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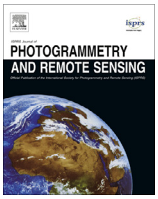

Calibration of a catadioptric omnidirectional vision system with conic mirror

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ABSTRACT

Omnidirectional vision systems that enable 360° imaging have been widely used in several research areas, including close-range photogrammetry, which allows the accurate 3D measurement of objects. To achieve accurate results in Photogrammetric applications, it is necessary to model and calibrate these systems. The major contribution of this paper relates to the rigorous geometric modeling and calibration of a catadioptric, omnidirectional vision system that is composed of a wide-angle lens camera and a conic mirror. The indirect orientation of the omnidirectional images can also be estimated using this rigorous mathematical model. When calibrating the system, which is composed of a wide-angle camera and a conic mirror, misalignment of the conical mirror axis with respect to the camera's optical axis is a critical problem that must be considered in mathematical models. The interior calibration technique developed in this paper encompasses the following steps: wide-angle camera calibration; conic mirror modeling; and estimation of the transformation parameters between the camera and conic mirror reference systems. The main advantage of the developed technique is that it does not require accurate physical alignment between the camera and conic mirror axis. The exterior orientation is based on the properties of the conic mirror reflection. Experiments were conducted with images collected from a calibration field, and the results verified that the catadioptric omnidirectional system allows for the generation of ground coordinates with high geometric quality, provided that rigorous photogrammetric processes are applied.

1. Introduction

Omnidirectional vision systems have been widely used in several research fields, including robot navigation, telepresence, close-range photogrammetry and virtual reality (Kang and Szeliski, 1997; Yagi, 1999; Spacek, 2005; Sturm et al., 2011). Omnidirectional images can be acquired using a fisheye lens; moving cameras or optical elements; catadioptric systems (Baker and Nayar, 1999); and multiple cameras with divergent view (Sturm et al., 2011). The all-reflective system, which camera objective is based on mirrors, also enable the imagery acquisition with wide field of view (Richter et al., 2013).

Catadioptric systems present the advantage of generating omnidirectional images by using a single camera in combination with a mirror; this arrangement eliminates the problems of camera synchronization and image stitching. Several types of mirrors are used for this purpose, including curved cross-sections (elliptic, hyperbolic and parabolic) mirrors; planar mirrors arranged in a pyramid; and conic mirrors. However, catadioptric systems have also been developed by combining several cameras and a pyramid of mirrors (Nalwa, 1996; Tan et al., 2004).

The main advantage of combining a perspective camera with a hyperbolic mirror and combining an orthogonal camera with a parabolic mirror is that the single viewpoint property is fulfilled. Catadioptric systems achieving this property are called central catadioptric systems (Baker and Nayar, 1999).

Several techniques for calibrating central catadioptric systems have been developed (Barreto and Araújo, 2002; Scaramuzza et al., 2006; Mei and Rives, 2007; Luber and Reulke, 2010; Puig et al., 2011; Puig et al., 2012). Some of these techniques can also be applied to the calibration of cameras with fisheye lenses. Schöenbein et al. (2014) developed an efficient and accurate technique to use quasi-central catadioptric systems, in which the calibration is conducted with a non-central camera model (Agrawal et al., 2011). Agrawal et al. (2011) proposed a generalized

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calibration model based on polynomials for non-central catadioptric systems, which uses quadratic mirrors.

In general, catadioptric systems with conic mirrors do not satisfy the single viewpoint property and thus cannot be classified as central systems. However, Spacek (2005) presented some advantages of using an omnidirectional catadioptric system that is composed of a camera and a conic mirror over other catadioptric systems. The conic mirror combines the benefits of the planar mirrors without radial distortion and radial loss of resolution and the advantages of the rotationally symmetric catadioptric sensor, requiring short exposure and providing isotropic imaging. The manufacturing cost is also an advantage of this mirror.

Catadioptric systems with conic mirrors present multiple viewpoints when the nodal point of the camera lens is farther from the cone apex. The locus of the effective viewpoint is a circle with radius $d \cdot \cos(2\tau)$, where d is the distance from the camera perspective center (PC) to the conic mirror apex and 2τ is the angle in the apex of the conic mirror (Baker and Nayar, 1999). The geometry of this catadioptric system is presented in Section 2.3.

