LINEAR FEATURES IN PHOTOGRAMMETRY

A. F. HABIB
M. F. MORGAN

Department of Geomatics Engineering, University of Calgary,
2500 University Drive, Calgary, AB, T2N 1N4, Canada
habib@geomatics.ucalgary.ca, mfmorgan@ucalgary.ca

ABSTRACT

Traditional photogrammetric activities such as orientation, triangulation, and object space reconstruction have been relying on distinct points in their underlying operations. With the evolution of digital photogrammetry, there has been a tremendous interest in utilizing linear features in various photogrammetric activities. This interest has been motivated by the fact that the extraction of linear features from the image space is easier to automate than distinct points. On the other hand, object space linear features can be directly derived form terrestrial Mobile Mapping Systems (MMS), GIS databases, and/or existing maps. Moreover, automatic matching of linear features, either within overlapping images or between image and object space, is easier than that of distinct points. Finally, linear features possess more semantic information than distinct points since they most probably correspond to object boundaries. Such semantics can be automatically identified in imagery to facilitate higher-level tasks (e.g., surface reconstruction and object recognition). This paper summarizes the use of linear features, which might be represented by analytical functions (e.g., straight-line segments) or irregular (free-form) shapes, in photogrammetric activities such as automatic space resection, photogrammetric triangulation, camera calibration, image matching, surface reconstruction, image-to-image registration, and absolute orientation. Current progress, future expectations, and possible research directions are discussed as well.

KEY WORDS: Linear Features, Straight Lines, Space Resection, Photogrammetric Triangulation, Camera Calibration, Scene Registration, Absolute Orientation

1. INTRODUCTION

The majority of manual orientation as well as map compilation processes rely heavily on point-based features, which are well determined in two-dimensional imagery. For these features, the human operator has to store their semantics for later use. After the introduction of softcopy workstations and digital image compilation and analysis, the majority of recent research activities have been focusing on the automation of various point-based procedures in photogrammetry (Ackermann, 1984; Mikhail et al, 1984; Förstner, 1986; Grün and Baltsavias, 1987; Haala and Vosselman, 1992; Gülch, 1994; Drewniok and Rohr, 1997). The main difficulty in this type of research is the automatic extraction of useful semantics for the identified point primitives.

Recently, more attention has been focused on using higher-level features (e.g., linear and areal features) in various photogrammetric operations. The emergence of digital images coupled with well-developed image processing tools motivated this direction of research. Also, the research has been propelled by the fact that automatic extraction of linear features is easier than distinct points (Kubik, 1991). The reliability of the extracted features is another factor to be considered. The reliability stems from the relationships among the sub-entities, which yields a robust extraction process that is not susceptible to inherent noise in the input imagery. Moreover, such features increase the system's redundancy and consequently improve the geometric strength and robustness in terms of the ability to detect blunders. Therefore, matching ambiguities can be resolved, occluded areas can be easily predicted, and/or changes can be detected. Moreover, higher-level features possess more semantic information, which can be automatically extracted, regarding the object space. This constitutes an important factor for facilitating subsequent processes such as surface reconstruction and object recognition. In the object space, linear features can be easily derived from existing maps, GIS databases, or terrestrial Mobile Mapping Systems (MMS).

There has been a substantial body of work dealing with the use of linear features that can be represented by analytical functions (such as straight lines and conic curves) in photogrammetric orientation (Mikhail, 1993; Mulawa and Mikhail, 1988; Tommaselli and Lugnani, 1988; Tommaselli and Poz, 1999; Habib, 1999; Habib et al., 1999; Heuvel, 1999; Heuvel, 2000). On the other hand, few research attempts have addressed the use of free-form linear features (Habib and Novak, 1994; Smith and Park, 2000; Zalmanson, 2000). The main objective of the presented research in this paper is to establish a model capable of incorporating linear features, whether represented by analytical functions or free-form shapes, in images captured by frame cameras as well as scenes acquired by linear array scanners (line cameras). The implementation should allow for possible incorporation of these features in multi-sensor photogrammetric triangulation and other photogrammetric activities (such as single photo resection, camera calibration, relative orientation, scene registration, and absolute orientation).

In the next section, a short discussion regarding the motivation for using linear features is introduced. Section 3 deals with various alternatives for image and object space representation of linear features as well as the corresponding perspective transformation. The main applications of these primitives in various photogrammetric operations are briefly discussed in Section 4. Finally, conclusions and recommendations for future work are presented in Section 5.

2. FEATURE TYPES

Features can be defined as discerned objects of interest that can be extracted in the working space. Therefore, features in a photogrammetric environment can be classified into image and object space features. The following subsections discuss the various types of features that can be found in the image and object space. The discussion will also elaborate on the most suitable and convenient feature types for photogrammetric operations.

2.1 Image Space Features

Image space is two-dimensional. Therefore, primitives that can be extracted from this space are either point, linear, or areal features. It can be argued that areal features are the most general features, because the image space can be classified into homogeneous areal features/regions without leaving any part of the space unclassified. Linear and point features can be considered as a subset of areal features whose dimension in one or two directions is negligible because of scale or application requirements. One can also argue that linear features can be used as a dual representation of areal features through the use of their boundaries. Therefore, linear features can also represent the entire image space without gaps.

