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Direct georeferencing of oblique and vertical imagery in different coordinate systems

Haitao Zhao [a], Bing Zhang [a,*], Changshan Wu [b], Zhengli Zuo [a], Zhengchao Chen [a], Jiantao Bi [a]

[a] *Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China*
[b] *Department of Geography, University of Wisconsin–Milwaukee, Milwaukee, WI 53201, USA*

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ABSTRACT

Reconstruction of 3D models through integrating vertical and oblique imagery has been studied extensively. For a 3D reconstruction, object point cloud coordinates could be calculated using direct georeferencing (DG) obtained from the direct orientation data of a GPS/INS system. This paper implemented DG approaches for vertical and oblique imagery in the earth centered earth fixed frame (e-frame), local tangent frame (l-frame), and map projection frame (p-frame), respectively. In the p-frame, the earth curvature correction formulas were derived through naturalizing oblique imagery to vertical imagery to achieve a high positioning precision. Five basic stereo-pair models for vertical and oblique imagery were simulated to verify the positioning accuracy of different frames. Simulation experiments showed that DG in the e-frame and l-frame of these five scenarios were rigorous, and no systematic errors were imported by the DG model as these frames are Cartesian. DG in the p-frame has obvious systematic errors which are aroused by the earth curvature and projection deformation unconformity in the vertical and horizontal directions. These errors, however, can be compensated effectively through correcting image coordinates of the oblique imagery by extending the standard image coordinate correction approach and the exterior orientation (EO) height term. After the correction, the absolute positioning error is lower than 1/20 GSD for simulation test-1. In the p-frame, the process is straightforward, and it is convenient for producing maps. For high accuracy DG, though, it is recommended to adopt e-frame or l-frame options.

1. Introduction

Vertical and oblique aerial photographs have been generated for military and civil applications since early twentieth century (Jensen, 2009). Prior to 1938, single and multiple lens cameras have been produced with oblique or combined vertical and oblique configurations in the United States, United Kingdom, Germany, France, Italy, and Switzerland (Jacobsen, 2009). Early applications of oblique aerial photos were mainly for military purposes (e.g. reconnaissance) (Grenzdörffer et al., 2008; Jacobsen, 2009). Recently, due to the rising demands of civil applications, accompanying with rapid technological progresses in digital camera systems and GPS/INS processing, the combination of vertical and oblique aerial photos for multi-view stereos with direct exterior orientation data were revived (Höhle, 2008; Karbø and Schroth, 2009; Petrie and Walker, 2007). These techniques have been widely applied to automatically reconstruct 3D models with high resolution facade texture information of terrain objects (Haala and Kada, 2010). These 3D reconstructions have been effectively employed in urban emergency response systems, virtual reality simulation, intelligent transportation, urban and infrastructural planning, security services, etc. (Grenzdörffer et al., 2008; Höhle, 2008; Petrie, 2009; Suveg and Vosselman, 2004; Xiao, 2013).

The high demand of oblique imagery has been notably pushed by the need of digital representations of the world. Such applications include Microsoft's Bing Maps, as well as special GIS viewers such as Pictometry and MultiVision. In addition, 3D model reconstruction through processing multi-view stereo imagery or developing computer vision technologies has been implemented (De Reu et al., 2013; Verhoeven et al., 2012), and such computer software include Street Factory, Agisoft Photoscan, Smart3DCapture of Acute3D, etc. In addition, numerous instrument manufacturers also developed numerous oblique camera systems, including MIDAS (Track'Air company), RCD30 oblique (Leica geosystem department), UltraCam Osprey (Vexel imaging of Microsoft company), A3 (VisionMap company), AMC580 (Shanghai Hangyao

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* Corresponding author. Tel.: +86 10 82178002; fax: +86 10 82178009.
E-mail address: zb@radi.ac.cn (B. Zhang).

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Information Technology company), Penta DigiCam (IGI), PIFFF, SWDC-5, TOPDC-5 and others.

For civil metric applications of photogrammetry, three important aspects are accuracy, efficiency, and processing cost. GPS/INS plays an essential role in all these three aspects (Cramer et al., 2000). GPS/INS has been widely equipped on frame cameras, line scanning sensors, LiDAR, SAR, etc. in airborne remote sensing for many years (Mostafa and Hutton, 2001). With GPS/INS, the position and spatial orientation of the inertial measurement unit (IMU) in the global reference frame can be effectively determined. The position and orientation data can be used for direct georeferencing, with which the required number of ground control points (GCPs) could be significantly lower or approaching zero with the help of the integrated sensor orientation method.

For direct georeferencing, two consecutive procedures, sensor orientation and scene restitution, are required (Legat, 2006). The former process aims to transform the exterior orientation provided by GPS/INS into the target reference frame. The latter process aims to calculate the object coordinates in the target reference frames by combining the EOs, interior orientations parameters and the image sensor observations (image coordinate) with spatial intersection. For aerial photogrammetry products, such as digital terrain models, ortho-images, and 3D models, national projection coordinates frames are usually required. The transformation may be achieved by either transforming the exterior orientation (EO) elements or the restitution results.

