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Exploiting line metric reconstruction from non-central circular panoramas

Jesus Bermudez-Cameo[a,*], Olivier Saurer[b], Gonzalo Lopez-Nicolas[a], Jose. J. Guerrero[a], Marc Pollefeys[b]

[a] Instituto de Investigación en Ingeniería de Aragón (I3A) - Universidad de Zaragoza, C/ María de Luna, 1, Zaragoza, 50018, Spain
[b] ETH Zurich, Universitatstrasse 6, Zurich, 8092, Switzerland

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ABSTRACT

In certain non-central imaging systems, straight lines are projected via a non-planar surface encapsulating the 4 degrees of freedom of the 3D line. Consequently the geometry of the 3D line can be recovered from a minimum of four image points. However, with classical non-central catadioptric systems there is not enough effective baseline for a practical implementation of the method. In this paper we propose a multi-camera system configuration resembling the circular panoramic model which results in a particular non-central projection allowing the stitching of a non-central panorama. From a single panorama we obtain well-conditioned 3D reconstruction of lines, which are specially interesting in texture-less scenarios. No previous information about the direction or arrangement of the lines in the scene is assumed. The proposed method is evaluated on both synthetic and real images.

1. Introduction

In central imaging systems any projection ray intersects a single point usually known as optical center. In the last decade, the need of a wider field of view increased the development of new imaging systems known as omnidirectional systems allowing complete panoramic images. For a better understanding of the images most of these systems were sought to be central (e.g. the para-catadioptric system, the hypercatadioptric system [2], multicamera systems with common optical center [11]). The advantage of central systems is that they also allow using previous standard algorithms. However, some of the proposed omnidirectional systems were non-central by construction (e.g. conical catadioptric systems, spherical catadioptric systems). In these systems, rays do not intersect in a single optical center, hence they can not be defined by a direction vector and require richer descriptions like the generalized camera model [9] based on Plücker lines [17,20] and [13]. Although the higher complexity is a disadvantage, the properties of line projections in non-central systems can turn this disadvantage into an advantage.

The projection surface of a 3D line in central systems is a plane. All lines lying in this plane share the same line-image because only two of the four degrees of freedom (DOF) of the 3D line are preserved in the projection. Hence, the only way to recover the direction of the lines and depth up to scale from a single view is imposing additional constraints like dominant directions or perpendicularity [23]. By contrast, in non-central cameras the projection surface of a line encapsulates the four degrees of freedom of the 3D line. Hence, the geometry of a 3D line can be recovered from a single projection (see Fig. 1). In particular, four points on a line-projection (except some degenerate cases) define four projecting rays providing four independent constraints for computing the complete geometry of the line [26]. Unfortunately, this approach is difficult to implement in practice. The quality of the extracted 3D line depends on a magnitude we call the effective baseline of a set of rays which is related with the distances between the four defining skew rays. This effective baseline is too small when using non-central catadioptric systems, so for exploiting this property in practice the system has to be large, [13].

The motivations of using line-features in non-central systems are numerous. As in central systems, line-features are useful for reconstructing texture-less scenarios. Besides, in non-central systems metric reconstruction of 3D lines can be recovered from a single

* Corresponding author.
E-mail address: bermudez@unizar.es (J. Bermudez-Cameo).

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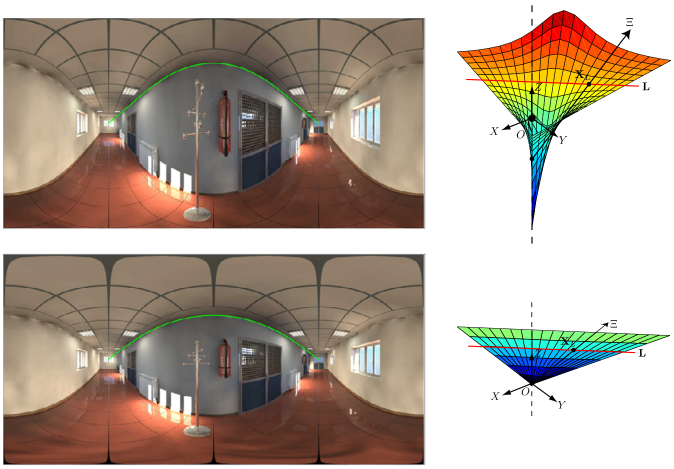

Fig. 1. Top: Line projection in a circular panoramic image with $R_c = 0.5$ m (Non-central). The line-projection (in green in Top-left) corresponds to the ruled projection surface (Top-right) intersecting only two lines not being projecting rays: the red line and the revolution axis of the system. Bottom: Line projection in a circular panoramic image with $R_c = 0$ m (A central spherical panoramic image). The line-projection (in green in Bottom-left) corresponds to a planar projection surface (Bottom-right) which is going to be the same projection surface for any 3D line contained in the plane. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

