AUTOMATED TRIANGULATION OF LINEAR SCANNER IMAGERY

Younian Wang
ERDAS Inc.

2801 Buford Highway
Atlanta, GA 30329, USA
Email: wang@erdas.com

KEYWORDS: Automated Triangulation, Linear Scanner, DLT, Automatic Tie Point Collection.

ABSTRACT
In this paper some new methods for determining the sensor orientation of linear scanner images are discussed. The image matching techniques are used for automatic identification, transfer and measurement of the image tie points, which connect all images in the block together. A new and simple sensor model based on direct linear transformation is developed and compared to the conventional model using interior and exterior orientation parameters. The test results with several different kinds of images are demonstrated. They show that a highly automated and sufficiently accurate triangulation system using the introduced methods can make the application of space imagery from linear scanners much more simple and affordable.

1. INTRODUCTION
Space imagery from linear scanners (also called pushbroom scanner) like SPOT, IRS-1C/1D and MOMS-02 has been shown for its great potential of generating orthophotos and updating map database. The upcoming new linear scanners with up-to one meter resolution from commercial satellites could bring more benefits and even a challenge to the traditional topographic mapping with aerial images (Fritz, 1995).

The normal procedure for geometric processing of linear scanner images is to measure the ground control points, the image tie points, then triangulate the images using polynomial approximation for the exterior orientation parameters. After triangulation the images can be orthorectified by using existing DEM or using the DEM extracted from the images.

So far the ground control points and image tie points are measured manually in many commercial and research software systems for linear scanner images. In the newly marketed IMAGINE OrthoBASE from ERDAS Inc., the image tie points can be collected fully automatically and the GCPs can be measured partly automatically.

The polynomial model of exterior orientation parameters has been widely used in many commercial and research software such as BLUH from University of Hannover and IMAGINE OrthoBASE. Because of the large amount of unknowns, the dynamic weighting technique is commonly used to overcome the correlation problem between the different orientation parameters, where the experiences play an important role for selecting proper weights.

There are some other investigations using the affine transformation or the direct linear transformation (DLT, Abdel-Aziz and Karara, 1971) to triangulate the pushbroom images (El-Manadili and Novak, 1996; Okamoto etc., 1998; Savopol and Armenakis, 1998). But the image systematic errors need to be pre-corrected by using the ephemeris information, which is usually not accurate enough for that purpose.

In this paper a new orientation model in the form of self-calibrating DLT (SDLT) is derived for the pushbroom image orientation. The new model does not require any sensor parameters like the interior orientation, the incident angle and the ephemeris information, also does not require any geometric pre-correction of the original image data. It is very convenient to be used with different kinds of linear sensor images, especially advantageous for processing the upcoming high-resolution commercial satellite images since the sensor and ephemeris information will unlikely be provided.

In addition, the approach that is used to fully-automatically collect the image tie points for pushbroom images is introduced. Using both the SDLT model and the automatic tie points collection approach, the triangulation and object point determination can be fully automated after several GCPs are measured.

The test results of several different kinds of images are demonstrated. They show a highly automated and sufficiently accurate triangulation system using
the introduced methods can make the application of space imagery from linear scanners more simple and affordable.

2. SDLT ORIENTATION MODEL

The common image orientation model is the collinearity equation with each orientation parameter represented in the form of polynomial (Wang, 1990):

\[
x = -f \frac{a_3(X - X_0) + b_3(Y - Y_0) + c_3(Z - Z_0)}{a_3(X - X_0) + b_3(Y - Y_0) + c_3(Z - Z_0)}
0 = -f \frac{a_2(X - X_0) + b_2(Y - Y_0) + c_2(Z - Z_0)}{a_3(X - X_0) + b_3(Y - Y_0) + c_3(Z - Z_0)}
\]

(1)

