ISPRS Journal of Photogrammetry and Remote Sensing 117 (2016) 92–107

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

An asymmetric re-weighting method for the precision combined bundle adjustment of aerial oblique images

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ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 8 January 2016
Accepted 21 March 2016
Available online 18 April 2016

Keywords:
Oblique images
Bundle adjustment
Asymmetric re-weighting
Robust estimation

ABSTRACT

Combined bundle adjustment is a fundamental step in the processing of massive oblique images. Traditional bundle adjustment designed for nadir images gives identical weights to different parts of image point observations made from different directions, due to the assumption that the errors in the observations follow the same Gaussian distribution. However, because of their large tilt angles, aerial oblique images have trapezoidal footprints on the ground, and their areas correspond to conspicuously different ground sample distances. The errors in different observations no longer conform to the above assumption, which leads to suboptimal bundle adjustment accuracy and restricts subsequent 3D applications. To model the distribution of the errors correctly for the combined bundle adjustment of oblique images, this paper proposes an asymmetric re-weighting method. The scale of each pixel is used to determine a re-weighting factor, and each pixel is subsequently projected onto the ground to identify another anisotropic re-weighting factor using the shape of its quadrangle. Next, these two factors are integrated into the combined bundle adjustment using asymmetric weights for the image point observations; greater weights are assigned to observations with fine resolutions, and those with coarse resolutions are penalized. This paper analyzes urban and rural images captured by three different five-angle camera systems, from both proprietary datasets and the ISPRS/EuroSDR benchmark. The results reveal that the proposed method outperforms the traditional method in both back-projected and triangulated precision by approximately 5–10% in most cases. Furthermore, the misalignments of point clouds generated by the different cameras are significantly alleviated after combined bundle adjustment.

1. Introduction

As interest in urban 3D reconstruction increases (Rottensteiner et al., 2014), aerial oblique images have become objects of public attention due to their ability to display a building facade from different directions and their re-invention by Pictometry (Petrie, 2009). Since then, similar penta-view oblique camera systems, including Pictometry, MIDAS, IGI, Leica RCD30, Icaros, and SWDC-5, have prospered (Rupnik et al., 2014). For photogrammetric practitioners, these novel platforms have numerous applications, which range from building verification (Nyaruhuma et al., 2012a, 2012b), damage assessment (Gerke and Kerle, 2011), and public mapping services to creating textures for models of buildings (Kada, 2009).

In most of their previous applications, oblique images were only used as "pretty images". But recent advances in dense image matching (DIM) have triggered interest in exploiting their potential for 3D applications (Fritsch et al., 2012; Fritsch and Rothermel, 2013; Xiong et al., 2014; Rupnik et al., 2015), in which a combined bundle adjustment (BA) of all the images is necessary. However, making a combined BA is non-trivial compared to the sophisticated solutions available for nadir images. The difficulties are due to the irregular configurations of the oblique images, which have consequences for feature matching, as indicated in previous study (Hu et al., 2015), and for determining the *a priori* uncertainties of the observations in a bundle block.

BA is regarded as the gold standard for solving 3D reconstruction problems using image correspondences (Snavely et al., 2008), and the errors in observations are commonly assumed to

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http://dx.doi.org/10.1016/j.isprsjprs.2016.03.017
0924-2716/

have normal distributions, which is known as the Gaussian assumption (Baselga, 2007). Traditional bundle adjustment, which was designed for nadir images with rectangular footprints and similar scales, usually applies identical and symmetrical weights to the different parts of point observations made from different directions, in accordance with the assumption that all of the point observations are of the same quality. However, due to the peculiar characteristics of their tilted viewpoints (Höhle, 2008; Gerke, 2009), oblique images have trapezoidal footprints on the ground, and different parts of them have conspicuously different ground sample distances (GSDs), even when the terrain is flat. Hence, the accuracies of matching points in different regions of oblique images are no longer identical. In other words, the error distribution for all the observations does not conform to the same Gaussian distribution; in fact, the error becomes a function of the image's scale and GSD. Therefore, weighting the points in an image asymmetrically according to the image's scale and the area of each pixel's projection onto the ground is more rigorous.

Aiming at correctly modeling this kind of systematic inhomogeneity, in this paper, we present an asymmetric re-weighting method for the combined BA of aerial oblique images. Two factors are considered in the determination of the *a priori* weight of each image observation: (1) a normalized scale factor represents the scale of each pixel, and (2) a relative anisotropic GSD represents the different GSDs of a single pixel for different directions. The integration of these factors assigns greater weights to observations with fine resolutions and penalizes those with coarse resolutions. Initial exterior orientation (EO) parameters, which are derived from the onboard global navigation satellite system (GNSS) and pre-calibrated platform parameters, are exploited to initialize the re-weighting factors and update them according to the renewed EO parameters during each iteration of the BA.

