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A fast and accurate calibration method for the structured light system based on trapezoidal phase-shifting pattern

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ABSTRACT

Calibration plays an important part in the structured light system. It used to be regarded as time-consuming, expensive and hard to implement. In this paper, we introduce a novel and fast method to calibrate the structured light system by using the camera to control the projector to "capture" images. Firstly, we projected just six trapezoidal grayscale pattern to establish the corresponding pixel between the camera and the projector, then we converted the camera image to its corresponding projector image. Thus the structured light system can be easy controlled by the camera calibration. Experiments showed that the present calibration method is fast, easy and accurate.

1. Introduction

In industrial production, there is a growing need for accurate 3D measurement or surface acquisition with relatively high-speed. In the past, CMM (Coordinate Measuring Machining) was frequently used in this field. CMM is expensive, time-consuming and is limited to hard materials only.

With the development of computer, optical measurement has been widely accepted and used in this field. Various optical techniques have recently been developed for measuring 3-D shape and they can be divided into the following several parts: time/light in flight, laser scanning, moire, laser speckle pattern sectioning, interferometry, photogrammetry, laser tracking system, structured light [1]. Compared to other techniques, structured light method is easy to implement, fast full field measurement and since patterns projected by LCD/DMD can be controlled by a computer, the measurement can be done without any motion. Owing to these merits, some schools and industries have started to bring the structured light method into commercialization and some can be found in Refs. [2–4]. However, if this method needs to be developed to become even more reliable and more widely accepted in application, some issues have to be addressed. To minimize the error during the measurement, calibration for the structured light system plays an essential part in it.

In this paper, a fast and novel method is proposed for high-accurate calibration of the structured light system with relatively sufficient calibration points. Firstly, the principle of the proposed structured light calibration method is reviewed in Section 2. In Section 3, some experimental results are presented, followed by a complete error analysis in Section 4. Finally, the result of the work is summarized in Section 5.

2. Basic principle of the structured light system

2.1. Camera model

To get the information of size or surface texture of the object, we need to use the Euclidean Space and the homogeneous coordinates to describe them. Calibration is just doing the process of constructing the relationship between the world coordinate system $(O,x^w y^w z^w)$ and the camera coordinate system $(O,x^c y^c z^c)$ and the relationship between the camera coordinate system $(O,x^c y^c z^c)$ and the image coordinate system(O,uv).

This pinhole model is often used in camera calibration. From Fig. 1, we can see the schematic diagram of that model. To describe the model precisely, we need to know the intrinsic parameters such as focal length (**fc**), principle point (**cc**) and skew coefficient (**alpha_c**). In addition, due to lens distortion, some other parameters should also be included in the intrinsic parameter. **kc** contains both radial and tangential distortion coefficients [5]. The extrinsic parameters include rotation matrix R and translation vector T. Hence, an arbitrary point p in the world coordinate system and its

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0030-4026/

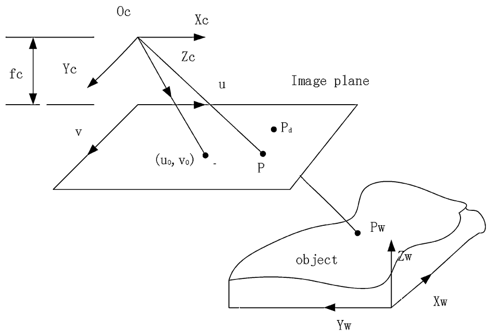

Fig. 1. The pinhole camera model.

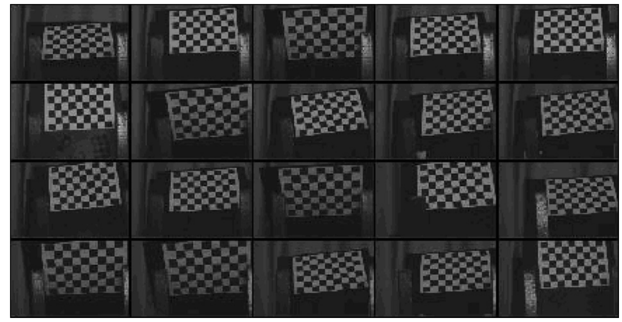

Fig. 2. A complete set of images used for calibration in thumbnail format.

