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Calibration method for line-structured light vision sensor based on a single ball target

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ABSTRACT

Profile feature imaging for ball targets is unaffected by the position of the target. On this basis, this study proposes a method for the rapid calibration of a line-structured light system based on a single ball target. The calibration process is as follows: the ball target is placed at least once and is illuminated by the light stripe from the laser projector. The vision sensor captures an image of this target. The laser stripe and profile images of the ball target are then extracted. Based on these extracted features and the optical centre of the camera, the spatial equations of the ball target and a cone profile are calculated. The plane on which the intersection line of the two equations lies is the light plane. Finally, the optimal solution for the light plane equation is obtained through nonlinear optimization under a maximum likelihood criterion. The validity of the proposed method is demonstrated through simulation and physical experiments. In the physical experiment, the field of view of the structured light vision sensor measures 300 mm × 250 mm. A calibration accuracy of 0.04 mm can be achieved using the proposed method. This accuracy is comparable to that of the calibration method which utilizes planar targets.

1. Introduction

The pioneer research on the structured measurement of light vision dates back to the 1970s. As one of many vision-measuring methods, the 3D vision measurement technique based on structured light is characterized by a wide range, non-contact, rapidity and high precision. It has been widely applied in industrial environments [1–3].

Line-structured light vision sensors are the most frequently used type of structured light vision sensor. The calibration process consists of two steps: the calibration of the intrinsic parameters of the camera and of the light plane parameters. Much research [4–12] has examined the former. Nonetheless, methods to calibrate light plane parameters are also described in many related studies [13–19]. For instance, Dewar [13] used a wire-drawing method, whereas Huynh [14] and Xu [15] derived a calibration method by determining the light plane calibration point according to the principle of cross-ratio invariability using a 3D target. The core idea of this calibration method is to obtain the coordinates of the intersection point between the structured light stripe and the line on which the three collinear points are located (the precise coordinates of the collinear points are known). This process is in accordance with the principle of cross-ratio invariability. The high-precision light plane calibration point can thus be located. Zhou [16] proposed a method for the on-site calibration of line-structured light vision sensors using a planar target. This method determines the light plane calibration point on the planar target based on the principle of cross-ratio invariability. Many light plane calibration points can be obtained by moving the planar target repeatedly. This method requires no high-cost auxiliary equipment; thus, it is especially suitable for on-site calibration. Liu [17] also adopted the planar target and applied the Plüker formula to describe the line of the light stripe. Xu [18] calibrated a structured light vision sensor using a flat board with four balls. Wei [19] proposed a method to calibrate a line-structured light system based on a 1D target. The 3D coordinates of the intersection point between the light plane and the 1D target were identified based on the constraints on the distance between the feature points of the 1D target. The light plane equation was solved by fitting the 3D coordinates of several intersection points.

Based on the fact that the profile feature of the ball target is unaffected by the placement angle of the ball target, a method is proposed in this paper for the on-site calibration of a line-structured light vision sensor using a single ball target. Firstly, the cone equation which is defined by the profile of the light stripe on the ball target and the optical centre of camera is determined. Secondly, the spatial equation of the ball target is obtained. The

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light plane equation is derived by combining these two equations. Finally, the optimal solution for the light plane equation is determined through nonlinear optimization. The contents of this paper are structured as follows: Section 2 briefly introduces the model of the line-structured light vision sensor; Section 3 describes the basic principle of the algorithm in detail; Sections 4 and 5 contain information regarding the simulation and the physical experiment, respectively; and Section 6 presents the conclusion.

2. Model of the line-structured light vision sensor

The geometric structure of a structured light vision sensor is shown in Fig. 1. $O_wx_wy_wz_w$ is the world coordinate frame (WCF). $O_cx_cy_cz_c$ is the camera coordinate frame (CCF). $O_ux_uy_u$ is the image coordinate frame (ICF).

The arbitrary point P on the light plane presumably has a projection point p on the image plane. The undistorted image coordinate of P in ICF is $\tilde{\boldsymbol{p}}$. The homogeneous coordinate of P in WCF is $\boldsymbol{P}_w=[x_w,y_w,z_w,1]^T$.

Based on the camera imaging model, the following equation is obtained:

$$\rho\tilde{\boldsymbol{p}}=\boldsymbol{K}(\boldsymbol{R}\ \boldsymbol{t})\boldsymbol{P}_w=\boldsymbol{M}\boldsymbol{P}_w, \tag{1}$$

where ρ is the coefficient. $\boldsymbol{K}$ is the matrix of the camera's intrinsic parameters. $\boldsymbol{R}$ and $\boldsymbol{t}$ are the rotation matrix and translation vector from WCF to CCF, respectively. $\boldsymbol{M}$ is the projection matrix of the camera. The image coordinate of P is undistorted to obtain $\tilde{\boldsymbol{p}}$ based on the calibration of the intrinsic parameters of the camera [5].

P satisfies the light plane equation. Suppose the light plane equation in WCF is expressed as

$$ax_w+by_w+cz_w+d=0, \tag{2}$$

where a, b, c and d are the four coefficients of the light plane equation.

