Robotics and Autonomous Systems 62 (2014) 1175–1186

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

Modeling and compensation of dynamic effects in camera-based position measurement[☆]

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HIGHLIGHTS

- The dynamical effects in camera-based position-measurement systems are considered.
- The developed models improve simulation and control.
- These models are validated experimentally with a dedicated experimental setup.
- The methodology allows reconstructing accurately the continuous-time trajectory.
- The methodology is applied to the reconstruction of a periodic movement.

ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form
4 April 2014
Accepted 11 April 2014
Available online 26 April 2014

Keywords:
Camera-based position measurement
Visual servoing
Kalman filter
Camera model
Dynamic effects

ABSTRACT

Cameras are used as position sensors for camera-based control or metrology, the goal being to estimate the position of some markers or features. When one of these markers has significant displacement over the exposure time, the measurement delivered by image processing cannot be considered as a sample of the actual trajectory as dynamic effects become effective. In this paper, models are proposed that allow to reproduce accurately the measurements provided by a camera. Various cases are considered: with full or partial exposure time; with global shutter mode or rolling shutter mode. An experimental evaluation in the global shutter case shows the accuracies of the models.

When the continuous-time trajectory of a device needs to be reconstructed, these accurate models of the camera-based position measurement can be used in order to improve the trajectory provided by the camera. A methodology based on a hybrid Kalman filter is proposed to solve this general issue. An experimental evaluation is provided for the global shutter case, based on real images inspired from the problem of heart motion reconstruction.

1. Introduction

Vision systems with real-time image processing have been developed during the last decades and, in association with efficient image processing algorithms, are now able to provide measurements of the position of an object at relatively high frequency. Based on this measurement, specific control schemes have been developed for controlling robotic manipulators [1]. For instance, Andersson developed a robot playing ping-pong based on a 60 Hz stereo vision system [2]. In 2000, Nakabo et al. reached a frame rate of 1000 Hz in a vision servo loop [3].

In vision-based systems, the camera and the associated image-processing algorithm can be considered as a sensor that provides discrete-time (DT) measurements of the continuous-time (CT) image position of a marker or an object. When considering the imperfections of this sensor, one generally focuses on the geometrical aspects, i.e. the projection model whose parameters can be estimated from a calibration procedure [4]. This model is static and deals with the distortion in the projection on the camera plane. Concerning the dynamic effects, one generally considers that the measurement behaves as a sampler that delivers the position at given sampling instants.

When the object or the camera is moving and the displacements over an integration period of the image are significant, the image

☆ This work has been supported by CNRS and JST through the project "Information Processing and Control for Robotized Endoscopic Surgery" form the Strategic Japanese–French Cooperative Program on "Information and Communications Technology including Computer Science", 2007–2008.

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http://dx.doi.org/10.1016/j.robot.2014.04.003
0921-8890/

is altered and the object or the marker appears as a blur or a blob. Several authors have introduced methods that allow to take profit of this effect for the estimation of some features of the movement. Klein and Drummond use the blur effects to estimate the camera rotation [5] whereas Borrachi estimates its translation [6]. Some works also consider the rolling shutter effect: Liang et al. compensate the effects due to a translational motion [7]; Ait-Aider et al. rely on the deformation of lines to estimate the velocity [8].

Modeling the alteration of the measurement of the position of a marker, in the case of fast displacements, is a different subject. Due to the movement, the markers do not appear any more as simple disks but rather as more complex shapes, depending on the trajectory. Then, the measurement provided by the image processing differs from what would be provided by a pure sampler. Very few papers consider more complex models. Among them, Ranftl et al. used a simple discrete-time (DT) model of the camera for performing visual servoing for a fast ultrasonic actuator [9]. Following Luna et al., fast dynamics can be considered as a perturbation and one could try to attenuate them [10].

For reducing the blur effect, common sense recommends to reduce the exposure time. But this leads to images with less amplitude in the pixel values and makes the detection less accurate, particularly when sufficient luminance is not available. Therefore, we consider that there is a need for models reproducing this phenomenon.

The less attention devoted to the current subject can be attributed to the fact that in most of the applications, the DT nature of the measurement is the final information. For instance, in visual servoing, a DT model of the system with a speed reference as input and the DT measurement of the position provided by the camera can be identified and used for control, globally accounting for all the dynamics of the robotic system, including the camera. However, in some applications, the CT signal is of interest. For instance, Cuvillon et al. used a high-speed camera in order to reconstruct the CT trajectory of the heart [11]. Neglecting the camera dynamics, it was considered that a high-speed camera was necessary, with a frame rate higher than the heart-beating harmonics with some margin. Instead of selecting a high-speed camera, one can wonder if a more simple one could have been used in combination with an accurate model, therefore reducing the cost of the system. Notice that the reconstruction of the CT trajectory from the DT measurements provided by the camera requires a model. When such a model is available, the Kalman filter is an usual tool allowing to combine both model and measurement data in order to reconstruct the CT trajectory.