2.2 Object Space Features

Object space is a three-dimensional spatial space. Following the same line of thought in the previous section, one can consider volumetric features as the basis and most general primitives capable of representing the entire object space. However, appropriate object space features have to be based on the photogrammetric procedure for object space reconstruction. In photogrammetry, observing conjugate primitives in overlapping images is utilized to derive corresponding object space elements. The process usually starts by the extraction of image space primitives, either manually or automatically. Then, corresponding primitives need to be identified in overlapping images. Finally, geometric attributes of the imaging system, represented by the Interior and Exterior Orientation Parameters (IOP & EOP), as well as matched primitives are used in an intersection procedure to generate the corresponding object space. Therefore, suitable object space primitives are those that can be reliably extracted and matched in the input imagery. So far, photogrammetric object space reconstruction has been solely based on utilizing point and linear features. In other words, there has not been an established procedure for object space reconstruction using image space areal features. This leads us to conclude that point and linear features are the most suitable primitives for object space reconstruction from imagery and consequently they should be the chosen primitives. However, it should be noted that 3-D areal features (sometimes called surface patches) could be considered when implementing its dual representation, the bounding linear features.

2.3 Linear Features for Photogrammetric Activities: Why?

Traditionally, most of the photogrammetric applications are based on the use of distinct points, which are manually measured. Experienced human operators usually select few and well distributed points with high quality. With the introduction and continuous evolution of digital photogrammetry as a result of the availability of high-resolution scanners and advances in digital image processing, automated procedures are becoming popular. However, most of these procedures are still point-based. Image processing techniques allow for the extraction of numerous points with lower quality than these selected manually. Moreover, automatic matching of the extracted points in overlapping images is complicated and often unreliable procedure due to variations in the imaging system point of view and relief displacements in the image space. Due to the above limitations, recent photogrammetric research has been focusing on the use of linear features. This line of research has been motivated by the following facts:

1. Image space linear features are easier to extract when compared to distinct points. This is attributed to the nature of linear features since they represent discontinuities in the gray value function in one direction. On the other hand, point features represent discontinuity in all directions.
2. Linear features in the image space can be extracted with sub-pixel accuracy across the direction of the edge.
3. Images of man-made environments are rich with linear features.
4. Linear features allow for the incorporation of areal features through the use of their boundaries. Moreover, linear features are easier to use in change detection applications than areal features. The superiority of linear features stems from the possibility of dividing them into smaller subsets. On the other hand, breaking areal features into smaller subsets is not a trivial task.
5. Mobile Mapping Systems (MMS) can economically provide accurate and current object space linear features in real time.
6. Linear features possess higher semantic information, which are desirable for subsequent processes (such as DEM generation, map compilation, and object recognition). On the other hand, it is hard to derive useful semantic information regarding the real world from distinct points. Moreover, geometric constraints are more likely to exist among linear features than points. This will facilitate subsequent automatic matching and object recognition activities.
7. Linear features increase the redundancy and improve the robustness and the geometric strength of various photogrammetric adjustment activities.

Image space linear features can be either represented by an analytical function (e.g., straight-lines and conic sections) or by an irregular (free-form) shape. Among these representation alternatives, one can argue that straight-line features are appropriate for photogrammetric activities for following reasons:

1. Man-made environments are rich in straight lines.

2. Straight lines are easier to detect and the correspondence problem between overlapping images as well as between the image and object space becomes easier.
3. Straight-line parameters can be obtained with sub-pixel accuracy.
4. Free-form linear features can be represented with sufficient accuracy as a sequence of straight-line segments (poly-lines).
5. Straight lines are valuable for the recovery of the IOP of frame cameras, where object space straight lines should appear as straight lines in the image space in the absence of distortions. Therefore, deviation from straightness in the image space can be attributed to distortions (e.g., radial and de-centering lens distortions).
6. Straight lines are valuable for the recovery of the EOP of linear array scanners, where object space straight lines will not appear as straight lines in the image space due to perturbations (changes in the EOP) along the flight trajectory.

3. UTILIZING STRAIGHT-LINE FEATURES IN PHOTOGRAMMETRIC ACTIVITIES

So far, it has been established that among possible primitives, straight-line segments constitute the most appropriate features for various photogrammetric activities. Incorporating these primitives in photogrammetric applications has to address two key issues. First, one should determine the most convenient alternative for representing straight-line features in the image and object space. Then, a mathematical model has to be derived to incorporate the geometric attributes of these primitives to solve the photogrammetric problem in question (e.g., photogrammetric triangulation, image-to-image registration, absolute orientation). The following subsections will discuss these issues in detail.

3.1 Object Space Representation of Straight Line Features

In this section, two different representations will be analyzed and compared. The first approach is based on optimal representations that require minimal and unique parameters to define the straight line. The second approach deals with convenient representations from a photogrammetric point of view.