Fig. 1: A linear scanner image

Where \((x, y)\) are the image coordinates (Fig. 1), \(f\) is the camera focal length, \((X, Y, Z)\) are the ground coordinates, \((X_0, Y_0, Z_0)\) is the projection center of each scan line, \((a_1, a_2, \ldots, c_3)\) is the rotation matrix component which is compound from the three rotation angles \((\omega, \varphi, \kappa)\). Since \((X_0, Y_0, Z_0)\) and \((\omega, \varphi, \kappa)\) are different from scan line to scan line, they are commonly approximated to polynomials:

\[
X = X_0 + k_{1t} + \ldots
Y = Y_0 + k_{2t} + \ldots
Z = Z_0 + k_{3t} + \ldots
\omega = \omega_0 + k_{4t} + \ldots
\varphi = \varphi_0 + k_{5t} + \ldots
\kappa = \kappa_0 + k_{6t} + \ldots
\]

(2)

With the polynomial, model the interior orientation parameters (the focal length and the principal point) and the initial exterior orientation parameters \((X_0, Y_0, Z_0, \varphi_0, \omega_0, \kappa_0)\) should be known. But this information can be unavailable in some cases, e.g. for the cases dealing with part of images or for the images from some new sensors.

If we approximate the exterior orientation parameters only to the first order polynomial as shown in equation (2), i.e. we assume:

\[
R = R_0 \Delta R
R_0 = R_ωR_ϕR_κ
\]

(3)

\[
\Delta R = R_{\Delta ω}R_{\Delta ϕ}R_{Δκ} = \begin{bmatrix}
1 & -\Delta κ & \Delta ϕ \\
\Delta κ & 1 & -\Delta ω \\
-\Delta ϕ & \Delta ω & 1
\end{bmatrix}
\]

(4)

With the image \(y\) indicating the flight direction, we can rewrite the collinearity equation as the following:

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \lambda R_0 \Delta R
\begin{bmatrix}
x \\
0 \\
-f
\end{bmatrix} + \begin{bmatrix}
X_0 \\
Y_0 \\
Z_0
\end{bmatrix}
\]

\[
= \lambda R_0 (E + Ky)
\begin{bmatrix}
x \\
0 \\
-f
\end{bmatrix} + \begin{bmatrix}
X_0 \\
Y_0 \\
Z_0
\end{bmatrix} + \begin{bmatrix}
k_1 \\
k_2 \\
k_3
\end{bmatrix}
\]

(5)

where \(E\) is the unit matrix. Since it is the orthogonal projection in the \(y\)-direction, \(y\) is proportional to the ground radial distance along the flight direction (r-direction in Fig. 2). Therefore the \((X, Y, Z)\) can be represented as:

\[
\begin{bmatrix}
X_0 \\
Y_0 \\
Z_0
\end{bmatrix} + \begin{bmatrix}
k_1 \\
k_2 \\
k_3
\end{bmatrix}(X \cos α + Y \sin α)
\]

(6)

where \((X_0, Y_0, Z_0)\) and \((k_1, k_2, k_3)\) are the new constant unknowns for \((X_0, Y_0, Z_0)\) and \((k_1, k_2, k_3)\).
Combining equation (4) and (5) together will produce the following:

\[
\begin{bmatrix}
    x - k_5 y_f \\
    k_4 y_f - k_6 x_f \\
    -f - k_5 x_f
\end{bmatrix} = \begin{bmatrix}
    l_1 X + l_2 Y + l_3 Z + l_4 \\
    l_5 X + l_6 Y + l_7 Z + l_8 \\
    l_9 X + l_{10} Y + l_{11} Z + l_{12}
\end{bmatrix}
\]

(6)

with \((l_1, l_2, ..., l_{12})\) the constant coefficients. The equation (6) is still non-linear. If we assume that the systematic rotation error around the flight direction is less significant than its random error, we can omit the influence of \(k_5\). This assumption could be acceptable since one could imagine that the satellite inclination around the flight direction has less correlation with the flying orbit. The real effects for this omission can be investigated through the tests.

