

# POSE ESTIMATION OF LINE CAMERAS USING LINEAR FEATURES.

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## ABSTRACT

Pose estimation, which determines the position and the attitude of the camera, is a prerequisite for a variety of photogrammetric tasks such as image matching, surface reconstruction, ortho-photo generation, and object recognition. As digital imagery is becoming more popular in photogrammetric applications, features other than points are increasingly employed in pose estimation. For frame imagery, prior research has incorporated geometric constraints into the bundle adjustment to take advantage of high-level features, such as straight lines. This study introduces high-level feature constraints into the pose estimation problem for aerial line scanners. Traditionally, it has been assumed that robust pose estimation for a dynamic (non-frame) sensor cannot be obtained without direct measurements using Global Positioning System (GPS) and Inertial Navigation system (INS). This study attempts to challenge, in part, this argument by showing that the unknown orientation parameters for all scan lines, within a scene captured by line scanner, can be estimated by including linear features in an indirect orientation procedure that is less dependent on GPS/INS data. This indirect orientation is achieved by incorporating straight-line constraints in the bundle adjustment for aerial line array scanners. A scene captured by an aerial line scanner is composed of sequence of scan lines, each of which may be slightly shifted against each other due to changes in the system's trajectory. As a result, straight lines in object space do not appear as straight lines in image space. The straight-line constraint is proposed in this study to cope with this phenomenon. This constraint makes use of straight-line features in object space to aid independent recovery of exterior orientation parameters of the entire scan lines as well as to increase geometric strength of the bundle adjustment. Straight lines have been adopted since imagery of manmade environments is rich with straight lines. Moreover, free-form linear features can be represented with sufficient accuracy by a sequence of straight lines (poly-lines). Experiments conducted in this study show the effectiveness of using free-form linear as well as straight-line features in the recovery of the exterior orientation parameters of aerial line scanners.

## 1 INTRODUCTION

Pose estimation, the determination of Exterior Orientation Parameters (EOP), is an essential pre-requisite for deriving three-dimensional information from any kind of imagery captured by terrestrial, airborne or satellite based sensors. Traditionally, pose estimation is solved using a number of well-defined ground control points. With the recent trend towards automatic extraction and recognition of features from digital imagery, it is becoming advantageous to utilize features in photogrammetric applications. Those features can be used to increase the redundancy and improve the geometric strength of photogrammetric adjustments. In addition, it is easier to automatically extract features than distinct points from imagery. Moreover, images of man-made environment are rich with linear features (Kubik, 1991), (Tommaselli and Lugnani, 1988). Recently, linear array scanners have been incorporated in aerial platforms (e.g., ADS40). Due to the high dynamics of an airborne environment, the exterior orientation is required for each scan line. A general approach for estimating the EOP in this situation is based on interpolation functions of the flight trajectory, which requires many ground control points and often fails to obtain the desired accuracy due to high frequency changes in the sensor orientation param-

eters. Another approach is based on direct measurements of the EOP using high-quality GPS/INS units. (Zhang et al., 1994), (Cannon, 1994), (Ackermann, 1996), (Toth, 1998), (Skaloud and Schwarz, 2001), (Cramer and Haala, 1999). Pose estimation based on features is especially important for airborne line scanner systems. The objective of this research is to estimate the EOP for every scan line without any interpolation or modeling of the flight trajectory. This study challenges the common belief that the EOP for all scan lines cannot be estimated without direct orientation using high quality GPS/INS. It is usually assumed that the EOP for adjacent scan lines are correlated. We believe that the parameters are numerically similar but not correlated. Complete estimation of those parameters is contingent on having enough observations/information. Traditional ground control points are not useful for indirect estimation of the EOP. However, unknown orientation parameters for each scan line can be recovered by including ground control linear features in an indirect orientation procedure that is less dependent on GPS/INS data. Automation of the pose estimation is only possible after establishing the correspondence between image and object space control points and/or features. Much research has focused on automatic identification and correspondence between image and object space features (Forstner, 1986),

