ISPRS Journal of Photogrammetry and Remote Sensing 102 (2015) 62–72

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Zoom lens calibration with zoom- and focus-related intrinsic parameters applied to bundle adjustment

Shunyi Zheng, Zheng Wang, Rongyong Huang *

School of Remote Sensing and Information Engineering, Wuhan University, No. 129 Luoyu Road, Wuhan 430079, People's Republic of China

ARTICLE INFO

Article history:
Received 5 November 2014
Received in revised form 12 January 2015
Accepted 13 January 2015

Keywords:
Single-lens reflex cameras
Zoom lens
Intrinsic parameter
Collinearity equation
Self-calibration
Bundle adjustment

ABSTRACT

A zoom lens is more flexible for photogrammetric measurements under diverse environments than a fixed lens. However, challenges in calibration of zoom-lens cameras preclude the wide use of zoom lenses in the field of close-range photogrammetry. Thus, a novel zoom lens calibration method is proposed in this study. In this method, instead of conducting modeling after monofocal calibrations, we summarize the empirical zoom/focus models of intrinsic parameters first and then incorporate these parameters into traditional collinearity equations to construct the fundamental mathematical model, i.e., collinearity equations with zoom- and focus-related intrinsic parameters. Similar to monofocal calibration, images taken at several combinations of zoom and focus settings are processed in a single self-calibration bundle adjustment. In the self-calibration bundle adjustment, three types of unknowns, namely, exterior orientation parameters, unknown space point coordinates, and model coefficients of the intrinsic parameters, are solved simultaneously. Experiments on three different digital cameras with zoom lenses support the feasibility of the proposed method, and their relative accuracies range from 1:4000 to 1:15,100. Furthermore, the nominal focal length written in the exchangeable image file header is found to lack reliability in experiments. Thereafter, the joint influence of zoom lens instability and zoom recording errors is further analyzed quantitatively. The analysis result is consistent with the experimental result and explains the reason why zoom lens calibration can never have the same accuracy as monofocal self-calibration.

1. Introduction

Compared with a fixed lens, a zoom lens has inherent advantages in terms of flexibility and controllability. A zoom camera system is capable of changing the focal length, focus distance, and aperture value to suit different fields of view (FOVs), depths of field (DOFs), and lighting conditions. Thus, zoom lens devices have been extensively used in various applications, e.g., robotic vision and active vision (Utsumi et al., 2012; Warren et al., 2013), augmented reality (Chendeb et al., 2013; Tatzgern et al., 2014), object detection or tracking (Kim et al., 2013; Tao et al., 2009; Tarhan and Altug, 2011), and traffic monitoring (Schmidt et al., 2009; Song and Tai, 2006). However, in the field of close-range photogrammetry, fixed lenses are more commonly used than zoom lenses mainly because of difficulties in metric modeling and calibration of zoom lens cameras (Ahmed and Farag, 2000; Wu et al., 2013).

With regard to zoom lens calibration, common camera calibration should be conducted first. Camera calibration is the process of determining the intrinsic parameters of the camera, including principal distance, principal point offsets, and lens distortions (Fraser, 1997; Tsai, 1987). The principal distance and principal offsets are also known as interior orientation (IO) parameters in the field of photogrammetry. IO parameters, together with extrinsic parameters also known as exterior orientation (EO) parameters, are able to obtain the space information of an object through images. Thus, camera calibration is an indispensable procedure for photogrammetric 3D measurements.

To date, a large number of mature methods for camera calibration are being used (Remondino and Fraser, 2006; Salvi et al., 2002). Among these methods, self-calibration bundle adjustment is considered to achieve superior accuracy (Remondino and Fraser, 2006) and has been extensively used in the photogrammetry community since its introduction in the early 1970s (Lichti et al., 2012; Parian and Gruen, 2010; Tang et al., 2012; Zhang et al., 2012). However, self-calibration requires the strong geometric configurations of image networks (Lichti et al., 2010; Wu et al., 2013), which is impossible in some cases, such as vulnerable

* Corresponding author.
E-mail addresses: syzheng@263.net (S. Zheng), zheng.wang@whu.edu.cn (Z. Wang), hry@whu.edu.cn (R. Huang).

http://dx.doi.org/10.1016/j.isprsjprs.2015.01.005
0924-2716/

cultural heritage recording, urban traffic monitoring, mud–rock flows, and landslides. Therefore, to use zoom lenses in cases wherein self-calibration cannot be conducted, zoom lens calibration as a stand-alone step is necessary.

With regard to zoom lens calibration, the most challenging problem is that intrinsic parameters vary with changing lens setting. To solve this problem, general strategies are based on a lookup table (Tarabanis et al., 1992) or interpolation with fitted functions between the lens settings and corresponding calibrated intrinsic parameters. From the viewpoint of the number of monofocal calibrations involved, previous methods for zoom lens calibration can be mainly divided into the following three categories.

