Automatica 46 (2010) 1129–1140

Contents lists available at ScienceDirect

Automatica

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

Range identification for nonlinear parameterizable paracatadioptric systems ☆

Nitendra Nath [a,*], Enver Tatlicioglu [b], Darren M. Dawson [a]

[a] Department of Electrical & Computer Engineering, Clemson University, Clemson, SC 29634-0915, United States

[b] Department of Electrical & Electronics Engineering, Izmir Institute of Technology, Urla, Izmir, 35430, Turkey

ARTICLE INFO

Article history:
Received 20 July 2009
Received in revised form
5 January 2010
Accepted 15 March 2010
Available online 20 April 2010

Keywords:
Nonlinear parameterization
Range identification
Paracatadioptric systems
Lyapunov methods
Vision-based estimation
min–max algorithm

ABSTRACT

In this paper, a new range identification technique for a calibrated paracatadioptric system mounted on a moving platform is developed to recover the range information and the three-dimensional (3D) Euclidean coordinates of a static object feature. The position of the moving platform is assumed to be measurable. To identify the unknown range, first, a function of the projected pixel coordinates is related to the unknown 3D Euclidean coordinates of an object feature. This function is nonlinearly parameterized (*i.e.*, the unknown parameters appear nonlinearly in the parameterized model). An adaptive estimator based on a min–max algorithm is then designed to estimate the unknown 3D Euclidean coordinates of an object feature relative to a fixed reference frame which facilitates the identification of range. A Lyapunov-type stability analysis is used to show that the developed estimator provides an estimation of the unknown parameters within a desired precision. Numerical simulation results are presented to illustrate the effectiveness of the proposed range estimation technique.

1. Introduction

The problem of range identification, the estimation of the unknown time-varying distance of the object from the camera along its optical axis, has received noteworthy attention over the last several years due to its significance in several applications such as autonomous vehicle navigation, aerial tracking, path planning, surveillance, etc. These applications require either the range or the 3D Euclidean coordinates of features of a moving or a static object to be recovered from their two-dimensional (2D) image sequence. The range estimation is usually done by mounting a camera on a moving vehicle such as a mobile robot or an unmanned aerial vehicle (UAV) which captures images of the static objects or features. However, the use of conventional (perspective) cameras poses restrictions for some applications because of their limited field-of-view (FOV).

One efficient way to enhance the FOV is to use mirrors (spherical, elliptical, hyperboloid, or paraboloid) in conjunction with conventional cameras, commonly known as catadioptric systems (Baker & Nayar, 1999). However, the use of curved mirrors reduces the resolution and distorts the images to a large extent. As stated in Hu, Aiken, Gupta, and Dixon (2008), the distorted image mapping can be dealt with by using computer vision techniques, but the nonlinearity which is introduced in the transformation makes it difficult to recover the 3D coordinates of the object features. Catadioptric systems that have a single effective viewpoint are known as central catadioptric systems, and are desirable because they allow a distortion-free reconstruction of panoramic images (Orghidan, Mouaddib, & Salvi, 2005). A paracatadioptric system is a special case of central catadioptric systems which employs a paraboloid mirror along with an orthographic lens. These systems are advantageous due to the fact that the paraboloid constant of the mirror and its physical size do not need to be determined during the calibration. Furthermore, mirror alignment requirements are relaxed, so the mirror can be arbitrarily translated enabling the camera to zoom in on a part of the paraboloid mirror for higher resolution; however, with a reduced FOV (Baker & Nayar, 1999).

