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3D shape measurement based on structured light projection applying polynomial interpolation technique

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ABSTRACT

Because of the intrinsic drawbacks of existing 3D measurement methods, which are based on structured light projection, they often need precise linear z stage or other precise devices involvement, and the projector's parameter or relative position between projector and camera needs to be calibrated; therefore, the system costs very high and the processing time is very long. In this paper, we present a 3D shape measurement method based on structured light projection applying polynomial interpolation technique. We have deduced that phase and depth coordinates meet a polynomial relation, and the relation is used to calibrate relative position between camera and projector. The proposed approach can realize 3D shape measurement without projector calibration, without system calibration, and without precise linear z stage to be used. The relative position between camera and projector can be arbitrary, and the only involved device is a plane board. Experiment results validated that the accuracy of the proposed approach is not lower than that of many previous methods, but our approach costs lower and can be set up more easily.

1. Introduction

A well established 3D shape measurement technique applying optical principle is triangulation with structured light. It projects a regular pattern of light onto the measured space to encode scene surfaces, and hence creates contrasted features that can be reliably extracted from image. In this way, the corresponding point's problem in classical photogrammetry stereo system is avoided [1–4]. The key to accurate reconstruction is proper calibration of each element used in structured light system.

Currently many researchers present polynomial-based calibration approach. Usually, a plane is positioned successively at different positions from camera. A marked point on the first calibration plane is used as the origin of world reference system; then the following calibration planes are chosen parallel to the first one and their displacements with respect to the first plane have to be known with high accuracy. Therefore, to obtain good calibration results, a precise linear z stage has to be used. The main drawback of this system comes from practical limitations, such as its plane position restriction, the difficulty of calibrating big measurement volumes [5–7,10–12], or the running time of calibration process is very large [13].

Other researchers model the projector as an inverse camera [5,6,9,14]. The main drawback of this method is that the technique needs previous assumptions about the camera and projector model, after which the data are fitted using typical nonlinear optimizations that suffer from intrinsic problems, such as the risk of not converging if a bad seed is used or converging to a local minimum instead of the global minimum [5,6,8].

The key for structured light system calibration is the phase–height relationship establishment [15–17]. In order to perform measurement with higher precision, some researchers proposed 3D mathematic models [18,19]. However, in their investigations, projector model is simplified such that only extrinsic parameters are considered.

In this paper, a "3D shape measurement method based on structured light projection applying polynomial interpolation technique" is presented. We have proved that phase and depth coordinates meet a polynomial relation, and the polynomial relation is used to decide relative position between projector and camera. The proposed approach can realize 3D shape measurement using structured light projection technique without precise linear z stage, projector calibration, system calibration, and without setting up relative space orient between camera and projector, and the only

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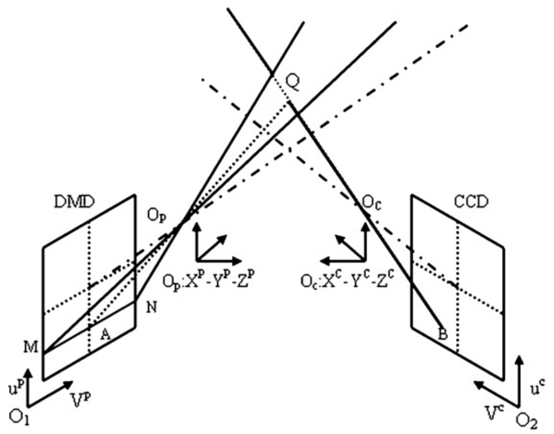

Fig. 1. The structured light projection system.

used device is a plane board. Therefore, the proposed method can be easily realized, flexible and it costs fewer than many previous methods.

This paper is organized as follows: In Section 2, the theoretical relation between phase and depth coordinates is deduced. In Section 3, the whole algorithm framework is given. In Section 4, the detailed approach is explained. At last, the experiment results are reported, and the conclusions are given.

2. Theoretical relation between phase and depth coordinates

To give a clear explanation to this research, we first deduce the theoretical relation between phase and depth coordinates. Fig. 1 shows figure of the structured light projection system, which constitutes one projector and one camera, the projector and the camera are fixed. O_c: X^c–Y^c–Z^c denotes camera coordinate system; O_p: X^p–Y^p–Z^p denotes projector coordinate system. O_p and O_c are the lens centre for projector and camera, respectively. The image buffer coordinates (u^C, v^C) in pixels on CCD, and the image buffer coordinates (u^P, v^P) in pixels on DMD (digital micromirror device). The image frame buffer coordinate axis u^C and axis v^C are parallel to camera coordinate system axis X^c and axis Y^c, respectively. The image frame buffer coordinate axis u^P and axis v^P are parallel to projector coordinate system axis X^p and axis Y^p, respectively. (u_0^c, v_0^c) is the coordinate of principal point on CCD, and (u_0^p, v_0^p) is the coordinate of principal point on DMD. We assume the direction of structured light pattern on DMD is along axis u^P, and is parallel to axis v^P. For an image point B on CCD, connects point B and camera lens centre O_c, we obtain straight-line BO_c. For a three-dimension space point Q located on straight-line BO_c, we first deduce the underlying theoretical relation between point Q's phase and point Q's depth coordinate.

