Accuracy analysis of indirect georeferencing about TH-1 satellite in Weinan test area

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Abstract. Optical linear scanning sensors can be divided into single-lens sensors and multi-lens sensors according to the number of lenses. In order to build stereo imaging, for single-lens optical systems such as aerial mapping camera ADS40 and ADS80, there are more than two parallel linear arrays placed on the focal plane. And for a multi-lens optical system there is only one linear CCD arrays placed on the center of every focal plan for each lens which is often carried on spacecraft. The difference of design between these two kinds of optical systems leads to the systematic errors, calibration in orbit and approach of data adjustment are different completely. Recent years the domestic space optical sensor systems are focused on multi-lens linear CCD sensor in China, such as TH-1 and ZY-3 both belong to multi-lens optical systems. The parameters influencing the position accuracy of the satellite system which are unknown or unknown precisely even changed after sensor posted launch can be estimated by self-calibration in orbit. So after self-calibration in orbit the accuracy of mapping satellite will often be improved strongly. Comparing to direct georeferencing, the indirect georeferencing as a research approach is introduced to TH-1 satellite in this paper considering the systematic errors completely. Parameters about geometry position systematic error are introduced to the basic co-linearity equations for multi-lenses linear array CCD sensor, and based on the extended model the method of space multi-lens linear array CCD sensor self-calibration bundle adjustment is presented. The test field is in some area of Weinan, Shaanxi province, and the observation data of GCPs and orbit are collected. The extended rigors model is used in bundle adjustment and the accuracy analysis shown that TH-1 has a satisfied metric performance.

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**1. Introduction**

Linear scanning sensors can be divided into single-lens sensors and multi-lens sensors (Figure 1). In order to build stereo imaging, for single-lens optical systems such as aerial mapping camera ADS40 and ADS80, there are more than two parallel linear arrays placed on the focal plane. And for a multi-lens optical system there is only one linear CCD array placed on the center of every focal plane for each lens that are often carried on spacecraft [1]. The difference of design between these two kind of systems lead to the systematic errors, calibration in orbit and approach of data adjustment are different. Recent years the domestic space optical sensor systems are focused on multi-lens linear CCD sensor, such as TH-1 and ZY-3 all belong to multi-lens optical systems. The parameters influencing the position accuracy of the satellite system which are unknown or unknown precisely even changed after sensor posted launch can be estimated by self-calibration in orbit [2]. So after self-calibration in orbit the accuracy of mapping satellite will often be improved strongly. Comparing to direct georeferencing, the indirect georeferencing as a research approach is introduced to TH-1 satellite in this paper considering the systematic errors completely. The test field is in some area of Weinan, Shaanxi province, and the observation data of GCPs and orbit are collected. The extended rigors model is used in bundle adjustment and the accuracy analysis shown that TH-1 has a satisfied metric performance.

**Figure 1.** Linear scanning sensor (a: Single-lens sensor, b: Multi-lens sensor).

**Figure 2.** The relative position of camera j and nadir camera.

**2. Sensor geometry modelling**

**2.1. Multi-lens sensor modelling**

For sensors whose optical systems consist of more lenses, additional geometric parameters describing the relative position and attitude of each lens with respect to the nadir one are imported in the collinearity equations [3]. For each lens \( j \), \( d_x, d_y, d_z \) represent the relative position and \( \alpha_j, \beta_j, \gamma_j \) the relative attitude with respect to the reference one (Figure 2.). Calling \( x_{pj} \) and \( y_{pj} \) the principal point positions and \( f_j \) the focal length, such the relationship between camera and ground coordinates are described by equation (1) [4],

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
X_c \\
Y_c \\
Z_c
\end{bmatrix} + R(\omega_c, \varphi_c, \kappa_c) \begin{bmatrix}
d_x \\
d_y \\
d_z
\end{bmatrix} + kS(\omega_c, \varphi_c, \kappa_c, \alpha_j, \beta_j, \gamma_j) \begin{bmatrix}
x - x_{pj} \\
y - y_{pj} \\
f_j
\end{bmatrix}
\]

namely

\[
x - x_{pj} = -f_j \cdot \frac{s_{11} (X - X_c) + s_{21} (Y - Y_c) + s_{31} (Z - Z_c) - (m_1 d_x + m_2 d_y + m_3 d_z)}{s_{13} (X - X_c) + s_{23} (Y - Y_c) + s_{33} (Z - Z_c) - (m_1 d_y + m_2 d_y + m_3 d_z)}
\]

\[
y - y_{pj} = -f_j \cdot \frac{s_{12} (X - X_c) + s_{22} (Y - Y_c) + s_{32} (Z - Z_c) - (m_1 d_y + m_2 d_y + m_3 d_z)}{s_{13} (X - X_c) + s_{23} (Y - Y_c) + s_{33} (Z - Z_c) - (m_1 d_y + m_2 d_y + m_3 d_z)}
\]
where,

\[ [X, Y, Z] \text{: point coordinates in the ground system; } [X_C, Y_C, Z_C] \text{: PC position in the ground system; } [x, y] \text{: point coordinates in the camera system, and x is equals to zero; } [\nu_x, \nu_y] \text{: principal point coordinates in the cameras system; } \]