In the past, many researchers have proposed various range identification techniques for perspective vision systems. Some of these have utilized the extended Kalman filter (EKF) (Chiuso, Favaro, Jin, & Soatto, 2002; Kano, Ghosh, & Kanai, 2001; Matthies, Kanade, & Szeliski, 1989). However, EKF involves linearization of the nonlinear vision model and requires *a priori* knowledge of the noise distribution. To overcome the shortcomings of the linear model, many researchers focused on utilizing nonlinear system analysis and estimation tools to develop nonlinear observers to

☆ This work is supported in part by a DOE Contract, and a Honda Corporation Grant. The material in this paper was partially presented at the IEEE International Conference on Systems, Man, and Cybernetics, October 11–14, 2009, San Antonio, TX USA. This paper was recommended for publication in revised form by Associate Editor Shuzhi Sam Ge under the direction of Editor Miroslav Krstic.

* Corresponding author. Tel.: +1 864 656 7218; fax: +1 864 656 7220.
E-mail addresses: nnath@clemson.edu (N. Nath), enver@envertatlicioglu.com (E. Tatlicioglu), darren.dawson@ces.clemson.edu (D.M. Dawson).

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doi:10.1016/j.automatica.2010.03.017

identify the range when the motion parameters were known (Chen & Kano, 2002, 2004; Dixon, Fang, Dawson, & Flynn, 2003; Jankovic & Ghosh, 1995; Karagiannis & Astolfi, 2005; Ma, Chen, & Moore, 2004). More recently, in Nath, Braganza, and Dawson (2008a), the measurement of camera position was utilized to develop an adaptive estimator to recover the structure; this was extended in Nath, Braganza, Dawson, and Burg (2008b) to recover the range.

Although there have been several reports on range identification for perspective vision systems, very few results have been shown for range identification for catadioptric systems. Ma, Chen, and Moore (2005) proposed a range identification technique for paracatadioptric system based on a sequence of linear approximation-based observers. Gupta, Aiken, Hu, and Dixon (2006) designed a nonlinear observer to asymptotically identify the range for a paracatadioptric system. However, both of these reports assumed the focal point of the paraboloid mirror to be at its vertex. This assumption was recently relaxed in Hu et al. (2008). In the current work, we also base our development on a more practical approach that the focus of the paraboloid mirror is not at its vertex. In Orghidan et al. (2005), an omnidirectional light projector was embedded in a paracatadioptric system, and the range was calculated by triangulation. Hu et al. (2008) developed a nonlinear estimator similar to Dixon et al. (2003) to identify the range for paracatadioptric systems where the motion parameters were assumed to be known, and it assumed that the object must translate in at least one direction.

In this paper, we present a method to identify the range of a static object using a moving paracatadioptric system whose position is measurable. For many applications, position measurements are considerably less noisy than velocity measurements; hence, we are motivated to develop an estimator based on position measurements. The estimator is designed by first developing a geometric model along with a paracatadioptric projection model that relates an object feature with the paracatadioptric system mounted on a moving mechanical system. The novelty of this work lies in the compensation for nonlinear parameterization of the model which relates the projected pixel coordinates to the Euclidean coordinates of the object feature. It should be noted that contrary to Nath et al. (2008a), where the unknown terms appear linearly in the parameterized model for a perspective vision system, in the current work, the unknown parameters appear nonlinearly in the model for a paracatadioptric system. This fact makes it difficult to use a standard adaptive estimator or a gradient based estimator (Annaswamy, Skantze, & Loh, 1998). The estimator presented in this paper which facilitates range identification to the desired precision is based on a min–max optimization algorithm. We show that the developed estimator identifies the range and the 3D coordinates of the object feature upon the satisfaction of a Nonlinear Persistent Excitation (NLPE) condition and is robust to noise, as demonstrated by the simulation results. The contributions of this paper are that: (i) the developed estimator utilizes position measurements instead of velocity measurements, (ii) is continuous, and (iii) provides estimation of unknown parameters within a desired precision. A preliminary version of this paper has appeared in Nath, Tatlicioglu, and Dawson (2009a).

