RESAMPLING DIGITAL IMAGERY TO EPIPOLAR GEOMETRY

Woosug Cho   Toni Schenk

Department of Geodetic Science and Surveying
The Ohio State University, Columbus, Ohio 43210-1247
USA

Mustafa Madani

Intergraph Corporation, Huntsville, Alabama
USA

Commission III

ABSTRACT

Most algorithms in computer vision and digital photogrammetry assume that digital stereo pairs are registered in epipolar geometry (normalized images) in order to confine the search of conjugate features along the same scan lines. In this paper we describe the procedure of computing normalized images of aerial photographs with respect to the object space. Based on the exterior orientation of the stereo pair the rotation matrix for the normalized images is computed. The focal length of the new images may be determined according to different criteria. We show the case of minimizing the decrease in resolution. During the same process systematic errors of the scanning device can be considered. Several examples demonstrate the feasibility of our approach.

KEY WORDS: Epipolar geometry, Resampling, Normalized image.

1. INTRODUCTION

Most algorithms in computer vision and digital photogrammetry are based on the assumption that digital stereo pair is registered in epipolar geometry. That is, the scan lines of stereo pairs are epipolar lines. This condition is satisfied when the two camera axes of a stereo vision system are parallel to each other and perpendicular to the camera base. In conventional aerial photogrammetry, imagery is obtained directly by scanners, such as Landsat or SPOT, or indirectly by digitizing aerial photographs. Thus an aerial stereo pair is not likely to be in epipolar geometry since the attitude of the camera at the instant of exposure is different at every exposure station.

[Kreiling 1976] described a method for recovering the epipolar geometry from the parameters of an independent relative orientation. The epipolar geometry is only recovered with respect to the model space. In many instances it is desirable to establish epipolar geometry with respect to object space. The procedure to obtain resampled epipolar images with exterior orientation elements after absolute orientation was developed by [Schenk 90]. In this paper we call the resampled epipolar image reconstructed with respect to object space the *normalized image*. The original photograph obtained at the instant of exposure is referred to as the *real image*. The image which is parallel to the XY-plane of the object space system is called the *true vertical image*.

In this paper we describe the procedure to compute normalized images of aerial images with respect to the object space and the method to minimize the decrease in resolution. By considering systematic errors of the scanning device, we show that the normalized image is free of geometric distortion of the scanning device. The next section provides some background information followed by a detailed description of how to determine normalized images.

2. EPIPOLAR GEOMETRY

Fig. 1 shows a stereo pair in epipolar geometry with C', C'' the projection centers. The epipolar plane is defined by the two projection centers and object point P. The epipolar lines e', e'' are the intersection of the epipolar plane with the image planes. The epipoles are the centers of bundles of epipolar lines which result from intersecting the photographs with all possible epipolar planes.
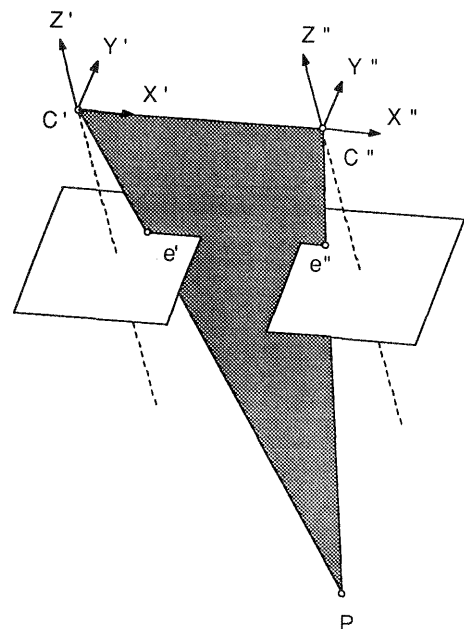

Figure 1: Epipolar geometry

The conjugate epipolar lines in Fig. 1 are parallel and identical to scan lines. The epipoles are in infinity because of

vertical photographs. However, in most cases, two camera axes are neither parallel nor perpendicular to the air base $(C'C'')$. We transform images into a position that conjugate epipolar lines are parallel to the x-axis of the image coordinate system such that they have the same y-coordinate. The transformed images satisfying the epipolar condition are called *normalized images* in this paper. The normalized images must be parallel to the air base and must have the same focal length. Having chosen a focal length, there is still an infinite number of possible normal image positions (by rotating around the air base).