\[ f \text{: focal length; } \]

\[ \mathbf{R}(\omega_C, \phi_C, \kappa_C) \text{: rotation matrix from camera to ground system, with the attitude angles } \omega_C, \phi_C, \kappa_C; \]

\[ \mathbf{M}(\alpha_j, \beta_j, \gamma_j) \text{: rotation from camera system centred in the off-nadir lens } j \text{ to cameras system with origin in the central lens; } \]

\[ S(\omega_C, \phi_C, \kappa_C, \alpha_j, \beta_j, \gamma_j) \text{: complete rotation from camera system centred in the off-nadir lens } j \text{ to ground system. ( } j = 1, 2, 3, \ldots, n \text{ )} \]

2.2. Trajectory model

The sensor external orientation (EO) is modelled by Piecewise Polynomial Functions (PPM) depending on time. Due to the possibility of changing the number of segments and the polynomial degree, this function results quite flexible and applicable to both satellite and airplanes trajectories, as shown in [6], [7] and [8]. If one segment only is used, the PPM becomes a parabolic function (Figure 3).

![Figure 3. Trajectory modelling with piecewise polynomials.](image)

The platform trajectory is divided into segments according to the number and distribution of available GCPs and TPs. For each segment \( i \), with line extreme \( t_{\text{init}}^i \) and \( t_{\text{fin}}^i \), the variable \( \tilde{t} \) is defined as

\[
(\tilde{t} = (t - t_{\text{init}}^i)/(t_{\text{fin}}^i - t_{\text{init}}^i))
\]

The sensor attitude and position of each image line \( l \) belonging to segment \( i \), indicated with \[ [X, Y, Z, \omega_C, \phi_C, \kappa_C] \] are modelled as the sum of the measured position and attitude data for that line \[ [X_{\text{instr}}, Y_{\text{instr}}, Z_{\text{instr}}, \omega_{\text{instr}}, \phi_{\text{instr}}, \kappa_{\text{instr}}] \]. Plus the second order polynomial functions depending on \( \tilde{t} \), resulting in

\[
\begin{align*}
X_C(\tilde{t}) &= X_{\text{instr}} + X_0^i + X_1^i \tilde{t} + X_2^i \tilde{t}^2 \\
Y_C(\tilde{t}) &= Y_{\text{instr}} + Y_0^i + Y_1^i \tilde{t} + Y_2^i \tilde{t}^2 \\
Z_C(\tilde{t}) &= Z_{\text{instr}} + Z_0^i + Z_1^i \tilde{t} + Z_2^i \tilde{t}^2 \\
\omega_C(\tilde{t}) &= \omega_{\text{instr}} + \omega_0^i + \omega_1^i \tilde{t} + \omega_2^i \tilde{t}^2 \\
\phi_C(\tilde{t}) &= \phi_{\text{instr}} + \phi_0^i + \phi_1^i \tilde{t} + \phi_2^i \tilde{t}^2 \\
\kappa_C(\tilde{t}) &= \kappa_{\text{instr}} + \kappa_0^i + \kappa_1^i \tilde{t} + \kappa_2^i \tilde{t}^2
\end{align*}
\]

\[ [X_0, X_1, X_2, \ldots, \kappa_0, \kappa_1, \kappa_2] \] are the 18 parameters modelling the misalignment and systematic errors contained in the observations in segment \( i \). The constant terms \[ [X_0, Y_0, Z_0, \omega_0, \phi_0, \kappa_0] \] compensate the shifts and angular drifts between the image system and the GPS and INS systems, while the linear and quadratic terms \[ [X_1, X_2, Z_1, \omega_2, \phi_2, \kappa_2] \] and \[ [X_2, Y_2, Z_2, \omega_2, \phi_2, \kappa_2] \] model the additional systematic errors contained in the GPS and INS measurements.

At the points of conjunction between adjacent segments, constraints for the zero, first and second order continuity are imposed on the trajectory functions: we force that the values of the functions and their first and second derivatives computed in two neighboring segments are equal at the segments boundaries.
3. Experiment and analysis

3.1. Test data
The test area is about 60km × 60km, lies in southeast of Weinan, Shaanxi province (Figure 4). There are 35 well-distributed GCPs in the test area. The accuracy of the GCPs is less than 1m in X, Y and Z direction. The collected data includes triple images, GPS and star tracker of orbit observations about domestic satellite TH-1 which was through the area in January, 2011. The photogrammetric observation parameters are about the focal length and the relative position of the three cameras, GPS and sensor tracker to be integrated. These parameters are already observed in lab before satellite to be launched.

