four parameters do not need additional constraints to define a point uniquely.

2.2.2 4 – Parameter Representation

Let $\boldsymbol{L}$ be a line given in 3D Cartesian space O-XYZ. Let O-X′Y′Z′ be a coordinate system with the same origin and which is rotated such that to find its Z′ axis is parallel to $\boldsymbol{L}$. The direction of the line is given by the mutual rotation of two systems. Two angles are sufficient to define the direction while the third angle which is the rotation about the line itself is kept fixed, for example by setting it to zero. For more information reader is referred to Schenk (2004).

The proposed representation of a line is based on two orientation parameters and two positional parameters. Two orientation parameters define the direction of the line. Positional parameters are the intersection point of the line and a plane, which is perpendicular to the line and passes through the origin.



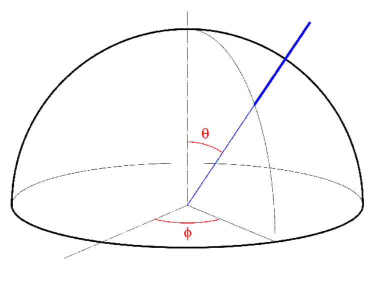


Figure 1: Illustration of the 4-parameter representation (taken from Schenk 2004.)

Figure (1) illustrates the concept of 4-parameter representation. Two parameters $(\phi,\ \theta)$ which are bounded by $0 \le \phi \le 2\pi$ and $0 \le \theta \le \pi$, define the direction of the line L. All possible directions of the line $\boldsymbol{L}$ are defined with these two angles. The positional parameters are denoted as (x_o, y_o) which are the coordinates of the intersection point of the line with the (X',Y')-plane. Then the line can uniquely be represented by the 4_tuple $\{\phi,\ \theta,\ x_o,\ y_o\}$. (Schenk 2004).

2.2.3 4- Parameter Transformation

A straight line in 3D space can be represented in the form of $L\{\mathbf{p},\mathbf{d}\}$ where $\mathbf{p} = (X_P, Y_P, Z_P)$ is the position and $\mathbf{d}$ = (a, b, c) is its direction vector. If the same line is represented by the four parameters $\{p_1, p_2, p_3, p_4\}$ the procedure to find the line's 4-parameter representation can be given as follows. Two orientation parameters of the 4-parameter representation can be determined by converting the direction vector into spherical coordinates ϕ, θ and ρ where ϕ is the azimuth, θ the zenith angle and ρ the radius of the sphere. The two parameters ϕ, θ can be found independent of ρ hence $\mathbf{d}$ does not need to be a unity vector. The rotation matrix $R_{\phi\theta}$ is formed as,

$$R_{\phi\theta} = \begin{bmatrix} \cos\theta\cos\phi & \cos\theta\sin\phi & -\sin\theta \\ -\sin\phi & \cos\phi & 0 \\ \sin\theta\cos\phi & \sin\theta\sin\phi & \cos\theta \end{bmatrix} \quad (6)$$

$R_{\phi\theta}$ rotates the point $\mathbf{p}$ from the original object space into the 4-parametric space whose Z axis is parallel to the object control line. Then the transformed point $\mathbf{p}'$ is given by the following relationship.

$$p' = R_{\phi\theta} \cdot p = \begin{bmatrix} x_0 \\ y_0 \\ z \end{bmatrix} \quad (7)$$

It is obvious that any point on the line will have the same planimetric coordinates (x_o, y_o) but a different z coordinate. In fact this represents a vertical line in the 4-parametric space. The inverse relationship of Equation 7 maps any point in the 4-parametric space to the corresponding point in the original object space. The equation 8 shows the inverse relationship as

$$p = R^T_{\phi\theta} \cdot p' = \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix} \quad (8)$$

which can be used to replace Equation (1) within the adjustment process.

