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Full-field phase error analysis and compensation for nonsinusoidal waveforms in phase shifting profilometry with projector defocusing

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ABSTRACT

Phase shifting profilometry (PSP) using binary fringe patterns with projector defocusing is widely used for high-speed three-dimensional (3D) shape measurement. In this technique, the projector projects binary fringe patterns instead of the sinusoidal fringe patterns to perform 3D shape measurement. However, inappropriate defocusing degree of the projector causes the captured fringe patterns to be nonsinusoidal waveforms or remaining binary structure, which results in phase error and therefore measurement error. In this paper, a novel method was proposed not only to measure the phase error directly but also to extract the full-field phase error distribution in a large depth range of projector defocusing. Then a mathematical phase error function in terms of the depth z was established. Finally, with help of the detected phase error distribution, the phase error function was calibrated and used to compensate the phase error at arbitrary depth ranges within the calibration volume. The experimental results demonstrated that the proposed method can detect full-field phase error distribution successfully, and improve the phase accuracy significantly.

1. Introduction

In recent years, the optical three-dimensional (3D) shape measurement based on digital fringe projection technique has been widely used in many fields due to its numerous advantages of measurement speed, high accuracy and flexibility, etc. [1–3]. A typical digital fringe projection system consists of a camera and a projector. The projector projects the digital fringe patterns on the object, the reflected patterns, which are distorted by the shape of the measurement object, are captured by a camera. Then the computer uses these distorted patterns to perform 3D shape measurement by fringe patterns analysis. Traditionally, sinusoidal fringe patterns are used for digital fringe projection 3D shape measurement. However, there are some major disadvantages such as the nonlinear gamma distortion of the projection system, speed bottleneck and the precise synchronization between the camera and the projector [4,5].

In order to circumvent these drawbacks associated with sinusoidal fringe patterns projection, Su et al. [6] and Li et al. [7] proposed the binary defocusing technique. In this method, the projector projects binary structured patterns instead of sinusoidal patterns for 3D shape measurement. Then the binary patterns are blurred into quasi-sinusoidal patterns by properly defocusing the projector. This technique can not only eliminate the gamma distortion, but also achieve a high-speed 3D measurement [8]. However, the binary defocusing technique is not trouble free. This is because, if the defocusing degree is too small, the patterns are not sinusoidal, and contain many high-order harmonics. While the contrast of the patterns is low if the projector is defocused too much. As a result, the nonsinusoidal structure caused by high-order harmonics in the binary defocusing technique introduces error into the demodulated phase, and reduce the accuracy of 3D measurement. In addition, the binary defocusing technique is sensitive to the measurement distance, thus phase error caused by high-order harmonics will vary within the measurement range.

Various solutions have been proposed to reduce the adverse effect of nonsinusoidal error in the binary defocusing technique. They can be classified into three categories. In the first category, the pattern modulation techniques are applied to suppress high-order harmonics, and a high-quality sinusoidal pattern is obtained with a small defocusing level [9–13]. In the second category, the improved algorithms are used to analyze and compensate phase error caused by high-order harmonics in binary defocusing technique [14]. In the third category, a simple and potential approach uses unaltered binary fringe patterns, but it requires an additional phase compensation, for example, establishing a look-up table (LUT) or a mathematical phase error function [15]. All of these methods are contribute to reduce the phase error caused

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by high-order harmonics. However, each of them has its own peculiarities. Ayubi et al. [9] introduced a technique called sinusoidal pulse width modulation (SPWM). In this technique, a high quality sinusoidal pattern has been generated by utilizing a spatial version of the well-known pulse-width modulation technique and slightly defocused binary fringe projection. Wang and Zhang [10] proposed a binary pattern generation technique called optimal pulse-width modulation (OPWM) technique. Although the SPWM and OPWM methods can produce better 3D shape measurement results especially when the defocusing degree is small, the phase error caused by some nonsinusoidal waveforms is still nonnegligible, especially when the projector is nearly focused [16]. To further improve the accuracy of binary defocusing technique, Zuo et al. [11] proposed a technique called tripolar SPWM, in which the undesired high-order harmonics can be removed so far away from the fundamental frequency that ideal sinusoidal patterns can be generated with very small defocusing level. Xu et al. [12] proposed a framework for generating a periodic fringe patterns based on optimized patches, which can significantly lower the noise floor and suppress the harmonic distortion in the constructed phase map. Dai et al. [13] presented an intensity-based optimization method for 3D shape measurement with binary dithering techniques, this phase-based optimization method can generate high-quality phase map under a given condition, but it is sensitive to the degree of defocusing. In the second category, Zheng et al. [14] adapted two algorithms for phase shifting profilometry (PSP) using binary defocusing patterns, which include a Hilbert three-step PSP and a double three-step PSP, to increase phase accuracy. However, the Hilbert transform (HT) always leads to a weak edge effect, especially for objects with discontinuous parts or a sharp height change. Chen et al. [17] proposed a novel phase error suppression approach to reduce the significant system error caused by HT. Moreover, Wang et al. [18] proposed a phase error self-compensation algorithm, whose advantage is that the measurement accuracy is close to that of the traditional double three-step PSP with only a set of three-step phase shifting fringe patterns. Although the fringe pattern modulation techniques and improved PSP algorithms can work effectively to diminish the phase error caused by high-order harmonics in binary defocusing technique, the shortcoming of these methods is complex operation and high cost computing. To overcome these deficiencies, Xu et al. [15] proposed a method based on three-step phase shifting to compensate the high-order harmonics phase error, its key step is to detect the phase error and establish a mathematical phase error function in terms of the wrapped phase and the depth z, and then the mathematical function is calibrated to compensate the phase error at arbitrary depth within the calibration volume. However, this method adopts the phase value obtained from three-step phase shifting with computer-generated sinusoidal fringe patterns as the gold standard for research. Therefore, the nonlinear gamma of projector is necessary to be corrected, which adds complexity to the experiment. Moreover, because the sinusoidal fringe patterns are adopted in the experiment and the DLP projector uses time modulation to generate grayscale images, the exposure time must be properly controlled. It affects the speed of measurement. In addition, Chen et al. [19] proposed two real-time phase error correction method to reduce the effect of the instability of projection light source. Chen et al. [20] presented a generic exponential fringe model for decreasing the phase error caused by gamma nonlinear response.

