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An improved phase to absolute depth transformation method and depth-of-field extension

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ABSTRACT

In order to improve the depth measurement accuracy, an improved phase to absolute depth transformation method by considering camera and projector lens distortion is presented in this paper. What is more, generally the depth measurement range is very small for fringe projection three-dimensional measurement. In order to extend the depth-of-field to a large range, a cubic curve fitting depth error compensation method by considering camera and projector lens defocus is proposed and verified in this paper. The experimental results demonstrate the effectiveness and accuracy of the proposed methods.

1. Introduction

Phase-shifting digital fringe projection technique has been playing a prominent role in 3D shape measurement for its high resolution, high speed, and non-contact measurement. The projector projects light patterns with sinusoidally changing intensity onto an object and the camera captures the deformed pattern images. The 3D information is uniquely extracted from the absolute phase map which is generated by the captured deformed fringe images [1,2].

The current literature provides a few phase-to-depth transformation methods [3–11]. Jesus et al. [3] uses a phase-to-depth calibration-based transformation method [4] based on polynomial fitting. However, this phase-to-depth calibration method requires a high accurate translation stage to obtain a series of absolute phases and the associated depths mapping relationship at each pixel in advance. Lei Huang et al. [5] uses the least-squares method [6,7] to determine the phase to depth relationship. The drawback of this technique is that several standard gauge blocks with known heights are needed. What is more, the depth measurement range is limited by the calibration range of the translation stage and the standard gauge blocks, respectively for above two techniques. There is another phase-to-depth transformation method which can avoid the disadvantages mentioned above that is called geometrical modeling method. It establishes the mathematical model to obtain the 3D coordinates by taking fully advantage of triangular relationship of the fringe projection system. It does not need precise control and alignment to calibration plane, and it also does not require additional standard gauge blocks to do calibration. So it is widely studied by researchers for three-dimensional measurement [8–13].

For fringe projection with geometrical modeling technique, due to the complexity of the practical projection system, the geometrical models are always not very accurate with some assumptions, which results in the depth measurement error. Therefore, much effort has been devoted to improve the depth measurement accuracy by considering camera lens distortion [5,14]. However, for fringe projection measuring system, besides camera lens distortion which brings the measurement error, projector lens distortion will also introduce the measurement error. So in this paper, both camera lens distortion and projector lens distortion are considered for the measuring system on improving the measurement accuracy.

What is more, in theory, the three-dimensional measurement can be explored to a large scene reconstruction with geometrical modeling fringe projection technique. However, in fact, the depth measurement range is generally very small since the object must be properly placed before the fringe projection system so that to get good quality sinusoidal fringe pattern for high measurement accuracy. Few literatures have explored its potential on 3D object reconstruction in a large scene. In this paper, we explore the reconstruction to a large range by applying cubic curve fitting depth error

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compensation method. This opens enormous potential in a wide range of application areas.

This paper is organized in the following way: In Section 2 we explain the proposed transformation method on 2D phase map to absolute 3D coordinates. Section 3 describes how we improve the depth measurement accuracy by considering camera and projector distortion. Section 4 introduces how to extend the depth-of-field of the fringe projection measurement to a large range. Experimental results are given to demonstrate the effectiveness of the proposed methods. Finally conclusions are given in Section 5.

2. Measurement principle

2.1. Fringe projection technique

In phase-shifted fringe projection technique, three phase-shifted sinusoidal fringe patterns are projected onto the object surface with phase shift of 0, $2\pi/3$, and $-2\pi/3$ within one fringe period in this study. The intensity distributions with phase shift can be written as the following equations.

$$\begin{cases} I_1(x,y) = I'(x,y) + I''(x,y)\cos[\varphi(x,y) - 2\pi/3] \\ I_2(x,y) = I'(x,y) + I''(x,y)\cos[\varphi(x,y)] \\ I_3(x,y) = I'(x,y) + I''(x,y)\cos[\varphi(x,y) + 2\pi/3] \end{cases}, \tag{1}$$

where $I'(x,y)$ is the average intensity, $I''(x,y)$ is the intensity modulation, $\varphi(x,y)$ is the phase to be solved. By solving the above equations simultaneously, the phase at each point in the image plane can be obtained as follows.

$$\varphi(x,y) = \tan^{-1}\left[\frac{\sqrt{3}(I_1 - I_3)}{2I_2 - I_1 - I_3}\right] \tag{2}$$

The obtained phase is in a relative value between $-\pi$ and $+\pi$. Phase unwrapping algorithm is carried out to remove the phase ambiguities and get the absolute phase.

