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Fitting line projections in non-central catadioptric cameras with revolution symmetry

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A B S T R A C T

Line-images in non-central cameras contain much richer information of the original 3D line than line projections in central cameras. The projection surface of a 3D line in most catadioptric non-central cameras is a ruled surface, encapsulating the complete information of the 3D line. The resulting line-image is a curve which contains the 4 degrees of freedom of the 3D line. That means a qualitative advantage with respect to the central case, although extracting this curve is quite difficult. In this paper, we focus on the analytical description of the line-images in non-central catadioptric systems with symmetry of revolution. As a direct application we present a method for automatic line-image extraction for conical and spherical calibrated catadioptric cameras. For designing this method we have analytically solved the metric distance from point to line-image for non-central catadioptric systems. We also propose a distance we call *effective baseline* measuring the quality of the reconstruction of a 3D line from the minimum number of rays. This measure is used to evaluate the different random attempts of a robust scheme allowing to reduce the number of trials in the process. The proposal is tested and evaluated in simulations and with both synthetic and real images.

1. Introduction

In central systems the projection surface of a 3D line is a plane passing through the viewpoint of the camera. In this class of projection some of the information of the 3D line is lost because any 3D line lying on this plane is projected on the same line-image. In other words, a 3D line occludes any other line located behind because the projection surface is a plane.

By contrast, in non-central systems the projection rays do not intersect a common viewpoint. The locus of the viewpoint is, in general, tangent to a caustic (Agrawal et al., 2010) which is an envelope surface of the projection rays. In particular, when the non-central system is axial and has symmetry of revolution the projection rays intersects the axis of symmetry (see Fig. 1) and the projection surface of a 3D line is composed by skew lines forming a ruled surface. If we consider a set of 4 skew projection rays, being generic lines[1], there exist only two lines intersecting the given set (Teller and Hohmeyer, 1999): the original 3D line and, if the system is axially symmetric, the axis of revolution. This means that no additional line can intersect the set of projection rays. Hence in axial non-central projections, it is not possible to occlude a 3D line with other line. Main consequence of this property is that the complete geometry of a 3D line is mapped on a single non-central image. Therefore, if the system is calibrated, the 3D line can be completely recovered from at least 4 line-image points or projection rays. On the contrary, image-points do not provide 3D information since points always occlude other 3D points along the projection ray.

This property implies a great geometric advantage of lines with respect to points in non-central cameras and generates new possibilities in line-features based 3D vision and entails promising applications in robotics and scene modelling. The richer information about the localization of the line in the space facilitates the tracking of the features even if the photometric information is not very discriminative. Notice also that line features usually represent boundaries of the scene that remain even in texture-less scenes. These advantages have a direct influence in robot pose estimation and Simultaneous Localization and Mapping(SLAM) where texture-less scenes can induce drift in pose estimation due to the lack of significant features.

Some previous approaches have tried to fit 3D lines from a single image in non-central catadioptric systems. The approach presented by Teller and Hohmeyer (1999) exploits the intersection operator between lines for defining a linear system from 4 rays computing the two incident lines. Since in non-central systems with symmetry of revolution

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[1] Four lines are generic if no two of them are coplanar, no three of them are coconical or cocylindrical, and the four are not cohyperbolic, i.e. do not lie on the same ruled quadric surface.

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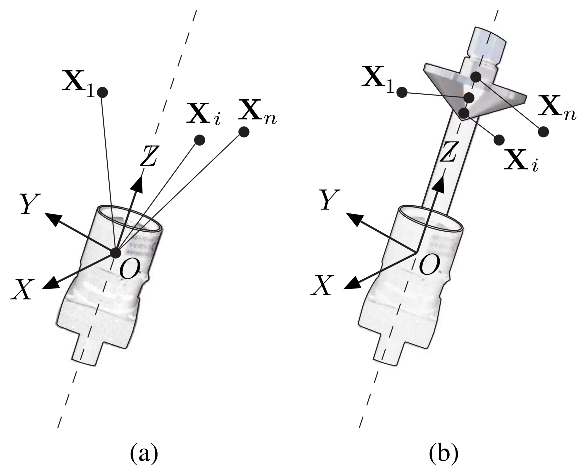

Fig. 1. (a) Central camera: all the projection rays intersect the optical center O. (b) Non-central axial catadioptric camera: depending on the 3D point $\mathbf{X}$ the projection rays intersect a different point of the axis of revolution.

one of these lines is the axis of revolution, this approach is used in Caglioti and Gasparini (2005); Caglioti et al. (2007a); Gasparini and Caglioti (2011) for estimating 3D lines from line projections of non-central catadioptric images and studying the degeneracies and singular configurations. In Lanman et al. (2006) the same approach is used with spherical catadioptric mirrors for 3D reconstruction. Work in Swaminathan et al. (2008) extends the approach from lines to planar curves. In Agrawal et al. (2010) the line-image for spherical catadioptric systems is indirectly shown as the epipolar curve. This epipolar curve represents in fact the projection of a 3D line (the epipolar ray of other system) an is represented through a second order line complex. Some simplifications have been used to improve the reconstructions by reducing the DOFs of the problem: considering horizontal lines (Chen et al., 2011; Pinciroli et al., 2005), exploiting cross-ratio properties (Perdigoto and Araujo, 2012) or imposing additional constraints such as parallelism or perpendicularity (Bermudez-Cameo et al., 2014).