In this paper, we aim at compensating the phase error caused by high-order harmonics in a small-step phase shifting algorithm with binary defocusing fringe patterns. After analyzing the phase error caused by high-order harmonics, it found that the phase errors had similar structures but different amplitudes on the different depth z. Therefore, a mathematical function of the phase error in terms of the depth z has been established. To calibrate this function, a uniform flat white board was placed in front of the system. The camera and projector focused on the white plane, which was set as $z = 0$. Then the white plane was moved toward the projector with an increment of $\Delta z = 5$ mm by a linear translation stage, and a number of 18 planes were measured for the phase error function calibration. For each plane, we recorded 36 phase shifting patterns for detecting the full-field phase error $\Delta\phi$ and 5 gray code patterns for recovering the absolute phase with four-step phase shifting algorithm. The high accurate phase value was obtained by all phase shifting exposures with a large-step phase shifting algorithm, and nine low accurate phase values were obtained by selecting a set of four phase shifting exposures for every pixel with a four-step phase shifting algorithm. Then nine phase errors of every pixel were obtained, and the weighted value of phase errors of each pixel can be achieved by N-shifting technique. After that, the full-field phase errors of each pixel were calculated. In the meantime, a full-field phase error LUT was created as the rule described in Section 3.4 for reducing the computing cost and memory of array elements storing the coefficients of fitting polynomials, Finally, the function of the phase error in terms of the depth z was fit by the 4th-order polynomials, and it was calibrated by a set of phase errors on the different depth. Once the phase error function was calibrated, the phase error of arbitrary position can be compensated with known depth z within the calibration volume. Experiment results verified that the proposed method can perfectly compensate the phase error and significantly improve the accuracy of the 3D profile measurement.

The organization of this paper is as follows. In Section 2 briefly explains the principles related to this paper. The phase error analysis and compensation method are explained in Section 3. Section 4 shows some experimental results that demonstrate the success of proposed error compensation method. Finally, Section 5 summarizes this paper.

2. Theory

2.1. Digital binary defocusing technique

Digital binary defocusing technique uses the computer-generated binary structured fringe patterns, and the defocused projector blurs them into quasi-sinusoidal ones. The intensity of the normalized squared binary structured patterns can be described as follows:

$$p(x) = rect(\frac{2x}{T}) \otimes comb(\frac{x}{T}) \tag{1}$$

where T is the pattern period, and $\otimes$ represents convolution. In order to understand how the binary pattern alters when the projector is defocused, the variation of one horizontal cross section of the pattern has been studied. The Fourier transform of $p(x)$ is

$$P(f_x) = C \sum_{j=-\infty}^{+\infty} \sin c(\frac{f_x}{2f_0}) \cdot \delta(f_x - jf_0) \tag{2}$$

where C is a constant, and $f_0 = 1/T$ stands the spatial frequency of the pattern. The amplitude of the harmonics of frequency is shown in Fig. 1. It can be seen that binary defocusing technique generates a monotonically decreasing high-order harmonic distortion spectrum. Specifically, the nonzero frequency components all exist in the odd-order harmonics.

Mathematically, the defocusing effect can be simplified to a convolution operation and can be written as follows:

$$I(x, y) = I_b(x, y) \otimes Psf(x, y). \tag{3}$$

Here, $\otimes$ represents convolution, $I_b(x, y)$ indicates the input binary fringe patterns, $I(x, y)$ denotes the output smooth fringe patterns, and $Psf(x, y)$ is the points spread function [21]. Simply, $Psf(x, y)$ can be approximated by a circular Gaussian function [16,22],

$$Psf(x, y) = G(x, y) = \frac{1}{2\pi\sigma^2} \exp(-\frac{1}{2\sigma^2}(x^2 + y^2)) \tag{4}$$

where the standard deviation σ is proportional to the defocusing levels. As shown in Fig. 2, a binary fringe pattern is simulated to generate the quasi-sinusoidal fringe pattern with σ increasing. Fig. 2(a) shows the initial binary structured fringe pattern. Fig. 2(b) and (c) represent the