3.1.1 Optimal Representation

Optimal representations of object space straight lines are capable of modeling only infinite lines and require four parameters per line. There exist a variety of optimal representation alternatives of 3-D lines (Roberts, 1988; Faugeras and Hebert, 1986). As an illustration, we will briefly explain the approach adopted by Faugeras and Hebert (1986), where they represented the 3-D straight line as the intersection of two planes (Equations 1).

$$X = AZ + P$$
$$Y = BZ + Q \tag{1}$$

Equations 1 represent two planes parallel to the *Y* and *X* axes, respectively. In this case, the 3-D line is uniquely defined by the four-parameter vector (*A*, *B*, *P*, *Q*). It can be easily proven that (*P*, *Q, 0*) represent the intersection point of the line with the XY-plane. On the other hand, (*A*, *B, 1*) represent the direction vector of this line. However, this representation is incapable of representing lines parallel to *XY* plane (the z-component of the direction vector is zero). For these lines, different planes have to be chosen (e.g., two planes parallel to the *Y* and *Z* axes). The reader can refer to Habib (1998) and Habib (2000) for more details regarding the use of such representation to establish the perspective transformation between image and object space linear features.

In general, optimal representations of 3-D lines suffer from the following problems (Habib, 1999):

1. They represent infinite lines rather than line segments, which are more interesting for mapping applications.
2. Minimal representations always have singularities. In other words, they cannot represent all 3-D lines in space.
3. Error measures pertain to infinite lines. These measures might be completely different from the error measures associated with the line segments.
4. They lead to complicated models for establishing the perspective transformation between image and object space features. This will make it difficult to incorporate these techniques in existing bundle adjustment programs.

Due to the abovementioned shortcomings of optimal representations, the authors opted for the development of a convenient representation methodology of 3-D straight-line segments from photogrammetric point of view. The main motivation of such representation is the ability of defining well-localized line segments with straightforward perspective transformation functions between image and object space.

3.1.2 Convenient Representation

In this representation, the line-segment will be defined by two 3-D points along the line (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2), which can be the beginning and end points of that segment. Therefore, we will end up with a well defined line segments in space, which can be directly incorporated in GIS databases. In addition, such representation will have no singularity (i.e., it is capable of representing all line segments in space). Moreover, free-form linear features can be represented with sufficient accuracy by a set of connected finite straight-line segments. Finally, such representation would lead to a straightforward perspective transformation between the image and object space features. Such transformation functions can be easily incorporated in existing bundle adjustment procedures.

The next section outlines different alternatives for establishing the perspective transformation between corresponding image and object space line segments (i.e., perspective transformation between 2-D and 3-D line segments). Section 3.3 deals with the mathematical model for utilizing straight-line segments in other photogrammetric activities; namely image-to-image registration using 2-D line segments and surface-to-surface registration (i.e., absolute orientation) with the help of 3-D line segments.

3.2 Perspective Transformation of Straight Line Features

So far, we have established a convenient representation of 3-D line segments using two points along the line. The formulation of the perspective transformation between corresponding object and image space segments depends on the representation methodology of the linear features in the image space. In this section, we will discuss two methods for image-to-object space perspective transformation of straight-lines. The first method assumes that 2-D straight-line segments can be used to represent image space linear features. One should note that an object space straight-line would be projected into an image captured by a frame camera as a straight line in the absence of distortions (e.g., radial and de-centering lens distortions). In other words, this approach requires prior removal of various distortions, which can be determined through a calibration procedure, from the input imagery. The second perspective transformation method is more general since it can handle raw images captured by frame cameras in the presence of distortions (i.e., it allows for possible deviations from straightness in the image space features). Therefore, such a methodology can be incorporated in a bundle adjustment with self-calibration procedure to solve for the IOP of the implemented camera. Moreover, it is suitable for dealing with linear features in scenes captured by linear array scanners since perturbations in the flight trajectory would cause deviations from straightness in the acquired images of these features.

3.2.1 Dealing with Straight Lines in the Absence of Distortions

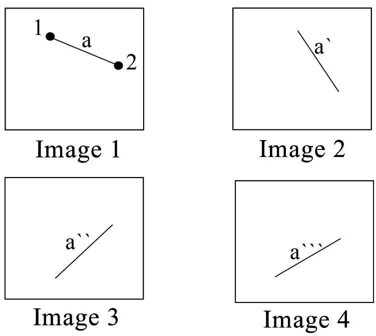
As depicted in Figure 1, for a frame camera, a straight line in the object space will be projected as a straight line in the image space in the absence of distortions.

In this section, we are aiming at the incorporation of straight-line segments together with some tie and control points appearing in overlapping images in a bundle adjustment procedure to solve for the following:

(a) EOP of the involved imagery,
(b) Ground coordinates of tie points, and
(c) Ground coordinates of the points defining object space straight lines.