![Figure 4. The well distributed GCPs in the test area.](image)

3.2. Processing and result

3.2.1. Test 1: validation of symmetric errors and data.
Firstly the image coordinates of GCPs are counted according the observations of EO and GCPs through the space resection. The counted result can reflect the quality of all observation data including the camera characteristic parameter, etc.

| Table 1. The residuals of the image coordinates of GCPs (unit: pixel). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Nadir view      | Forward view    | Backward View   |
|                 | $x' - x$        | $y' - y$        | $x' - x$        | $y' - y$        | $x' - x$        |
| Mean            | -14.9154        | -31.6459        | -11.4024        | -40.5074        | -14.9704        |
| [Min]           | 11.5050         | 27.2660         | 6.6950          | 35.7900         | 10.8750         |
| [Max]           | 17.8750         | 34.8500         | 15.0990         | 43.2690         | 18.7250         |
| Std.             | 1.7856          | 1.6473          | 1.7154          | 1.9345          | 1.9166          |

Table 1 shows the statistics of the residuals for image coordinates about GCPs, and which shows that obvious systematic errors exist. If the systematic errors are to be corrected, the RMS of residuals for GCPs image coordinates should be less than 2 pixels, corresponding 2GSD (10m) in object system through DGR.

Now next step is to do DGR for the further validation of the existing systematic errors. Then the object coordinates of GCPs are calculated according the observations of EO and image coordinates for GCPs through the space intersection. The calculated results are shown in Table 2, which are consistent with Table 1. Figure 5 shows the residuals of GCPs (A point is detected as a gross error).
The statistics of residuals for all GCPs through DGR.

| Statistics | $\Delta X$ | $\Delta Y$ | $\Delta Z$ |
|------------|------------|------------|------------|
| Mean       | 176.4120   | 63.8659    | -35.0310   |
| [Min]      | 157.4198   | 27.9408    | 1.0915     |
| [Max]      | 189.9225   | 89.0616    | 66.4352    |
| Std.       | 8.6944     | 13.2438    | 14.3422    |

3.2.2. Test2: Self-calibration bundle adjustment (indirect georeferencing).

The sensor model above in this paper should be introduced in self-calibration bundle adjustment. The 4 GCPs at the test area corner are shown in Table 3.

| Point ID | X             | Y             | Z             |
|----------|---------------|---------------|---------------|
| 1102     | 1737707.792   | 4969234.826   | 3589558.532   |
| 1502     | 1771267.701   | 4962247.651   | 3583263.586   |
| 6102     | -1738261.807  | 4944465.073   | 3623256.377   |
| 6502     | -1781190.208  | 4932167.332   | 3619065.290   |

Through the self-calibration bundle adjustment, the corrections of star tracker attitude and the mounted angles between cameras are shown in Table 4. The residuals of 31 check points in test area are shown in Table 5 and Figure 6. The sigma naught is 8.03u in self-calibration bundle adjustment.

| Sensor               | $\Delta \omega$ | $\Delta \phi$ | $\Delta \kappa$ | Std. ($\Delta \omega$) | Std. ($\Delta \phi$) | Std. ($\Delta \kappa$) |
|----------------------|-----------------|---------------|-----------------|-------------------------|----------------------|-------------------------|
| Backward-nadir       | -2.020e-05      | 1.848e-04     | 7.600e-05       | 5.213e-06               | 3.610e-06            | 1.388e-04               |
| star tracker         | 1.481e-04       | -2.946e-04    | 2.174e-04       | 4.365e-06               | 3.971e-06            | 1.065e-04               |
| Forward-nadir        | 6.300e-06       | -6.610e-05    | -1.457e-04      | 5.237e-06               | 3.607e-06            | 1.385e-04               |

| Table 5. The residuals of 30 check points in test area (unit: m). |
|------------------------------------------------------------------|
| Statistics | $\Delta X$ | $\Delta Y$ | $\Delta Z$ |
| Max        | 17.921    | 23.226    | 10.638    |
| Mean       | 9.092     | 5.372     | 2.024     |
| RMS        | 7.521     | 9.869     | 5.798     |
| Std.       | 7.594     | 8.420     | 5.527     |
4. Conclusion
The indirect georeferencing test declares that the sensor geometry modeling is good enough, the processing of data adjustment is robust and the accuracy of GCPs and image point measurement is satisfied.

The prior accuracy of GPS carried on satellite is less than 5m. The accuracy of point transfer is nearly 2 pixels though the accuracy of GPS observation for GCPs in field survey is less than 1m, so the accuracy of GCPs is properly about 10m. Significance test shows that the corrections of GPS carried on satellite, optical lenses’ distortions and CCDs distortions are all not significant. The correction of attitude of star tracker is most remarkable and the last sigma naught is 8.03u, little bigger than one pixel (the pixel size is 6u corresponding 5m GSD). The accuracy of georeferencing is improved from 176.4120m, 63.8659m, 35.031m to corresponding 6.1642m, 7.8883m and 4.9669m in X,Y and Z directions, less than 2 GSD. If the conditions of GCPs are better, the result are ought to be better as well.

The one GCP, 4 and all 34 GCPs are used in self-calibration bundle adjustment separately. In order to get an ideal result there at least 4 GCPs should be needed. Further work is that the test should be done in different and bigger test field areas during long time cycle.

The only published paper about TH-1 focused on RPC model [9], but now we focus on rigors model considering the systematic errors. Because the limited data the result and conclusion need to be validated further more.

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