Optics Communications 383 (2017) 491–499

Contents lists available at ScienceDirect

Optics Communications

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

A dual-frequency online PMP method with phase-shifting parallel to moving direction of measured object

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ARTICLE INFO

Article history:
Received 15 June 2016
Received in revised form
25 August 2016
Accepted 21 September 2016

Keywords:
Modulation
Dual-frequency grating
Pixel matching
Phase unwrapping

ABSTRACT

A dual-frequency online phase measurement profilometry (PMP) method with phase-shifting parallel to moving direction of measured object is proposed in this paper. The high-frequency fringe is used for the better modulation patterns in pixel matching and it is not modified by the measured object's surface. Based on the relative positive between the moving measured object and digital light processing (DLP), the high-frequency fringe in each dual-frequency deformed pattern after pixel matching is the same. As a result, the phase can be calculated directly by the improved Stoilov algorithm without filtering out the low-frequency component containing the measured object's height information. As there is no filtering process in phase calculation, the valid information loss can be avoided so that the accuracy of the proposed method can be guaranteed. Simulations and experiments prove the method's feasibility and precision.

1. Introduction

Non-contact and full-field optical three-dimensional (3D) measurement methods based on the structured light is widely used in mechanical engineering, quality detection, national defense, dress making and some other fields [1,2]. Among kinds of optical 3D measurement methods, phase measurement profilometry (PMP) [3–11] is an effective way to reconstruct the measured object with high accuracy and fast speed. Usually PMP can only be used to measure the static object as at least three deformed patterns should be captured. However, by pixel matching process after which the measured object in each pattern is at the same position, it is valid to measure the online object by PMP.

Modulation is a parameter reflecting the reliability of phase unwrapping so that phase can be unwrapped under the guidance of the modulation distribution. When the modulation of a pixel is bigger, the reliability of phase unwrapping for this pixel is higher. In the meanwhile, the position of the measured object's modulation is moving with the measured object's movement. Then an online phase measuring profilometry based on modulation is proposed by Yingchun Wu et al. [10]. As the modulation is the measured object's trait itself, compared with the method proposed by Cheng Chen et al. [11], in which some specific markers are designed for pixel matching, it is of great convenience to match pixel by the measured object's modulation [10–16].

In online PMP measurement, the fringe frequency has a significant impact on the reconstruction accuracy. When a high fringe frequency is set, there is less spectrum aliasing in the deformed pattern's spectrogram and the better modulation pattern can be obtained which is meaningful for pixel matching. On the other hand, the high fringe frequency may lead unwrapping error and reconstruction failure [10–16]. To solve the contradiction of requiring different frequency between pixel matching process and phase unwrapping process, a method using orthogonal two-frequency grating is proposed in online 3D measurement [17]. As it is necessary to filter low-frequency component in phase calculation in this method, a part of valid information is lost and the precision of the reconstruction is affected. Based on it, we propose here a dual-frequency online PMP method with phase-shifting parallel to moving direction of measured object. The high-frequency fringe information, phase-shifting of which is perpendicular to moving direction of measured object, is extracted to match pixels and it is not modified by the measured object's height. The low-frequency fringe information, phase-shifting of which is parallel to moving direction of measured object, can be used to calculate the phase without filtering out from the dual-frequency deformed patterns after pixel matching based on the relative position between the digital light projector (DLP) and the moving measured object. What is more, there is a large difference between the intensity distributions of the low-frequency component and that of the high-frequency component so that the designed dual-frequency fringe pattern can be regarded as a single-frequency fringe pattern with a small rippled background light. As the phase can be calculated directly, the valid information loss during the filtering

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http://dx.doi.org/10.1016/j.optcom.2016.09.048
0030-4018/

process can be avoided so that the measurement precision is promoted.

2. Principle

As the phase is calculated based on Stoilov algorithm [18,19], only one dual-frequency fringe pattern coded by the computer is needed for 3D measurement. The function of the coded dual-frequency grating is shown as Eq. (1):

$$I_T(x_T, y_T) = I_{TL}(x_T, y_T) + I_{TH}(x_T, y_T) \tag{1}$$

In Eq. (1):

$$\begin{cases} I_{TL}(x_T, y_T) = a + b\cos(2\pi f_L x_T) \\ I_{TH}(x_T, y_T) = c + d\cos(2\pi f_H y_T) \end{cases} \tag{2}$$

where (x_T, y_T) presents the coordinate of pixel in the coded digital fringe pattern. $I_{TL}(x_T, y_T)$ and $I_{TH}(x_T, y_T)$ present the low-frequency fringe and the high-frequency fringe, respectively. The frequency of $I_{TL}(x_T, y_T)$ is f_L and its phase-shifting direction is along x axis. The frequency of $I_{TH}(x_T, y_T)$ is f_H ($f_H > f_L$) and its phase-shifting direction is along y axis. a and c are the background light intensity of $I_{TL}(x_T, y_T)$ and $I_{TH}(x_T, y_T)$. b($a \ge b$) and d ($c \ge d$) are the fringe contrast of $I_{TL}(x_T, y_T)$ and $I_{TH}(x_T, y_T)$. a > > c and b > > d. That means the weight (grayscale) of the high-frequency fringe $I_{TH}(x_T, y_T)$ is small while that of the low-frequency fringe $I_{TL}(x_T, y_T)$ is large. The designed dual-frequency fringe $I_T(x_T, y_T)$ can be regarded as a single-frequency fringe pattern with a small rippled background light. The coded dual-frequency fringe pattern can be seen in Fig. 1.

Fig. 2 shows online PMP setup based on Stoilov algorithm. The optical axis of charge-coupled device (CCD) is CO and that of DLP is PO. Point C, P, O are in the plane XOZ. The measured object is moving along x axis. As the relative position between DLP and moving measured object, only the low-frequency fringe, the phase-shifting direction of which is along x axis and parallel to the direction of the measured object, will be modified by the measured object's surface.