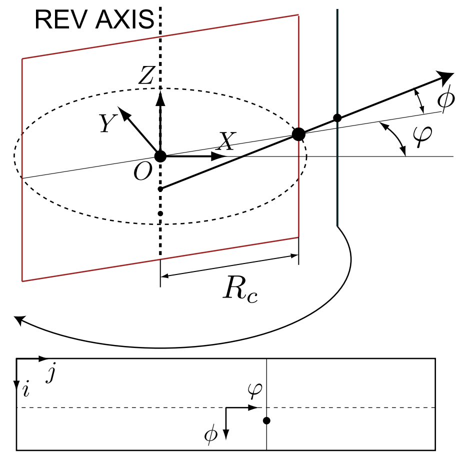

Fig. 2. Non-central circular imaging projection system. Projecting rays intersect a circle of radius R_c and the vertical axis. The image coordinates of a pixel (j, i) are linearly related with the azimuth angle φ and the elevation angle ϕ of the corresponding ray Ξ.

panoramic view and no assumption about the direction or the arrange of the 3D lines is needed. In addition, considering sequences of images, long lines can be seen along large fragments of the sequence reducing the drift in pose estimation.

1.1. Previous work

The geometry of non-central systems has previously been studied for computer vision applications. The back projection of different non-central catadioptric systems is introduced in [24]. Contrary to the back projection case, the forward projection of non-central systems does not necessarily have a closed form solution. Polynomial solutions for the forward projection models in axial non-central catadioptric systems based on quadric mirrors are compiled in [1]. In [14] the epipolar geometry of conical catadioptric systems and its corresponding calibration are presented.

Another way to obtain non-central images are images generated from moving cameras without common viewpoint. The epipolar geometry is studied for the case of linear pushbroom camera in [10] and for the case of non-central circular panorama in [15]. A multi-camera system can be also tackled as particular case of a non-central system. Lee et al. [13] propose a new method to solve the pose estimation in a multi-camera system represented by a set of ray bundles in a non-central description using Plücker coordinates.

As previously said, in a non-central image the geometry of 3D lines can be recovered from a single line projection. The fundamentals of this approach are exposed in [26] where it is shown that two lines are the intersection of four generic lines. In [8] this approach is exploited to compute 3D lines from 4 rays in non-central catadioptric systems. Different computation methods are considered and the degeneracies and singular configurations are studied. In [12] the approach is used with spherical catadioptric mirrors, and in addition two non-central systems are used for reconstruction. Work in [25] extends the approach to planar curves. In [5] the approach is derived to the case of conical catadioptric systems obtaining both the 3D line and the mirror geometry. To improve the accuracy in reconstruction using catadioptric systems some approaches have been proposed: considering only horizontal lines [7,19] , exploit cross-ratio properties by [18], imposing constraints like parallelism or perpendicularity by Bermudez-Cameo et al. [3] or imposing prior information about the gravity direction by Bermudez-Cameo et al. [4]. Using off-axis systems [6] allows avoiding the degeneracies caused by the revolution symmetry. As application, the pose of non-central catadioptric systems is estimated in an image sequence [16] using known 3D lines.

1.2. Open issues

The underlying difficulties of line-image fitting and the low accuracy with current non-central systems have left a considerable list of open issues involving non-central 3D line reconstruction. That includes automatic line-image extraction, line-image tracking, visual odometry and calibration.

1.3. Contributions

In this paper, we rediscover the circular panoramic imaging system as a non-central system [15], and we propose it through a multi-camera configuration as a way to have enough effective baseline for a practical application of 3D line reconstruction from a single non-central line projection [8]. We present a new method for automatic line extraction valid for the proposed non-central system. The result is a metric reconstruction of lines-based scenarios from a single panorama without making assumptions about the direction or the arrangement of the lines. The non-central circular panoramic system is compared with other catadioptric non-central systems to evaluate the proposed system advantages. We also propose a multi-camera architecture for obtaining an approximation of a circular panorama without the disadvantages of a moving camera. The extraction method is then particularized to the multi-camera case. The methods are tested on realistic simulated scenarios and on real images.

2. Non-central circular panorama model

In this section, we describe the projection model of non-central circular panoramas. A circular imaging panoramic projection [8,15], is a projection model with symmetry of revolution in which any projecting ray intersects both an axis of revolution and a circle of a given radius R_c (see Fig. 2). A camera configuration fulfilling this constraint is a linear sensor turning around an axis of revolution. The resulting image of this system is a panoramic image in which