To have a single viewpoint, Lin and Bajcsy (2001) developed a catadioptric system in which the conic mirror apex coincides with the camera PC by cutting off the cone upper part, at the cost, however, of reducing the amount of incoming light and the imaging area. Another alternative is to build a conic mirror with an opening angle of 90° (Spacek, 2003).

In general, the mathematical models for this type of system consider the camera optical axis to be rigorously aligned with the conic mirror axis (Yagi et al., 1994; Joung and Cho, 1998; Lin and Bajcsy, 2001; Spacek, 2003; Burbridge and Spacek, 2006; López-Nicolás and Sagues, 2010). However, this perfect alignment is unfeasible to achieve in practice, which introduces an additional source of error.

Burbridge et al. (2008) developed mathematical models in which the alignment between the conic mirror and camera axis is not necessary. The authors validated mathematical models that project from the object space to the image space and vice versa by using simulated data that were generated using the POVRay software. To the best of the authors' knowledge, calibration methods for a catadioptric system composed of a camera and a conic mirror were not applied in the aforementioned paper.

Cauchois et al. (1999) developed a calibration method for the SYCLOP (Conic SYstem for LOcalization and Perception). The developed mathematical model considers the conic mirror apex, the camera perspective center, the point in the object space and the normal to the cone in the reflection point to all be in the same plane, which is a simplification of the reflection in the conic mirror surface, as Burbridge et al. (2008) pointed out.

The aim of this work is to present a novel technique for the calibration of a catadioptric omnidirectional vision system that is composed of a wide-angle lens camera and a conic mirror for mobile applications. The main advantage is that the misalignment between the camera optical axis and conical mirror axis is modeled. In Section 2, the methods applied to achieve the main goal of this work and the results are presented and discussed. In Section 3, the exterior orientation procedure and results are presented. Finally, Section 4 presents the conclusions derived from the Sections 2 and 3.

2. Omnidirectional vision system calibration

The following sections present a description of the omnidirectional system calibration (Fig. 1) and its technical steps: camera calibration (Section 2.1); conic mirror modeling (Section 2.2); and estimating the transformation parameters between the camera and the conic mirror reference systems (Section 2.3).

Fig. 1. Omnidirectional vision system composed of a wide-angle camera and a conic mirror. The system also has a double frequency SPAN-CPT/Novatel GNSS (Global Navigation Satellite System) receiver and an IMU (Inertial Measurement Unit) for direct image georeferencing.

2.1. Wide-angle lens camera calibration

A wide-angle lens was introduced in the proposed catadioptric system to increase both the coverage angle and the depth of field in a compact system with the camera positioned near (4 cm) to the mirror apex, enabling the acquisition of wider field of view when compared to a normal lens camera located at the same distance from the mirror.

In the experiments used to validate the proposed techniques, a Fuji Finepix S3 pro camera with a Bower–Samyang 8 mm lens was used. The Bower–Samyang lens that was used in this work is neither a fisheye lens nor a perspective lens. Charles (2009) classified this lens as quasi-stereographic because it is based on stereographic fisheye lens projection. In general, the perspective camera is calibrated using the collinearity mathematical model, which is based on perspective projection using points as features. Hughes et al. (2010) described the geometric properties of the models for a fisheye lens.

Abraham and Förstner (2005) and Schneider et al. (2009) presented mathematical models for calibrating a fisheye lens camera based on stereo-graphic, equi-distant, orthogonal and equi-solid-angle projections. Schneider et al. (2009) combined these models with symmetric radial, decentering and affinity distortion models.

The calibration of the Fuji Finepix S3 pro camera with the quasi-fisheye Bower–Samyang 8 mm lens was performed using stereographic projection models (Eq. (1)). Tommaselli et al. (2014) and Marcato Junior et al. (2015) showed that the results obtained using the stereo-graphic, equi-distant, equi-solid-angle and orthogonal