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Single-shot camera position estimation by crossed grating imaging

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ABSTRACT

A simple method to estimate the position of a camera device with respect to a reference plane is proposed. The method utilizes a crossed grating in the reference plane and exploits the coordinate transformation induced by the perspective projection. If the focal length is available, the position of the camera can be estimated with a single-shot. Otherwise, the focal length can be firstly estimated from few frames captured at different known displacements. The theoretical principles of the proposed method are given and the functionality of the approach is exhibited by correcting perspective-distorted images. The proposed method is computationally efficient and highly appropriate to be used in dynamic measurement systems.

1. Introduction

Nowadays, many applications in image processing and optical metrology, for instance, perspective correction [1–7] and three-dimensional surface imaging [8–13], depend critically on the relative position of a camera device with respect to a reference plane [14–20]. Moreover, in real-time applications such as visual control of robot systems [21–23], automatic localization [24], and augmented reality guiding [25], the position parameters of the camera are required to be estimated in a dynamic manner [26]. Therefore, an accurate single-shot method to obtain the position parameters of the camera is a staple requirement of considerable importance.

The position of a camera device can be obtained with a calibration procedure that estimates the extrinsic parameters of the camera [27–30]. For this purpose, plenty of camera calibration methods have been suggested that make emphasis on different attributes, for instance, accuracy, efficiency, and versatility [31–35]. Nevertheless, because the camera calibration process involves a considerable amount of parameters, these methods require complicated calibration checkerboards, the processing of multiple images of the target at different positions and orientations, or assistance by the user [36–39]. These issues avoid practical simplicity of the calibration procedure and make it unfeasible for real-time applications.

The parametric approach is an attractive alternative for single-shot camera orientation estimation [40]. This approach exploits the coordinate transformation induced by the perspective projection of the reference plane into the image plane [41]. However, this approach has only been used to estimate two rotation angles, which corresponds to the orientation of the reference plane (or the camera).

In general, the position of a camera is a problem with six unknowns; that is, three for spatial translation and three for angular rotation. Nonetheless, some of them are redundant when the position of the camera is referred to a plane. Actually, the plane is invariant to translation along a vector lying on it (two spatial unknowns are omitted). Therefore, by considering the focal length of the camera lens, five parameters are sufficient to describe the position of the camera.

In this paper, we present a simple method to estimate the position of a camera device with respect to a reference plane. For this, the imaging process of points in the reference plane is analysed using the geometrical optics approach. A crossed grating in the reference plane is used to retrieve the required coordinates. The proposed method only requires a single image of the grating when the focal length of the imaging lens is available. Moreover, if the focal length is unknown it can be firstly estimated by processing few images of the grating captured at different known displacements. The feasibility of the proposed method is verified by correcting perspective-distorted images obtained with a laboratory setup. The key attributes of the proposed method are its low computational complexity, non-iterative execution, and single-shot parameter estimation capability. These attributes make the proposed method highly appropriate to be used in dynamic measurement systems.

The paper is organized as follows. The theoretical model of the

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coordinate transformation induced by the perspective projection of the reference plane is described in Section 2. Section 3 explains the proposed single-shot estimation procedure to obtain the camera position parameters when the focal length is known. The application of the proposed method for estimation of the focal length of the camera lens from two or more images of the grating is given in Section 4. The functionality of the proposed method is illustrated through computer simulations in Section 5. The experimental results in the estimation of the focal length of the camera lens as well as in correcting the perspective distortion of images are provided in Section 6. Section 7 presents our conclusions. Finally, Appendix A provides the details about the intensity patterns obtained by the imaging of a crossed grating and a simple criterion of how to chose the spatial frequencies of the grating.

2. Theoretical model of coordinate transformation

We consider a local coordinate system with the origin at the pinhole and with the z-axis being parallel to the optical axis, as shown in Fig. 1(a). Let the xy-plane be the reference plane. The origin can be fixed in an arbitrary point on the plane. Therefore, we consider that the origin is at the intersection point of the optical axis of the camera and the xy-plane as shown in Fig. 1(b). The orientation of the camera can be described by the rotation matrix R^T, where $[\cdot]^T$ denotes the transpose, and R is the rotation matrix defined by the Euler sequence

$$R = R_z(\phi)R_y(\theta)R_z(\gamma), \tag{1}$$

where R_y and R_z are 3×3 rotation matrices around the y- and z-axes, respectively. The position of the camera is given by

$$\boldsymbol{t} = -dR^T\hat{\boldsymbol{k}}, \tag{2}$$

where d is the distance from the pinhole to the reference plane along the optical axis, and $\hat{\boldsymbol{k}}$ is a unit vector in the direction of the z-axis.