2.3 Redundancy Considerations

The coordinates of the perspective centre and the three attitude angles of the rotation matrix are the six exterior orientation parameters. Every measured point on the image renders two observations to the model. It needs at least three points to solve the problem in the standard point-based calculations of exterior orientation. The line parameters are additional parameters that have to be solved along with the exterior orientation parameters in the extended collinearity linear feature based model. Each point on the line adds one additional line parameter to the bulk of unknowns. Three non-collinear control lines measured by two edge points per line lead to 3 x 4 equations of the collinearity model (Equations 2 and 3). Thus three lines are needed to solve 6 orientation unknowns and 6 unknown line parameters. Observing more than two points per image line does not reduce rank deficiency but increases the redundancy. Alternatively the orientation can be solved with six control lines using only one point per line.

3 METHODOLOGY

The extended collinearity model contains additional unknowns and looks more complex than the standard formulation with points. Line parameters are the added unknowns to the model with one additional unknown for each measured point on the line. The implementation of the algorithm is done using simulated data to study properties of the proposed model. Replicating the process with real data follows once the elementary behaviour is understood.

Image flight parameters are simulated assuming a camera with 150 mm focal length at the altitude of 1500 m. The perspective centre is fixed at (1150.0, 1150.0, 1500) m. 1^0, 1^0, 3^0 are the rotations that have been applied on the image as Omega (ω), Phi (ϕ) and Kappa (κ) respectively. Size of the image is 230 ×230 mm^2 as the standard. Control lines in different configurations are selected (see section 2.3) using starting and end points of a 3D line and corresponding image coordinates are calculated accordingly. A similar methodology is used to calculate the image coordinates when the measured points along the control line are increased. Randomly generated noise is added finally on to the calculated image coordinates in order to obtain more realistic image coordinates.

3.1 Implementation of Algorithms

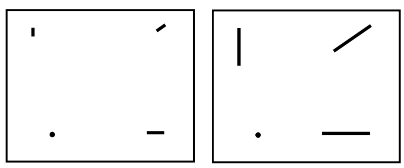
To compute the exterior orientation parameters for both points and linear features the collinearity equations for the standard and the extended version of the line feature based model (4-parameter line representation) are implemented. This will help to compare the results subsequently.

The implementation takes into account that 3D control lines are typically collected by field survey or taken from available GIS or map data. The directional parameters (azimuth ϕ, and the zenith angle θ) are computed by converting the direction vector of the line into spherical coordinates. Further the positional coordinates (x_o,y_o) are determined and introduced into adjustment model for further computations as mentioned in the Equations 6 and 7. Each line has its orientation (azimuth and zenith) and gives different rotation matrices $R_{\phi\theta}$.

3.2 Geometrical Configuration

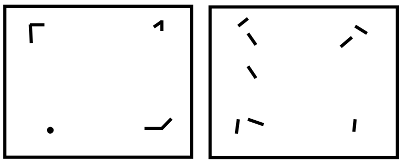
Different geometrical configurations are used to determine the exterior orientation of each simulated image and results are compared accordingly. Various orientations in object lines configuration permit to analyze the behaviour of the computational model. Line configurations consist with dissimilar geometrical orientations of each other, for example, exact vertical lines, lines parallel to the X axis, parallel to the Y axis and slanted lines. It gives a platform to evaluate the contribution of the line geometry towards the accuracy in the process.

Four line configurations (A, B, C & D) as can be seen from above in object space are shown in Fig. 2 and 3 and are used for the computation. Line arrangement B and C are formed based on configuration A. A vertical line is denoted as a dot in Figures 2 and 3. The minimum of three lines with two points is sufficient to solve the exterior orientation parameters as described in Section 2.3. The line geometry B in Figure 2 (b) shows almost the same orientation but with longer lines than A.



(a) (b)

Figure 2: Line geometry A & B; (a) Configuration A includes four lines with different orientations; (b) Configuration B uses the same line orientation but longer lines.



(a) (b)

Figure 3: Line geometry C & D; (a) Configuration C includes 3 more lines than A & B, (b) Configuration D consists of arbitrarily collected lines with different orientations.

The major difference between configuration C and A is some additionally added short lines. Finally short lines have been randomly selected and added in configuration D which is shown in Figure 3 (b).