3. COMPUTATION OF NORMALIZED IMAGE

3.1 Camera Calibration

Digital imagery can be obtained either directly by using digital cameras, or indirectly by scanning existing aerial photographs. In both cases, the digitizing devices (digital camera or scanner) must be calibrated to assure correct geometry. For our applications we use the rigorous calibration method suggested by [Chen and Schenk 92]. The method is a sequential adjustment procedure to circumvent the high correlation between DLT parameters and camera distortion parameters. The distortion consists of two parts: lens distortion and digital camera error. Lens distortion is composed by radial and tangential distortion. Digital camera error is scan line movement distortion since EIKONIX camera used in our applications is a linear array camera. For more details about digital camera calibration, refer to [Chen and Schenk 92]. With the camera calibration, we can obtain a digital image free of systematic distortion. The image is called *pixel image* in this paper.

3.2 Transforming pixel image to normalized image

The normalized image is a pixel image in epipolar geometry with reference to the object space. Thus, exterior orientation elements after absolute orientation are to be used for transforming the pixel image to a normalized image. The exterior orientation elements consist of three rotation angles and the location of perspective center in the object space system. The relationship between pixel image and object space is expressed by the collinearity equation

$$x_p = -f_p \frac{r_{11}(X - X_C) + r_{12}(Y - Y_C) + r_{13}(Z - Z_C)}{r_{31}(X - X_C) + r_{32}(Y - Y_C) + r_{33}(Z - Z_C)} \quad (1)$$

$$y_p = -f_p \frac{r_{21}(X - X_C) + r_{22}(Y - Y_C) + r_{23}(Z - Z_C)}{r_{31}(X - X_C) + r_{32}(Y - Y_C) + r_{33}(Z - Z_C)},$$

where x_p, y_p are image coordinates and $r_{11} \cdots r_{33}$ are elements of an orthogonal rotation matrix R that rotates the object space to the image coordinate system. X_C, Y_C, Z_C are the coordinates of the projection center; X, Y, Z, the coordinates of object points.

There are two steps involved in the transformation of the pixel images (P', P'') to normalized images(N', N''). First, pixel images are transformed to *true vertical images* and from there to normalized images. Fig. 2 shows the relationship between pixel images and normalized images.

The first transformation from pixel image to true vertical position simply involves a rotation with R^T, where R is an
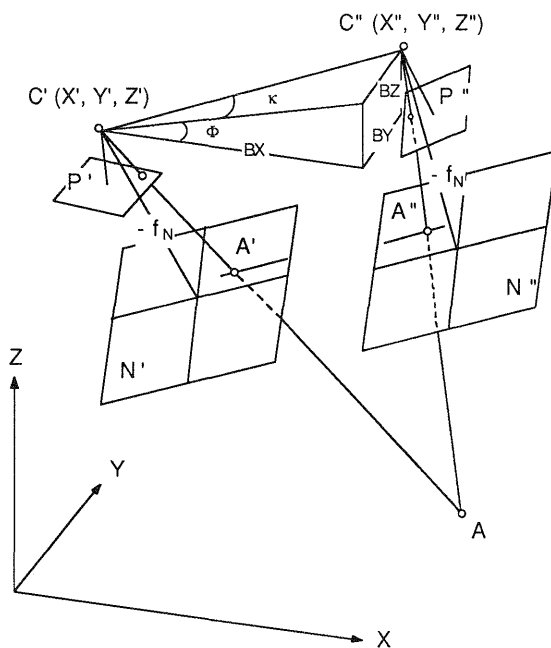

