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A fast three-dimensional shape measurement method based on color phase coding

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ABSTRACT

Gray code plus phase-shifting method embed the codeword into intensity to reconstruct complex three-dimensional shape. Owing to surface reflectivity and noise, it is less robust for measuring the surfaces of object with low contrast. In order to solve the problem, the codeword is embedded into phase to determine fringe order for obtaining the unwrapped phase. However, measurement speed is limited. Therefore, a fast three-dimensional shape measurement method based on color phase coding is proposed. As it adopts a color sinusoidal fringe to obtain wrapped phase and an additional color phase coding fringe to determine fringe order, the method can achieve fast complex three-dimensional shape measurement with different contrast. Color crosstalk and gamma nonlinearity are compensated to improve the measurement accuracy. The experiment results confirm the effectiveness and robustness of the proposed method.

1. Introduction

Three-dimensional (3D) shape measurement is widely used in size measurement, non-contact detection, product quality control, reverse engineering, and computer vision. Fringe projection profilometry (FPP) has widespread application prospect in 3D shape measurement, due to its advantages of non-contact, high resolution, and high-speed [1,2].

Dual-frequency [3], multi-frequency fringe projection [4], and Gray code plus phase-shifting method [5] are typical methods for complex shape measurement. Gray code plus phase-shifting method embed the codeword into intensity to reconstruct complex 3D shape. It is susceptible to surface reflectivity and noise, so it is less robust for measuring the surface of object with low contrast. In order to solve the problem, the codeword is embedded into phase to determine fringe order for obtaining the unwrapped phase [6–8]. It can achieve 3D shape measurement with different contrast. Measurement speed is limited, because it requires at least three phase shifting fringes and three phase coding fringes. Compared with gray pattern, the color pattern has more abundant information and better identification characteristics. Color coding fringe based on permutation and combination of mathematics is presented [9]. Huang proposed a method of color sinusoidal fringe, the phase difference between the neighboring channels is 120° [10]. Chen proposed a new color-projection-based FPP approach where each sinusoidal fringe is identified by a unique binary sequence, capable of measuring the color object [11]. Nevertheless, Channel crosstalk is inevitable for color coding method. Pan proposed two ways based on software and hardware to solve this problem [12]. Hu proposed an algorithm for estimating the color demixing matrix based on the color fringe without color calibration [13]. Pan proposed an iterative method to compensate the non-sinusoidal phase error in consequence of projector gamma nonlinearity [14]. Guo proposed a detailed mathematical gamma model to determine the relationship between phase error and gamma [15].

This paper presents a fast 3D measurement method based on color phase coding. This method just adopts a color coding sinusoidal fringe and a color phase coding fringe to achieve fast complex 3D shape measurement with different contrast. Wrapped phase is obtained by color sinusoidal fringe, and fringe order is determined by color phase coding fringe, then the unwrapped phase is retrieved. Coupling matrix is calibrated to compensate color crosstalk of three channels. The approach of phase error look-up-table (LUT) is established to correct gamma nonlinearity, thereby improving measurement accuracy.

This paper is organized as follows. In Section 2, the working principle of color fringe is presented. The procedure and result of the experiment is given in Section 3. Finally, Section 4 draws the conclusions.

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2. Principle

2.1. Measurement system

The measurement system is shown in Fig. 1. The fringes are projected onto the measured object. The distorted patterns are captured by the color CCD camera. The optical axis of the projector and that of the color CCD camera intersect at point O, which is the origin. Point E is the optical center of the projector and point C is the optical center of the color CCD camera, they have the same distance which is noted l_0 from the reference plane. d is the distance between the entrance pupil of the CCD camera and the exit pupil of the projector. f_0 is the spatial frequency of the fringe patterns on the reference plane. $\Delta\varphi$ is the phase difference between the corresponding point on the object and reference plane. The height of the measured object is as follows [16]:

$$h = \frac{l_0 \Delta\varphi}{2\pi f_0 d + \Delta\varphi} \tag{1}$$

The parameters l_0, d and f_0 are obtained by calibration. The verticality and parallel of the system are calibrated by the method of reference [17].