For the EO transformation, intensive studies have been carried out, but they are mainly for vertical frame camera images (Legat, 2006) and LiDAR data restitution in the p-frame (Zhang and Shen, 2013). Although many studies have pointed out that the Cartesian frame is the most rigorous, no test has been implemented. Moreover, to our knowledge, no DG experiments have detailed the differences between global and local frames for oblique images. Further, in projection frames, two important factors should be considered in restitution: earth curvature and length projection distortion (Legat, 2006; Skaloud and Legat, 2008). Although correction methods for these two factors have been developed for vertical frame imagery and LIDAR data, it is still questionable whether these algorithms can be transferred to oblique imagery. Because of the large tilt angles of oblique imagery, the compensation algorithms may not be suitable. We found that while Legat's method is still effective for calculating EOs in projection frame for oblique imagery and the height systematic compensation approach is also useful, the earth curvature correction approach should be improved. To address these issues, this paper first introduces the calculation procedure of EOs in Cartesian frames and in non-Cartesian frames. Later, this paper details the restitution method with the spatial intersection algorithm. Especially, we derive the earth curvature correction procedure in the projection frame for DG of oblique images by generalizing vertical imagery to oblique imagery. Finally, we design two simulation tests to verify the accuracy of DG in different frames and analyze the influential factors.

The organization of the paper is as follows. The next section presents DG procedures in different frames, focusing on the procedure of calculating the EOs and restituting the stereo-pair model in the three frames for vertical and oblique imagery. Later, we introduce the coordinate transformation procedure to the projection frame. Section 3 describes the means of compensating the earth curvature in projection frame for oblique imagery and introduces the length projection distortion correction approach. Section 4 details two simulation tests with five basic stereo pair model scenarios for oblique and vertical imagery with different orientation angles and projection center (PC) positions. In addition, with the simulation tests, accuracy analysis is performed in different frames and their influential factors are discussed. Finally, Section 5 concludes this paper.

2. DG approaches in different coordinate frames

In this section, we introduce the approaches of DG in three coordinate frames, including (1) the global (e-) frame, (2) the local tangent (l-) frame, and (3) the map projection (p-) frame, and the terrain object coordinates were transformed to the p-frame following the requirements of aerial photogrammetry mapping products. Specifically, these three frames are introduced briefly in Section 2.1; DG procedures in different coordinate frames are summarized in Section 2.2; the EO calculation procedure is described in Section 2.3; and the stereo-pair restitution is presented in Section 2.4.

2.1. Reference frames and map projections

The relevant definitions and descriptions of the terms associated with those reference frames and map projections required for this paper are presented in Table 1. All frames are right-handed.

2.2. DG procedures in different coordinate frames

Spatial intersection of oblique images can be implemented in e-, l-, and p-frame for DG. The EOs calculation procedure in different frames varies significantly. After spatial intersection, the object coordinate in the reference frame should be transformed to p-frame for generating mapping products. This section introduces the procedures of DG in the three frames. The procedure is listed in Fig. 1, from which the differences among the e-frame, l-frame, and p-frame are clearly presented.

2.3. Calculation procedures of EOs in different coordinate frames

From Fig. 1, we can identify that one key procedure of DG is to calculate the EOs in the reference frames. This section describes the calculation procedures in e-frame, l-frame and p-frame.

2.3.1. Calculating exterior orientations in the e-frame

For direct georeferencing, the first step is to compute the EOs using the GPS/INS post-processed data. An oblique camera system usually has several cameras sharing the same IMU, and all the cameras connect firmly with the IMU as a rigid body (Fig. 2). For multiple sensors integrated with the same IMU, the GPS/INS reference frame origin can be set as the IMU body frame (b-frame) center; the lever arm of GPS can be measured in the b-frame. After the post-process of GPS data and IMU data, the final position and attitude can be applied to obtain the b-frame origin in the g-frame and the b-frame attitude relative to the local tangent frame. The image EOs can be transformed from the attitude and position of IMU using a sequential conversion procedure.

If we label the camera frame (c-frame) origin coordinates in the b-frame as $(X_{pc}, Y_{pc}, Z_{pc})_b^T$, then the c-frame origin (always called projection center, PC) in e-frame can be calculated using Eq. (1).

$$(X_{pc}, Y_{pc}, Z_{pc})_e^T = R_{l_n}^e R_b^{l_n} (X_{pc}, Y_{pc}, Z_{pc})_b^T + (X_{b0}, Y_{b0}, Z_{b0})_e^T \tag{1}$$

where $(X_{pc}, Y_{pc}, Z_{pc})_e^T$ is the PC coordinates in e-frame, also called line elements of EOs. $(X_{b0}, Y_{b0}, Z_{b0})_e^T$ is the b-frame origin coordinates in e-frame, and can be calculated with F_g^e (the coordinate transforming functions from g-frame to e-frame). $R_b^{l_n}$ is the rotation matrix from b-frame to l_n-frame. $R_{l_n}^e$ is the rotation matrix from l_n-frame to e-frame. Because the PC of the camera is invisible, it cannot be measured directly in the b-frame. We can, however, obtain the plot explanation of the PC and the camera external reference points from the technical notes. By measuring the camera external reference point in the b-frame, $(X_{pc}, Y_{pc}, Z_{pc})_b^T$ can be calculated using the following formula.