The methodology starts by defining two points along the line segment in <u>one</u> of the images. These points can be chosen and measured in any image within which the line appears, such as $p_1(x_1, y_1)$ and $p_2(x_2, y_2)$, Figure 1. One must note that these points need not be identifiable or even visible in the remaining images (i.e., they will be measured only once). The relationship between the measured image and corresponding object coordinates, (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2), is established through the collinearity equations. Conjugate line segments in overlapping images will be represented by their polar coordinates; for example, $(\rho`, \theta`)$, $(\rho``, \theta``)$ and $(\rho```, \theta```)$ in Figure 1. For each of these measured lines, constraints have to be introduced to ensure that the image line represented by (ρ_i, θ_i) belongs to the plane defined by the object points (X_1, Y_1, Z_1), (X_2, Y_2, Z_2), and the perspective center O_i (Figure 2). Before deriving such constraints, let us introduce the terms *object plane* and *image plane* to denote the plane through the perspective center and the object line as well as the plane through the perspective center and the image line, respectively (Figures 2 and 3). The image plane can be defined using the two vectors $(\rho_i / \cos(\theta_i), 0, -c)$ and $(0, \rho_i / \sin(\theta_i), -c)$, which connect the perspective center to the intersections of the line with x and y axes, respectively (Figure 3). Therefore, the normal to the image plane, n_i, can be derived through the cross product of these vectors as $(c \cos(\theta_i), c \sin(\theta_i), \rho_i)$. On the other hand, the object plane includes the vector $(X_1\text{-}X_{0i}, Y_1\text{-}Y_{0i}, Z_1\text{-}Z_{0i})$, Figure 2. This vector is perpendicular to n_i. Therefore, the dot product of these vectors should be zero, Equation 2.

Figure 1. Straight-line segment in overlapping images is defined by two points in one image and by polar coordinates in the other images.



$$R^T_{\omega i,\varphi i,\kappa i} \begin{bmatrix} X_1 - X_{0i} \\ Y_1 - Y_{0i} \\ Z_1 - Z_{0i} \end{bmatrix} \bullet \begin{bmatrix} c\cos(\theta_i) \\ c\sin(\theta_i) \\ \rho_i \end{bmatrix} = 0 \qquad (2)$$

Figure 2. The object line and the perspective center define the object plane.

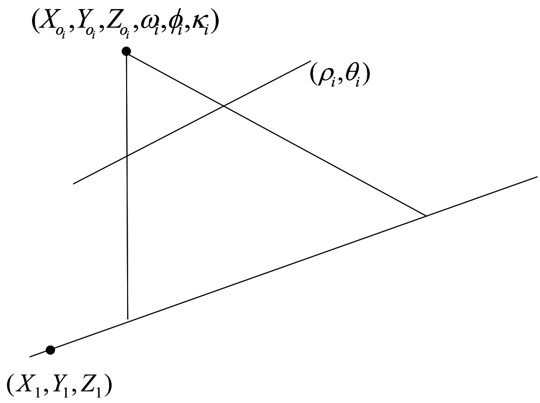
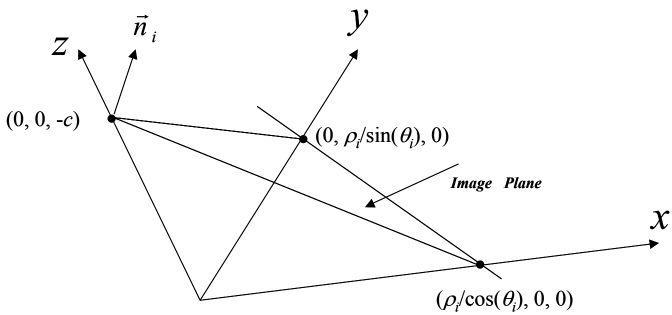


Figure 3. The image line and the perspective center define the image plane.



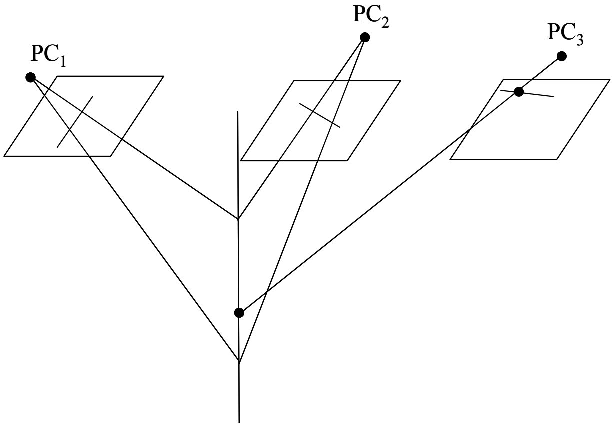
The rotation matrix, R, has been included in Equation 2 to ensure that the two vectors are defined relative to the same coordinate system (i.e., the image coordinate system). The constraint in Equation 2 incorporates the object coordinates (X_1, Y_1, Z_1), the image line parameters (ρ_i, θ_i), and the EOP of the corresponding image. Another constraint can be written for the second object point (X_2, Y_2, Z_2).

The above constraints can be conceptually explained as follows (see Figure 4):

1. In one image, one defines the object points along the line through single light rays (as expressed by the collinearity equations).
2. In the remaining images, one defines the object plane through the object line, the image line, and the corresponding perspective center.

3. The ground points along the object line are derived as the intersection of the light rays with the defined object planes.

Figure 4. Object space point along the line is obtained through the intersection of the object planes and a single light ray.