By the grating counting sensor, N($N \ge 3$) frames of dual-frequency deformed patterns, in which the measured object is at the same interval in each two adjacent dual-frequency deformed patterns, can be captured by CCD. N is set to be 5 and they can be expressed as Eq. (3):

$$I_n(x, y) = R_n(x, y)[I_{Ln}(x, y) + I_H(x, y)],\ n = 1, 2, 3, 4, 5 \tag{3}$$

In the above equation:

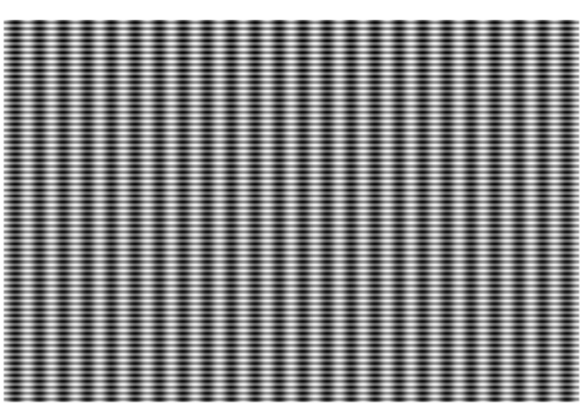

Fig. 1. Dual-frequency fringe pattern.

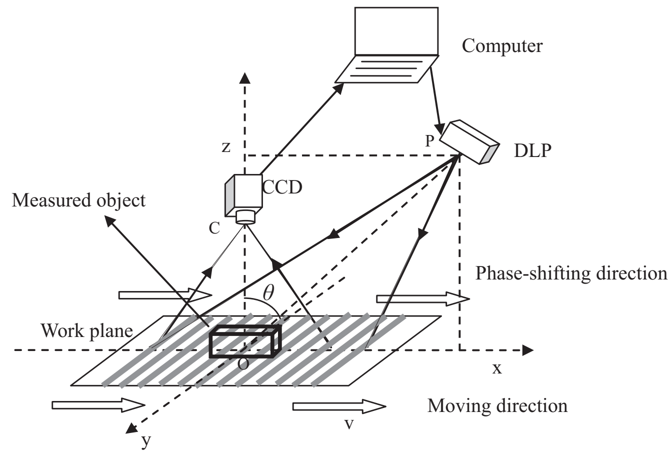

Fig. 2. Online PMP setup based on Stoilov algorithm.

$$\begin{cases} I_{Ln}(x, y) = A(x, y) + B(x, y)\cos(2\pi f_L x + \phi_n(x, y)) \\ I_H(x, y) = C(x, y) + D(x, y)\cos(2\pi f_H y) \end{cases} \tag{4}$$

where (x, y) present the coordinate of pixel in CCD. $R_n(x, y)$ is the reflectivity distribution. $I_{Ln}(x, y)$ is the low-frequency fringe which is modified by the measured object's height. $I_H(x, y)$ is the high-frequency fringe which is not modified by the measured object's height. $A(x, y)$ and $B(x, y)$ are the background light intensity distribution and the fringe contrast of $I_{Ln}(x, y)$. $C(x, y)$ and $D(x, y)$ are the background light intensity distribution and the fringe contrast of $I_H(x, y)$. As the measured object is moving along x axis and its height only modify the low-frequency fringe, $R_n(x, y)$, $I_{Ln}(x, y)$ and $\phi_n(x, y)$ is different in each dual-frequency deformed pattern.

2.1. A. pixel matching by extracting the modulation patterns

Pixel matching is a process to make all the pixels one-to-one corresponding in each two dual-frequency deformed patterns so that the phase can be calculated correctly [10,12]. After the Fourier transformation to Eq. (3):

$$\begin{aligned} G_n(\xi, \eta) &= B_n(\xi, \eta) + P_n(\xi - f_L, \eta) + P_n^*(\xi + f_L, \eta) \\ &+ Q_n(\xi, \eta - f_H) + Q_n^*(\xi, \eta + f_H) \end{aligned} \tag{5}$$

where $G_n(\xi, \eta)$, $B_n(\xi, \eta)$, $P_n(\xi, \eta)$ and $Q_n(\xi, \eta)$ are the Fourier spectrum of $I_n(x, y)$, $R_n(x, y)\cdot[A(x, y) + C(x, y)]$, $\frac{1}{2}R_n(x, y)\cdot B(x, y)\cdot\exp[-j\cdot\phi_n(x, y)]$ and $\frac{1}{2}R_n(x, y)\cdot D(x, y)$, respectively.

+1 order term $Q_n(\xi, \eta - f_H)$ can be filtered out by the proper filtering window and then carry out inverse Fourier transform to it shown as Eq. (6):

$$\begin{aligned} g_n(x, y) &= \iint_{-\infty}^{+\infty} Q_n(\xi, \eta - f_H)\exp\left[j2\pi(\xi x + \eta y)\right]d\xi d\eta \\ &= \frac{1}{2}R_n(x, y)B(x, y)\exp(j2\pi f_H x),\ n = 1, 2, 3, 4, 5 \end{aligned} \tag{6}$$

Modulation patterns $M_n(x, y)$ can be obtained after modulus operation to $g_n(x, y)$:

$$M_n(x, y) = abs[g_n(x, y)] = \frac{1}{2}R_n(x, y)\cdot D(x, y),\ n = 1, 2, 3, 4, 5 \tag{7}$$

To make the best of the measured object's surface information, the measured object's entire modulation in the first modulation pattern is cut and used to be the template. Then correlation operation is shown as Eq. (8) [10,20]: