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Line structured light vision sensor calibration using parallel straight lines features

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ABSTRACT

Line structured light vision sensor (LSLVS) calibration is to establish the relation between the camera and the light plane projector. This paper proposes a geometrical calibration method for LSLVS via three parallel straight lines on a 2D target. The approach is based on the properties of vanishing points and lines. During the calibration, one important aspect is to determine the normal vector of the light plane, another critical step is to obtain the distance parameter d of the light plane. In this paper, we put the emphasis on the later one. The distance constraint of parallel straight lines is used to compute a 3D feature point on the light plane, resulting in the acquisition of the parameter d. Thus, the equation of the light plane in the camera coordinate frame (CCF) can be solved out. To evaluate the performance of the algorithm, possible factors affecting the calibration accuracy are taken into account. Furthermore, mathematical formulations for error propagation are derived. Both computer simulations and real experiments have been carried out to validate our method, and the RMS error of the real calibration reaches 0.134 mm within the field of view 500 mm × 500 mm.

1. Introduction

Line structured light vision sensors are widely used in the 3D surface profiling techniques owing to its advantage of avoiding the so-called correspondence problem. A basic LSLVS consists of one camera and one light plane projector, which are fixed once the system is set up. Up to now, researchers have already presented advanced techniques for camera calibration. So the key to obtain accurate 3D measurement is the proper calibration for the projector.

Projector calibration for LSLVS is to establish the location relationship between the camera and the light plane. Many calibration approaches are presented in the past several years. We can classify those techniques roughly into two categories according to the way to obtain 3D coordinates of the feature points on the light plane (control point). One is with the assistance of apparatus [1–3], which is hard to operate and unsuitable for on-site calibration. The other obtains the control points using targets with a relative high precision [4–8].

In Ref. [5], Huynh proposed a method based on the invariance of the cross-ratio using 3D target, which consists of two or three surfaces orthogonal to each other. Wei [6] improved this technique to acquire enough 3D control points. In order to get rid of the mutual occlusion problem of the 3D target, Zhou [7] and Sun [8] proposed 2D target methods, which are more available in LSLVS calibration. Without restriction to the target motion, the projector can be readily calibrated on site by computing control points in different (at least two) local world coordinate frames (LWCF) respectively. However, these approaches need to unify all the control points at different orientations to the same given world coordinate frame, which will inevitably bring in errors and propagate the errors until the last step.

On the other hand, geometric features as circulars and vanishing points, have been extensively used in camera calibration [9,10] due to their computation easiness, but it has not earned equal attention in LSLVS calibration. Xiao [11] and Yang [12] have proposed methods relative to this aspect. In order to calculate the vanishing point of the light stripe in the same direction, Xiao used additional facilities to make the target move in precisely pure translation, and Yang used a 3D channeled target which must have two precisely parallel planes visible at the same time. To simplify the calibration procedure, Wei [13] proposed another way to calibrate LSLVS based on two derivative properties of vanishing points and lines. This method used planar rectangle target to overcome 3D target's

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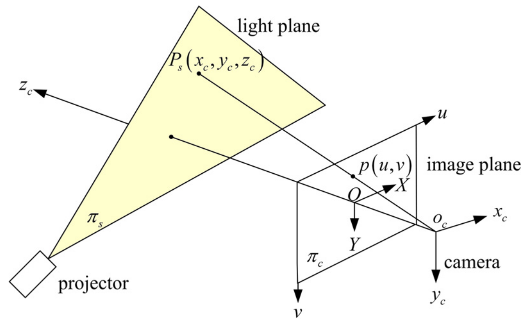

Fig. 1. Measurement model of LSLVS.

defect, and also avoided the computation on the unification of control points. But it is not robust due to the location accuracy of the vanishing point which is determined by only two parallel straight lines on the planar target. To improve the robustness against noise, we need to add more parallel straight lines to the two existed directions. However, this pattern is not typical enough in reality. We could hardly find similar object to replace the planar target in real life if essential. In our another paper published by journal *Optical Engineering* [14], we use only a set of parallel straight lines (at least three) to obtain the normal vector of the light plane based on the theory in Ref. [15], however, the way to determine the distance parameter d is a little complicated and lacks geometrical concept. In practice, parallel features commonly occur in man-made structures, such as stairs, fences, zebra crossings and windows on the wall of a building. So our paper will further discuss the calibration method using parallel straight lines, especially the acquisition of the distance parameter d.

This paper is organized as follows. Section 2 presents a brief review about the measurement model of LSLVS. Section 3 details the proposed calibration method. Section 4 studies some factors affecting the calibration accuracy and presents the computer simulations. Section 5 provides real data to validate the proposed technique. Section 6 comes to conclusions.