(Ebner and Ohlhof, 1994), (Schenk, 1998), (Habib et al., 1998). However, since this research is focused on the pose estimation for dynamic sensors, the following items are assumed: (1) the interior orientation parameters are treated as known (2) the correspondence of features between image and object space is assumed to be known. However, there is no need for the knowledge about point-to-point correspondences along the involved linear features. Therefore, this paper is focused on developing rigorous mathematical models for complete recovery of the EOP of a dynamic sensor using indirect orientation techniques based on linear features. In this research, we will be concentrating on incorporating straight lines since they are abundant in scenes over manmade environments. Moreover, free-form linear features can be represented with sufficient accuracy as a sequence of straight lines (poly-lines).

## 2 BACKGROUND

### 2.1 Linear array scanner imagery

Linear array scanners have been introduced as an alternative for digital frame camera. Due to technical limitations, we do not expect the availability of a large format digital frame camera suitable for high accuracy photogrammetric applications in the near future. Linear array scanners capture scenes over the area of interest by successive exposure of one or more scan lines along the focal plane. For aerial platforms, the aircraft might be buffeted by air turbulence and/or shifting winds. As a result, the EOP of adjacent scan lines might be significantly different. Such perturbations might obscure certain object space features, making them undetectable to image analysts. Moreover, they would affect the raw scene in such a way that it might look different from what is visible in the object space. Therefore, accurate estimation of the EOP is necessary prior to any subsequent tasks such as stereo viewing, image matching, surface reconstruction, ortho-photo generation, and object recognition.

### 2.2 Previous pose estimation methods

Although there are numerous studies on pose estimation for frame cameras using various control features ( (Mullawa and Mikhail, 1988), (Haralick, 1988), (Habib, 1998), (Tommaselli and Poz, 1999), (Ji et al., 2000)), most research for line cameras is dedicated to space imagery since commercial airborne line cameras are still in their infancy. Moreover, the majority of previous methods require the use of point features and only few studies used linear features for the pose estimation (Zalmanson and Schenk, 2001), (Lee et al., 2000). A scene captured by a linear array scanner is composed of scan lines, each having a set of unknown EOP. That is, each row has its own EOP. This results in a large number of unknown parameters. Thus, the objective of previous approaches was to reduce the number of involved parameters to avoid singularities in the solution process. A very simple way is the use of a polynomial modeling the system's trajectory, which determines the changes in the EOP with time. However, this approach

has some disadvantages: (1) the flight trajectory might be too rough to be represented by a polynomial and (2) it is difficult to incorporate additional information from GPS/INS observations. Another approach to reduce the number of EOP is using the concept of orientation images. Orientation images are usually designated at equal intervals along the system's trajectory. However, these methods are often used for space borne line cameras with the strong assumptions: (1) the sensor system is traveling in smooth trajectory and (2) its orientation is almost constant over the image acquisition duration. Since these assumptions are not valid for airborne scanner systems, there are problems in applying either model. Lee et al. present a mathematical model that rectifies a single band of HYDICE (Hyperspectral Digital Imagery Collection Experiment) imagery to transform each pixel of an image into its ground location using Gauss-Markov model with linear features (Lee et al., 2000). Zalmanson and Schenk present a mathematical framework for determining the EOP of a push-broom image using parametrically represented 3-D curves (Zalmanson and Schenk, 2001). This method develops a unified mechanism for combining any prior information regarding the EOP from GPS/INS through the incorporation of 3-D curves. Their method assumed that  $6N$  ( $N$  is the number of image lines) parameters are essentially not independent, but highly correlated, and independent recovery of all exterior parameters is physically impossible.