The local coordinate system of the camera as the reference frame is most convenient for subsequent analysis, see Fig. 1(c). In this configuration, the orientation of the reference plane is given by the rotation matrix R. The intersection between the optical axis of the camera and the reference plane is the point

$$\boldsymbol{p}_0 = d\hat{\boldsymbol{k}}. \tag{3}$$

The normal of the reference plane is given by

$$\hat{\boldsymbol{n}} = R\hat{\boldsymbol{k}} = \begin{bmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{bmatrix} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}. \tag{4}$$

Notice that the angles θ and ϕ align the vector $\hat{\boldsymbol{k}}$ with $\hat{\boldsymbol{n}}$; and γ is a rotation angle around $\hat{\boldsymbol{n}}$.

Let $\boldsymbol{\alpha} = [\alpha_x, \alpha_y]^T$ be a point in the reference plane with $\boldsymbol{\alpha}$ given in the local coordinate system $x_p y_p z_p$. Similarly, $\boldsymbol{\beta} = [x, y]^T$ is a point in the image plane with $\boldsymbol{\beta}$ given in the coordinate system x, y, z. The point $\boldsymbol{\alpha}$ is seen as the point $\boldsymbol{p}$ from the camera viewpoint through the relation

$$\boldsymbol{p} = R\begin{bmatrix} \boldsymbol{\alpha} \\ 0 \end{bmatrix} + \boldsymbol{p}_0. \tag{5}$$

Similarly, the image point $\boldsymbol{\beta}$ seen from the camera viewpoint is given by

$$\boldsymbol{c} = \begin{bmatrix} \boldsymbol{\beta} \\ f \end{bmatrix}, \tag{6}$$

where f denotes the focal length of the camera lens, see Fig. 2. By considering the intersection points of a line passing through the origin and crossing the observation and reference planes, it can be shown that $\boldsymbol{p}$ and $\boldsymbol{c}$ are related as

$$\boldsymbol{p} = \frac{\hat{\boldsymbol{n}}^T\boldsymbol{p}_0}{\hat{\boldsymbol{n}}^T\boldsymbol{c}}\boldsymbol{c}. \tag{7}$$

By substituting Eqs. (5) and (6) in Eq. (7), and after few algebraic manipulations, we obtain

$$\begin{bmatrix} \boldsymbol{\alpha} \\ 0 \end{bmatrix} = R^T\left(\frac{\hat{\boldsymbol{n}}^T\boldsymbol{p}_0}{\begin{bmatrix} \boldsymbol{\beta}^T & f \end{bmatrix}\hat{\boldsymbol{n}}} \begin{bmatrix} \boldsymbol{\beta} \\ f \end{bmatrix} - \boldsymbol{p}_0 \right). \tag{8}$$

Furthermore, by using the property $R = \mathrm{cof}(R)$ where $\mathrm{cof}(\cdot)$ denotes the cofactor matrix, we obtain

$$\boldsymbol{\alpha} = \frac{d}{\begin{bmatrix} \boldsymbol{\beta}^T & f \end{bmatrix}\hat{\boldsymbol{n}}}\mathrm{adj}(\bar{R})\boldsymbol{\beta}, \tag{9}$$

where $\mathrm{adj}(\cdot)$ returns the adjugate matrix, and R was partitioned as

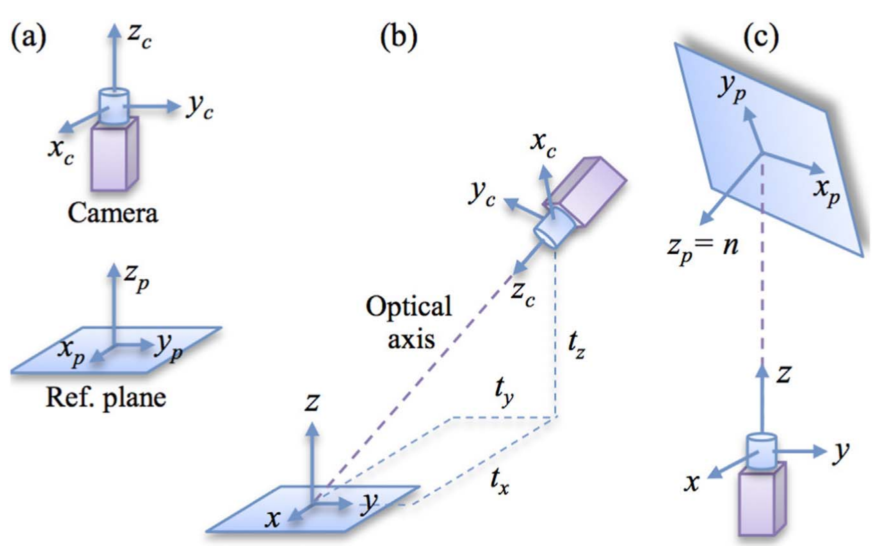

Fig. 1. (a) Local coordinate systems of the camera and the reference plane. Perspective projection using the coordinate system (b) $x_p y_p z_p$, and (c) $x_c y_c z_c$.