On the one hand, as shown in Fig. 1, for a point A located on DMD, we draw a line MN which passes through point A, and is parallel to axis v^P. The coordinate of point A on DMD image coordinate system and projector coordinate system is denoted as (u_A^p, v_A^p) and (X_A^p, y_A^p, z_A^p), respectively. The phase value for point A can be calculated by Eq. (1). In Eq. (1), p_0 denotes period of sinusoidal structured light pattern on DMD, s_u^p denotes unit length on DMD along u^p direction:

$$\begin{aligned}\phi &= \frac{2\pi x_A^p}{p_0}\\ &= \frac{2\pi s_u^p(u_A^p - u_0^p)}{p_0}\end{aligned} \tag{1}$$

We draw a plane MNO_p whose phase value is equal to ϕ, and MNO_p passes through projector's lens centre O_P, which is shown in Fig. 1. The equation for plane MNO_p on projector coordinate system can be expressed by Eq. (2).

$$x^p\cos\alpha + y^p\cos\beta + z^p\cos\gamma = 0 \tag{2}$$

where α, β and γ denote the angles between normal vector of plane MNO_p and X^p axis, Y^p axis and Z^p axis, respectively. And $\beta = 90^\circ$ since plane MNO_p is parallel to Y^p axis. α, β and γ can be calculated by Eq. (3).

$$\left.\begin{aligned}\cos\alpha &= \frac{f_p}{\sqrt{(x_A^p)^2 + (f_p)^2}}\\ \cos\beta &= 0\\ \cos\gamma &= \frac{x_A^p}{\sqrt{(x_A^p)^2 + (f_p)^2}}\end{aligned}\right\} \tag{3}$$

where f_p denotes the focus length of projector lens.

At the same time, based on Eq. (2), plane MNO_p on camera coordinate system can be expressed by Eq. (4). In Eq. (4), m_{11}–m_{34} are the entries of the matrix $M_{4\times4}$ which transforms the coordinate from camera coordinate system to projector coordinate system.

$$\begin{aligned}(\cos\alpha\cdot m_{11} &+ \cos\beta\cdot m_{21} + \cos\gamma\cdot m_{31})\cdot x^c\\ &+(\cos\alpha\cdot m_{12} + \cos\beta\cdot m_{22} + \cos\gamma\cdot m_{32})\cdot y^c\\ &+(\cos\alpha\cdot m_{13} + \cos\beta\cdot m_{23} + \cos\gamma\cdot m_{33})\cdot z^c\\ &+(\cos\alpha\cdot m_{14} + \cos\beta\cdot m_{24} + \cos\gamma\cdot m_{34}) = 0\end{aligned} \tag{4}$$

On the other hand, for point B (u_B^c, v_B^c) on CCD image coordinate system, and its coordinate on camera coordinate system (x_B^c, y_B^c, z_B^c). The coordinates for a point (x^c, y^c, z^c) located on the straight-line BO_c on camera coordinate system can be denoted by Eq. (5). In Eq. (5), f_c denotes focus length of camera lens.

$$\left\{\begin{aligned}x^c &= \frac{x_B^c z^c}{f_c}\\ x^c &= \frac{y_B^c z^c}{f_c}\end{aligned}\right. \tag{5}$$

Substitutes x^c and y^c from Eq. (5) to Eq. (4), we obtain the depth coordinate for the intersected point Q between plane MNO_p and straight-line BO_c, the depth coordinate on camera coordinate system is denoted by Eq. (6).

$$z^c = \frac{-f_c(m_{14}\ \cos\alpha + m_{24}\cos\beta + m_{34}\cos\gamma)}{(m_{11}x_B^c + m_{12}y_B^c + m_{13}f_c)\cos\ \alpha + (m_{21}x_B^c + m_{22}y_B^c + m_{23}f_c)\cos\ \beta + (m_{31}x_B^c + m_{32}y_B^c + m_{33}f_c)\cos\ \gamma} \tag{6}$$

Because projector and camera are fixed, the parameters m_{11}–m_{34} and f_c are all constant values. For a given image coordinate (u_B^c, v_B^c), the coordinates x_B^c, y_B^c are also constant values. Therefore, the coefficients of $\cos\alpha$, $\cos\beta$ and $\cos\gamma$ in Eq. (6) are all constant values, Eq. (6) can be simpled to Eq. (7). In Eq. (7), k_1–k_6 are constant values.

$$z^c = \frac{k_1\cos\alpha + k_2\cos\beta + k_3\cos\gamma}{k_4\cos\alpha + k_5\cos\beta + k_6\cos\gamma} \tag{7}$$