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Non-iterative three dimensional reconstruction method of the structured light system based on polynomial distortion representation

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ABSTRACT

In monocular structured light system, the iterative reconstruction method makes the measurement time-consuming, and the measurement accuracy is often hindered by the fact that the first-order radial distortion is included only. Compared with the conventional projector model, a new projector model, including both radial and tangential distortion, is proposed in this paper, which is described with the pinhole model according to the light direction. Furthermore, the iterative method is replaced by solving a quartic polynomial problem directly based on the proposed projector model. Experimental results show that the measurement accuracy and the efficiency are improved obviously. The standard deviation of the proposed method is 0.037mm, which is about a third of 0.113mm of the iterative method. The time consumed by the proposed method is 3.3% of that by the iterative method when one hundred thousand points are reconstructed.

1. Introduction

Structured light system is a three dimensional measurement system with high accuracy, simple equipment and satisfactory speed, which generally consists of one or more cameras and a projector [1,2]. It has been widely used in industrial precision inspection, three dimensional body scanning, heritage conservation, and so on [3–6]. The keys to a structured light system are system calibration, structured light encoding, and reconstruction. Many researchers contributed to these fields and made remarkable achievements.

As the most important problem, system calibration had been focused in the last decades [7–11]. Zhang solved the camera calibration accurately by observing a planar pattern [7], whose method had already been widely used in structured light system. Zhang and Huang treated the projector as an inverse camera [8], thus making the calibration of a projector the same as that of a camera. Then, Li et al. improved the projector calibration by reducing the phase error and interpolating the Digital Mirror Device (DMD) images [9]. To deal with the distortion, Huang et al. presented an error surface compensation method [10], which minimized mapping error caused by camera and projector distortion. Recently, Liu et al. proposed a projector calibration method by making use of photodiodes to directly detect the light emitted from a projector [11], and a polynomial distortion representation is employed to reduce the error of traditional projector model. Structured light encoding is another essential problem. Sinusoidal grating encoding and phase shifting algorithm are the most advanced and effective methods [12], by now they had already been utilized in most commercial structured light systems. An advanced topic of encoding is to reduce the number patterns for real-time measurement [13–15]. For example, Trusiak et al. proposed a hybrid single shot algorithm [14] for a composite structured light system, in which empirical mode decomposition was employed, aided by the principal components analysis, and He et al. reduced measurement error caused by spectrum overlapping [15] in a composite structured light system based on fringe parameter calculation. The final problem is reconstruction. Theoretically, reconstruction can be achieved directly based on optical triangle principle in the linear system model. However, there are two primary problems that make reconstruction more difficult, the phase error and the lens distortion. Numerous effective methods were proposed to reduce the phase error. Zhang and Yau improved the traditional look up table generation method [16] for the phase error by analyzing the captured fringe image of a flat board. Then, Liu et al. studied the gamma effect and developed a mathematical model [17] for predicting the effects of non-unitary gamma. Furthermore, Yatabe et al. proposed a post-processing method [18] for compensating general fringe distortion based on the inverse map estimation, which made the fringe patterns accurate enough. Lens distortion were also considered by many scholars [19–22], especially the first-order radial distortion. Valkenburg solved the reconstruction with iterative method [19] when including first-order radial distortion, which also gave a general description of reconstruction equations. Huang and Han simplified the iterative method [20] by undistorting the camera images firstly, and then solved the reconstruction with the first order radial distortion of projector. Ma et al. extended the reconstruction equations

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to appropriate for complex distortion models [21], and corrected the error pixel by pixel based on iterative method. To make the measurement efficient, Li et al. eliminated the projector distortion by projecting distorted fringe patterns [22], which were generated according to the projector model. However, the solution to analytic reconstruction equations is always iterative and time-consuming, and the specific distortion model is also related to the measurement accuracy and efficiency. In a word, the lens distortion restricts the precision of structured light system and an appropriate non-iterative method is expected.

A non-iterative method is proposed in this paper to solve the lens distortion efficiently. This method is based on a projector model, which applies the pinhole model to the projector description according to the light direction. In this projector model, the measuring object is considered as the image plane, while the Digital Mirror Device (DMD) reflects light to it. Corresponding to this model, lens distortion description equations are reorganized, and the reconstruction is simplified to a problem of solving a polynomial. As the iteration is inevitable when the polynomial order exceeds four, the reconstruction is described by two polynomials of three order and four order, whose coefficients are obtained by curve fitting algorithm. The experimental results prove the validity of the proposed non-iterative method.

The rest of this paper is organized as follows: Section 2 describes the basic nonlinear model of structured light system. Section 3 discusses the proposed method, together with the ideas to it. In Section 4, experiments are implemented to verify the proposed method. Finally, Section 5 concludes this work.

2. Structured light system model

A monocular structured light system consists of a camera and a projector. The camera is described by a pinhole model, which is represented by intrinsic and extrinsic parameters, together with nonlinear compensation items to represent lens distortion [20]. The projector is generally considered as an inverse camera and it can capture DMD images [8], thus the camera model can be applied appropriately to the projector.

2.1. Camera and projector model

The pinhole model is described to present an ideal camera without lens distortion. M_c is an arbitrary point in the space with coordinates $X^w = [x^w, y^w, z^w]^T$ in the world coordinate system $\{O_W; X_W, Y_W, Z_W\}$, and $X^c = [x^c, y^c, z^c]^T$ in the camera coordinate system $\{O_C; X_C, Y_C, Z_C\}$, as shown in Fig. 1.

The relationship between M_c and its projection point m on the image plane $\{o; u, v\}$ is expressed as Eq. (1).

$$z^c \begin{bmatrix} u^c \\ v^c \\ 1 \end{bmatrix} = A^c \begin{bmatrix} R^c & T^c \end{bmatrix} X^w \tag{1}$$

where $[u^c, v^c, 1]^T$ is the homogeneous pixel coordinate of m in the image coordinate system $\{o; u, v\}$. A^c is the intrinsic parameters matrix of the camera, $[R^c \quad T^c]$ is the extrinsic parameters matrix that represents the rotation and translation between X^w and X^c. A^c and R^c are invertible matrices with 3×3 elements. T^c is a vector with 3×1 elements, expressed as $[t_1^c, t_2^c, t_3^c]^T$. A^c is expressed as Eq. (2).

$$A^c = \begin{bmatrix} \alpha^c & \gamma^c & u_0^c \\ 0 & \beta^c & v_0^c \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where $[u_0^c, v_0^c]^T$ is the principle point, α^c and β^c are the focal lengths along with the axes of the image plane, γ^c is the skew factor, normally set as zero.

On the basis of the pinhole model, lens distortion is included to improve the system accuracy. A typical lens distortion model including radial and tangential distortion is expressed as polynomials with normalized coordinate [23]. X_n^c is the normalized coordinate when lens distortion is ignored, which is expressed as Eq. (3).

$$X_n^c = [x_n^c, y_n^c]^T = \left[\frac{x^c}{z^c}, \frac{y^c}{z^c}\right]^T \tag{3}$$

When lens distortion is included, the normalized coordinate X_d^c is expressed as Eq. (4),

$$X_d^c = \begin{bmatrix} x_d^c \\ y_d^c \end{bmatrix} = LDF(X_n^c) = (1 + k_1^c r^2 + k_2^c r^4) X_n^c + D_t + O[(x_n^c, y_n^c)^5] \tag{4}$$

where LDF is the lens distortion function, k_1^c and k_2^c are radial distortion coefficients, D_t is the tangential distortion item caused by decentering distortion, r^2 is expressed as $r^2 = (x_n^c)^2 + (y_n^c)^2$. D_t is expressed as Eq. (5) [23].

$$D_t = \begin{bmatrix} p_1^c(3(x_n^c)^2 + (y_n^c)^2) + 2p_2^c x_n^c y_n^c \\ 2p_1^c x_n^c y_n^c + p_2^c((x_n^c)^2 + 3(y_n^c)^2) \end{bmatrix} \tag{5}$$

where p_1^c and p_2^c are tangential distortion coefficients. Therefore, the coordinate transformation process of nonlinear camera model is concluded as $X^w \to X^c \to X_n^c \to X_d^c \to ([u^c, v^c]^T)$.

In structured light system, the conventional projector model treats the projector as an inverse camera [9], whose emitted encoding patterns are imagined as the captured images. Thus the projector can capture a series of images and be modeled with the pinhole model. The coordinate transformation process of nonlinear projector model is specialized as $X^w \to X^p \to X_n^p \to X_d^p \to ([u^p, v^p]^T)$.

Here the superscript p means the projector coordinate. v^p is unknown to the structured light system [19]. Projecting enough encoding patterns in different directions will solve this problem easily, but it is not used in commercial systems because of time-consuming, increasing phase error and so on. Therefore, only u^p of a point on the emitter is available.

2.2. Iterative reconstruction method

Based on the pinhole model and Eq. (1), there are

$$\begin{aligned} z^c \begin{bmatrix} X_n^c \\ 1 \end{bmatrix} &= \begin{bmatrix} R^c & T^c \end{bmatrix} X^w \\ z^p \begin{bmatrix} X_n^p \\ 1 \end{bmatrix} &= \begin{bmatrix} R^p & T^p \end{bmatrix} X^w \end{aligned} \tag{6}$$

The relationship between X_n^c and X^p is deduced, expressed as Eq. (7),

$$z^c \begin{bmatrix} X_n^c \\ 1 \end{bmatrix} = \begin{bmatrix} R^c & T^c \end{bmatrix} \begin{bmatrix} R^p & T^p \end{bmatrix}^{-1} X^p \tag{7}$$

where $[R^p \quad T^p]^{-1}$ means the transformation from X^p to X^w rather than an actual inverse matrix. There are four unknowns, z^c and $X^p = [x^p, y^p, z^p]^T$, while only three linear equations are available in Eq. (7).

Considering the constraints provided by encoding patterns, there is

$$\frac{u^p - u_0^p}{\alpha^p} = LDF\left(\frac{x^p}{z^p}\right) \tag{8}$$

Combining Eq. (7) and Eq. (8), X^p and X^w can be solved theoretically. In view of the nonlinearity of Eq. (8), it generally is solved by iterative algorithm, such as a quasi-Newton strategy. It should be mentioned that the camera image point is undistorted directly regardless of the camera distortion models [20], thus only one non-linear equation, Eq. (8) appears in reconstruction to express the projector distortion.

3. Non-iterative reconstruction method

Although the iterative method is available, it is not always a good solution, especially when complex distortion model is included. Therefore, it is necessary to develop a non-iterative method for the reconstruction.