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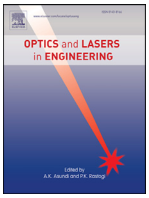

Flexible calibration method for line-scan cameras using a stereo target with hollow stripes

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ABSTRACT

With the advantages of ultrahigh resolution and acquisition rate, stereo line-scan sensors are gradually being developed for three-dimensional (3D) measurements. Calibration is crucial for line-scan cameras. However, viewing targets of line-scan cameras from different angles cause eccentricity errors. This paper presents a flexible calibration method for line-scan cameras to solve the eccentricity error problem. The calibration quality is improved by the accurate extraction of one-dimensional (1D) points on line-scan images, and the corresponding 3D points in space. Through the analysis of the eccentricity error in 1D image point extraction when utilizing targets with solid stripes, a stereo target with hollow stripes is designed. An algorithm is described to calculate the 3D points of intersection between the centerlines of hollow lines on the target and the viewing plane of the camera. A robust optimization is proposed to enhance the stability of parameter estimation. Experiments are performed to compare the re-projection error between the cross-ratio-based method and proposed method. A simulation is also performed to estimate the combined uncertainty. The comparative results of the experiments verify that the proposed method is accurate, low cost, and easy to implement.

1. Introduction

The precise measurement of the three-dimensional (3D) surface shape of workpieces has been studied extensively for many years. In most cases, measurement systems based on matrix cameras (conventional two-dimensional (2D) imaging devices) can be used. With the advantages of high resolution and acquisition rate (up to 16,384 pixels at 27 kHz), line-scan cameras are gradually replacing matrix cameras in the accurate 3D surface measurement of high-speed moving objects such as in vehicle-borne 3D scene reconstruction and space-borne remote sensing areas. Hitherto, numerous stereo line-scan sensors have been used for 3D shape measurement [1–5]. Calibration is crucial for line-scan cameras owing to its significant influence on measurement accuracy. The well-known calibration methods [6,7] for matrix cameras, which require the projection of all feature points on every image, fail, as line-scan cameras have to be shifted relative to the moving object, or only the information on a single line is available. The authors have performed several investigations on line-scan camera calibration. Generally, the calibration methods found in the literature can be classified into scanning calibration and static calibration.

Scanning calibration acquires unidimensional images continuously with relative motions between the line-scan camera and the target, resulting in a 2D image. Drareni et al. [8] obtained the scanned image of a camera with a planar grid pattern. The algorithm was linear and simple but the motion of the target had to be along the Y-axis with a constant speed. Hui et al. [9–11] used a stereo target to simplify the experimental operation. The algorithms were modified using the velocity in three directions as the pending parameters. Although scanning calibrations provided high accuracy under laboratory conditions, they were inapplicable in industrial sites because the movements were not reproducible owing to vibrations.

Static calibration with independent movements, by contrast, is advantageous. According to the one-dimensional (1D) imaging information on a single line, static calibration methods establish a correspondence between the target and the image. Generally, patterns on the target consist of several solid feature lines. Horaud [12] was the pioneer in using cross-ratio invariance to calculate the intersection of 3D points between the feature lines and viewing plane during calibration. However, the target had to translate with the exact increments along the Y and Z axes, as the accuracy of displacement determined the calibration quality. Sun et al. [13,14] acquired noncollinear feature points in multiple locations freely using high-precision apparatuses. The target had to be measured every time it moved, thus resulting in operational burdens. Hence, static calibration methods using stereo targets are considered superior. Luna et al. [15] and Lilienblum et al. [16] built a stereo target model with parallel planes placed at different heights, thus overcoming the limitations of the scanning calibration method and the tedious operation. However, as the angle between the target plane and image

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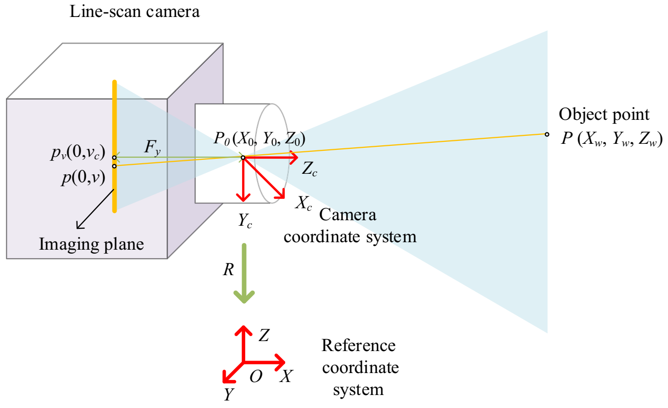

Fig. 1. Image relationship of perspective projection.

plane increased, the eccentricity error caused by the stripes center extraction increased, thus affecting the calibration results significantly. Niu et al. [17] and Li et al. [18] proposed a pattern comprising two orthogonal planes with block patterns to avoid eccentricity. However, the orthogonal structure limited the calibration from large angles. Song et al. [19] proposed a coded eight-trigram pattern that required highly precise edge extraction technology for 1D information.

The eccentricity error is widely recognized in the projection transformation of a circle in a matrix camera, but is hardly emphasized in line-scan cameras. The perspective projection transformation can degenerate a space circle into an ellipse. The ellipse center cannot exactly represent the projection of the circle center [20–22]. The gap between the ellipse center and the projection of the circle center is called the eccentricity error. When targets with feature lines are used for line-scan camera calibration, a similar error also occurs in line projection in line-scan cameras. However, little research has been performed to analyze or mitigate this error. Therefore, this study presents a flexible calibration method for line-scan cameras to address the eccentricity issue from nonperpendicular angles.