The above methodology outlines the utilization of tie straight-lines in a unified bundle adjustment that might also incorporate some tie and control points. However, the methodology can be slightly modified to handle control linear feature, which might be derived from existing GIS databases and terrestrial MMS. For control straight line, the end points (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) are already available. In other words, there is no need to measure the end points in the image space (i.e., all the image lines will be defined by their respective polar coordinates). Only two constraints of the form in Equation 2 are written for each image where this line appears.

3.2.2 Dealing with Straight Lines in the Presence of Distortions

The previous methodology cannot be used whenever images of object space straight lines exhibit deviations from straightness. However, such deviations are expected when dealing with un-calibrated cameras (due to radial and de-centering lens distortions) as well as scenes captured by line scanners (due to perturbations in the flight trajectory). Therefore, a more general methodology has been developed. This approach allows for the determination of the IOP of frame cameras as well as the recovery of the EOP associated with scenes captured by line scanners.

Similar to the previous method, the object line is defined by two points, which can be selected in one or two images within which this line appears. These points need not be visible in other images, Figure 5. The relationship between these measured coordinates and the corresponding ground coordinates, (X_1, Y_1, Z_1) and

(X_2, Y_2, Z_2), is established through the collinearity equations. On the other hand, corresponding linear features in overlapping images will be defined by a sequence of intermediate points along these features. Once again, the measured intermediate points need not to be conjugate. Figure 5 illustrates two scenarios for the measurement of the end and intermediate points. The end points can be either identified in a single image (Figure 5-a) or in two different images (Figure 5-b).

For every intermediate point, a constraint has to be introduced to ensure that the two ground points, the intermediate image point, and the corresponding perspective centre are coplanar. This constraint can be expressed as the triple product in Equation 3, Figure 6.

Figure 5. End points can be measured in one image (a) or in two different images (b) while the intermediate points are measured in all images within which the line appears.

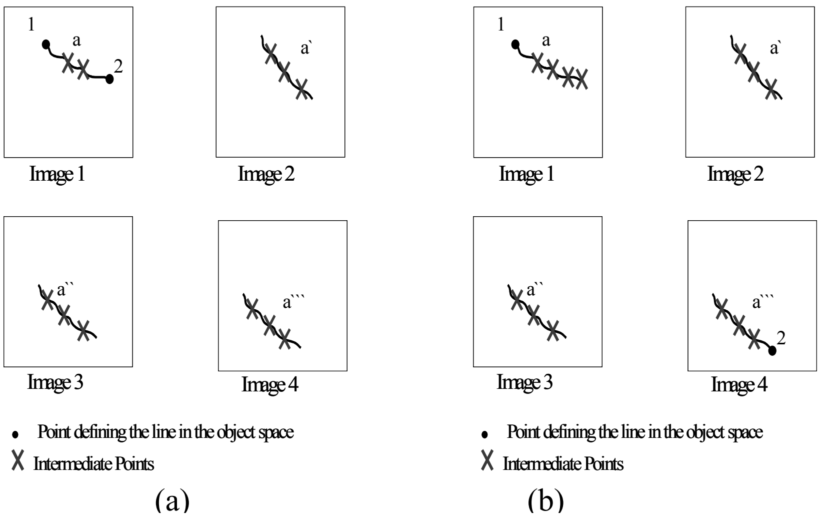
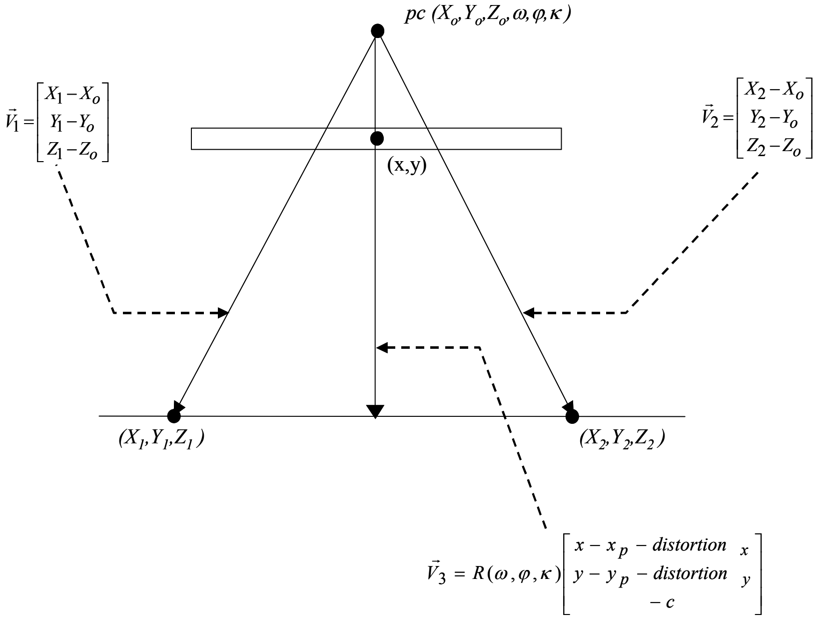


Figure 6. The mathematical model: the coplanarity condition



$$\left(\mathbf{v}_1 \times \mathbf{v}_2\right) \bullet \mathbf{v}_3 = 0 \qquad (3)$$

Where:

$\mathbf{v}_1$, $\mathbf{v}_2$ are the vectors connecting the perspective center and the two object points (the end points), and

$\mathbf{v}_3$ is the vector connecting the intermediate point and the perspective center, rotated into the ground coordinate system.