2.2. Principle of color sinusoidal fringe

The RGB image is compounded by the three channels (Red, Green, and Blue). The phase difference between two channels is 120°. The fringe is simulated by computer, as shown in Fig. 2. The color sinusoidal fringe is projected onto the reference, and received by color CCD camera. Three-step phase-shifting method is used to obtain the phase. The Red, Green, and Blue channels are separated, the intensity of each pixel in the three channels is as follows:

$$I_R(x,y) = I'(x,y) + I''(x,y)\cos\left[\phi(x,y) - \frac{2\pi}{3}\right] \tag{2}$$

$$I_G(x,y) = I'(x,y) + I''(x,y)\cos\left[\phi(x,y)\right] \tag{3}$$

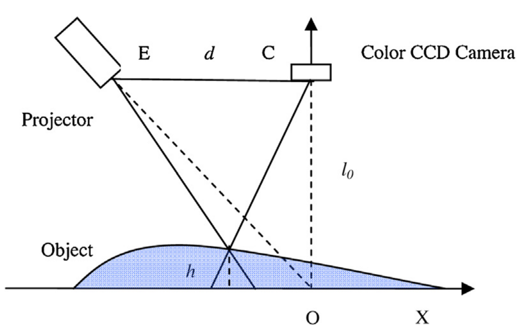


Fig. 1. Measurement system.

Fig. 2. Color sinusoidal fringe. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$I_B(x,y) = I'(x,y) + I''(x,y)\cos\left[\phi(x,y) + \frac{2\pi}{3}\right] \tag{4}$$

where $I_R(x, y)$, $I_G(x, y)$, $I_B(x, y)$ are the intensities of each pixel in the red, green, and blue channels, respectively. $I'(x, y)$ is the average intensity and $I''(x, y)$ is the intensity modulation. $\phi(x, y)$ is the desired phase related to the object profile. Solving Eqs. (2)–(4), the $\phi(x, y)$ can be achieved by

$$\phi(x,y) = \tan^{-1}\left(\sqrt{3}\frac{I_R - I_B}{2I_G - I_R - I_B}\right) \tag{5}$$

The arctangent function will result a value in range of $[-\pi \sim \pi]$ with 2π discontinuities.

2.3. Principle of color phase coding fringe

A stair phase $b(x, y)$ ranging from $-\pi$ to π is shown in Fig. 3. The phase is coded into intensity of three channels, and phase difference between two channels is 120°, as shown in Fig. 4. Fig. 5 shows the compositing process of color phase coding fringe.

The procedure of solving fringe order in the paper can be summarized as follows:

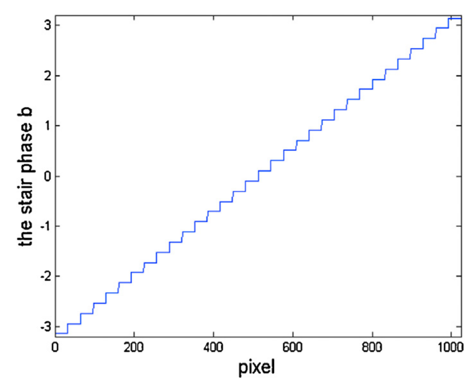


Fig. 3. The stair phase.

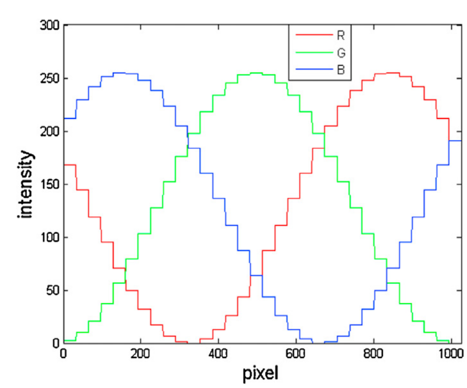
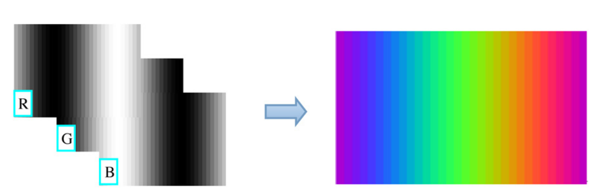


Fig. 4. The intensity of three channels.



(a) Phase coding fringe in RGB (b) Color phase coding fringe

Fig. 5. The compositing process of color phase coding fringe. (a) Phase coding fringe in RGB (b) Color phase coding fringe. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)