### 2.3 Linear features in linear array scanner imagery

The linear features of interest to this research include straight lines and free-form curves. For utilizing the straight line and free-form curve, two issues need to be addressed to successfully include them into existing photogrammetric applications. The first issue deals with the representation of linear features in both image and object space. The other is the formulation of the mathematical perspective relationship between image and object space linear features. This research will concentrate on straight lines for two main reasons. First, scenes captured over manmade environments are rich with straight lines. Second, free-form linear features can be represented with sufficient accuracy as a sequence of straight-line segments (poly-lines).

### 2.4 Line feature representation

Before starting with the explanation of the mathematical model relating corresponding image and object space features, one should settle the issue of representing the image and object space features. In the object space, alternative straight-line representations have been analyzed in the literature and it has been established that the most convenient representation, from a photogrammetric point of view, is the one using two points along the line segments (Habib, 1999). This argument is supported by the following: (1) Using two points to represent a straight-line segment is more helpful since we define well-localized line segments rather than infinite lines. (2) This representation is capable of representing any line segment in space (i.e., it does not have any singularities). (3) It will allow us to reliably represent free-form linear features with sufficient

accuracy as a sequence of straight-line segments (i.e., poly lines). (4) It will lead to a straightforward model for establishing the perspective transformation between image and object space line segments. Therefore, a pair of 3-D distinct points will be required to represent the line segment in the object space. The perspective projection of an object space straight line using line scanners may not be a straight line due to the motion of the platform during data acquisition as well as interior orientation deformations. Therefore, image space line features will be represented by a sequence of 2-D points along that feature. This representation will allow us to consider the EOP of the platform at different scan lines as well as the IOP of the imaging sensor in the case of self-calibration. A natural line (or a free-form curve) can be represented by an analytical function or by a sequence of 2-D points and 3-D straight-line segments along the linear feature in the image and object space, respectively. Representation of a natural line by an analytical function minimizes the amount of information required to describe the line. However, a natural line in object space might not be represented well enough by an analytical function that describes its slightest detail without any generalization. Therefore, we will represent object space free-form linear features as a sequence of straight-line segments. Object space control linear features can be captured by a terrestrial mobile mapping system (e.g. GPSVan) or obtained from an existing GIS database (e.g. roads, train tracks).

### 3 MATHEMATICAL MODEL

Traditional photogrammetric orientation procedures are point based. In this research, the mathematical model establishes the relationship between the sequence of points along the image space linear feature and the object space straight-line segment, which is represented by its end points. The underlying principle in this mathematical model is that the vector from the perspective center to an intermediate point along the image space linear feature lies on the plane defined by the perspective center and the two object points defining that feature (Figure 1). The resulting equation will be denoted as the coplanarity constraint (Habib et al., 2000). Figure 1 shows the geometry of coplanarity condition in two scenes.

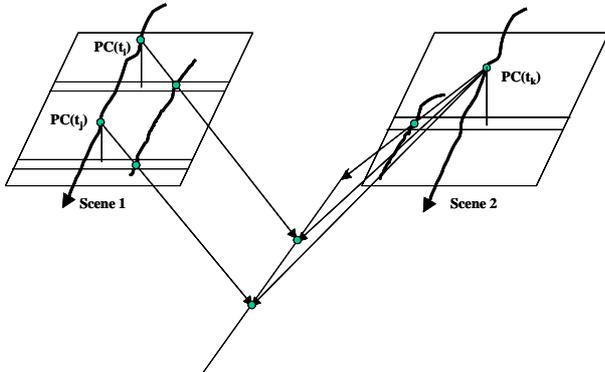


Figure 1: Perspective geometry and straight lines in linear array scanner imagery

For each scan line containing the linear feature under consideration, the vector from the perspective center to the first object point  $A$  along the line is defined as  $\vec{V}_1$ . Similarly, the vector from the same perspective center to the second object point  $B$  along the line is defined as  $\vec{V}_2$ . Finally, the vector from the perspective center to an image point, along the linear feature, in the scan line under consideration can be defined as  $\vec{V}_3$ . Figure 2 shows the defined plane and object points. The mathematical model enforces the coplanarity of the three vectors ( $\vec{V}_1$ ,  $\vec{V}_2$  and  $\vec{V}_3$ ), see equation:

$$(\vec{V}_1 \ \vec{V}_2) \bullet \vec{V}_3 = 0 \quad (1)$$

Figure 2 shows the defined plane and object points.