By combining the equations,

$$\begin{cases}\rho\tilde{\boldsymbol{p}}=\boldsymbol{K}(\boldsymbol{R}\ \boldsymbol{T})\boldsymbol{P}_w\\ ax_w+by_w+cz_w+d=0\end{cases}. \tag{3}$$

In WCF, the equation of line O_cp is determined based on the camera model. The light plane equation is determined with Eq. (2). Therefore, the point of intersection between O_cp and the light plane can be applied to determine the 3D coordinates of P uniquely.

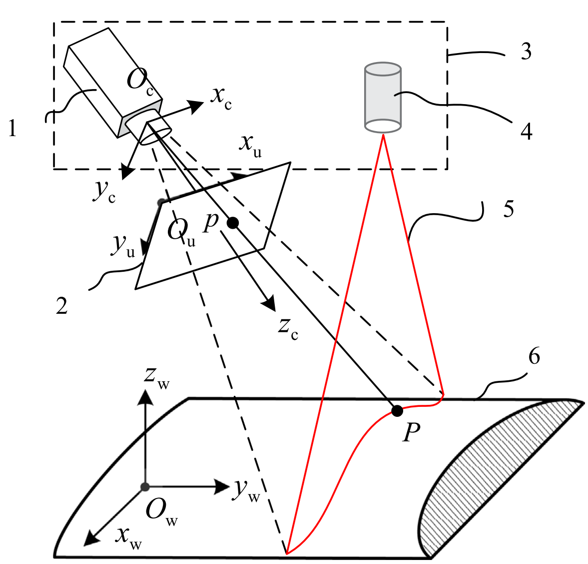

Fig. 1. Geometric structure of line-structured light vision sensor. (1) Camera; (2) image plane; (3) line structured light sensor; (4) laser projector; (5) light plane; and (6) measured object.

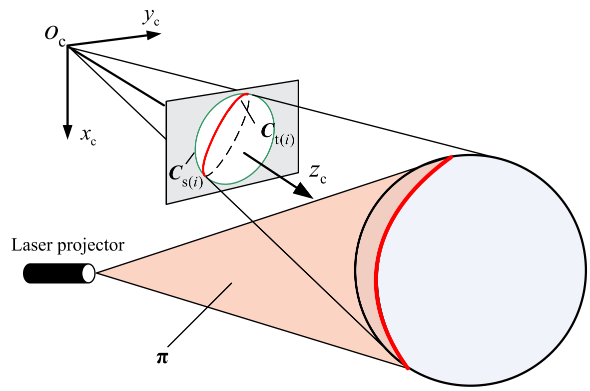

Fig. 2. Calibration process of a line-structured light vision sensor.

3. Algorithm principle

The intrinsic parameters of the camera in the line-structured light vision sensor are calibrated using Zhang's method [5]. The following section describes the calibration of the light plane parameters of a structured light vision sensor in detail.

WCF is defined under the CCF of the line-structured light vision sensor. The calibration process of light plane parameters is illustrated in Fig. 2. $O_cx_cy_cz_c$ is presumably CCF and π is the light plane. Hence, the light plane equation can be expressed as $ax+by+cz+d=0$, where $\sqrt{(a^2+b^2+c^2)}=1$. At the ith position of the ball target ($i=1,2,3\ldots n$, n is the number of positions in which the ball target is placed), the profile of light stripe $\mathbf{C}_{t(i)}$ and the profile curve of the ball edge are obtained for target $\mathbf{C}_{s(i)}$. This target is determined through ellipse fitting.

The calibration process of light plane parameters consists of the following steps:

Step 1: The ball target is placed in the correct position at least once. It is illuminated by the laser projector. The line-structured light sensor captures the light stripe image on the ball target and the image points of the light stripe are extracted. The image point of the light stripe is undistorted based on the intrinsic parameters of the camera before $\mathbf{C}_{t(i)}$ is obtained by ellipse fitting. The profile of the ball target is determined by the same distortion, and then $\mathbf{C}_{s(i)}$ is also obtained by ellipse fitting.
Step 2: The spatial cone equation $\mathbf{Q}_{t(i)}$ determined by $\mathbf{C}_{t(i)}$ and the optical centre of the camera is solved by back projection. Similarly, the spatial cone equation $\mathbf{Q}_{s(i)}$ determined by $\mathbf{C}_{s(i)}$ and the optical centre of the camera is solved. Then the sphere equation of the ball target $\boldsymbol{B}_i$ is solved as well. The equation for the light plane is formulated by combining $\boldsymbol{B}_i$ and $\mathbf{Q}_{t(i)}$. The circular ring is tangential to the ball target on this plane.
Step 3: The optimal solution for the light plane equation is obtained through nonlinear optimization in accordance with the maximum likelihood criterion.

3.1. Solving $\mathbf{C}_{t(i)}$ and $\mathbf{C}_{s(i)}$

An image of the ball target as captured by the line-structured light vision sensor is shown in Fig. 3(a). In the proposed method, the image point of the light stripe on the ball target must be