2. Measurement model of line structured light vision sensor

The measurement model of LSLVS is illustrated in Fig. 1. It is useful to identify several coordinate frames as shown in Fig. 1. $o_c x_c y_c z_c$ is the camera coordinate frame. ouv is the image coordinate frame in pixel and OXY is the image coordinate frame in millimeter. According to the perspective projection model, we have the following equation between the point $\boldsymbol{P} = (x_c, y_c, z_c)^{\mathrm{T}}$ in CCF and its image coordinate $\boldsymbol{p} = (u, v)^{\mathrm{T}}$

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \boldsymbol{K}\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \quad (1)$$

where $\boldsymbol{K} = \begin{bmatrix} a_x & \gamma & u_0 \\ 0 & a_y & v_0 \\ 0 & 0 & 1 \end{bmatrix}$ is the camera intrinsic parameter matrix obtained by camera calibration. a_x and a_y denote the effective focal-length of the camera, (u_0, v_0) is the principal point, γ describes the skewness of two image axes. s is an unknown scale.

In the measurement model of LSLVS, let $\boldsymbol{P}_s$ be an arbitrary point lying on the light plane π_s. $\boldsymbol{p}$ is an ideal projection point in the image plane π_c. As shown in Fig. 1, $\boldsymbol{P}_s$ is the intersection point of $o_c p$ and π_s. Knowing the light plane equation of π_s and the line equation of $o_c p$ in CCF, then the 3D position of the measured point $\boldsymbol{P}_s$ can be computed.

Thus, the mathematical model of structured light vision sensor can be written as follows:

$$\begin{cases} s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \boldsymbol{K}\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \\ a_c x_c + b_c y_c + c_c z_c + d_c = 0 \end{cases} \quad (2)$$

In this research, our task is to obtain the normal vector $\boldsymbol{n}_c = (a_c, b_c, c_c)^{\mathrm{T}}$ and the parameter d_c of the light plane, assuming the camera has already been calibrated.

3. Projector calibration

Our calibration method based on parallel straight lines features can be carried out by two steps. Compute the normal vector $\boldsymbol{n}_c$ of the light plane by the properties of vanishing points and the vanishing line of the light plane proved in Ref. [13], which is also used in our another paper published by journal *Optical Engineering*. Here, we will pay more attention to the acquisition of the parameter d_c using the distance constraints of the parallel straight lines.

3.1. Acquisition of the normal vector $\boldsymbol{n}_c$ of the light plane

This section will briefly give the way to determine the normal vector. Parallel nature does not remain under perspective projection. As shown in Fig. 2, $\boldsymbol{l}'_0, \boldsymbol{l}'_1, \boldsymbol{l}'_2$ are not parallel in picture anymore but converting to an intersection. This property contributes to determine the vanishing line of the planar target. Inspired by the conclusion in Ref. [15], we construct the vanishing line through three imaged parallel straight lines directly, rather than using vanishing points as an intermediate step in Ref. [13].

Conclusion 1. *The vanishing line $\boldsymbol{l}$ of a plane π in 3D space is determined by $\boldsymbol{l}'_0, \boldsymbol{l}'_1, \boldsymbol{l}'_2$, which are the images of three coplanar equally spaced parallel straight lines, and the following equation stands* [15]:

$$\boldsymbol{l} = (\boldsymbol{l}'_0 \times \boldsymbol{l}'_2)^{\mathrm{T}}(\boldsymbol{l}'_1 \times \boldsymbol{l}'_2)\boldsymbol{l}_1 + 2(\boldsymbol{l}'_0 \times \boldsymbol{l}'_1)^{\mathrm{T}}(\boldsymbol{l}'_2 \times \boldsymbol{l}'_1)\boldsymbol{l}'_2 \quad (3)$$

Secondly, we need to use the derivative properties of vanishing points and lines in LSLVS which have been proved in Ref. [13].

Derivation 1. *For a planar target with a light stripe on it, the image of light stripe will intersect the vanishing line of the planar target plane at a point $\boldsymbol{v}$, which is exactly the vanishing point of the light stripe.*

Derivation 2. *If we place the planar target with a light stripe at different positions, the vanishing line $\boldsymbol{l}$ of the light plane is formed by the different vanishing points of the light stripes.*

As shown in Fig. 2, $\boldsymbol{l}$ denotes the vanishing line of the planer target. $\boldsymbol{l}'_s$ denotes the image of the light stripe projected by the light plane. Their intersection $\boldsymbol{v}_2$ is just one vanishing point of the light plane. Let us denote vanishing line of the light plane by $\boldsymbol{l}_v$. To form $\boldsymbol{l}_v$, we just need to find another vanishing point by placing the planar target at another position within the camera's view field.

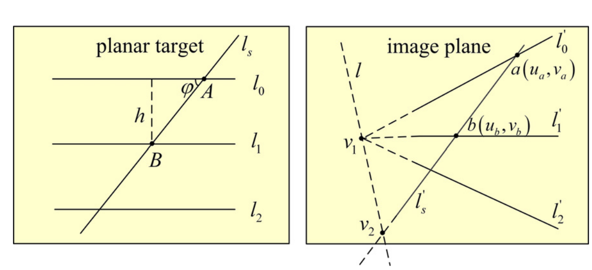

Fig. 2. Planar target and its image.