Geometric Rectification Using Feature Points Supplied by Straight-lines

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Abstract

As the geometric rectification methods are mostly based on ground control points (GCPs), the geometric accuracy of remote sensing image usually fails to meet the demand in the area of lack of feature points. Straight-line features can be the supplement of GCPs. The advantages and disadvantages of ground control straight-lines (GCLs) used for geometric rectification were discussed in detail first. After introducing the conventional geometric correction methods based on points, this paper proposed a novel geometric correction method based on straight-line features, which is not confined to a specific imaging geometric model. Feature points and straight-line features can be united to estimate the geometric model. In the test, instead of merely using control points, the geometric accuracy of model was guaranteed by using control points together with control straight-lines in the region deficient in feature points.

Keywords: Linear feature, Ground control straight-line, Geometric rectification, Generic imaging model

1. Introduction

The conventional geometric correction model in photogrammetry and remote sensing describes the relationship between the points in image and object space. Although it is simple, intuitive and accurate, some problems prevent this model from achieving perfection. For instance, it is difficult to automatically extract feature points in the areas where cross points and corners are not available, and image registration based on feature points is greatly confined to acquisition time, resolution and spectrum.

Researchers began to study the image rectification and stereo location using linear features in 1980s, and Habib was the first to establish the theoretical framework for remote sensing image geometric processing based on linear features. Habib represented the space lines using two points along each line and represented the image lines using polar parameters, and deduced the aerial triangulation methods for frame...
imagery and linear array scanner imagery[1]. He also introduced the Modified Iterated Hough Transform (MIHT) to simultaneously establish the correspondence between object and image space conjugate line segments and estimate the Relative Orientation Parameters (EOPs) of an image captured by a frame camera[2],[3]. Zitová B. indicated that the majority of image registration methods consist of four steps[4]: feature detection, feature matching, transformation model estimation, and image resampling and transformation. In the above methods, the first three steps are finished simultaneously. Meanwhile, some researches are separately focused on the estimation of transformation model using straight-line features. Zhang Z. et al proposed the photogrammetric theory based on generalized points, which took the linear elements as control points to perform the image orientation and correction[5]-[7]. Zhang H. W. proved that the correlation and redundancy among the observation values exist in straight-line photogrammetry and the affection on accuracy of the distribution of observation values [8].

The methods which detect straight-line features, match straight-line features and estimate the transformation model simultaneously are not convenient to involve the control points into the model. Furthermore, the existing methods are model-specific, therefore can not be directly applied to different data source. This paper proposed a novel geometric correction method based on Ground Control straight-Lines (GCLs), which is not confined to a specific imaging geometric model, and Ground Control Points (GCPs) can also be used to estimate the geometric correction model together with GCLs.

2. Advantages and Disadvantages of Straight-line

Compared to feature point, the straight-line feature is superior mainly in these aspects:

- It is easier to automatically extract straight-line features than feature points[9];
- The high-level geometric feature increases the redundant observations, which is easier for the detection and rejection of gross errors;
- Both natural and man-made environments are rich in straight-line features [3];
- Image registration with straight-line features is not confined to the acquisition time, resolution and band.
- When applied to higher level tasks such as object recognition, straight-line features are more practical than feature points.

However, defects of straight-line feature are also evident:

- Straight-line feature is not as accurate as feature point.
- Straight-line feature is much more redundant than feature point.

Considering the characteristics of straight-line features and feature points, GCPs have the priority to be used if they are available, and GCLs can be used as supplement of GCPs when feature points are deficient or higher level tasks are needed.

3. The Geometric Model Based on GCLs

3.1. Generic imaging model based on GCPs

The imaging model describes the relationship between the points in image and object space, and various imaging models can be found in photogrammetry and remote sensing, such as the collinear equation, affine model, polynomial model, RPC model, etc. Equation (1) represents these models generically.

\[
\begin{align*}
    x &= f_x(X,Y,Z,t) \\
    y &= f_y(X,Y,Z,t)
\end{align*}
\]  

(1)
Where \((X,Y,Z)\) denotes the ground coordinate of GCP, \((x,y)\) denotes the measure coordinate of GCP in imagery, and \(t = (t_1, t_2, \cdots t_n)^T\) denotes the parameters of sensor’s geometric model, which can be also called EOPs.

### 3.2. Solve imaging model with GCLs

According to Zhang Y. [9], the straight-line \(\hat{L}\) in object space and corresponding straight-line \(\hat{l}\) in image space are coplanar. The coplanar condition can be decomposed into two collinear conditions [6]: the corresponding point \((\hat{a}'_1(x'_1, y'_1))\) of point \(A_1\) in image space is collinear with point \(a_1\) and point \(a_2\), while the corresponding point \((\hat{a}'_2(x'_2, y'_2))\) of point \(A_2\) in image space is collinear with point \(a_1\) and point \(a_2\), shown in Figure 1.

![Figure 1 The coplanar condition is decomposed into collinear conditions](image)

Zhang Z. X. et al [6] took the distances from points \(a'_1\) and \(a'_2\) to straight-line \(\hat{l}\) along \(x\)-direction or along \(y\)-direction as residuals, which could be easily calculated. However, this strategy omits the impact of the distance along certain direction on the residuals. In this paper, the direct distances from points \(a'_1\) and \(a'_2\) to straight-line \(\hat{l}\) were taken as residuals, and the distances are the quotients of the areas (may be positive or negative) of \(\Delta a'_1a_1a_2\) and \(\Delta a'_2a_1a_2\) divided by \(a_1a_2\), where \(a_1a_2 = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}\) is the distance between points \(a_1\) and \(a_2\).

Considering point \(a'_1\) first, its coordinates are

\[
x'_1 = f_1(X_1, Y_1, Z_1, t)
y'_1 = f_2(X_1, Y_1, Z_1, t)
\]

The area of \(\Delta a'_1a_1a_2\) is \(S_{\Delta a'_1a_1a_2} = \begin{vmatrix} 1 & 1 & 1 \\ x_1 & x_2 & x'_1 \\ y_1 & y_2 & y'_1 \end{vmatrix}\), so the distance from point \(a'_1\) to straight-line \(\hat{l}\) is

\[d_{a'_1} = \frac{2S_{\Delta a'_1a_1a_2}}{a_1a_2}.\]

Let

\[w = \frac{x_2y_1 - x_1y_2}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}},\]

\[k_x = \frac{y_1 - y_2}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}},\]
\[ k_y = \frac{x_1 - x_2}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \], the collinear condition \( d_{ai} = 0 \) can be expressed as

\[ w = F(X_1, Y_1, Z_1, t) = k_x f_x(X_1, Y_1, Z_1, t) - k_y f_y(X_1, Y_1, Z_1, t) \]  \( (3) \)

Where \( t \) is the unknown parameter vector of geometric model, and the model \( F(X_1, Y_1, Z_1, t) \) can be linearized by calculating the partial derivatives of \( t \):

\[ v_1 = \left( k_x \frac{\partial f_x(X_1, Y_1, Z_1, t)}{\partial t} - k_y \frac{\partial f_y(X_1, Y_1, Z_1, t)}{\partial t} \right) \Delta t - l_1 \]  \( (4a) \)

And for point \( a_i^c \), similar error equation can be derived as

\[ v_2 = \left( k_x \frac{\partial f_x(X_2, Y_2, Z_2, t)}{\partial t} - k_y \frac{\partial f_y(X_2, Y_2, Z_2, t)}{\partial t} \right) \Delta t - l_2 \]  \( (4b) \)

In equation (4a) and (4b), \( v_1 \) and \( v_2 \) are random errors,

\[ l_1 = w - (w) = w - k_x f_x(X_1, Y_1, Z_1, t) + k_y f_y(X_1, Y_1, Z_1, t) \],

\[ l_2 = w - (w) = w - k_x f_x(X_2, Y_2, Z_2, t) + k_y f_y(X_2, Y_2, Z_2, t) \],

\[ \Delta t = (\Delta t_1, \Delta t_2, \cdots, \Delta t_n)^T \] is the correction vector for \( t \).

Equation (4a) and (4b) can be rewrite into matrix form

\[ \mathbf{V} = \mathbf{A} \Delta \mathbf{t} - \mathbf{L} \]  \( (5) \)

Where \( \mathbf{V} = \begin{bmatrix} v_1^T \\ v_2^T \end{bmatrix}, \ \mathbf{L} = \begin{bmatrix} l_1^T \\ l_2^T \end{bmatrix}, \ \mathbf{A} = \begin{bmatrix} k_x \frac{\partial f_x(X_1, Y_1, Z_1, t)}{\partial t} - k_y \frac{\partial f_y(X_1, Y_1, Z_1, t)}{\partial t} \\ k_x \frac{\partial f_x(X_2, Y_2, Z_2, t)}{\partial t} - k_y \frac{\partial f_y(X_2, Y_2, Z_2, t)}{\partial t} \end{bmatrix} \)

In order to apply in all geometric imaging models, the partial derivatives are not resolved analytically. Instead, numerical method is used to approximate the partial derivatives of the function, such as

\[ \frac{\partial f(X, Y, Z, t)}{\partial t_i} = \lim_{\Delta t_i \to 0} \frac{f(X, Y, Z, t_i + \Delta t_i, t_2, \cdots)}{\Delta t_i} \]  \( (6) \)

As one GCL derives two equations like (4a) and (4b), theoretically, \( m > \frac{n}{2} \) GCLs, which are not collinear, are enough to solve all the \( n \) parameters of the model. However, due to the strong relevance between the two equations derived from one control line, the solution of model is not stable if the redundant observations are not adequate. And the strong relevance between the equations also leads to ill-condition, which makes the Least Square solution unstable and greatly deviate from the true value. Moreover, the potential gross errors among the GCLs may also cause the solution to be incorrect. In this case, the robust Levenberg–Marquardt (LM) algorithm [10] is applied to solve the error equations, which can overcome the impact of ill-condition as well as gross errors.
3.3. Solve imaging model with GCLs and GCPs

The remote sensing imaging model based on GCPs is expressed as formula (1), and the error equations can be written as equation (7a) and (7b) after the model is linearized.

\[ v_1 = \frac{\partial f_x}{\partial t} \Delta t - l_1 \]  

\[ v_2 = \frac{\partial f_y}{\partial t} \Delta t - l_2 \]  

Where \( v_1 \) and \( v_2 \) denotes the random errors,

\[ l_1 = x - f_x(X, Y, Z, t), \quad l_2 = y - f_y(X, Y, Z, t), \]

\( \Delta t = (\Delta t_1, \Delta t_2, \cdots, \Delta t_n)^T \) is the correction vector for \( t \).

As the equation (4a) and (4b) can be rewritten into the same matrix form as equation (5), it is possible to solve the simultaneous equations derived from both GCPs and GCLs.

As discussed earlier, the GCPs are considered more accurate than GCLs, thus ought to make more contributions to the model than GCLs. Consequently, when combined into the simultaneous equation group, the equations derived from GCPs should be set greater weights than those derived from GCLs.

4. Experimental Results

According to the proposed method, two tests were conducted respectively using the Landsat5 data (spatial resolution is 30 meters) in some district of Henan, and the ALOS data (spatial resolution is 2.5 meters) in some district of Heilongjiang, and the SRTM DEM was used in the tests with the spatial resolution of 90 meters.

In test 1, geometric rectification was based on the rigorous physical sensor model\cite{10}. Firstly, 10 uneven-distributed GCPs were used to correct the image, as shown in Figure 2a. Secondly, 6 GCPs were chosen from the 10 GCPs, and 6 well-distributed GCLs were added to perform the rectification, as shown in Figure 2b. Thirdly, 10 well-distributed GCPs were used to correct the image, as shown in Figure 2c. Then 10 check points were used to check the accuracy of three rectifications. The accuracy report is shown in Table 1, where the last line shows the root mean square errors.

In test 2, geometric rectification was based on the Rational Polynomial Coefficient (RPC) model and image transformation \cite{11}. Firstly, 4 uneven-distributed GCPs were used to correct the image, as shown in Figure 3a. Secondly, 2 GCLs were added to perform the rectification, as shown in Figure 3b. Thirdly, 6 well-distributed GCPs were used to correct the image, as shown in Figure 3c. Then 10 check points were used to check the accuracy of three rectifications. The accuracy report is shown in Table 2, where the last line shows the root mean square errors.
Figure 2 The distribution of control data in Test 1, including GCPs or (and) GCLs. (a) The uneven distribution of GCPs. (b) The distribution of GCPs and GCLs. (c) The even distribution of GCPs.