2.2. Derivation of the phase map to depth map

Fig. 1 illustrates a typical setup of fringe projection three-dimensional measuring system and the geometrical model on how the 3D coordinates are derived from the phase map[15]. In Fig. 1, the camera and the projector are all described by a pinhole model. The camera imaging plane and the projection plane are arbitrarily arranged and the imaginary reference plane OXY is set up which is parallel to the projection plane. $O_pX_pY_pZ_p$ denotes the projector coordinate system. $O_cX_cY_cZ_c$ denotes the camera coordinate system. $OXYZ$ denotes the imagined reference plane coordinate system. P represents an arbitrary point on the object with coordinates (x, y, z), (x^c, y^c, z^c), (x^p, y^p, z^p) in the imaginary reference

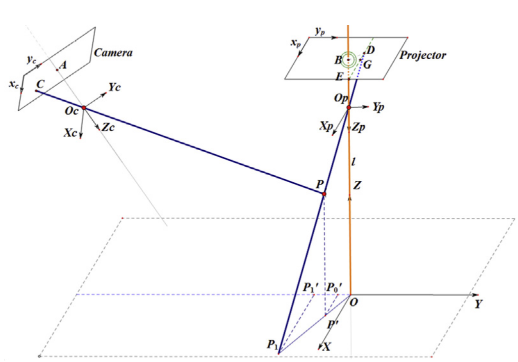

Fig. 1. Schematic illustration of a generalized phase-shifting fringe projection system and how the 3D coordinates are derived from the phase map.

coordinate system, camera coordinate system and projector coordinate system, respectively. C indicates the imaging point of point P. D indicates the fringe point which projects at point P in space. And A and B denote the lens centers of the camera and the projector, respectively. Line $\overline{EF}$ is one of the sinusoidal fringes which is parallel to x_p – axis. Line $\overline{BG}$ is vertical to Line $\overline{EF}$. Line $\overline{PP'}$ is parallel to Z-axis and crosses the imaginary reference plane at point P'. $\overline{PP_1}$ is the extension line of ray $\overline{DP}$ and crosses the imaginary reference plane at point P_1. $\overline{P'P'_0}$ and $\overline{P_1P'_1}$ are parallel to X-axis and cross the Y-axis at point P'_0 and P'_1, respectively.

Based on a projective model, the relationship between the point P and C can be described as

$$s\begin{pmatrix} u_c \\ v_c \\ 1 \end{pmatrix} = \mathbf{A^c}\begin{pmatrix} x^c \\ y^c \\ z^c \end{pmatrix}, \tag{3}$$

where s is an arbitrary scale factor. In which (u_c, v_c) is the captured pixel coordinate in image plane. $\mathbf{A^c}$ is the camera intrinsic parameter matrix. Likewise, $\mathbf{A^p}$ is the projector intrinsic parameter matrix. They are expressed as:

$$\mathbf{A^c} = \begin{bmatrix} f_x^c & 0 & u_0^c \\ 0 & f_y^c & v_0^c \\ 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{A^p} = \begin{bmatrix} f_x^p & 0 & u_0^p \\ 0 & f_y^p & v_0^p \\ 0 & 0 & 1 \end{bmatrix}.$$

The transformation from camera coordinate system to projector coordinate system is written as,

$$\begin{pmatrix} x^p \\ y^p \\ z^p \end{pmatrix} = \mathbf{R}^{-1}\left[\begin{pmatrix} x^c \\ y^c \\ z^c \end{pmatrix} - \mathbf{T}\right], \tag{4}$$

where $\mathbf{R}$ and $\mathbf{T}$ are the rotation and translation matrixes from projector coordinate system to camera coordinate system. They are expressed as:

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}, \quad \mathbf{T} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix},$$

From Ref. [15], there exists the relationship,

$$-z^p + \frac{2\pi y^p f^p}{(\varphi - \varphi_0)\lambda_0} = 0. \tag{5}$$

Connecting Eqs. (3)–(5), the mathematical description on phase to absolute depth transformation is,

$$z^c = \frac{K(r_{21}^{-1}t_x + r_{22}^{-1}t_y + r_{23}^{-1}t_z) - (r_{31}^{-1}t_x + r_{32}^{-1}t_y + r_{33}^{-1}t_z)}{K(r_{21}^{-1}D_1 + r_{22}^{-1}D_2 + r_{23}^{-1}) - (D_1r_{31}^{-1} + D_2r_{32}^{-1} + r_{33}^{-1})}, \tag{6}$$

where $K = \frac{2\pi f^p}{(\varphi-\varphi_0)\lambda_0}$, $D_1 = \frac{u_c - u_0^c}{f_x^c}$, and $D_2 = \frac{v_c - v_0^c}{f_y^c}$.

Furthermore, the coordinates (x^c, y^c) at the given (u_c, v_c) are obtained by calculated depth z^c as follows,

$$x^c = D_1z^c, \tag{7}$$

$$y^c = D_2z^c, \tag{8}$$

By solving Eqs. (6)–(8), (x, y, z) coordinates for each point of the detected object in space are obtained. (u_0^c, v_0^c) is principal point of the camera plane. f_x^c and f_y^c are the scale factors in the image x_c and y_c axes. (u_0^p, v_0^p) is principal point of the projector plane. f_x^p and f_y^p are the scale factors in the DMD x_p and y_p axes.