The remaining parts of this paper are organized as follows: Section 2 depicts the imaging model of line-scan cameras. Section 3 presents the calibration approach. First, by analyzing the eccentricity error, a stereo target with hollow stripes on the patterns is proposed. Subsequently, to acquire 1D image points, a reasonable algorithm using the principle of harmonic conjugate and cross-ratio invariance is designed. In addition, an algorithm is described to extract 3D points. Finally, a robust optimization is proposed to enhance the stability of parameter estimation. Experiments comparing the proposed method with the cross-ratio-based method are reported in Section 4. Furthermore, a simulation is designed to estimate the combined uncertainty. The conclusions are presented in Section 5.

2. Imaging model of line-scan camera

Line-scan cameras, as one-dimensional imaging devices, can be regarded as simplified forms of matrix cameras. A model mapping a 3D point in space to a 1D point in a unidimensional image is necessary for calibrating a line-scan camera based on static methods. Fig. 1 shows the image relationship of perspective projection. According to the collinearity equation of a space point P (X_w, Y_w, Z_w), the projection point P_0 (X_0, Y_0, Z_0), and image point p (0, v), the line-scan camera model is described as follows [13]:

$$\begin{cases} 0 = r_{11}\left(X_w - X_0\right) + r_{12}\left(Y_w - Y_0\right) + r_{13}\left(Z_w - Z_0\right) \\ v = v_\mathrm{c} + \Delta v + F_\mathrm{y}\frac{r_{21}(X_w-X_0)+r_{22}(Y_w-Y_0)+r_{23}(Z_w-Z_0)}{r_{31}(X_w-X_0)+r_{32}(Y_w-Y_0)+r_{33}(Z_w-Z_0)} \end{cases}. \tag{1}$$

An object point P (X_w, Y_w, Z_w) in space projects onto the line-scan image at point p (0, v), where r_{ij} (i = 1, 2, 3, j = 1, 2, 3) are the entries of the rotation matrix R that represents the rotation relationship from the camera coordinate system to the reference coordinate system. The parameter v_c is the coordinate of the principle point p_v and F_y is the focal length of the line-scan camera. Point P_0 (X_0, Y_0, Z_0) represents the projection center, and it is also the origin of the camera. The first two orders of radial and tangential distortion are considered in Δv, where k_1, k_2, k_3 are the distortion coefficients [23,24].

$$\Delta v = k_1\left(v - v_c\right)^5 + k_2\left(v - v_c\right)^3 + k_3\left(v - v_c\right)^2. \tag{2}$$

Therefore, the purpose of calibration is to estimate the camera parameters including five intrinsic parameters (v_c, F_y, k_1, k_2, k_3) and six extrinsic parameters (r_1, r_2, r_3, X_0, Y_0, Z_0). The rotation matrix R can be represented as a vector $(r_1, r_2, r_3)^\mathrm{T}$ by the Rodrigues formula [6]. The key to solving the calibration parameters is to acquire 1D image points on the line sensor and the corresponding 3D points in space.

3. Calibration approach

3.1. . Analysis of eccentricity error

In cross-ratio-based calibration [12], patterns with solid stripes are used. The principle of cross-ratio invariance is utilized to calculate the intersection of 3D points between the solid feature lines and viewing plane during calibration. However, an eccentricity error exists in this method. As shown in Fig. 2, because the stripes are of a certain width, the projection of an intersection point between the feature line and viewing plane always occupies a few pixels and appears as a narrow band on a line-scan camera image. The center of the narrow band is regarded as the projection of the line center, which is not always accurate. Consequently, the eccentricity error must be considered.

The projection of one feature line is shown in Fig. 3. The line has a certain width that cannot be ignored. Point P_0 is the projection center. If the image plane and target plane are parallel to each other (Fig. 3(a)), the feature point C in the line-width center on the target plane projects onto C', which is exactly the same with the line center E' in the image plane. However, if an angle exists between the two planes (Fig. 2(b)), a slight gap occurs between E' and C'. Thus, the eccentricity error e' occurs.

The schematic diagram of the eccentricity error is shown in Fig. 4. Through geometric calculations, the expression of the eccentricity error e' can be estimated as follows [25]:

$$e' = r_m - \frac{c}{2}\left(\frac{R_m + \frac{d}{2}\sin\left(90 - \alpha\right)}{Z_m - \frac{d}{2}\cos\left(90 - \alpha\right)} + \frac{R_m + \frac{d}{2}\sin\left(90 - \alpha\right)}{Z_m - \frac{d}{2}\cos\left(90 - \alpha\right)}\right), \tag{3}$$

where

e'	eccentricity error;
d	width of feature line in target plane;
r_m	distance from projection of feature line center to optical axis;
α	viewing direction, equal to angle between image plane and target plane;
P_0	projection center;
R_m	lateral offset of feature line center in target plane from optical axis;
Z_m	distance from feature line center to the plane parallel to the image plane through P_0;
F_y	focal length of the line-scan camera.

The error is primarily affected by the viewing direction, width of the feature line, and object distance. Generally, if the projection of a feature line occupies less than 10 pixels, the eccentricity error is negligible. However, the eccentricity error must be considered in the proposed calibration method to fulfill the high accuracy requirement.

3.2. . Accurate calculation of 1D points by hollow stripes

In the cross-ratio-based method, solid lines are adopted and the line centers in the image plane are treated as the projection of feature points. When an angle exists between the image plane and target plane, the direct extraction of the line center causes the eccentricity error. Therefore, the hollow stripes pattern is proposed. In Fig. 5, every hollow line