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A flexible and high precision calibration method for the structured light vision system

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ABSTRACT

Calibration is the process of estimating the intrinsic and extrinsic parameters of the device. In the field of photogrammetry, structured light measurement system is one of the frequently used active vision measurement systems. The accuracy of the estimated parameters of the system determines the measurement results in the later experiments and applications. Traditional methods were often not easy to implement and time-consuming. In this paper, a flexible and accurate method for calibrating the structured light system and a hybrid pattern which takes both the advantages of time multiplexing method and spatial neighborhood method is proposed. To make full use of the available open source of the camera calibration toolbox, this method treats the projector as a virtual camera. By analyzing the projected patterns and establishing the relationship between the projector and the camera, the projector of the structured light system is able to "capture" images on its own and thus can be calibrated easily and accurately like the usual camera as well. The experimental results show that the intrinsic and extrinsic parameters of the structured light system were estimated with high precision.

1. Introduction

In industrial fields, the quality of the products relies highly on its level of the precision. Traditionally, the size and dimension of the products were measured by the expensive and heavy device-CMM (Coordinate Measuring Machining). Though the measurement data were accurate and precise enough, the process of measurement is cumbersome and the data cannot be obtained reliably at a relative high speed. Nowadays, a variety of non-contact optical measurement techniques, like time/light in flight, stereo cameras and structured light system, become available and are frequently applied to different situations [1]. The time/light in flight technique can obtain the highest precision data but can only obtain the information of a single point each time, thus the process of measurement is time-consuming. The stereo camera system is cheap to implement and can obtain relatively high precision data but can not measure the object with smooth surface and can not do the measurement under poor light conditions. To take the speed, accuracy, cost, portability and scope of application into account, the structured light system is the most suited for the applications of 3D reconstruction [2], virtual reality [3], etc.

Calibration is a necessary work in the application of high precision 3D measurement [4]. A great deal of deal of calibration methods were proposed [5] in the past, such as two stages method [6], nonlinearity optimization method [7], direct linear transform method [8], etc. Wang proposed a mechanical shift algorithm to determine the system structured parameters [9]. Davis replaced the monocular camera with the stereo camera to simplified the optical model of the structured light system and treated the projector as a light source [10]. Some intelligent artificial algorithms were also applied in the process of calibration. Dipanda [11] used the Genetic Algorithm and Feng used the neural network technique to calibrate the structured light system directly without estimating the camera intrinsic, extrinsic and the systematic parameters.

In this paper, a flexible and accurate calibration method is presented. Some basic notations and principle of the structured light system is declared in Section 2. The details of the calibration method and the projected patterns were explained in Section 3. Section 4 is devoted to the experimental results and the error analysis, followed by our conclusions in Section 5.

2. Basic principle and notations

2.1. Camera model

The camera is like a function which maps the 3D space points to the 2D image points. The most specialized and simplest

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0030-4026/

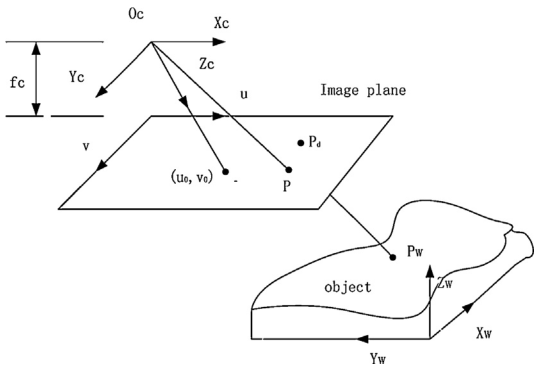

Fig. 1. The pinhole camera model.

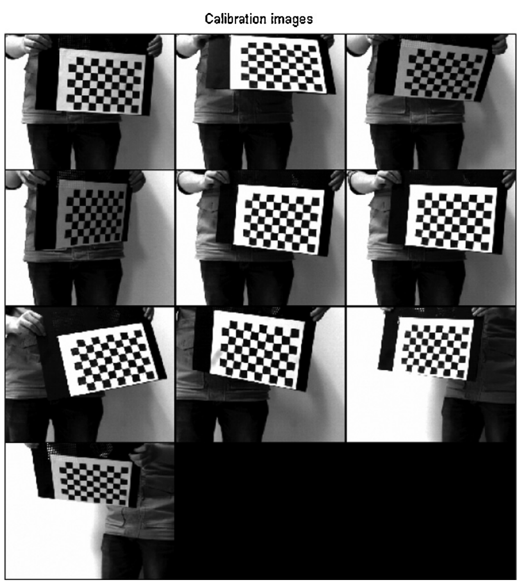

Fig. 2. A sequence of images used for calibration in thumbnail format.