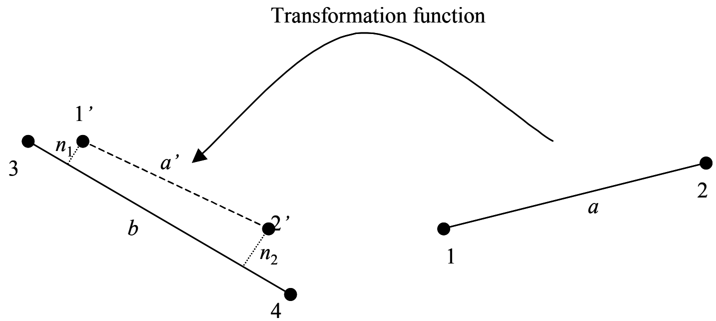
The constraint in Equation 3 incorporates the ground coordinates of the points defining the object line, the IOP of the camera, the image coordinates of the intermediate point, and the EOP of the image. Thus, it does not introduce new parameters. Similar to what has been mentioned in the previous section, control lines can be also considered. In such a case, there is no need to measure the end points in the imagery since the control line already defines them. The depicted constraint in Equation 3 is suitable for the estimation of distortion parameters associated with frame cameras. Moreover, for scenes captured by linear array scanners, it can be used to estimate variations in the EOP of the scanner along the flight trajectory. Such capability is attributed to measuring numerous intermediate points along the linear feature in the image space.

3.3 Straight-Lines in Other Photogrammetric Applications

So far, we have discussed the utilization of straight-line segments in photogrammetric triangulation procedures. In this section, we will investigate the use of linear features in other photogrammetric activities; namely, image-to-image registration (using 2-D line segments) and surface-to-surface registration (i.e., absolute orientation using 3-D line segments). For these applications, the line segments will be represented by their end points, which need not be conjugate. The correspondence of the line segments is described by a mathematical constraint, which ensures the coincidence of conjugate line segments after applying the proper transformation function relating the involved images or surfaces.

To illustrate the concept of the registration procedure using line segments, let us consider Figure 7, where a line segment *a*, defined by the end points 1 and 2, in the first dataset is known to be conjugate to the line segment *b*, defined by the end points *3* and *4*, in the second dataset. Let us assume that the line segment *a′*, defined by the end points *1′* and *2′*, is the same line segment *a* after applying the transformation function relating the two datasets in question. In this case, we need to introduce a mathematical constraint, which guarantees that the end points *1′* and *2′* lie along line *b* but not necessarily coincide with points *3* and *4*. In other words, the mathematical model should minimize the normal distances between the transformed end points in the first data set, points *1′* and *2′*, and the corresponding line in the second dataset, line *b*. The implemented transformation function depends on the nature of involved datasets. For example, either 2-D similarity or affine transformations can be used for image-to-image registration. On the other hand, 3-D similarity transformation can be used for surface-to-surface registration applications.

Figure 7: Correspondence of conjugate line segments in two datasets.



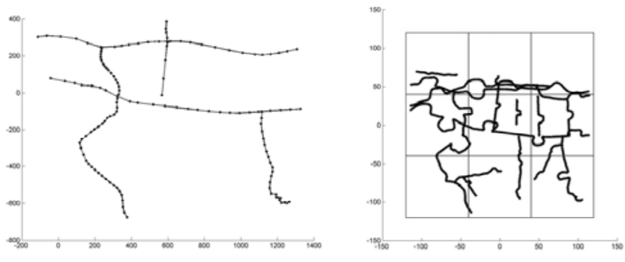
4. APPLICATIONS

This section briefly outlines the implementation of linear features in various photogrammetric activities such as automatic space resection, photogrammetric triangulation, camera calibration, image matching, surface reconstruction, image-to-image registration, and absolute orientation. It should be mentioned that we will not go through great details within the discussion of these applications (i.e., we are mainly illustrating the value and the benefits of using linear features). However, detailed analysis of such applications can be found in the provided references.

4.1 Single Photo Resection (SPR)

In single photo resection, the EOP of an image are estimated using control information. Traditionally, the SPR problem has been solved using distinct control points. However, the SPR can be established using control linear features, which can be derived from MMS, existing GIS databases, and/or old maps. Corresponding image space linear features can be either manually digitized or automatically extracted using dedicated image processing operators. Conjugate object and image space straight-line segments can be incorporated in a least squares procedure, utilizing either the constraints in Equations 2 or 3, to solve for the EOP. A minimum of three non-parallel line segments is needed to solve for the six elements of the EOP. This approach can be expanded to handle free-form linear features, which can be represented by a set of connected straight-line segments, Figure 8. Habib et al (2003c, d) introduced the Modified Iterated Hough Transform (MIHT) to simultaneously establish the correspondence between object and image space line segments as well as estimate the EOP of an image captured by a frame camera. The MIHT successfully estimated the EOP while finding the instances of five object space linear features within 21 image space features, Figure 8. This approach has been used to detect discrepancies between common features in image and object space (Habib et al, 2001b; 2002b). Lee and Habib (2002) used the same approach to estimate the EOP of a scene captured by linear array scanner.

Figure 8. SPR using control linear features (a) while establishing the correspondence with image space features (b).



(a) (b)

4.2 Photogrammetric Triangulation

In this application, straight lines can be implemented as tie features, control features, or combination of both. Habib, 1999 and Habib et al., 2001a showed the feasibility of using straight lines in photogrammetric triangulation using straight line segments in imagery captured by frame cameras and linear array scanners, respectively. It has been proven that the photogrammetric triangulation of scenes captured by linear array scanners incorporating straight-line segments led to a better recovery of the EOP when compared to these derived using distinct points (Habib et al., 2000; 2001a).

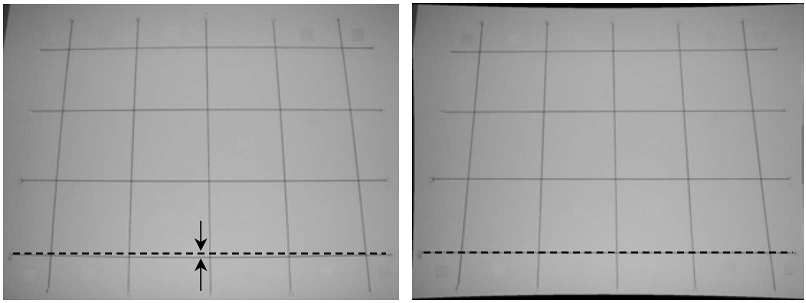
4.3 Digital Camera Calibration

Straight lines could be beneficial for estimating the internal characteristics of frame cameras. Deviations from straightness in the image space are attributed to various distortions (e.g., radial and de-centering lens distortions). Habib and Morgan (2002, 2003) and Habib et al (2001a; 2002a, c) used object space straight-lines in a calibration test field as tie features for digital camera calibration. Figure 9-a shows an image of the test field comprised of straight lines, where distortion parameters led to deviations from straightness in the image space. Figure 9-b illustrates the recovery of the straightness property using the estimated IOP from the calibration procedure. Moreover, the calibration results turned out to be almost equivalent to these derived from traditional point-based calibration procedures. However, the test field incorporating linear features is very easy to establish. In addition, the features can be automatically extracted allowing non-photogrammetric users of digital cameras to produce high quality positioning information from imagery. Current research is focusing on using this approach for stability analysis of low cost digital cameras.

4.4 Image Matching and 3-D Reconstruction

Habib and Kelley (2001) used the MIHT strategy to estimate the Relative Orientation Parameters (ROP) between the images of a stereo-pair using linear features. This approach utilized the geometric attributes of the linear features as well as the geometric characteristics of the imaging system to derive a robust estimate of the ROP. The suggested approached was successful in dealing with large-scale imagery over urban areas, which proved to be difficult when using traditional matching procedures. Habib et al (2003b) extended this approach to allow for the reconstruction of corresponding 3-D linear features, Figure 10. Such an approach can be expended to allow for surface reconstruction, ortho-photo generations, and object recognition applications.

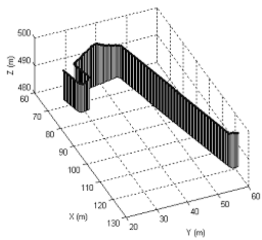
Figure 9. Straight line before calibration (a) and after calibration (b). Straight dotted lines were added to show the recovery of the straightness property.



(a) (b)

Figure 10: Left (a) and right (b) images containing matched linear features and the reconstructed 3-D linear feature (c).

(a) (b)

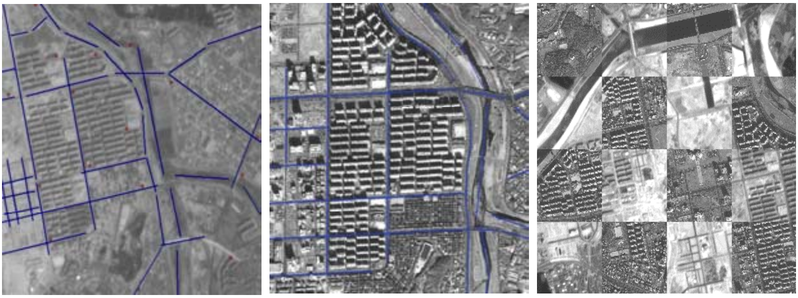


(c)

4.5 Image-to-Image Registration

With the enormous increase in earth observing satellites, there has been an urgent need for establishing automatic and accurate registration techniques of multi-source imagery with varying geometric and radiometric properties. Traditional image registration techniques require distinct points, which have to be identified in the imagery. However, identifying conjugate points in imagery with varying geometric and radiometric resolutions is difficult. Habib and Al-Ruzouq (2003) used linear features for the co-registration of scenes captured by space-borne linear array scanners. The MIHT strategy has been implemented to automatically establish the correspondence between conjugate linear features as well as estimate the parameters relating the involved scenes. Figure 11 shows straight-line features digitized in SPOT and IKONOS scenes as well as a mosaic scene generated after establishing the registration.