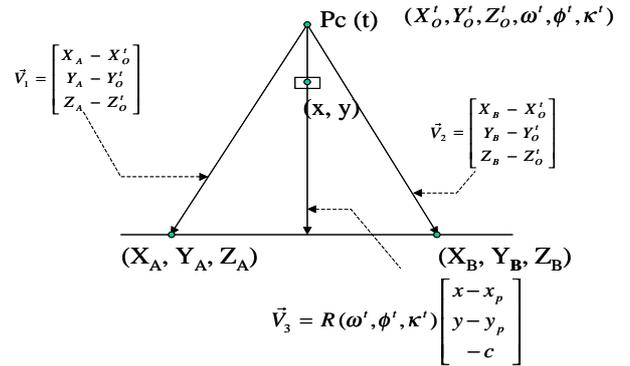


Figure 2: Plane defined by two object points and perspective center

The coplanarity constraint involves the IOP of the imaging sensor, the ground coordinates of the end point defining the object space line, the image coordinates of the intermediate point along the image space line, and the EOP of the corresponding scan line. In each scan line where the line is visible, the constraint in equation 1 can be applied, regardless of whether or not the defining end points are visible. Those intermediate points are mono-scopically measured, that is they need not be identifiable or even visible in other scenes. Since the EOP change from one point to the next, the number of independent constraints will be equal to the number of measured intermediate points along the line. The ground coordinates of those intermediate points along the straight line are not determined during the bundle adjustment. In other words, the constraints do not introduce any new parameters. These intermediate points contribute towards increasing the geometric strength of the adjustment. It should be noted that this constraint does not depend on the chosen model dealing with the EOP for the various scan lines, such as modeling the system trajectory with a polynomial, using orientation images, direct observations of the EOP from GPS/INS, or any other model.

## 4 EXPERIMENTS

### 4.1 Pose estimation of line scanner

The performance of the proposed approach has been tested with synthetic data generated through a simulation procedure involving three-line scanner whose specifications are

simulation parameters	specification
Sensor size	12K (12288 pixels)
Scene width	1311m
Pixel size	10.0micron
Focal length	300.0mm
Spacing between sensors	150mm
Ground resolution	10.7cm
Line rate	2481 lines/second
Flying height	3200.0m
Speed for consecutive coverage	265 m/second

Table 1: Three line scanner : sensor specification

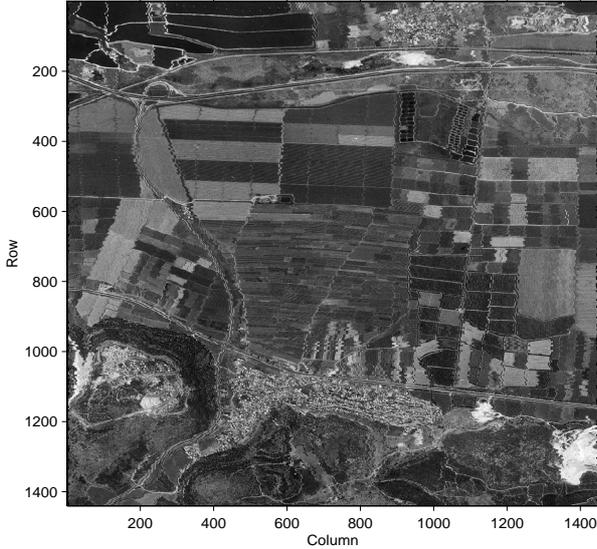


Figure 3: The simulated aerial line scanner image

summarized in table 1. Approximate values for the EOP have been generated by adding white noises to the true ones. The number of constraints for one scan line is equivalent to the number of control lines that are visible within that scan line. Having enough linear features with various orientations along the scan lines would allow us to independently and accurately determine the EOP of that scan line. The accuracy of estimated parameters is checked by comparing true values and estimated ones.

