Calibration of digital camera integration accuracy for low-cost oblique aerial photogrammetry

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This work describes a calibration process for inexpensive consumer cameras integrated into a low cost and compact aerial multi-view imager for remote sensing and photogrammetry. The main advantage of this design is to make the filming component lightweight and rapidly deployable, as well as reducing cost when compared with mainstream commercial oblique imagery. An in situ flight test was carried out in Guiyang. In that experiment, a meridian convergence-based approach was adopted to adjust preprocessing, the residue error and the captured images’ exterior orientation linear and angular parameters were calculated by means of the direct geo-referencing approach yielding a favorable outcome for exterior orientation linear parameters of the camera, around 0.2–0.3 m deviation from the actual measured results at 1000 m flight above ground level. The camera’s exterior orientation angular parameters φ, ω whose difference compared with the standard aerial aero triangulation approach reached a high accuracy level within the intended endurance of 0.005°. These results indicate that the compact implementation of the oblique aerial imager comprised of consumer level off-the-shelf digital cameras achieved competitive accuracy at a low cost and high versatility.

Keywords: oblique photogrammetry; aerial imager; calibration; digital camera; position and orientation

1. Introduction

Administrative authorities need efficient ways of earth observation and assessment given the drastic changes in urban landform and layout (1). Advancements in photogrammetry and aerial orthophotos on film are the traditional perspective for urban development monitoring (2). However, orthographical imagery has its own limits as the technique only captures two-dimensional graphical information contrary to intuitive human perception, and surface features are likely to be falsely identified. With the advent of spaceborne imaging technology, classical airborne photogrammetry is being replaced to certain extent by high-resolution satellite images (3). The finer scale images from satellite sensors exhibit more detailed ground information than traditional analog aerial photographic images. Nevertheless, satellite images have the same problems as orthography when it comes to interpretation and monitoring. The process of stereoscopic analysis can somewhat mitigate this shortcoming for homogeneous terrain features in the open area, but automation of the environmental observation is still elusive when a mission focuses on a complex urban built-up area (4).

In the instrumental field of surveying and mapping, oblique photogrammetry is a fast evolving techniques for geographical environment monitoring and land information capture (5, 6). The aerial solution subverts the limitations of previous orthophoto techniques that only shot from a perpendicular angle using multiple sensors on one flight platform. This method usually captures images from several vertical and oblique down-looking angles. Aided by high definition onboard global positioning system (GPS) receivers and inertial measurable units (IMUs), the absolute position of captured images can be stereo geo-referenced. Oblique photogrammetry integrates traditional aerial photography and close ranging technology, creating a real intuitive world for human visual cognition. Combining the tilted and vertical aerial photographs, detailed texture information of building façades and sidewalls could be obtained from these non-orthographical images at the same time. The use of oblique photogrammetry not only could assist in improving the efficiency and the production of ground feature observation and three-dimensional models, but also can provide a variety of direct measurements, such as distance, height, area, and volume (7). Oblique photography can be used in various disciplines such as urban planning, construction, and management. Compared with other classical geographical data sources in surveying and mapping such as digital elevation models (DEMs), the technique has irreplaceable value in the area of object interpretation, environmental monitoring, and emergency response, since the side perspective can deliver more stereo geographical and environmental contextual information from these typically four-angled images than traditional products from an orthographic perspective (8). For example, only roofs can be seen in orthophotos from above, while emergency exits on the
walls are easily caught in the line of sight from the tilted images. The distance between any points in the image also can be accurately computed according to the known relative position relationship between cameras, such as the calculation of sight distance, the determination of dominant points, and the volume computation or other three-dimensional features. However, due to the complex geometrical configuration of onboard sensors, the current processing approaches usually perform poorly on non-vertical aerial imagery (9). For more stringent cases, as multi-angled image stitching and dense matching, optimal adjustment and direct geo-referencing are mandatory (10, 11).