4 RESULTS AND ANALYSIS

With noise free data the simulated exterior orientation parameters (1^0, 1^0, $3^{0,}$ 1150m, 1150m, 1500m) have been obtained for all configurations as expected. By adding small noise to the image coordinates of configuration A and B, corresponding deviations of the simulated parameters are observed which was to be expected. By increasing the number of points within the lines an improvement towards the simulated orientation parameters was expected because or the increased redundancy. The following table shows the estimated coordinates of the projection centre for configuration A.

	Number of points per line				
	2	6	10	15	20
X_0	1149.5	1147.7	1149.7	1151.3	1151.5
Y_0	1149.7	1146.9	1149.3	1152.3	1152.0
Z_0	1497.7	1497.4	1500.4	1497.3	1501.1

Table 1. Estimated projection centre coordinates of configuration A for a different number of points per line.

Adding points within the lines leads to non-systematic deviations from the simulated coordinates of the perspective centre. A similar behaviour was observed in the rotation parameters for the same line geometry. The lines of configuration B follow the same non-systematic behaviour. Obviously the impact of the randomly generated noise on the orientation estimates was bigger than the accuracy improvement which was expected with increased redundancy.

The line configuration C shows a significant improvement compared to the results of configurations A and B. Seven lines with ten points for each line were used. Table 2 gives the results for the orientation parameters of line-based model. For comparison the results of the standard point based exterior orientation method are listed as well. The end points of each line are taken as the ground control points for the point based calculation.

	Line based Method	Point based Method
Observations	140	14
Unknowns	76	6
X_0	1149.947 m	1149.915 m
Y_0	1150.030 m	1149.988 m
Z_0	1499.996 m	1499.982 m
ω	0.9994^0	1.0006^0
ϕ	0.9978^0	0.9984^0
κ	3.0000^0	2.9991^0
σ_0(estimated)	5 µm	7 µm

Table 2. Exterior orientation parameters of configuration C calculated with the line based method and the point based method.

The estimated orientation parameters of configuration C are much better than those found for configurations A and B. The result obtained for line geometry D was quite similar to the result of configuration C. Surprisingly the line based method and the point based method lead to results with fairly similar quality.

From the results we can learn, that the quality of the estimated exterior orientation parameters depends on the geometry of the lines which are selected. The length of the lines seems to have no significant impact on the results found by comparing the results of A and B. The geometrical stability of the line constellation can be assessed using the condition number of the normal matrix of the adjustment model. The condition number of a matrix measures the sensitivity of the solution of a system of linear equations to errors in the data. With very high condition numbers the accuracy of the results from matrix inversion and the linear equation solution gets doubtful.

	Line Configuration			
	A	B	C	D
Condition Number	$2x10^{12}$	$3x10^{10}$	$4x10^8$	$6x10^8$

Table 3. Condition numbers of line configurations with 2 points per line.

Table 3 reveals that extending the lines leads to an improvement of the condition number by a factor of 100 if configurations A and B are compared. Another improvement by a factor of 100 is observed for line combinations C and D compared to B. This improvement indicates the higher geometrical stability obtained by adding additional lines to the 4 line configurations A and B. The condition number for the standard point based calculation with four points at corners is also in the order of 10^8.

5 CONCLUSIONS

Single photo resection is performed successfully with the 4-parametric line based model proposed by Schenk (2004) and compared with the traditional point based calculation. Investigations with configurations of only four lines showed that the length of the lines seems to have no significant impact on the results of the line based method. An improvement could also not be observed by using more points within the lines, e.g. ten instead of just two points per line. One of the reasons might be the weak condition number of the normal equation matrix (in the order of 10^9 or more) which has been observed for four lines configurations.

Experiments with different line configurations confirm that the quality of the estimated parameters depends on the stability of the line geometry. A significant improvement of the estimated orientation parameters was observed for the 7 and 8 line configurations compared to the 4 line geometry. Somewhat unexpected was the result found by comparing line based and traditional point based solutions. The accuracy of the estimated parameters is only slightly better with the line feature based orientation than the standard point based method.

The 4-parametric representation has a potential to handle control lines irrespective of its orientation in the object space and this property encourages testing the Aerial Triangulation with linear features.

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