Optics Communications 312 (2014) 302–311

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Absolute phase retrieval for defocused fringe projection three-dimensional measurement

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ARTICLE INFO

Article history:
Received 20 May 2013
Received in revised form
29 August 2013
Accepted 24 September 2013
Available online 9 October 2013

Keywords:
Three-dimensional measurement
Fringe projection
Absolute phase retrieval
Pulse-width modulation

ABSTRACT

Defocused fringe projection three-dimensional technique based on pulse-width modulation (PWM) can generate high-quality sinusoidal fringe patterns. It only uses slightly defocused binary structured patterns which can eliminate the gamma problem (i.e. nonlinear response), and the phase error can be significantly reduced. However, when the projector is defocused, it is difficult to retrieve the absolute phase from the wrapped phase. A recently proposed phase coding method is efficient for absolute phase retrieval, but the gamma problem leads this method not so reliable. In this paper, we use the PWM technique to generate fringe patterns for the phase coding method. The gamma problem of the projector can be eliminated, and correct absolute phase can be retrieved. The proposed method only uses two grayscale values (0's and 255's), which can be used for real-time 3D shape measurement. Both simulation and experiment demonstrate the performance of the proposed method.

1. Introduction

Three-dimensional (3D) shape measurement based on digital fringe projection technique has been widely used [1–3], because of its non-contact, low cost, high speed, and high accuracy, etc. [4]. Recently, there has been a lot of research on defocused technique for 3D shape measurement [5]. A mechanical device generated Ronchi grating has been used for defocused technique [6], which is not flexible to change fringe pitches or shift the phase [7]. Lei and Zhang presented a method to generate ideal sinusoidal fringe patterns by defocusing binary square structured patterns [8]. Ayubi et al. first introduced the well-known pulse-width modulation (PWM) technique to generate sinusoidal patterns through slightly defocusing binary patterns [9]. Then, Wang and Zhang proposed an optimal pulse-width modulation method for wide fringe patterns generation [10]. Zuo et al. presented a tripolar pulse-width modulation technique to generate high-quality sinusoidal fringe patterns [11].

For these defocused techniques, the gamma problem (i.e. nonlinear response) of the projector existed in the measurement system can be mostly eliminated [8]. When combined with phase shifting algorithms, the phase error can be significantly reduced [7]. On the other side, if the defocused techniques only use two grayscale values (0's and 255's) [12], each micro-mirror of the commercial DLP projector will remain stationary. The camera does not need to be precisely synchronized with the projector to correctly capture the fringe patterns. This attribute can be successfully used for real-time 3D shape measurement [7].

The previously defocused techniques mainly concentrate on generating high-quality sinusoidal fringe patterns. By using of phase shifting algorithm [8], we can calculate high-accuracy wrapped phase (i.e. in the range of $[+\pi, -\pi]$) based on high-quality phase shift fringe patterns. However, how to correctly retrieve the absolute phase from the wrapped phase is still a challenge. For example, when the projector is defocused, the retrieved absolute phase will have some undesirable noises for the commonly used Gray-code method [13]. A recently proposed method uses coding phase to determine the codeword for absolute phase retrieval [14], which is inherently better than the Gray-code method using of intensity, because phase is less sensitive to the object surface contrast, camera noise, and ambient. However, the measurement system always has the gamma problem, which can be simply described as

$$I_{\langle n\rangle} = I_{\langle 0\rangle}^{\gamma_0} \tag{1}$$

where $I_{\langle n\rangle}$ and $I_{\langle 0\rangle}$ are the normalized value of the CCD camera captured fringe pattern and computer generated ideal fringe pattern, respectively. γ_0 is the gamma value of the measurement system. This gamma value will be different for different systems. In general, it is close to the value of 3.0 [15]. For the phase coding method combined with phase shifting algorithm, this gamma problem always leads to additional phase error, which can be illustrated by

$$\phi^{S'}(x,y) = \phi^{S}(x,y) + \Delta\phi^{S}(x,y) \tag{2}$$

where $\phi^{S'}(x,y)$ is the actual coding phase, $\phi^{S}(x,y)$ is the ideal coding phase, and $\Delta\phi^{S}(x,y)$ is the additional phase error. The actual coding

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http://dx.doi.org/10.1016/j.optcom.2013.09.056

phase is obtained by using of three step phase shifting algorithm with a phase shift of $2\pi/3$ [14], which can be described by

$$I_1(x,y) = I'(x,y) + I''(x,y)\cos(\phi) \tag{3}$$

$$I_2(x,y) = I'(x,y) + I''(x,y)\cos(\phi + 2\pi/3) \tag{4}$$

$$I_3(x,y) = I'(x,y) + I''(x,y)\cos(\phi - 2\pi/3) \tag{5}$$

where $I'(x,y)$ is the background intensity, $I''(x,y)$ is the intensity modulation, ϕ is the phase to be solved for. Solving Eqs. (3)–(5) can lead to

$$\phi(x,y) = \tan^{-1}(\sqrt{3}(I_3 - I_1)/(2I_2 - I_3 - I_1)) \tag{6}$$

This function of Eq. (6) can be used to calculate the coding phase with a range of $[+\pi, -\pi]$. The calculated phase $\phi^{S'}(x,y)$ can determine the codeword. When the number of the codeword becomes relatively large, the additional phase error $\Delta\phi^{S}(x,y)$ will introduce wrong phase orders [16]. The retrieved absolute phase will have errors.