The research group of State Key Laboratory of Information Engineering in Surveying, Mapping, and Remote Sensing and Collaborative Innovation Center for Geospatial Technology at Wuhan University has been long working in the instrumental innovation for surveying and mapping. In 2007, a prototype of terrestrial mobile mapping system which integrated onboard GPS receiver, charge-coupled device cameras, inertial navigation system, and dead reckoning instrument for environment surveying and mapping was put into pilot study (12). The system not only can provide captured images on the move, but also enables the image to be loaded into a new surveying product form as digital measurable image, measurable from the photo, as an enrichment to traditional DEM (13). Thenceforth, as a supplement to terrestrial mobile mapping, the group continued the research and development of aerial oblique photogrammetric equipment. Since the cost of mainstream multi-view photogrammetric products such as Pictometry Imagery (14) or Microsoft UltraCam Osprey (15) is out of the range of an academic research budget, the group had to utilize more accessible commercial lenses to integrate and calibrate an equivalent filming device for research, something attempted by other researchers in the field of remote sensing (16). At the beginning of this study, the design of the equipment is described; then, a meridian convergence-based method is adopted to calculate the exterior orientation parameters of randomly selected images from two in situ calibration fields. The root-mean-square error, average residual error, and maximum residual of X, Y, coordinate planar and elevation error are computed to evaluate the system’s calibration accuracy. The overall objectives of this study were (1) to use feasible and inexpensive components to build an original aerial multi-lens imager suitable for oblique photogrammetry at a low cost; (2) to evaluate the calibration accuracy of the equipment design by calculating the exterior orientation parameters; (3) to test whether the calculated coefficients can meet the tolerance extent.

2. Description of multi-lens imager

The aerial multi-lens imager is designed in a streamlined oval pod composed of three sensors: (a) one orthographic Phase One (Phase One A/S, Frederiksborg, Denmark) camera; (b) four tilted high definition Nikon lens; (c) an onboard positioning and orientation system (POS) and associated onboard control and computing systems. The orthographical camera is vertically deployed in the middle of the structure, with four lenses configured at an angle of ±45° around the middle one, and each two of them are grouped at the lateral direction (y-axis), others are grouped along the flight direction (x-axis). Above them, a POS component is arranged to record time, position, elevation, heading, speed, and other operational status information. The onboard control unit is responsible for adjusting the position of the pod. The controlling unit receives orders from the IMU in the POS and determines the rotation or lock-on movement of the dimensional frame, respectively. It can stabilize the filming platform and bore sight to avoid oscillation from the carrier. The bearing platform and the rolling arm are the implementation for two degrees of freedom; each frame is sensed by the IMU and responsive to rotation and rolling of the cameras. Such configuration can ensure the filming component is non-fixed and adjustable to account for small offset changes, and the four tilted lens are able to cover an entire panoramic view of the ground. Compared with the one hundred kilograms payload for common oblique photographic systems, the total weight of this compact integrated system can be reduced to around thirty kilograms (Figure 1).

3. Calibration of the oblique imager system

The oblique imager system is the key measurement equipment in aerial oblique photogrammetry, composed of a vertical and four tilted digital cameras as described in Section 2. Since current mainstream digital cameras are nonmetric and not specifically designed for photogrammetry, the inner orientation parameters cannot be obtained directly and also there is significant optical distortion. Since the multi-camera combination is assisted with the POS apparatus to get the target image and POS data, the relative positioning between each camera and the instability between the system and POS can cause indirect and slow execution of subsequent data processing. Therefore, the strict calibration of the oblique imager is one of the basic tasks in aerial oblique photogrammetry (17).

To achieve fast integrated calibration of the oblique aerial imager, each camera’s inner orientation parameters, distortion correction parameters, camera relative positions, and orientation parameters must be fully taken into account. A meridian convergence compensation-based aerial instrument calibration is adopted. The basic principle is as follows:

\[
\begin{align*}
    x - x_0 + \Delta x &= -f_y \left( a_3(x_T - x_0) + b_3(y_T - y_0) + c_3(z_T - z_0) \right) \\
    y - y_0 + \Delta y &= -f_y \left( a_1(x_T - x_0) + b_1(y_T - y_0) + c_1(z_T - z_0) \right) \\
\end{align*}
\]

where \( x \) and \( y \) denote the coordinates of a control point, \( x_0 \) and \( y_0 \) are the coordinates of the principal point, \( f \) is
the principal distance, and $\Delta x$, $\Delta y$ are the distortion of the current point. Suppose $r^2 = (x - x_0)^2 + (y - y_0)^2$, then the calculation of the distortion will be as follows:

$$
\begin{align*}
\Delta x &= \bar{x}(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1 (r^2 + 2\bar{x}^2) + 2p_2 \bar{x}y \\
\Delta y &= \bar{y}(k_1 r^2 + k_2 r^4 + k_3 r^6) + 2p_1 \bar{x}y + p_2 (r^2 + 2\bar{y}^2)
\end{align*}
$$