Line projections have been also used to estimate the calibration of non-central systems in a generalization of the plumb-line approach. For example in Caglioti et al. (2007b) they exploit that there exists less ambiguity when the system is off-axis with impressive results. However, that approach does not allow to obtain an analytical expression of the line projection. In Agrawal and Ramalingam (2013) they exploit particular geometric properties of spherical mirrors for computing extrinsic calibration parameters. As application, the pose of non-central catadioptric systems is estimated in an image sequence (Miraldo and Araujo, 2014; Miraldo et al., 2015) using known 3D lines.

In Perdigoto and Araujo (2016) a method for estimating the mirror shape and extrinsic parameters for axial non-central catadioptric systems is presented. For the particular case of spherical mirrors quartic curves representing line projections are fitted. For this fitting they propose using the geometric distance by using a generic constrained optimization.

Automatically extracting the projection of a line in non-central images is a challenging task. In omnidirectional central systems the problem differs if the system is calibrated (Puig et al., 2012) or not. It has been recently solved for calibrated images (Bazin et al., 2010; Ying and Zha, 2005) and for uncalibrated axially symmetric images (Bermudez-Cameo et al., 2015; Tardif et al., 2006). In non-central images the difficulty of the extraction increases due to the high distortions induced on line-images, the elevated number of degrees of freedom involved in the extraction and the lack of effective baseline of current non-central systems. This problem has been successfully addressed for non-central circular panoramas in Bermudez-Cameo et al. (2017).

In this paper, we study the robust fitting of line projections in non-central catadioptric cameras with symmetry of revolution and present a method for automatic extraction of these line projections. Up to our knowledge, this is the first work addressing this problem in non-central catadioptric cameras. The proposal has been developed for conical catadioptric and spherical catadioptric systems. This procedure automatically segments the collection of edges corresponding to line-images. The complete 3D localization of a line is also recovered from the extraction in a single image even if the accuracy of the result is sensitive to noise. The contributions of this work are the following:

- A unified framework for describing line-images in non-central systems with revolution symmetry.
- Polynomial expressions of the line-images for conical and spherical catadioptric systems.
- A closed-form solution for computing the geometry of the mirror from 5 points lying on a line-image in conical catadioptric systems.
- Solutions based on polynomial roots for computing the Euclidean distance from point to line-image for conical and spherical catadioptric systems.
- A feature for measuring effective baseline in a set of rays in non-central systems.
- An algorithm for automatic line-image extraction in non-central images.
- Accuracy comparison of line reconstruction between catadioptric systems of similar sizes.

Preliminary results of this work have been presented in Bermudez-Cameo et al. (2014b) where we show the equation of the line-image and the metric distance for conical catadioptric systems. In this paper we extend the approach to spherical catadioptric systems developing the equation of the line-image and the metric distance. We also contribute with the measure of the effective baseline of a set of rays and the automatic line-image extraction procedure. The proposed approaches have been independently validated with a set of simulations. Then the complete pipeline has been tested with synthetic and real images (Fig. 2).

In Section 2 we introduce the required background of our proposal. In Section 3 we present our unified framework for describing rays and line projections in non-central systems with symmetry of revolution. In Section 4 we present the proposed description of the line-image for conical catadioptric system and we introduce the computing of the mirror geometry parameter from 5 points of the line-image. In Section 5 we show the polynomial description of the line-image for spherical catadioptric systems and we particularize the corresponding metric distance for this case. In Section 6 we analytically solve the metric distance from a point to the line-image. We particularize the corresponding metric distance for conical and spherical catadioptric systems. In Section 7 we present the algorithm for line-image extraction in non-central images including the proposed feature for measuring the effective baseline of a set of rays. In Section 8 we evaluate the method with synthetic and real images. Finally in Section 9 we present the conclusions.

2. Background

In this section, we introduce the relevant geometric concepts and notation used in this paper. In particular, we summarize the description used for lines, which is based on Grassmann–Cayley algebra (Kanatani, 2015), the transformations between systems of references, and the side operator between two lines.

2.1. Plücker coordinates

The Plücker coordinates of a 3D line (Pottmann and Wallner, 2001; Selig, 2004) is an homogeneous representation of a line $\mathbf{L} \in \mathbb{P}^5$ defined by the null space of two $\mathbb{P}^3$ points $\mathbf{X} = (X_1, X_2, X_3, X_4)^\top$ and