Figure 11: SPOT (a) and IKONOS (b) scenes with digitized linear features, which are used to generate a composite mosaic (c).

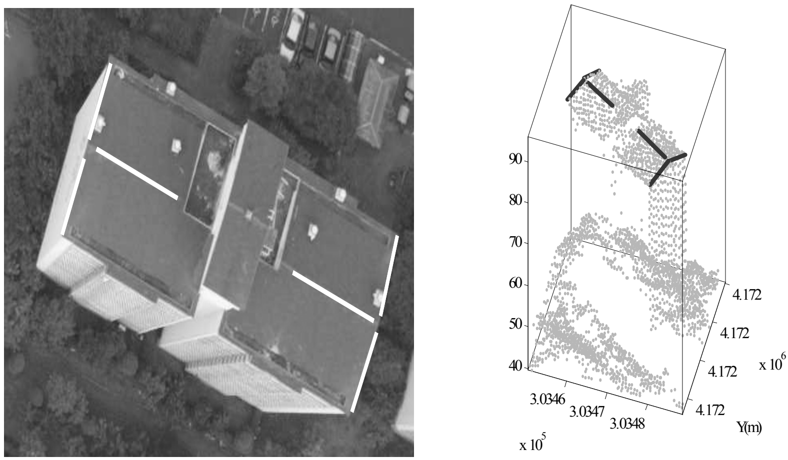


(a) (b) (c)

4.6 Surface-to-Surface Registration

With the increasing popularity of LIDAR systems, there has been an interest in establishing procedures for surface-to surface registration for change detection applications. Habib et al (2003a) used straight-line features for establishing the transformation parameters relating overlapping surfaces. The registration procedures used LIDAR features as control information to establish the absolute orientation of 3-D photogrammetric models. Photogrammetric triangulation incorporating tie linear features has been used to derive 3-D straight-line segments relative to an arbitrary coordinate system, Figure 12-a. On the other hand, homogeneous planar features have been identified in acquired LIDAR surfaces. Then, neighbouring planar surfaces are intersected to provide LIDAR linear features, Figure 12-b. Finally, conjugate photogrammetric and LIDAR features were used to determine the parameters relating the photogrammetric coordinate system to the LIDAR reference frame (i.e., solve for the absolute orientation parameters). The approach proved successful in detecting discrepancies between the involved surfaces. Such discrepancies can be either attributed to changes in the object space and/or un-accounted for systematic biases in the data acquisition systems.

Figure 12. Straight-line features obtained from photogrammetric (a) and LIDAR (b) systems.



(a) (b)

5. CONCLUSIONS AND RECCOMENDATION FOR FUTURE RESEARCH

With recent advances in digital image acquisition and processing systems, linear features proved to be useful primitives for various photogrammetric activities. The ability of automatically and reliably extracting the linear features from the input imagery is one of the major factors behind the increasing interest in utilizing these features. Moreover, object space linear features can be economically provided by terrestrial MMS, GIS databases, and existing maps. Finally, linear features can be used as a dual representation of areal features through the use of their boundaries. This paper discussed the key issues related to the incorporation of linear features in photogrammetric applications.

First, it has been established that among the possible types of linear features, straight-line segments are the most interesting ones. This can be attributed to the fact that they exist in abundance in imagery of man-made environments. Also, free-form linear features can be represented with sufficient accuracy as a sequence of straight-line segments (poly-lines). Moreover, straight-line segments are valuable for the self-calibration of frame camera and the recovery of the EOP for linear array scanners.

For straight-lines, it has been argued that using two points along the linear features is the most convenient representation methodology from a photogrammetric point of view. Using such representation, we introduced several mathematical models for incorporating linear features in photogrammetric problems (e.g., automatic space resection, photogrammetric triangulation, camera calibration, image matching, surface reconstruction, image-to-image registration, and absolute orientation). For example, straight-line segments from existing GIS databases can be used to estimate the EOP of a single image (SPR). Such integration of object space vector data with aerial imagery would allow for change detection and updating applications. Straight lines can be also used either as control or tie features in photogrammetric triangulation procedures involving frame or linear array scanners. For frame cameras, the straight-lines will allow for the recovery of the IOP of the implemented camera. On the other hand, straight-lines will lead to a reliable recovery of the EOP associated with scenes captured by linear array scanners. In addition, linear features offer a significant advantage in solving image matching and surface reconstruction problems, especially when dealing with large-scale imagery over urban areas. Finally, we outlined a methodology for incorporating linear features in image-to-image and surface-to-surface registration tasks. Such methodology is valuable for registering multi-source imagery with varying geometric and radiometric resolutions. Moreover, it can be used as a tool for utilizing LIDAR surfaces as control information for photogrammetric triangulation and the calibration of LIDAR/photogrammetric systems.

Current research is concentrating on reliable automation of the linear feature extraction from imagery as well as surfaces. More research is still needed to establish robust matching procedures working with linear features. Finally, future developments will focus on incorporating linear and areal features in surface reconstruction, object recognition, change detection, and map updating activities.

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