PWM is extensively used as a method of generating any variety of digital waveforms. One way is to compare the desired waveform with a triangular waveform, as shown in Fig. 1: when the value of the desired waveform is greater than the triangular waveform, the PWM output waveform is in the high state; otherwise, it is in the low state [9]. As we know, the defocusing effect of the projector can be approximated by a Gaussian smooth filter [8,9]. Therefore, with a Gaussian filter, i.e. with a waveform defocusing, the desired waveform can be obtained.

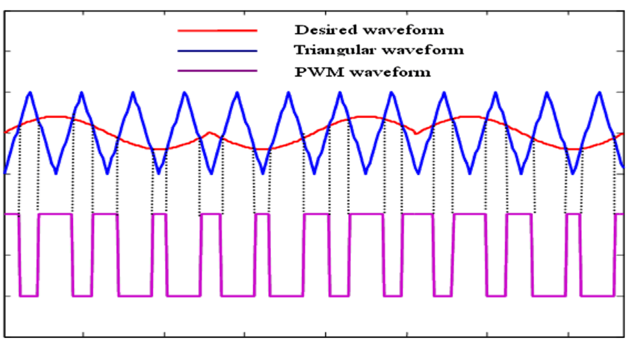

Fig. 1. Desired waveform, triangular waveform, and the resultant PWM waveform.

In this paper, we use the PWM technique to generate fringe patterns for the phase coding method. As the attribute of only two grayscale values (0's and 255's) are used, the gamma problem of the projector can be mostly eliminated. However, for traditional phase coding method, more grayscale values between 0's and 255's are needed. Therefore, the gamma problem of the projector is existed. Compared with the traditional method, the proposed method can obtain correct absolute phase even when the number of the codeword is relatively large. Both simulation and experiment verify that this method is efficient for defocused fringe projection technique.

2. Absolute phase retrieval for defocused fringe projection technique

2.1. Traditional phase coding method

The principle of the traditional phase coding method can be illustrated in Fig. 2. The red line and the blue line in Fig. 2(a) plot one row of the coding stair phase $\phi^{S}(x,y)$ and the 2π discontinuous wrapped phase $\phi(x,y)$, respectively. Both of them are embedded by three step phase shifting algorithm [14]. The stair phase is perfectively aligned with the 2π discontinuities in the wrapped phase. These stairs can be used to calculate the phase orders for the absolute phase retrieval. In this condition, there are eight phase orders. Therefore, the stair phase is quantized into eight

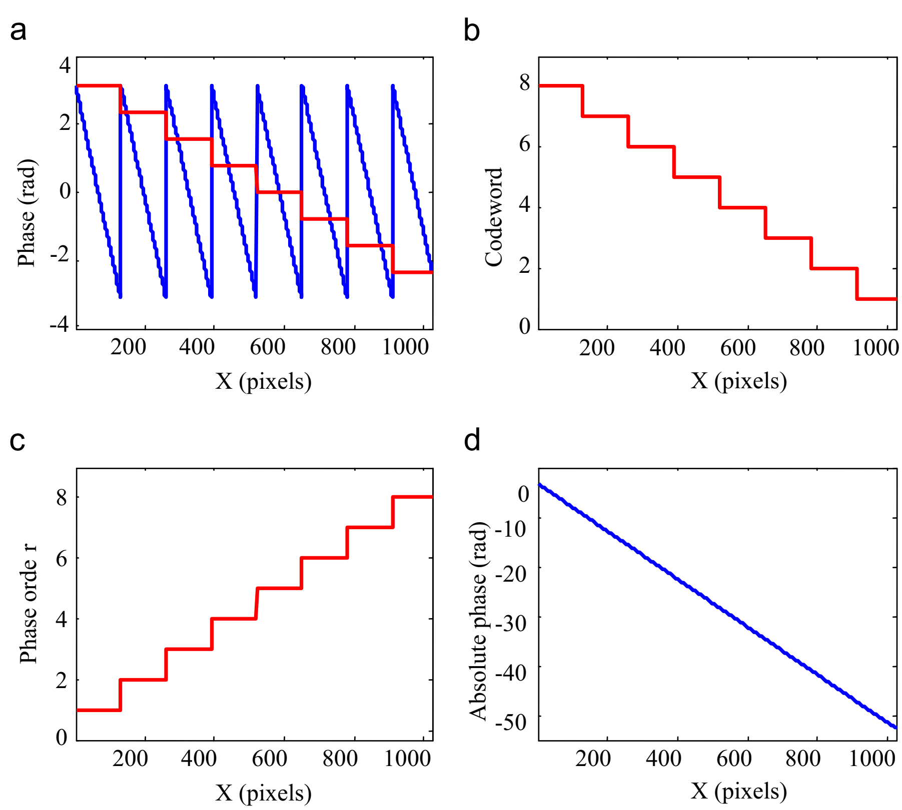

Fig. 2. Principle of the traditional phase coding method.