The relationship of image pixel coordinates \((x_p, y_p)\) to the image coordinates \((x, y)\) can be written as:

\[
\begin{align*}
x &= s_x x_p + x_0 \\
y &= s_y y_p + y_0
\end{align*}
\]

(7)

where \((s_x, s_y)\) are the pixel size in both directions, \((x_0, y_0)\) are the shift constants. Putting equation (7) to (6) and omitting the influence of \(k_5\), it produces:

\[
\begin{align*}
x_p &= \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1} \\
y_p - L_{12} x_p y_p &= \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1}
\end{align*}
\]

(8)

Again, \((L_1, L_2, ..., L_{12})\) are the constant coefficients. The equation (8) is a linear transformation between the image pixel coordinates and its ground coordinates with an additional correction to image coordinates, such as in self-calibrating for systematic errors. Therefore we temporarily call it self-calibrating DLT, i.e. SDLT. Using equation (8), no interior orientation parameters and approximate exterior orientation parameters (ephemeris information) are needed, the correlation between each unknown should also be smaller than in the polynomial model.

3. AUTOMATIC TIE POINT COLLECTION

Automatic tie point collection has become a standard function of any advanced softcopy photogrammetric systems for dealing with aerial images. Even though automatic tie point collection from satellite images are not reported very much, it seems it is not so difficult as with aerial images since the parallax variation on satellite images are normally much smaller than on aerial images. But the satellite images have also some special characteristics, e.g. the three rotation angles are normally not as small as aerial images. The overlap is also not so standardized. If the images come from the satellites with between-track stereo mode, like SPOT, there could be significant differences of image contrast, intensity and image details of a stereo pair, since there could be several days difference between the two images captured.

The most automated way to collect tie points from linear scanner images is to use structural matching technique (Wang, 1994 and 1998), since no a-priori information like interior and initial exterior orientation parameters, overlaps, etc., are needed.
over the whole image block automatically. These methods have already been incorporated into IMAGINE OrthoBASE from ERDAS Inc. The main procedure is demonstrated in Fig. 3. The feature extraction and matching currently mean feature point extraction and matching. The point transfer means transferring the matched tie point candidates to the next pyramid level.

The automated triangulation with SDLT model for linear scanner images can be carried out using the steps shown in Fig. 4. Except that the GCPs and the check points are measured semi-automatically, all of the other steps can be finished automatically. No interior orientation is required.

4. EXPERIMENTS

In order to test the applicability of SDLT model and the efficiency of automatic tie point collection, several examples have been investigated. The first example is a SPOT panchromatic pair shown in Fig. 5. The image pair covered some area in California of the USA. The image size is 6000x6000 pixels with ground resolution of 10 meters. The small crosses that appear on the images shown the measured GCPs, the check points, and the automatically extracted tie points. There are 22 known ground points that have been prepared. The horizontal coordinates come from an orthorectified SPOT multi-spectral images with 20-meter ground resolution. The height information comes from an existing DEM with grid size of 75x75 meters. Therefore the GCPs are not very accurate. 14 points have been chosen randomly as GCPs, and the rest 8 points as check points. In addition there are 50 tie points automatically extracted. It takes only about 1 minute on a Pentium II PC with 300MHz clock speed.

The triangulation has been carried out for both the SDLT model and the polynomial model with exactly same data. The results are shown in Table 1. It shows the accuracy of the check points in both models are comparable. It is also tested with second-order polynomial, but the results do not have visible improvement when compared to the first-order polynomial list in Table 1.

![Fig. 5: a pair of SPOT panchromatic images](image1)

![Fig. 6: a pair of IRS-1C images](image2)

The second example is the Indian IRS-1C data. Each image with IRS-1C scanner is scanned with three separate linear sensors, and each have 4096 nominal pixels for a scan line. Therefore, each scene has three image files. The image data we received has a scan line with 4320 pixels instead of 4096, so the principal point is unknown. Also, we are not sure of the focal length and rotation angles, since the rotation system has a non-conventional definition.

