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Lens distortion elimination for improving measurement accuracy of fringe projection profilometry

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ABSTRACT

Fringe projection profilometry (FPP) is a powerful method for three-dimensional (3D) shape measurement. However, the measurement accuracy of the existing FPP is often hindered by the distortion of the lens used in FPP. In this paper, a simple and efficient method is presented to overcome this problem. First, the FPP system is calibrated as a stereovision system. Then, the camera lens distortion is eliminated by correcting the captured images. For the projector lens distortion, distorted fringe patterns are generated according to the lens distortion model. With these distorted fringe patterns, the projector can project undistorted fringe patterns, which means that the projector lens distortion is eliminated. Experimental results show that the proposed method can successfully eliminate the lens distortions of FPP and therefore improves its measurement accuracy.

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1. Introduction

Fringe projection profilometry (FPP) has become one of the most prevalent methods for three-dimensional (3D) shape measurement because of its considerable advantages such as low cost, easy-to-implement, high accuracy, and full field imaging [1,2]. During the past three decades, the technique has been widely used in many fields such as product inspection, robot vision, reverse engineering, and quality control [3,4].

A diagram of the FPP system is shown in Fig. 1. For a typical 3D shape measurement, the projector projects a series of fringe patterns onto the object surface, and the camera captures the deformed fringe patterns. Then, a two-dimensional (2D) absolute phase distribution is extracted from the captured deformed fringe patterns with phase retrieval methods that have been well developed in the last three decades [5–10]. The 3D shape of the object is reconstructed by mapping the absolute phase distribution to real world 3D coordinates. The mapping relationship between the absolute phase distribution and the real world 3D coordinates can be determined through a system calibration procedure [11–20].

Lens distortions practically present in camera lens and projector lens causing non-uniform geometric distortion in the captured images and projected images, give rise to errors in the 3D shape measurement of FPP [15–20]. The camera lens distortion can be eliminated through various powerful camera calibration techniques [21–24]. However, the projector lens distortion is relatively hard to handle since the projector projects images rather than captures them. The lens distortion problem will cause more larger errors when testing large-size objects and becomes one of the major sources which hinder the measurement accuracy of FPP.

Many researchers have studied the lens distortion problem of FPP and a number of methods have been presented to solve this problem. The methods can basically be categorized into two groups. The first group only considers the camera lens distortion. Huang et al. [15] presented an improved least-squares calibration method considering camera lens distortion. The method improves the measurement accuracy of the original least-squares method [14]. However, the governing equation presented in the method suffers from divergence and instability in the numerical computation and another governing equation is then recommended in [16]. Feng et al. [17] realize a high-speed real-time FPP system, in which the camera lens distortion is eliminated by correcting the captured images. The measurement accuracy of the real-time FPP system is successfully improved. The second approach considers both the camera lens distortion and the projector lens distortion. Zhang et al. [18,19] use polynomial functions to establish the relationship between the absolute phase distribution and the real world 3D coordinates. The method is successful since the polynomial functions can well represent the nonlinear relationship between the absolute phase and the 3D coordinates caused by both the camera lens distortion and the projector lens distortions.

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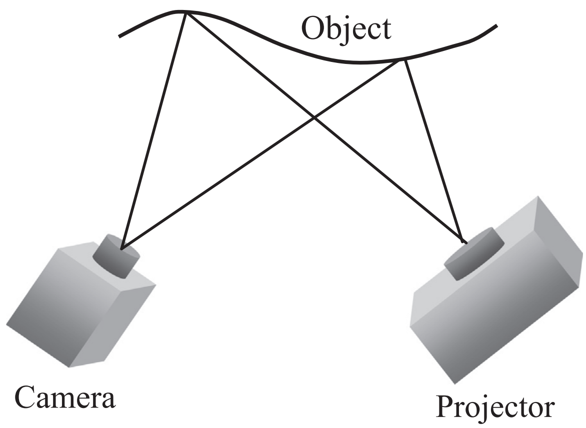

Fig. 1. Schematic diagram of the FPP system.

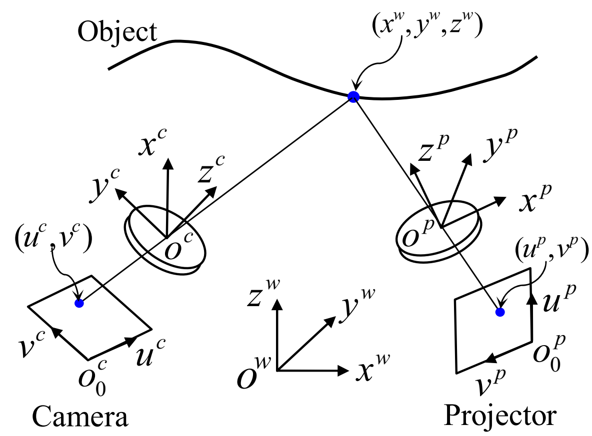

Fig. 2. Schematic diagram of a FPP system model without considering lens distortion.