(2)

Equations 1 and 2 are used as a mathematical model in the case that part of the three-dimensional spatial coordinates of the control points are already known, and the inner orientation parameters and the distortion correction parameters of the image are acquired simultaneously, and the exterior orientation parameters between the POS system and the camera center are calculated for calibration.

In order to achieve direct geo-referencing based on POS data, there is a need to employ the aero triangulation method for calibrating the exterior orientation parameters of the POS and camera center (18–20). An in situ experiment will verify the accuracy of the image and the POS data and test this calibration method for accuracy and determine the exterior orientation parameters. The specific steps adopted for this test are as follows:

(1) The aerial data processing software DPGrid (21) and the Inertial Explorer (NovAtel, Calgary, Alberta, Canada) are used to implement integration processing of the POS data and carry out meridian convergence compensation for the POS’s attitudinal angle data (22).

(2) Based on the coordinates of the control point in the calibration field, the aero triangulation method is implemented to obtain the exterior orientation parameters of the calibration field images.

(3) Based on the exterior orientation parameters of the calibration field images, and POS data, the relative coordinate offset and orientation parameters between the POS system and the camera center are calculated for calibration.

(4) Based on the POS data and calibration parameters, calibration field images can be directly geo-referenced, and their respective exterior orientation parameters can be obtained.

(5) Compare the processed exterior orientation parameters of the POS directly geo-referenced images with the actual aero triangulation results and then the experimental conclusions can be drawn.

The experimental images chosen for experiment are data from the Jinyang calibration field I and II (Figure 2), filmed by the proposed aerial imager on 3 February 2013 and 4 February 2013 separately. The above ground level is 1000 m, and the 20th, 21th, down-looking overlapped images were chosen and numbered successively as 01020ER014–01020ER018, 02021ER038–02021ER042 for calibration experiments. The down-looking camera’s focal length was set at 50.688 mm, and the pixel size was 6 $\mu$m, with a ground resolution of 0.12 m by calculation.

The control points were evenly selected from 20 ground feature points in the calibration field I and II, their coordinates were measured and outputted in the form of XIAN80 plane coordinates and WGS84 ellipsoid elevation data. After preprocessing, the planar root-mean-square (RMS) of the average control points was 0.38 cm, and the elevation RMS was 0.49 cm. To ensure the objectivity and reliability of the experiment results, the POS data were compensated by the meridian convergence angle in the experiment and then treated by the aero triangulation method (23).

Next, using the DPGrid software, the distortion-corrected calibration field images were rotated clockwise by 90° and then carried the POS-assisted aero triangulation processing to obtain the exterior orientation
parameters of the calibration field images. During the experiment, the POS data were considered as the observation values, and the adjustment calculation was applied to the GPS antenna variable and the IMU antenna variable separately.

4. Results

The aero triangulation results of the calibration field images are summarized in Table 1. Their separate exterior orientation parameters [easting, northing, elevation, φ, ω, κ] are associated with the captured images accordingly.

The residual values of respective control points are shown in Figure 3, and the residual error of the respective control points is presented in Table 2.

Based on the exterior orientation parameters of each image in the calibration field, and the compensated POS data, the relative coordinates offset between the POS system and the camera center and the orientation can be obtained through calibration. The results are shown in Table 3.

Comparing the calibration results in Table 3, the meridian convergence compensation method has an insignificant influence on the standard deviation of the relative calibration, but has a strong impact on the absolute value of each orientation angle. After conducting the meridian convergence compensation, the relative position relationship between the calibrated POS data and the camera center is more consistent with the actual equipment deployment situation, so the subsequent experiments accept results after the compensation calibration.