Figure 2: Relationship between pixel image and normalized image

orthogonal rotation matrix from the object space to image space. Next, a transformation from true vertical to the normalized position is applied. The first angle of the rotation matrix R_B transforming from true vertical to the normalized position is K about the Z-axis, then Φ about the Y-axis, Ω about the X-axis. The rotation angles K, Φ can be computed from the base elements BX, BY, BZ, and Ω from the exterior orientation angles:

$$K = tan^{-1} \frac{BY}{BX} \quad (2)$$

$$\Phi = -tan^{-1} \frac{BZ}{(BX^2 + BY^2)^{1/2}} \quad (3)$$

$$\Omega = \frac{\omega' + \omega''}{2}, \quad (4)$$

where $BX = X'' - X', BY = Y'' - Y'$, and $BZ = Z'' - Z'$.

The base rotation matrix R_B will be the following.

$$R_B = R_\Omega R_\Phi R_K, \quad (5)$$

where

$$R_K = \begin{bmatrix} cosK & sinK & 0 \\ -sinK & cosK & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_\Phi = \begin{bmatrix} cos\Phi & 0 & -sin\Phi \\ 0 & 1 & 0 \\ sin\Phi & 0 & cos\Phi \end{bmatrix}$$

$$R_\Omega = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\Omega & sin\Omega \\ 0 & -sin\Omega & cos\Omega \end{bmatrix}$$

The base rotation matrix R_B is a combined matrix in which the primary rotation axis is about the Z-axis, followed by a rotation about the Y-axis and X-axis. Depending on the Ω (X-axis rotation), there are many different normalized
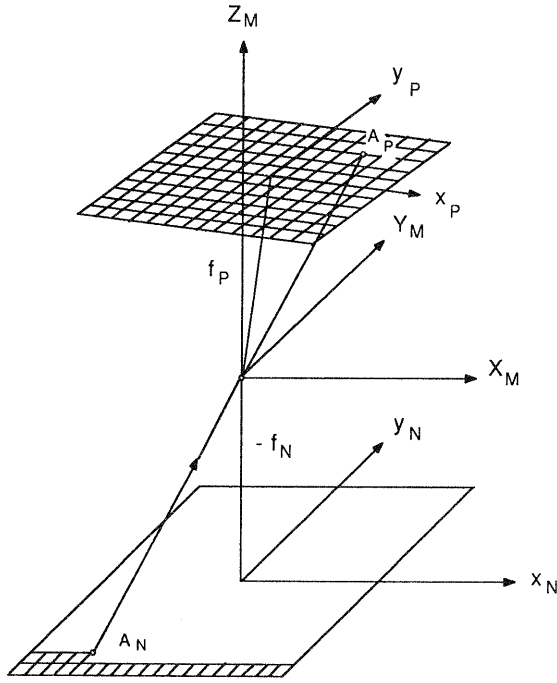
Figure 3: Transformation pixel image to normalized image

images. The rotation Ω about the X-axis influences the nonquadratic shape when computing the normalized images.

The normalized rotation matrix R_N is a multiplication of two rotation matrices: the rotation from pixel image to true vertical position and the rotation from true vertical to normalized position.

$$R_N = R_B R^T \qquad (6)$$

The R_N is an orthogonal rotation matrix which transforms the pixel image to the normalized image. Since in Eq.(6) R^T is the transposed rotation matrix of exterior orientation elements, the R_N matrix must be computed for both images in stereo. We may use one of two transformations from pixel image to normalized image: transformation using collinearity condition or projective transformation.

3.2.1 Transformation using collinearity
The collinearity condition equations can be used for the transformation of the pixel image to normalized image. The transformation is represented in the following equation and is illustrated in Fig. 3.

$$x_N = -f_N \frac{r_{11}x_P + r_{12}y_P - r_{13}f_P}{r_{31}x_P + r_{32}y_P - r_{33}f_P} \qquad (7)$$

$$y_N = -f_N \frac{r_{21}x_P + r_{22}y_P - r_{23}f_P}{r_{31}x_P + r_{32}y_P - r_{33}f_P},$$

where $r_{11} \cdots r_{33}$ are the elements of the R_N rotation matrix.