But the method is complicated and time/memory consuming because it needs to establish the relationship pixel-by-pixel. Ma et al. [20] presented another way to solve the lens distortions problem. Considering the projector as an inverse camera, both camera and projector are calibrated by a standard camera calibration procedure. Then, a nonlinear equation group can be established from which the real word 3D coordinates can be extracted through an iterative optimization algorithm. The method can successfully improve the measurement accuracy. However, it is complicated and time consuming since the iterative optimization algorithm needs to be performed on every pixel of the camera during the measurement.

In this paper, a simple and efficient method is presented to overcome the lens distortion problem and improves the measurement accuracy of FPP. The FPP system is calibrated as a stereovision system. Then, the camera lens distortion is eliminated by correcting the captured images. For the lens distortion of the projector, distorted fringe patterns are generated according to the lens distortion model. With these distorted fringe patterns, the projector can project undistorted fringe patterns, which means the lens distortion of the projector is in fact eliminated. Experimental results show that the proposed method can successfully improve the measurement accuracy and is more efficient compared with the existing methods.

2. System calibration

System calibration is an important step for the FPP system. The goal of this step is to determine the relationship between the retrieved 2D absolute phase distribution and the real word 3D coordinates. Various approaches have been presented for system calculation, such as stereovision method [12,13], least-squares approach [14–17] and phase-to-height mapping [18,19]. The stereovision method is adopted in this paper. In the method, the projector is treated as an inverse camera and the FPP system is considered to be a stereovision system. Then, the FPP system can be calibrated by the classic stereovision calibration method which has been well developed in the field of computer vision. The rest of this section will briefly describe the principle of this calibration method. For more details refer to Refs. [12,13].

2.1. System calibration without considering lens distortion

Fig. 2 shows a schematic diagram of a FPP system, where $(o^c; x^c, y^c, z^c)$ and $(o_0^c; u^c, v^c)$ are the camera coordinate system and its image coordinate system. $(o^p; x^p, y^p, z^p)$ and $(o_0^p; u^p, v^p)$ represent the projector coordinate system and the its image coordinate system. $(o^w; x^w, y^w, z^w)$ is the world coordinate system.

The relationship between a point on the object and its corresponding camera image pixel can be described as

$$s^c \boldsymbol{I}^c = \boldsymbol{A}^c [\boldsymbol{R}^c, \boldsymbol{t}^c] \boldsymbol{X}^w \tag{1}$$

where $\boldsymbol{I}^c = (u^c, v^c, 1)$ is a camera image point in the homogeneous image coordinate system, $\boldsymbol{X}^w = (x^w, y^w, z^w, 1)$ is the corresponding point on the object in the homogeneous world coordinate system, and s^c denotes the scale factor. The matrix $[\boldsymbol{R}^c, \boldsymbol{t}^c]$ is composed of extrinsic parameters, where $\boldsymbol{R}^c$ is a 3×3 matrix representing the rotation between the world coordinate system and the camera coordinate system, whereas $\boldsymbol{t}^c$ is a 3×1 vector representing the translation between these two coordinate systems. $\boldsymbol{A}^c$ is the matrix of the intrinsic parameters described by

$$\boldsymbol{A}^c = \begin{bmatrix} f_x^c & 0 & c_x^c \\ 0 & f_y^c & c_y^c \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where (c_x^c, c_y^c) is the coordinate of the principle point, f_x^c and f_y^c are the focal lengths expressed in pixel units along the u^c and v^c axes, respectively.

Considering the projector as an inverse camera, the relationship between a point on the object and its corresponding projector image pixel can be described like the camera as

$$s^p \boldsymbol{I}^p = \boldsymbol{A}^p [\boldsymbol{R}^p, \boldsymbol{t}^p] \boldsymbol{X}^w \tag{3}$$

$$\boldsymbol{A}^p = \begin{bmatrix} f_x^p & 0 & c_x^p \\ 0 & f_y^p & c_y^p \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

For simplicity, a detailed description of the parameters in Eqs. (3) and (4) is omitted here. The meanings of them are the same as those in Eqs. (1) and (2), but for the projector.

The aim of system calibration is to determine the intrinsic and the extrinsic parameters of the camera and the projector. The intrinsic parameters includes the matrices $\boldsymbol{A}^c$, $\boldsymbol{A}^p$. The extrinsic parameters consist of the matrices $\boldsymbol{R}^c, \boldsymbol{t}^c, \boldsymbol{R}^p, \boldsymbol{t}^c$. We use Zhang's camera calibration method [22] to calibrate the system, which can be implemented with the standard OpenCV camera calibration toolbox.

After the system calibrated, the real world 3D coordinates of the points on the object can be extracted. From Eqs. (1) and (3), three linear equations can be obtained

$$u^c = f_1(x^w, y^w, z^w) \tag{5}$$

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