Table 1. The aero triangulation results of the calibration field images.

| Image         | Easting (m) | Northing (m) | Elevation (m) | φ (°)   | ω (°)   | κ (°)   |
|---------------|-------------|--------------|---------------|---------|---------|---------|
| 01020ER014    | 360699.311  | 2970183.231  | 2214.871      | -0.60136 | -1.1536 | -91.8234 |
| 01020ER015    | 360697.431  | 2969982.257  | 2215.129      | -0.83601 | -1.30673 | -90.3542 |
| 01020ER016    | 360694.630  | 2969775.754  | 2215.223      | -0.87985 | -1.63201 | -90.5369 |
| 01020ER017    | 360691.823  | 2969563.692  | 2216.104      | -0.49306 | -1.336   | -90.0065 |
| 01020ER018    | 360689.547  | 2969361.356  | 2216.382      | -0.69095 | -1.42063 | -90.1389 |
| 02021ER038    | 361822.342  | 2947626.624  | 2214.973      | -1.12836 | -1.43398 | -89.9256 |
| 02021ER039    | 361822.821  | 2947603.134  | 2213.981      | -0.78201 | -1.22365 | -89.0036 |
| 02021ER040    | 361821.965  | 2947435.467  | 2214.597      | -0.38962 | -1.53641 | -90.9632 |
| 02021ER041    | 361821.981  | 2947211.359  | 2215.112      | -0.49620 | -1.45691 | -90.2675 |
| 02021ER042    | 361821.893  | 2947068.091  | 2215.326      | -0.89256 | -1.69243 | -91.8364 |
After the meridian convergence compensation, the mean value of orientation linear parameters $[dX, dY, dZ]$ are $[-2.217, -0.337, 1.297]$, with around 0.2–0.3 m deviation from the actual measured results $[-2.271, -0.355, 1.476]$. The deviation was mainly induced by the correlation between linear parameters and angular parameters, but also includes actual measurement error.
After these steps, the mean values of the calibrated results for each image are used as the real values of the orientation angles, and the relative coordinate offset between the POS system and camera center. Combined with the POS data, direct geo-referencing of captured images can be realized to get the exterior orientation parameters of each calibration field image. The calculated exterior orientation parameters are listed in Table 4.

Figure 4 shows the difference of orientation angular parameters comparing the calculated orientation angular parameters with standard aero triangulation results. After analyzing the orientation angular parameters difference, the calibrated accuracy of orientation angular parameters $[\phi, \omega, \kappa]$ is $[0.0021^\circ, 0.0035^\circ, 0.0068^\circ]$ now meet the requirements for intended accuracy endurance $[0.005^\circ, 0.005^\circ, 0.01^\circ]$.

5. Conclusion
In our approach, compared with traditional photogrammetry, the research group developed a new aerial multi-view imager with inexpensive, commercial cameras for versatility and availability. It was comprised of four tilted cameras and one perpendicular lens. With the aid of onboard GPS apparatus and IMU equipment, the imager package was made lightweight and compact, suitable for use in earth observation applications. This study describes the main configuration of the integrated equipment and the calibration of its exterior orientation parameters to test the system accuracy.

The process adopts the meridian convergence method for compensating the aerial images to obtain the modified exterior orientation parameters. After raw data acquisition and meridian convergence-based preprocessing, the aero triangulation approach and the POS-assisted direct geo-referencing approach are carried out separately to obtain the orientation parameters of the captured images for comparison; the difference of exterior orientation angular and linear parameters is made comparatively. The results of mean value of exterior orientation linear parameters are $[-2.217, -0.337, 1.297]$ m while the aero triangulation’s result is $[-2.271, -0.355, 1.476]$ m. The calculated results for the exterior orientation angular parameters are $[0.0021^\circ, 0.0035^\circ, 0.0068^\circ]$ and satisfies the intended objective of $[0.0025^\circ, 0.0025^\circ, 0.005^\circ]$ and are not too far off the endurance.

The calibration result indicates that the system can attain a lightweight and compact integration from commercially available cameras and lenses with high accuracy when compared with traditional photogrammetric aero triangulation methods. Using an onboard POS apparatus, the direct geo-referencing method can be feasible for rapid photogrammetry, and the small-size oblique multi-lens imager can be a great research tool for unmanned aerial vehicle payloads or future low attitude aerial photogrammetric missions for urban monitoring.

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