3.2.2 Projective transformation
The projective transformation can be applied since both pixel image and normalized image are planar.

$$x_N = \frac{c_{11}x_P + c_{12}y_P + c_{13}}{c_{31}x_P + c_{32}y_P + 1} \qquad (8)$$

$$y_N = \frac{c_{21}x_P + c_{22}y_P + c_{23}}{c_{31}x_P + c_{32}y_P + 1}$$

By comparing the coefficients in the projective transformation with those in the collinearity equations, we find the following identities:

$$
\begin{array}{ll}
C_{11} = \dfrac{f_N r_{11}}{f_P r_{33}} & C_{21} = \dfrac{f_N r_{21}}{f_P r_{33}} \\[2mm]
C_{12} = \dfrac{f_N r_{12}}{f_P r_{33}} & C_{22} = \dfrac{f_N r_{22}}{f_P r_{33}} \\[2mm]
C_{13} = -\dfrac{f_N r_{13}}{r_{33}} & C_{23} = -\dfrac{f_N r_{23}}{r_{33}} \\[2mm]
C_{31} = -\dfrac{r_{31}}{f_P r_{33}} & C_{32} = -\dfrac{r_{32}}{f_P r_{33}}
\end{array} \qquad (9)
$$

When performing the transformation pixel image to normalized image, the quadratic tesselation of the pixel image results in nonquadratic tesselation of the normalized image. In order to avoid interpolation into quadratic tesselation, it is recommended to project the tesselation of the normalized image back to the pixel image (see also Fig. 3). The coefficients for backward projection are obtained in the same fashion by R_N^T if the focal lengths of the pixel and normalized image are the same ($f_P = f_N$).

$$
\begin{array}{ll}
C'_{11} = C_{11} & C'_{21} = C_{12} \\[2mm]
C'_{12} = C_{21} & C'_{22} = C_{22} \\[2mm]
C'_{13} = C_{31}f_P f_N & C'_{23} = C_{32}f_P f_N \\[2mm]
C'_{31} = C_{13}\dfrac{1}{f_P f_N} & C'_{32} = C_{23}\dfrac{1}{f_P f_N}
\end{array} \qquad (10)
$$

For the more general case of different focal lengths ($f_P \neq f_N$), the backward projection is obtained by inverting R_N because $R_N^{-1} \neq R_N^T$.

3.2.3 Resampling
After applying a geometric transformation from the normalized image to pixel image, the problem now is to determine the gray value of the new pixel location in the normalized image, because the projected position in the pixel image is not identical to the center of the pixel. Therefore, gray values must be interpolated. This procedure is usually referred to as resampling. Several interpolation methods may be used.

- zero-order interpolation: the gray value of the nearest neighbor is chosen. This is identical to rounding the projected position to the integer, corresponding to the tesselation of the pixel image system. This simplest process may lead to unacceptable blurring effects.

- bilinear interpolation: the gray values of the four surrounding pixels contribute to the gray value of the projected point depending on the distance between the projected and four neighboring pixels.

3.3 Normalized image

The procedure discussed in the previous section establishes the transformation between pixel image and normalized image. The distortion parameters are determined during camera calibration. When resampling the gray values for the normalized image, we also apply the correction. Thus, the computation of the normalized image proceeds in four steps (see Fig. 4).