2. Model development

2.1. Geometric model

For the development of a geometric relationship between a moving paracatadioptric system and a stationary object, an orthogonal coordinate frame, denoted by $\mathcal{M}$, which is centered at the focal point of the moving paraboloid mirror whose Z-axis is aligned with the optical axis of the camera, is defined (see Fig. 1). As shown in Fig. 1, an inertial coordinate frame, denoted by $\mathcal{W}$, and an orthogonal coordinate frame, denoted by $\mathcal{B}$, are defined. $\mathcal{F}$ denotes a static feature on a stationary object. Let the unknown 3D Euclidean coordinates of the object feature be denoted as the constant $\theta \in \mathbb{R}^3$ relative to the world frame $\mathcal{W}$ and $m(t) \in \mathbb{R}^3$ relative to $\mathcal{M}$ be defined as follows

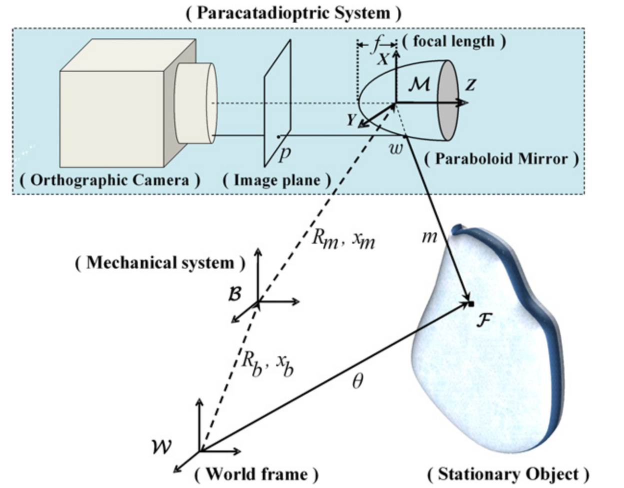

Fig. 1. Geometric relationships between the stationary object, mechanical system, and the paracatadioptric system.

$$m \triangleq [x \;\; y \;\; z]^T . \tag{1}$$

To relate the coordinate systems, let $R_b(t) \in SO(3)$ and $x_b(t) \in \mathbb{R}^3$ denote the measurable rotation matrix and the translation vector, respectively, from $\mathcal{B}$ to $\mathcal{W}$ expressed in $\mathcal{W}$. Let $R_m \in SO(3)$ and $x_m \in \mathbb{R}^3$ be the known rotation matrix and the translation vector, respectively, from $\mathcal{M}$ to $\mathcal{B}$ expressed in $\mathcal{B}$.

2.2. Paracatadioptric system projection model

In a paracatadioptric system, a Euclidean point is projected onto a paraboloid mirror and is then reflected to an orthographic camera (see Fig. 1); thus, to facilitate the subsequent development, and to relate the geometric model to the vision system, let the projection of the object feature on the surface of the paraboloid mirror with its focus at the origin be denoted by $w(t) \in \mathbb{R}^3$ relative to $\mathcal{M}$ and defined as follows

$$w \triangleq [u \;\; v \;\; q]^T . \tag{2}$$

The projection $w(t)$ can be expressed as follows (Geyer & Daniilidis, 2000)

$$w = \frac{2f}{\lambda} m = \frac{2f}{\lambda} [x \;\; y \;\; z]^T \tag{3}$$

where $f \in \mathbb{R}$ is the known focal length of the mirror and $\lambda(x, y, z) \in \mathbb{R}$ is the unknown nonlinear signal defined as follows

$$\lambda \triangleq -z + \sqrt{x^2 + y^2 + z^2}. \tag{4}$$

It is worthwhile to mention that the use of a paracatadioptric system results in an orthographic projection from the paraboloid mirror to the image plane. In other words, the reflected rays are parallel to the optical axis; thus, the distance from the mirror to the image plane is irrelevant. After utilizing (2) and (3), the projection can be expressed as follows

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{2f}{\lambda} \begin{bmatrix} x \\ y \end{bmatrix}. \tag{5}$$