| ID | 10GCPs (uneven distributed) | 6GCPs+6GCLs | 10GCPs (well distributed) |
|----|-----------------------------|-------------|---------------------------|
|    | x(m) | y(m) | x(m) | y(m) | x(m) | y(m) |
| 1  | 9.9  | 22.9 | 17.58 | 26.03 | 8.38 | 25.81 |
| 2  | 6.24 | -6.88 | 4.86 | -22.44 | -0.67 | -17.19 |
| 3  | 15.64 | -0.02 | 20.59 | -26.07 | 13.24 | -23.93 |
| 4  | -9.19 | 0.95 | -5.57 | -11.51 | -14.56 | 1.44 |
| 5  | -17.64 | 40.61 | 4.35 | -5.84 | -11.07 | 0.32 |
| 6  | 6.42 | 49.56 | 19.44 | 5.04 | 5.85 | 15.16 |
| 7  | -20.33 | -29.54 | 8.14 | -24.18 | -12.28 | 3.9 |
| 8  | 23.39 | 47.05 | 32.69 | 9.66 | 18.92 | 30.12 |
| 9  | -27.39 | 74.33 | -5.28 | 13.44 | -24.2 | 18.27 |
| 10 | 52.87 | -6.17 | 31.01 | -2.31 | 35.34 | -11.18 |
| RMS | 23.07 | 36.51 | 18.19 | 17.08 | 17.20 | 17.74 |

Figure 3 The distribution of control data in Test 2, including GCPs or (and) GCLs. (a) The uneven distribution of GCPs. (b) The distribution of GCPs and GCLs. (c) The even distribution of GCPs.

| ID | 4GCPs (uneven distributed) | 4GCPs+2GCLs | 6GCPs (well distributed) |
|----|-----------------------------|-------------|--------------------------|
|    | x(m) | y(m) | x(m) | y(m) | x(m) | y(m) |
| 1  | 2.53 | -6.02 | -0.93 | -0.27 | -0.8 | 1.27 |
| 2  | 4.74 | -3.03 | 3.81 | -0.72 | 3.7 | -0.92 |
| 3  | 5.07 | -8.16 | 1.77 | -2.97 | 1.95 | -1.2 |
| 4  | 0.01 | -4.52 | -3.34 | 0.24 | -3.05 | 2.52 |
| 5  | 0.22 | -3.67 | -3.94 | 3.5 | -3.85 | 5.04 |
| 6  | 0.5  | -2.66 | 0.46 | -3.03 | 0.57 | -2.42 |
| 7  | 0.82 | -9.26 | -0.67 | -6.28 | -0.72 | -6 |
| 8  | 5.9  | -6.09 | 4.23 | -4.18 | 4.49 | -2.51 |
| 9  | 0.32 | -7.68 | -4.91 | 0.98 | -4.72 | 3.25 |
| 10 | 12.7 | -8.2 | 7.97 | 0.82 | 7.9 | 1.8 |
| RMS | 5.02 | 6.34 | 3.89 | 2.99 | 3.85 | 3.12 |
The tests show that geometric rectification method proposed in this paper can be applied to different geometric models, and GCPs and GCLs can be united to solve the geometric model. Table 2 and Table 3 indicate that geometric rectification using uneven-distributed GCPs failed to meet the accuracy limits. By supplying the uneven-distributed GCPs with GCLs, the accuracy of rectification was evidently improved, which is not worse than that of rectification using well-distributed GCPs.

The well distribution of control data is the indispensable factor for the high accuracy of geometric rectification. Although the GCLs are not as accurate as GCPs, they did help to balance the distribution of control data, as well as to improve the accuracy of rectification.

5. Conclusions

The proposed geometric rectification method based on straight-line features used the geometric model based on feature points, so it is convenient to unite the error equations derived from straight-line features and feature points. Therefore, in the area of lack of feature points, GCLs can be used as the supplement to GCPs, and the united solution can overcome the impact of uneven distribution of GCPs. The proposed method is not confined to a specific imaging model. However, as GCLs are not as accurate as GCPs, the equations derived from GCPs should be set greater weights than those derived from GCLs when they are united to estimate the geometric model. In natural and man-made environments, the curve features are more prevalent than straight-line features, and how to take advantage of curve features has yet to be further studied.

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