Section 2 briefly reviews the existing combined BA methods for multi-camera systems. Then, in Section 3, the asymmetric re-weighting method is introduced in detail. The performance of the proposed method is evaluated in Section 4 using four blocks of images acquired by three different multi-camera systems, includes a proprietary dataset in China and two ISPRS/EuroSDR benchmark datasets. Finally, the conclusions are presented in Section 5.

2. Related work

In the photogrammetry and computer vision communities, BA is always formulated as a nonlinear least squares problem that assumes there is underlying Gaussian noise when it is viewed as an inference method in a probabilistic model (Triggs et al., 2000; Zach, 2014). In BA, a variety of observations and scene constraints can be incorporated, including image correspondences (points, lines, curves, and surfaces), ground control points (GCPs), GPS/IMU measurements (Ip et al., 2007), right angles (Gerke, 2011), and parallel lines (Zhang et al., 2011), to refine the camera parameters accurately and efficiently (Triggs et al., 2000). The observations have different scales and dimensions, and the standard practical method for combining them into a single BA is to weight their contributions to the block appropriately using their *a priori* uncertainties. For example, the uncertainties of points matched automatically is between 0.1 and 0.5 pixels (Gruen, 2012), while manually measured image points are assumed to have an uncertainties of 0.5 pixels. For GCPs, the uncertainties of the object space depends on the surveying technique; it ranges from 0.05 m to 0.5 m (Yuan et al., 2009; Gülch, 2012). For onboard GPS/IMU measurements, the positioning uncertainties is between 0.05 m and 0.3 m; the uncertainties of the attitudes, roll and pitch could reach 0.005°, and the uncertainty of the heading is 0.008° (Ip et al., 2007). The weights of constraints between points (horizontal and vertical lines, right angles) should be greater than those of the other observations (Gerke, 2011).

The primary difference between BA for oblique images and nadir images is in the pre-calibrated platform parameters, which represent the rotational and translational relationships between nadir and oblique cameras. For creating a combined BA, two models are widely used: orientation with and without platform parameters (Rupnik et al., 2013). When a BA is implemented without platform parameters, the framework becomes similar that of traditional image orientation. When a BA is processed with fixed platform parameters, one retrieves the EOs of oblique images from a combination of the EOs of the corresponding nadir images and the platform parameters (Tommaselli et al., 2010). This process stabilizes the image block and decreases the number of unknowns (Wiedemann and Moré, 2012). However, due to mechanical reliability and possible problems with synchronization and re-installation, others argue that the pre-calibrated platform parameters should be considered unknowns and be adjusted during the BA (Jacobsen, 2009). In this way, the observations of the initial platform parameters that were used for calibration in the laboratory environment should be weighted according to their calibration accuracies.

The weighting methods described above generally adopt the assumption that the observation errors have a Gaussian distribution; however, for outliers, this assumption does not hold. In applications of aerial triangulation, the majority of outliers come from mismatches of tie points. They can be modeled using the so-called mean-shift model and the variance inflation model (Cen et al., 2003), which lead to two fundamental techniques for handling them: (1) gross error detection and (2) robust estimation (Huber, 1971; Klein and Förstner, 1984). Due to the large number of observations and unknown parameters in aerial photogrammetry engineering, robust estimation is very efficient for practical applications, and the iteratively reweighted least squares method has become the standard strategy for exploiting robust estimation in a nonlinear least squares framework (Zach, 2014). As summarized in (Baselga, 2007), using an equivalent weight function, one can rescale *a priori* weights and obtain an updated minimized objective function for the next iteration. This allows robust estimators (also called loss functions) such as the L_1-norm (Appa and Smith, 1973) and Huber (Huber, 1971) estimators (see Fig. 1) to be embedded as equivalent weight functions, making the parameter estimation less sensitive to outliers. All of these robust estimators down weight outliers to make them less influential.

As described above, previous studies have generally categorized image correspondences into sets of inliers and outliers. It is expected that outliers are eliminated and that inliers have the same *a priori* uncertainty. Therefore, tie point observations receive identical weight in both directions and regardless of their locations during the combined BA. However, this is not the case for oblique images. Due to their large tilt angles, the image scale changes significantly in an oblique view, and the projection area of each pixel is trapezoidal instead of rectangular (Wiedemann and Moré, 2012). Therefore, the uncertainties of the different locations of corresponding points in each image are probably not the same. For digital images, pixel is the smallest unit to record information. When a certain point in object space has been captured in images with different GSDs, the differences in loss of information will result in different levels of random uncertainty. Image tie points that appear in locations with coarse resolutions are not as accurate as those that appear in locations with fine resolutions. Since their expectations remain zero, their error distributions still satisfies the zero-mean Gaussian assumptions, but their variances are larger. To correctly model the error distribution of a bundle block combining nadir images and oblique images, in this paper, we propose an asymmetric re-weighting method that gives each correspondence different