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Flexible Calibration of a Portable Structured Light System through Surface Plane

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Abstract For a portable structured light system, it must be easy to use and flexible. So the inconvenient and expensive equipment for calibration such as two or three orthogonal planes or extra fixed equipment should not be considered. For the purpose of fast 3D acquisition, the projection matrices of a portable structured light system should be estimated. This paper proposes a flexible calibration method to meet the requirements of the portable structured light system through a surface plane. A calibration board is attached to the surface plane, and a reference pattern is also projected by an LCD projector onto the surface plane. The camera observes the surface plane at a few different positions. Then, the world-to-image point pairs for the camera and projector are obtained based on the cross ratio and epipolar geometry, and the system is thus calibrated. The experiments conducted for the proposed calibration method demonstrate its accuracy and robustness.

Key words Projector calibration, camera calibration, portable structured light system

Research on shape reconstruction and object recognition by projecting structured light stripes onto objects has been active since the early 1970s. Due to their fast speed and non-contact nature, structured light techniques have found numerous applications. A basic structured light system consists of a camera and a light (or laser) stripe projector, in which the projector projects light stripes on a measured object and the camera obtains images of the light stripes modulated by the depth of the object. Unlike a classic stereo vision system, the structured light system can generate dense world points by sampling image points on each light stripe in the image and alleviate the so-called correspondence problem.

Although the difficult matching problem can be alleviated, the structured light system must be fully calibrated before measuring an object[1]. The existing approaches to calibrate a structured light system take two steps: camera calibration and projector calibration. The camera calibration has been well studied. The world-to-image perspective matrix and the distorted coefficients are estimated using at least 6 noncoplanar world points and their corresponding projected image points. For the projector calibration, two main approaches are proposed. One is to estimate the coefficients of the equation of each light stripe plane relative to the same world system. For each light stripe plane, at least 3 noncollinear world points that fall onto the light stripe plane are required[2−4]. The other is to view the projector as an inverse camera, and a set of world-to-image point pairs (at least 6) is used to estimate the perspective matrix of the projector[5−7].

For a portable structured light system, it must be easy to use and be flexible. So the inconvenient and expensive equipment for calibartion such as two or three orthogonal planes[2−3, 5] or extra fixed equipment[6−8] should not be considered. The calibration method to estimate each light stripe plane[2−4] will give much computation burden when many stripes that are not suited for rapid 3D acquisition are projected. Different from the above methods, a flexible calibration method is proposed for the portable structured light system in this paper. Our method uses a calibration board, which is a paper sheet with circular control points printed on a laser printer. It is attached to a surface plane and a reference pattern, which is an electronically designed pattern with some horizontal red stripes and one green stripe and projected onto the surface plane by an LCD projector. The surface plane is observed by the camera at a few different positions. Based on the cross ratio and the epipolar geometry, the world-to-image point pairs for the projector and camera are obtained, and the system is conveniently calibrated.

The rest of the paper is organized as follows. Section 1 presents some preliminaries. The proposed flexible calibration method is detailed in Section 2. Section 3 reports some experiments and some conclusions are listed in Section 4.

1 Preliminaries

Throughout the paper, we denote the known world points by upper case $\boldsymbol{M}$ with the superscript w, e.g. $\boldsymbol{M}^w = [x^w, y^w, z^w]^{\mathrm{T}}$, and denote the image points by lower case $\boldsymbol{m}$ with the superscript c for the image points of the camera and the superscript p for the image points of the projector, e.g. $\boldsymbol{m}^c = [u^c, v^c]^{\mathrm{T}}$ and $\boldsymbol{m}^p = [u^p, v^p]^{\mathrm{T}}$. Homogeneous coordinates are denoted by adding a "$\sim$" above the entities, e.g. $\widetilde{\boldsymbol{M}}^w = [x^w, y^w, z^w, 1]^{\mathrm{T}}$. $o^c x^c y^c z^c$ is the camera system. $o^w x^w y^w z^w$ is the world system with its $x^w y^w$ axes on the calibration surface plane, to which the calibration board is attached, and z^w axis perpendicular to the surface plane and pointing toward the structured light system.

1.1 Camera and projector model

The camera used here is of the pinhole model. Under the model, a 3D point $\boldsymbol{M}^w$ is projected to an image point $\boldsymbol{m}^c$ by

$$\widetilde{\boldsymbol{m}}^c \propto K^c [R^c\ \boldsymbol{t}^c] \widetilde{\boldsymbol{M}}^w \tag{1}$$

where "$\propto$" stands for the equality up to a scale factor; $[R^c\ \boldsymbol{t}^c]$, called the extrinsic parameters matrix, represents the rotation and translation between the world system and the camera system; and K^c is the camera's intrinsic parameters matrix of the form

$$K^c = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix}$$

where (u_0, v_0) are the coordinates of the principle point, α and β the focal lengths along the u and v axes of the image plane, and γ the parameter describing the skewness of the two image axes.

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For the camera lens distortion, we use the following model. Let (x_u, y_u) be the ideal (undistorted) image coordinates, and (x_d, y_d) the corresponding real observed (distorted) image coordinates; then,

$$x_d = x_u + x_u r^2(k_1 + k_2 r^2) + 2k_3 x_u y_u + k_4(r^2 + 2x_u^2) \quad (2)$$

$$y_d = y_u + y_u r^2(k_1 + k_2 r^2) + k_3(r^2 + 2y_u^2) + 2k_4 x_u y_u \quad (3)$$

where $r^2 = x_u^2 + y_u^2$, k_1 and k_2 are the coefficients of the radial distortion, k_3 and k_4 are the coefficients of the tangential distortion.