#### 4.2 Simulated panchromatic images

This section presents an experiment with a synthetic scanner scene. Figure 3 shows the scanner scene that have been simulated from an aerial frame image. As one can see, the smooth roads are distorted because of the unstable flight trajectory during scene capture. Thus, each scan line should be corrected according to its own orientation parameters prior to proper viewing of that scene. Figure 3 shows the scanner image that was simulated from a frame image. Figure 4 shows plots of digitized roads in both image and object spaces. Those roads are used as control features, which are represented by natural/free-form curves rather than strict straight lines. Table 2 summarizes estimation errors associated with the derived EOP by considering the above mentioned linear feature. As one can see, we have correctly determined the EOP associated with that scene. The image in figure 5 shows an ortho-rectified image generated using the estimated EOP from the adjust-

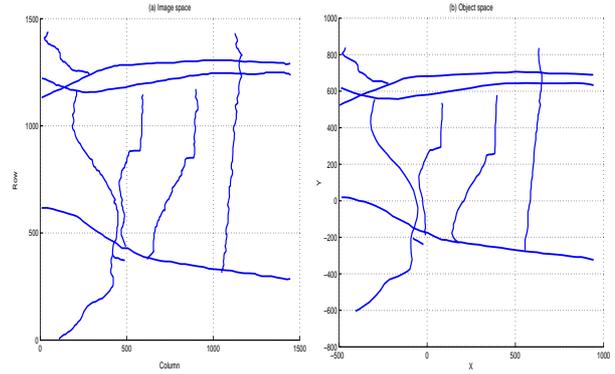


Figure 4: The image space and object space of control features

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Parameter	Difference (min)	Difference (max)
$\omega$ (sec)	-7.9306	9.9122
$\phi$ (sec)	-16.4138	19.4330
$\kappa$ (sec)	-1.5704	1.6784
$X_o$ (cm)	-24.5937	32.2536
$Y_o$ (cm)	-82.9741	50.3227
$Z_o$ (cm)	-5.7485	5.6316
Variance component	$(6.1449 \text{ } f_0^1)^2$	$(2.3447 \text{ } f_0^3)^2$
Condition number	3.0769 $f_0$	1.1133 $f_0$
Correlation ( $Y_o$ & $\omega$ )	-0.8200	-0.8334
Correlation ( $X_o$ & $\phi$ )	0.9995	0.9998

Table 2: Extreme values of estimation errors for the simulated line scanner image

ment. As one can see, distorted roads have been corrected after applying the estimated orientation parameters.

## 5 CONCLUSION

Aerial line camera is becoming another important source for mapping applications. However, since aerial scanner systems have unstable trajectories, the position and orientation should be estimated for every scan line. High-level features, such as straight-line or free-form curves, which are frequently encountered in object space, provide the possibility for the independent estimation of position and attitude for all scan lines. It is generally believed that a robust geometric solution from a dynamic non-frame sensor system cannot be accomplished without using high-quality GPS/INS units for direct and continuous determination of the sensor orientation. It is also believed that exterior orientation parameters of scan lines are dependent and strongly correlated. However, this study shows that it is possible to independently recover the exterior orientation parameters of all scan lines by utilizing control linear features, without GPS/INS measurements through indirect orientation approach. In future work, automatic extraction of image space features and automatic matching between image and object space features should be considered. Moreover, the bundle adjustment should be expanded to allow for self-calibration to determine the IOP of the imaging sensor.



Figure 5: Rectified ortho-image after the parameter estimation

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