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An accurate calibration method for a camera with telecentric lenses

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ABSTRACT

It is very important to achieve an accurate calibration to obtain high measurement accuracy for a telecentric imaging system. However, the conventional camera calibration methods typically based on a pinhole model are not suitable for telecentric lenses due to the unique behavior of orthographic projection of telecentric lenses. In this paper, we propose a new method to accurately calibrate the telecentric imaging system. An analytical camera model for telecentric lenses is presented with considering the major sources of lens distortions. Based on this model, a two-step calibration procedure is described for the telecentric imaging system. We use a camera with a telecentric lens to verify our model and study the impacts of different distortion models for properly characterizing the distortion of telecentric lens. The experimental results show the maximum distortion of the system reduces 26 times by the presented calibration technology.

1. Introduction

Telecentric lenses have the unique property of purely orthographic projections of scene points and maintaining a constant magnification over a specific range of object distances. Thus, they are being widely used in many machine vision applications especially for accurate dimensional measurements of three-dimensional (3D) parts and components of different heights [1,2]. Although high quality telecentric lenses normally show very low distortion degree, in the range of 0.1%, which seems to be very small, it would actually result into measurement errors approaching the size of one pixel of a camera. This must not happen in precise measurement. In fact, such as radial distortion and trapezoidal distortion are inevitably in telecentric lenses system. Therefore, the calibration of a camera with telecentric lenses is essential for metric measurement in high accuracy application.

Many techniques for camera calibration have been proposed. Hall and Faugeras-Toscani use a least-squares technique to obtain the parameters of the linear model. And later, nonlinear calibrating methods are developed for lens distortion. The widely used method proposed by Tsai is based on a two-step technique modeling only with radial lens distortion [3]. Weng presents a camera model with three different types of lens distortion and a two-step calibration procedure [4]. Zhang proposes a flexible camera calibration technique which uses images of a 2D template taken from different camera positions and orientations [5]. All these camera calibration methods use the pinhole model based on perspective projection, while telecentric lenses act as orthographic projection. Therefore, these calibration methods are not available for a camera with telecentric lenses. Zhu develops a system for deformation measurement with telecentric lens, and proposes a simple calibration method based on linear fitting [6]. However, this calibration does not take into account the lens distortion and could only get the intrinsic parameter magnification, in which the extrinsic parameters are not given. To the best of our knowledge, it has not an accurate calibration method for telecentric lens based camera.

According to the work principle of telecentric lenses, we proposed a calibration method for a camera with telecentric lenses in this paper. A camera model based on orthographic projection is presented, and the major sources of telecentric lens distortion including radial, decentering, and thin prism distortions are taken into account. We adopt a two-step approach to calibrate the telecentric lens system. In the first step, all the extrinsic parameters and an intrinsic parameter are estimated using a closed-form solution based on a distortion free camera mode. In the second step, a nonlinear optimization based on the camera model with distortions is carried out using the solution of the first step as an initial guess, and all the parameters are computed and refined. As different types of distortion are considered in the second step, the impacts of different distortions are studied.

The principle of telecentric imaging system is described and the mathematical expression of the camera model is proposed in Section 2. The calibration procedure is described in detail in

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Section 3. In Section 4, the performance of the calibration is shown on experimental measurements, then the results are analyzed to reveal the impacts of different distortions, which demonstrates the validity of the proposed method. Finally, conclusions are presented in Section 5.

2. Principle

2.1. Telecentric imaging

In a telecentric lens system, a small aperture stop is located at the focal point of the object lens [7]. Therefore, only the light rays that are approximately parallel to the optical axis of the lens pass through the aperture stop and form the image. As the image is formed by the parallel projection of the object onto the image plane, the image magnification does not depend on the object distance. Telecentricity in object and image space can be achieved by combining two single-sided telecentric lenses, as shown in Fig. 1. The two lenses are separated by the sum of their focal lengths f_1, f_2. The aperture stop is placed in the focal plane between the two lenses. A bilateral telecentric lens accurately reproduces dimensional relationships within its telecentric depth, and it is not susceptible to small differences in the distance between the lens and the camera's sensor. The magnification, $m=f_2/f_1$ from geometrical optics, is one of the most important parameters of a telecentric lens for imaging, which must be calibrated for high-precision measurements.

2.2. Camera model with telecentric lens

The imaging model of a camera with a telecentric lens can be illustrated by Fig. 2. (X_w, Y_w, Z_w) is the 3D coordinate of the object point P in the 3D world coordinate system. (X_c, Y_c, Z_c) is the 3D coordinate of the object point P in the 3D camera coordinate system. (x_u, y_u) is the image coordinate of $P(X_c, Y_c, Z_c)$ if a perfect orthographic projection model is used. (x_d, y_d) is the actual image coordinate which differs from (x_u, y_u) due to lens distortion. (u, v) is the image coordinate of the computer in pixels.