First, the simplest method to calibrate a zoom lens is to conduct monofocal calibration at each zoom and focus setting and then store the setting values and calibrated results in a lookup table (Tarabanis et al., 1992). This method involves a huge number of monofocal calibrations and becomes extremely inefficient. To reduce the calibration workload, (Chen et al., 2001) selected a sampled set of lens settings for calibration and then further constructed a sparse table to interpolate the desired intrinsic parameters. Nevertheless, this approach still needs to conduct more than 100 monofocal calibrations.

Second, (Sarkis et al., 2009) calibrated zoom lenses by fitting the continuous local functions of intrinsic parameters with respect to zoom and focus settings on the basis of the moving least square scheme. This method first completes separate monofocal calibrations at some scattered zoom and focus points. Thereafter, the scattered data are clustered into similar small regions, followed by the modeling of each cluster with a single bivariate polynomial. As stated previously, this strategy is relatively complex with several steps. Furthermore, the calibration workload will increase rapidly with a higher than expected interpolated accuracy.

Finally, in addition to the aforementioned two categories of methods, photogrammetric practitioners prefer to model the variations of intrinsic parameters regarding lens settings on the basis of global regression schemes, which involve less monofocal calibrations compared with the aforementioned methods. On the basis of this strategy, different types of models are adopted. The first model is the zoom-dependent model (Alvarez et al., 2012; Fraser and Al-Ajlouni, 2006; Fraser et al., 2012), which disregards the influence of focus on intrinsic parameters. The second model is the zoom/focus model (Atienza and Zelinsky, 2001; Wu et al., 2013), which considers the influence of zooming and focusing. Compared with the zoom-dependent model, the zoom/focus model involves more monofocal calibrations. On the basis of the zoom/focus model, (Wu et al., 2013) used a planar checkerboard to accomplish zoom lens calibration. This work has two main differences: (a) fixing and determining the principal point of an image position by using the focus of expansion, which is similar to the center of expansion (Li and Lavest, 1996; Willson, 1994); (b) use of a scale parameter modeled with a bivariate nth-order polynomial to compensate for the influence of focus changes on the principal distance. Moreover, the third type of model is the focus-dependent model (Sanz-Ablanedo et al., 2012), which is only for fixed lenses with alterable focus settings. Thus, this type of model is less significant than the two aforementioned models. Furthermore, some early models even contained the aperture (Hosoda et al., 1995; Willson, 1994). However, later research showed that intrinsic parameters do not change with changing aperture (Chentt et al., 2000; Läbe and Förstner, 2004; Li and Lavest, 1996).

Among the aforementioned methods, except for the lookup table-based zoom lens calibration method, other methods share the following strategy. First, individual monofocal calibrations at selected configurations are conducted. Second, the lens settings and corresponding calibrated results are used to model local or global functions. Finally, the desired intrinsic parameters are interpolated on the basis of the input lens settings and model coefficients. From the perspective of optimization theory, such methods do not find the global optimal solution for model coefficients of intrinsic parameters, because monofocal calibrations and the subsequent modeling undoubtedly mean separate local optimizations. Therefore, it is significant to develop an alternative zoom lens calibration method with a global optimal model coefficients of intrinsic parameters.

In such a background, a novel method for zoom lens calibration is proposed in this study. In contrast to previous methods, this study highlights the following aspects: (a) the development of the fundamental mathematical model by integrating zoom- and focus-related intrinsic parameters into conventional collinearity equations; (b) the contribution to conduct zoom lens calibration in only one self-calibration bundle adjustment; (c) the quantitative analysis of zoom lens instability and zoom recording precision. The details of this approach are specifically discussed in the following sections.

2. Methodology

2.1. Overview of the approach

In this study, the empirical models of the intrinsic parameters are first summarized on the basis of existing studies and then the proposed method is implemented by combining the empirical models with traditional collinearity equations to construct the fundamental mathematical model and further conduct a single self-calibration bundle adjustment. An advantage of the proposed method is that it solves all unknowns in only one bundle adjustment, thus, a global optimal solution for zoom lens calibration can be achieved. Fig. 1 shows the framework of the approach in detail.

2.2. Empirical zoom/focus models

Brown self-calibration model (Brown, 1971; Fraser, 1997; Tang et al., 2012) holds up as the optimal formulation for digital camera calibration (Remondino and Fraser, 2006) and it has been

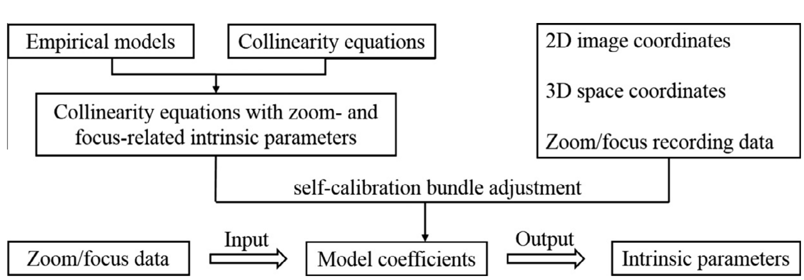

Fig. 1. Flowchart of the implementation of the proposed method.