camera model is the basic pinhole camera model, as shown in Fig. 1. There are three coordinate systems appearing in the model, namely, the world coordinate system $(O, x^w y^w z^w)$, the camera coordinate system $(O, x^c y^c z^c)$ and the image coordinate system (O, uv). Their relationship can be expressed by Eq. (1) (Fig. 2).

$$sx = K\begin{bmatrix} R & t \end{bmatrix} X \tag{1}$$

where s is a scalar, $x = (u, v, 1)^T$ in the image plane and $X = (x^w, y^w, z^w, 1)^T$.

$$K = \begin{bmatrix} f & sk & x_0 \\ 0 & f & y_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where K is a 3×3 matrix and contains all the intrinsic parameters, that is, focal length f, skew parameter sk and principal point $(x_0, y_0)^T$. The 3×3 orthogonal matrix R and 3×1 vector t form the extrinsic matrix, which describe the transformation between the camera coordinate system and the world coordinate system. Given a set of image points and their corresponding 3D space point, the intrinsic and extrinsic parameters can be estimated using Eq. (1). However, the pinhole camera is only an approximation of the real optical imaging model. When the problem comes to high precision measurement, the tangent and radial distortion coefficients must be considered as well. Eq. (3) is used for back-projecting the

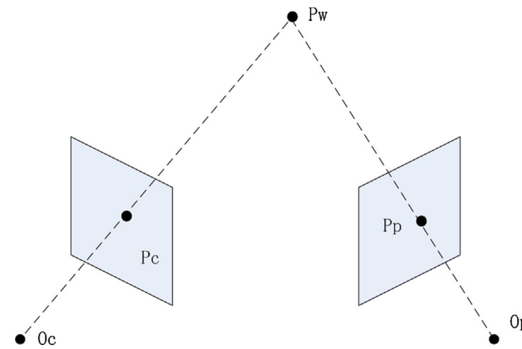

Fig. 3. A model of triangulation method.

distorted pixels to the rectified pixels [12].

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

where u^d, v^d is the distorted pixel coordinate in the captured image and u^{org}, v^{org} is the ideal pixel coordinate without distortion, the 5×1 vector kc is the distortion coefficients, $r^2 = (u - u_0)^2 + (v - v_0)^2$.

2.2. Camera calibration

Generally, a piece of paper with know square size chessboard pattern is used for calibration. By pasting it on a flat board and setting z axis of world coordinate system orthogonal to the flat board and the x,y axes parallel to the edges of the chessboard pattern, a set of 3D point coordinates is obtained. Generally, the top-left corner on the chessboard pattern is chosen to be the original point. For a better and more accurate experimental result, a sequence of images of the chessboard pattern with different orientations and distances were taken by the camera (DH-HV1351UM-ML) with a 16 mm fixed focal lens (Computar M1614-MP). To estimate the intrinsic parameters, the open source Matlab toolbox provided by Bouguet was used [13]. The captured images and the calibration result is shown below. The intrinsic matrix K:

$$K_{cam} = \begin{bmatrix} 2277.22844 & 0 & 671.00895 \\ 0 & 2283.88535 & 557.91760 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

and its distortion parameters are $kc_{cam} = \begin{bmatrix} -0.16834 & 0.79875 & 0.00338 & -0.00111 & 0.00000 \end{bmatrix}^T$.

2.3. Projector model

As mentioned in the previous chapter, a general central camera maps the 3D space point to 2D image point. In the process of this projection, the depth or the distance along the z axis is lost. The depth of every single 3D space point cannot be calculated by two independent equations provided by Eq. (1). A variety of algorithms and hardware designs were proposed in the past decades [14]. The basic idea behind these inventions, like structure from motion algorithm and stereo camera, is to construct one or more triangulation model, as shown in Fig. 3. By adding one or more images, two or more independent equations about the same 3D space point can be added and thus the depth information can be estimated. In structured light system, the projector acts both as a camera and as a light