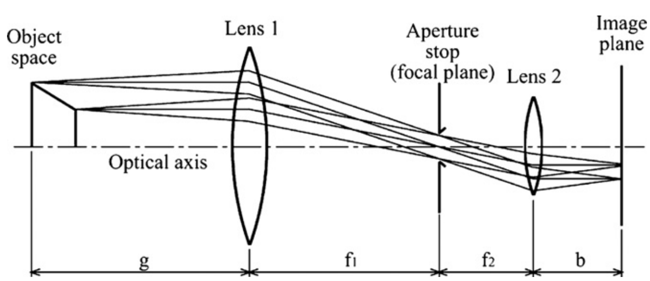

Fig. 1. The schematic of a bilateral telecentric lens.

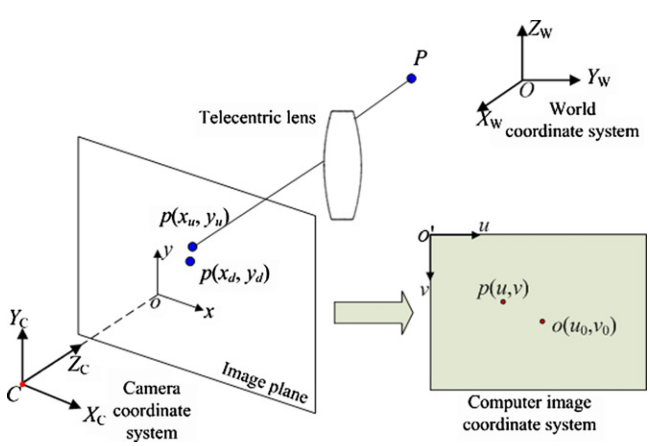

Fig. 2. The imaging model of a camera with a telecentric lens.

The most important premise for an accurate calibration is the correct mathematical expression of the camera model. The pinhole model of wide angle cameras was not applicable for the telecentric imaging system. Telecentric lenses perform scaled orthographic projection [8], thus the projection of an arbitrary point P to the ideal (undistorted) image plane in metrical units is expressed as

$$\begin{bmatrix} x_u \\ y_u \\ 1 \end{bmatrix} = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} \tag{1}$$

where m is the effective magnification of telecentric lens, which needs to be calibrated. And the relationship between the world and camera coordinate systems is given by

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \tag{2}$$

where $R=[r_{ij}]$ is the rotation matrix and $T=[\ t_x\ t_y\ t_z\ ]^{\mathrm{T}}$ is the translation matrix.

Without any loss of generality, we set the image coordinate system oxy coincident with the computer the image coordinate system. Thus, the transformation from image coordinate (x, y) to computer image coordinate (u, v) in pixels is described by

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} 1/du & 0 & 0 \\ 0 & 1/dv & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{3}$$

where du and dv are the sizes of a pixel in the x and y directions respectively.

Combining Eqs. (1)–(3), the orthographic projection of telecentric lenses is formed and expressed by the equation:

$$\begin{bmatrix} x_u \\ y_u \\ 1 \end{bmatrix} = \begin{bmatrix} m/du & 0 & 0 \\ 0 & m/dv & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \tag{4}$$

It is obvious that there is not a principal point (u_0, v_0) for telecentric lenses from Eq. (4), as telecentric lenses perform parallel projection and there is not a projection center.

2.3. Lens distortion

There are mainly three types of distortion in telecentric lens, namely radial, decentering, and thin prism distortions. The first one is caused by imperfect lens shape and manifests itself by radial positional error only, whereas the second and the third types of distortion are generally caused by improper lens and camera assembly and generate both radial and tangential errors in point positions. For each kind of distortion, an infinite series is required. However, experiments show that the terms of order higher than 3 could be neglected. Therefore, the effective distortion can be expressed by

$$\begin{cases} \delta_x = k_1 x_u (x_u{}^2 + y_u{}^2) + h_1 (3x_u{}^2 + y_u{}^2) + 2h_2 x_u y_u + s_1 (x_u{}^2 + y_u{}^2) \\ \delta_y = k_1 y_u (x_u{}^2 + y_u{}^2) + 2h_1 x_u y_u + h_2 (x_u{}^2 + 3y_u{}^2) + s_2 (x_u{}^2 + y_u{}^2) \end{cases}$$
$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = \begin{bmatrix} x_u \\ y_u \end{bmatrix} + \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix} \tag{5}$$