T_1: Transformation between pixel image and original photograph (diapositive). The transformation parameters are determined during camera calibration. Common references for these transformation parameters are fiducial marks, reseau points, and distinct ground features.
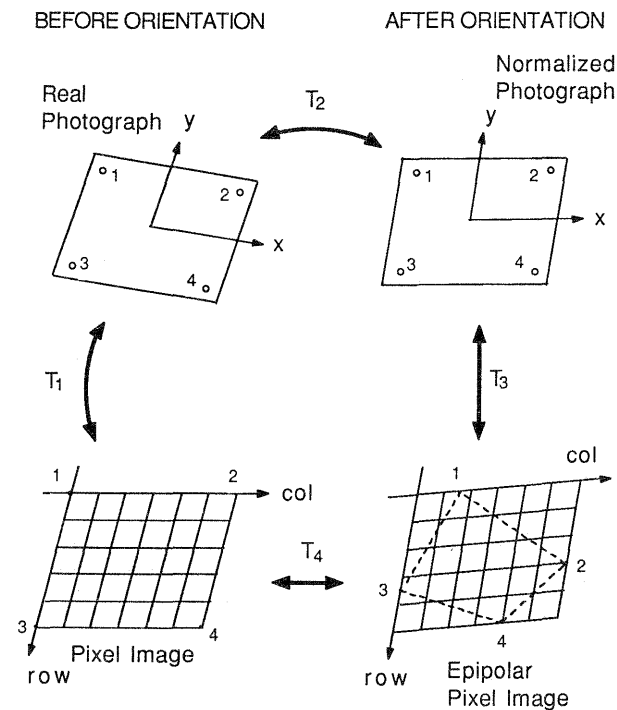
BEFORE ORIENTATION   AFTER ORIENTATION

Figure 4: Relationship between photograph and pixel image, both in real and epipolar position

T_2: Projective transformation between original photograph and normalized photograph. The detailed procedure is described in Section 3.2.

T_3: Definition of coordinate system for the pixel image in epipolar geometry (normalized image). In order to minimize the decrease in resolution (or to optimize the size), first the four corners of the pixel image((0,0), (0,N), (N,0), (N,N)) are transformed to real photographs and then to normalized photo coordinates through T_1, T_2. The following procedure defines the normalized image coordinate system.

1. Determine maximum y coordinate of four corner points in both images. This defines row 0 in both normalized images.

2. Determine x and y differences of corner points in both photos and compute the maximum distance d_{max} in either x or y direction (both photos). This determines the size of the epipolar pixel image in photo coordinates.

3. Change from photo coordinates to pixel coordinates by using the relationship d_{max} = resolution pixel image.

T_4: Transformation from normalized image to pixel image in order to perform resampling. This is accomplished by using T_3, T_2 and T_1.

4. EXPERIMENTAL RESULTS

The procedure discussed in section 3 to compute normalized images, has been implemented and tested with several pairs of aerial images. Some of our images are digitized by the PhotoScan scanner from Zeiss/Intergraph Corp. and some others by the EIKONIX camera (EC850). Here, we present the "Munich" model, scanned with the EIKONIX camera (see Fig. 5).

The real images have a resolution of 4096 by 4096, corresponding to $\approx 60\mu m$ and 256 gray values. As explained in detail in [Chen and Schenk 92], the EIKONIX camera introduces distortion to the scanned image. We remove this distortion during the procedure of computing normalized images. Fig. 6 shows the images normalized with respect to the object space. Note the curved margins of the normalized images. This is the effect of the camera distortion (now removed!). The transformation (T_1) discussed in section 3.3 must be well known in order to assure the correct geometry in normalized images. In our example, its accuracy is less than a half pixel in 4K resolution.

The normalized image coordinate system is established by transforming the four corner points of the pixel image so that the loss of information of the pixel image is minimized. By applying the rotation of the base by common omega (Ω) about the X-axis, we optimize the nonquadratic shape of normalized images. For resampling, the bilinear interpolation method is employed, which may introduce blurring effects into the normalized images.

5. CONCLUSIONS

We describe the procedure for obtaining the normalized images from exterior orientation after absolute orientation. We also present a direct solution to compute the coefficients of the projective transformation, and show a way to compute the inverse transformation parameters directly, without repeating the transformation backward.

The procedure of computing normalized images is successful and operational. The normalized images, with removed distortion caused by the scanning device, are in epipolar geometry with respect to the object space. Since scan lines are epipolar lines in normalized images, the automatic matching procedure for conjugate points will be performed on the same scan lines. The 3-D surface in object space can be reconstructed directly by using matched conjugate points.

6. ACKNOWLEDGMENTS

Figure 5: Stereo real images of Munich model (resolution: 512 × 512)

Figure 6: Stereo normalized images of Munich model (resolution: 512 × 512)

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