projection on the image sensor can be expressed by the following equation:

$$sI = A[R, T]X^{w} \tag{1}$$

Specifically, the distortion coefficient is not included in the equation, where s is a scalar; $I = \{u,v,1\}^T$ is the homogeneous coordinate of the image point in the image coordinate system; $X^W = \{x^w,y^w,z^w,1\}^T$ is the homogeneous coordinate of the point in the world coordinate system; R and T represents the rotation matrix and the translation vector; and A is the matrix that contains the intrinsic parameters:

$$\begin{bmatrix} fc(1) & alpha\_c * fc(1) & cc(1) \\ 0 & fc(2) & cc(2) \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where the $fc(1)$, $fc(2)$, $cc(1)$, $cc(2)$ are their focal length and principle coordinators in x or y axis respectively [6].

To take distortion into consideration, we should redefine the image coordinator of the projection of $p \cdot u^d, v^d$ which are the real coordinate of p after distortion. Then the redefined image coordinate of p can be expressed by the following equation:

$$\begin{bmatrix} u^d \\ v^d \end{bmatrix} = (1 + kc(1)r^2 + kc(2)r^4 + kc(5)r^6)\begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} 2kc(3)uv + kc(4)(r^2 + 2u^2) \\ kc(3)(r^2 + 2v^2) + 2kc4)uv \end{bmatrix} \tag{3}$$

where $r^2 = u^2 + v^2$, $kc(1)$, $kc(2)$ and $kc(5)$ represent the radial distortion coefficients, and $kc(3)$, $kc(4)$ represent the tangential distortion coefficients. More elaborate nonlinear models can be found in Refs. [7–10].

2.2. Camera calibration

In order to get the intrinsic parameters, we need to prepare a flat checkerboard and place it in front of the camera with different position and orientation. After 20 images were taken by our camera (Basler acA1300-30gm) with a 16 mm lens (Computar M1614-MP), as is shown in Fig. 2 below, the Matlab toolbox provided by Bouguet [11] was used to calculate the intrinsic parameters' matrix.

$$A = \begin{bmatrix} 1953.98628 & 0 & 442.81141 \\ 0 & 1975.60256 & 143.97243 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

And its distortion parameters are $kc = [\,-0.44429 \quad 0.48021 \quad 0.00267 \quad 0.00165 \quad 0.00000\,]T$.

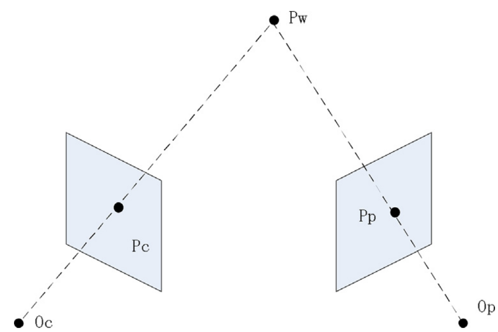

Fig. 3. A model of triangulation method.

2.3. Projector calibration

In the structured light system, the projector plays an essential part which can construct the triangulation with the camera and the object, as is shown in Fig. 3. And the 3D coordinates of the object are calculated based on this triangulation model. The structured light system is originated from the passive 3D range image sensor (stereo camera). The stereo camera systems need two or more cameras to construct the triangulation with the object. However, this measurement system is limited to some textured object. It is especially troublesome to find each correspondence of the pixels between the two or more images. For this purpose, structured light system solved the correspondence problem nicely and easily by projecting a set of striking patterns onto the object.

In the past, the method proposed Refs. [12–16] were often used in calibration. However, they all shared the following drawbacks: (1) it was difficult to obtain sufficient calibration points to get high-precision calibration parameters; (2) some calibration apparatus were expensive and therefore it was hard to put them into practical use; (3) the process of the calibration was complicated and it was not suitable for calibration on the workshop. Since the projector can be regarded as the inverse of the camera, we can calibrate the projector by another camera to help the projector to "capture" images. The action of "capturing" image can be done by constructing correspondence between each dot of CCD in camera and DMD in projector. Once the correspondence is established, the Matlab toolbox can be used again to get the intrinsic parameters of the projector and the relationship between the camera and the projector. Thus the projector can be regarded as an equipment which is a combination of a camera and a projector.

2.3.1. Calibration pattern

In our research, we discovered that the processes of the calibration and the 3D shape measurement have a lot in common. For example, they all need to find the relationship between the camera and the projector. The problem with the traditional sinusoidal phase-shifting algorithm which needs to calculate an