The model for the projector is the same as the one for the camera without lens distortion. So the relationship between a 3D point $\boldsymbol{M}^w$ and its image projection $\boldsymbol{m}^p$ can also be expressed as

$$\widetilde{\boldsymbol{m}}^p \propto K^p[R^p\ \boldsymbol{t}^p]\widetilde{\boldsymbol{M}}^w \quad (4)$$

where $[R^p\ \boldsymbol{t}^p]$ represents the rotation and translation between the world system and the projector system, and K^p is the projector′s intrinsic parameters matrix.

1.2 Cross ratio

Collinearity and cross ratio are known to be invariant under perspective projection. So, when the cross ratio r of collinear image points $\boldsymbol{p}^c, \boldsymbol{q}^c, \boldsymbol{r}^c, \boldsymbol{m}^c$ and their three corresponding world points $\boldsymbol{P}^w, \boldsymbol{Q}^w, \boldsymbol{R}^w$ are known, the coordinates of the fourth world point $\boldsymbol{M}^w$ can be determined by the cross ratio.

1.3 Epipolar geometry

The epipolar geometry is the intrinsic projective geometry between two views[9]. It is independent of scene structure and only depends on the cameras′ intrinsic parameters and relative pose. The fundamental matrix F encapsulates this intrinsic geometry. If a world point $\boldsymbol{M}^w$ is projected to an image point $\boldsymbol{m}^c$ in the first view, and $\boldsymbol{m}'^c$ in the second, then, the image points satisfy

$$\widetilde{\boldsymbol{m}}'^{c\mathrm{T}} F \widetilde{\boldsymbol{m}}^c = 0 \quad (5)$$

Given an image point $\boldsymbol{m}^c$ in the first image, we can obtain a line $\boldsymbol{l} = F\widetilde{\boldsymbol{m}}^c$ in the second image. The corresponding point $\boldsymbol{m}'^c$ in the second image must be lying on line $\boldsymbol{l}$. Line $\boldsymbol{l}$ is called the epipolar line corresponding to $\boldsymbol{m}^c$.

2 A flexible calibration method

2.1 Camera calibration

Our calibration board is a paper sheet with circular control points. It is attached to a surface plane. The surface plane shown at a few different positions is taken by the camera. Then, the centroids of the circular control points at each position are detected. Using Zhang′s method[10] and iterative refinement algorithms, the camera′s intrinsic and extrinsic parameters including distortion coefficients are calibrated.

This part is rather conventional. The core of our system calibration is to calibrate the projector, where the key step is to make the projector able to see the surface plane, in other words, to indirectly derive the point correspondences from the surface plane to the projector′s image (i.e. world-to-image point pairs). In the following section, this will be elaborated.

2.2 Fundamental matrix determination between the camera and the projector

To determine the fundamental matrix between the camera and the projector, a fundamental pattern is projected onto the surface plane by an LCD projector and captured by the camera. The fundamental pattern is an electronically designed grid composed of two green and some red lines, as shown in Fig. 1.

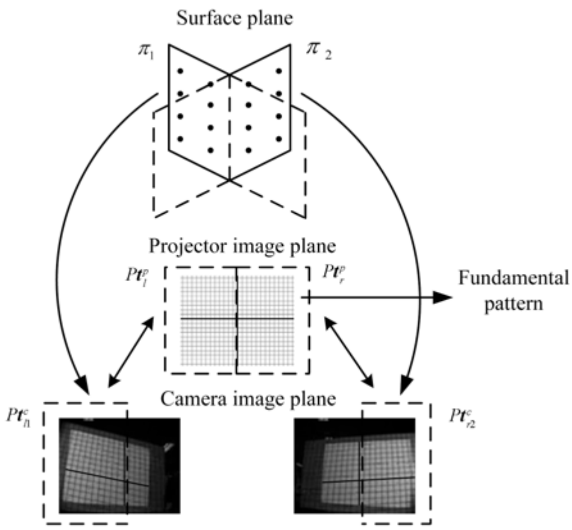

Fig. 1 Estimation of the fundamental matrix between the camera and the projector (Here, the bold lines denote the green lines and the grey lines denote the red lines. The meanings of the bold lines and grey lines in Figs. 2 ∼ 5 are the same as those in Fig. 1.)

The two orthogonal green lines are to define the absolute positions of the intersection points. Then, the projected intersection points of lines on the projector image plane (i.e. fundamental pattern) and their corresponding images on the camera image plane are used to estimate the fundamental matrix. Since the normalized 8-points algorithm needs at least 8 noncoplanar points to compute the fundamental matrix, the surface plane is moved to another position and the second image is captured. The new position should be noncoplanar with the first one. Here, in Fig.1, a pure rotation position is illustrated. The intersection points on the left side of the vertical green line in the fundamental pattern are denoted by $\boldsymbol{Pt}_l^p$ and those on the right side are denoted by $\boldsymbol{Pt}_r^p$. The corresponding points to $\boldsymbol{Pt}_l^p$ on the first image are denoted by $\boldsymbol{Pt}_{l1}^c$ and those to $\boldsymbol{Pt}_r^p$ on the second image are denoted by $\boldsymbol{Pt}_{r2}^c$. Then, the two sets of the corresponding point pairs $(\boldsymbol{Pt}_l^p, \boldsymbol{Pt}_{l1}^c)$ and $(\boldsymbol{Pt}_r^p, \boldsymbol{Pt}_{r2}^c)$ are noncoplanar and can be used to estimate the fundamental matrix F.

2.3 Determining the world-to-image point pairs for the projector

Although the projector is always viewed as an inverse camera, it can not capture the real image of the objects. So given the image points of the projector, its corresponding world position can not be decided directly. For determining the world-to-image point pairs for the projector, a reference pattern is projected onto the surface plane. The reference pattern is composed of one green and some red horizontal lines, as shown in Fig. 2.

The green line is to define the absolute positions of the