![Fig. 4: automated triangulation of scanner images](image3)

![Fig. 1: test results with SPOT image pair](image4)
full real width (4320 pixels) where enough known
ground points are available as shown in Fig. 6. The
small crosses shown on the images are again for the
GCPs, check points and tie points. The test pair has
4320x4100 pixels respectively, each pixel has 7
micrometers in image space and about 5.8 meters
ground resolution. There are 16 known ground
points available. 11 are used as GCPs, and 5 used as
check points. In addition there are 25 tie points
automatically collected. The function for automatic
tie points collection also works well in this example.
Some triangulation results are shown in Table 2. We
do not know how accurate the GCPs are, but from
the triangulation results it seems the GCPs in this
example have very good quality.

<table>
<thead>
<tr>
<th>Std. deviation</th>
<th>Accuracy from residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44 pixel</td>
<td>mX mY mY</td>
</tr>
<tr>
<td>GCPs</td>
<td>1.8 m 2.3 m 2.4 m</td>
</tr>
<tr>
<td>Check points</td>
<td>3.8 m 6.0 m 4.1 m</td>
</tr>
<tr>
<td>Total points: 11 GCPs, 5 checks, 25 tie points</td>
<td></td>
</tr>
</tbody>
</table>

The results listed in Table 2 show that this data set
with the SDLT triangulation model offers high
accuracy.

5. SUMMARY

In this paper a simple mathematical model in the
form of self-calibrating direct linear transformation
for the triangulation with linear scanner images has
been derived. Unlike the conventional polynomial
model, it does not need the known interior
orientation, nor the ephemeris information, nor the
approximate exterior orientation. Therefore the
SDLT model can be used when the necessary
information for the polynomial model is not
available.

The limited tests show that the triangulation results
with SDLT model is comparable to the results with
polynomial model.

This paper also introduces the procedure for the
automatic tie points collection from linear scanner
images. The test results show that the developed
method works well and fast, it should be able to
reduce some human labor for measuring tie points
and therefore to increase productivity.

Because of the limited availability of image data and
GCPs, the tests here are not enough to prove that the
SDLT model will works well in every circumstance
and for every kind of linear scanners. Further tests
and investigations for the SDLT model are still
needed before its practical applications.

ACKNOWLEDGEMENT

The author wishes to thank Dr. K. for providing the
IRS-1C test data set. Many thanks also go to my
colleagues Mr. P. Gonzalez, M. Stojic and X. Yang
for providing and preparing the SPOT data set.

REFERENCES

Abdel-Aziz, Y.A., Karara, H.M., 1971, Direct linear
transformation from comparator coordinates into
object space coordinates in close-range
photogrammetry, Proceedings of the ASP
symposium on Close-Range Photogrammetry, pp420-475.

El-Manadili, Y., Novak, K., 1996, Precision
rectification of SPOT imagery using the direct linear
transformation model, Photogrammetric

Fritz, Lawrence W., 1995, Recent developments for
optical earth observation in the United States,

Okamoto, A., Fraser, C., Hattori, S., Hasegawa, H.,
Ono, T., 1998, An alternative approach to the
triangulation of SPOT imagery, Intern. Archives of

Savopol, F., Armenakis, C., 1998, Modeling of the
IRS-1C satellite pan stereo-imagery using the DLT
4, pp511-514.

Wang, Y., 1994. Strukturzuordnung zur automa-
tischen Oberflächenrekonstruktion. Ph.D.
dissertation, wissenschaftliche Arbeiten der Fach-
richtung Vermessungswesen der Universität
Hannover, No. 207.

Wang, Y., 1998. Principles and applications of
structural image matching. ISPRS Journal of
154-165.

Wang, Z., 1990, Principles of photogrammetry
(With remote sensing), Press of Wuhan Technical
University of Surveying and Mapping and
Publishing House of Surveying and Mapping,
Beijing, China.