The Kalman filter has become a very common tool and is used in many fields including signal processing and robotics. Initially introduced for state and parameter estimation, it appeared to be a very flexible mean for the fusion of heterogeneous data. In its theoretical background, the noises affecting the system are assumed to be the realization of stochastic processes. However, in practice, the covariance matrices of these noises can be used as tuning parameters in order to obtain the proper behavior of the filter.

In robotics and metrology, the goal is often to reconstruct the 3D position of points or objects from a collection of 2D positions in images. Naturally, the evaluation of the effects of the camera on the 3D positions is of interest. However, the current paper focuses on the errors in the image. The models developed herein will be of interest for evaluating the impact on the 3D positions but this issue will not be considered in the current paper.

The scope of this paper is twofold. First, models of the camera-based position measurement (CBPM) are developed for different kinds of cameras. These models can be used to improve the simulation or to derive a more accurate model dedicated to control design. Second, a methodology is proposed for the estimation of the CT trajectory of a system where the measurement is made by a camera. This methodology is based on a Kalman filter that relies on a CBPM model, such as one of those presented in the first part of the work. The paper is organized as follows. Section 2 presents the models of CBPM. An experimental comparison of several models is made in Section 3. The Kalman filter and the adaptations needed for the reconstruction of the CT trajectory from the DT measurement are presented in Section 4. An application for the reconstruction of a periodic trajectory is presented in Section 5. Section 6 concludes the paper.

This paper summarizes several conference papers. The model of a full-shutter mode camera has been initially considered in [12]. In [13], a model of the rolling-shutter mode has been proposed. In addition, this paper presented the evaluation setup and included experimental results for the global-shutter mode camera. In [14], the methodology for the estimation of the CT trajectory was proposed in addition to its use in the reconstruction of a periodic signal.

2. Models of camera-based position measurement

2.1. Measurement of the position by camera

A scene being equipped with visual markers, it is possible to measure their positions in the image by some image processing algorithms. This technique is classically used for processing visual-servoing of robots [15]. The measurements can be used directly in a 2D visual servoing scheme or can be used in order to reconstruct a 3D pose, allowing to derive 3D control. Markers are generally spots of high luminous intensity that can be detected easily. In the visible spectrum, they can be obtained by LEDs or projection of laser beams [16]. It is also possible to use a dark marker over a bright surface [17,18]. Invisible electromagnetic radiation is also commonly used, as in the Polaris system by NDI that estimates the 3D pose from the 2D position of 3 spheres with high reflexion property in the infrared.

Usually, the elements of interest are simple circular markers and the goal of image processing is to compute the coordinates of their centers of mass in the image. In order to limit the computation cost for real-time implementation, the image processing often makes use of simple operations (binarization, threshold and computation of the center of mass in several sub-images centered around the current position).

Let us consider one marker and let $q(t) = \begin{bmatrix} x(t) & y(t) \end{bmatrix}^T$ denote the vector of the coordinates of its center in the camera image at time t. Images are acquired at the camera frame rate f_c. For Image I_k obtained at time $t_k = kT_c$ where $T_c = 1/f_c$, the vector of the coordinates of the marker center-of-mass is denoted $q_m(t) = \begin{bmatrix} x_m(k) & y_m(k) \end{bmatrix}^T$. Let us neglect the noise due to the spatial discretization of the image. In a static case or if displacements are small over the exposure time, one has $q_m(k) = q(t_k)$. In the case of significant displacements over the integration period, the equality is not valid any more. In this paper, we deal with models allowing to compute the DT trajectory $(x_m(k), y_m(k))$ from the CT trajectory $(x(t), y(t))$. Accounting for the dynamic effects induced by the camera, these models are of interest for simulation, identification and control purposes.

For illustration, the following experimental setup has been used: a rigid object containing seven light-emitting diodes (LED) used as markers is moved by a pan–tilt platform, as shown in Fig. 1. The images given by a gray-level camera (see Fig. 2) allow to distinguish the seven markers easily. In the right-hand image in Fig. 2, one can observe the effect of a significant motion over exposure time. The object has been used previously in order to estimate the movements of a beating heart [11].

Based on the analysis of the shape of the blur, more complex image-processing algorithms could be used in order to determine