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An improved two-step phase-shifting profilometry

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ABSTRACT

An improved two-step phase-shifting profilometry is put forward in three-dimensional (3D) shape measurement. Firstly, two phase-shifted randomly sinusoidal fringe patterns are projected onto the tested object by digital-light-processing (DLP) projector. The fringe patterns modulated with the object's surface are captured by a CCD camera. Secondly, the background and modulation components are obtained by parameter estimation using the least square method; fringe normalization is accomplished by the background bias removal and modulation normalization of a given deformed fringe. Then based on the statics characteristics of fringe gray, the phase step between two phase-shifted randomly sinusoidal fringe patterns is determined by using the inverse cosine function. Then, the phase is extracted from the two frame's normalized patterns and the step value. Finally, the experimental evaluation is conducted to prove the validity and performance of the proposed method. The experimental result is analyzed and compared with that of the method by reference 16. The effectiveness and superiority of the proposed method has been demonstrated.

1. Introduction

There are many phase demodulation methods, such as Fourier transformation method, window Fourier transform, wavelet transform, S transformation, phase-shift method [1–10]. The phase-shift method has been paid more attention by easy separation, excellent anti-noise performance and so on. But it generally needs three patterns, which does not suit for dynamic measurement. To reduce phase-shifting images and improve the measuring speed, many scholars have studied new methods. Almazan [11] proposed two-step phase-shifting algorithm based on the visibility. Zhang [12] proposed a modified two-plus-one phase-shifting algorithm. It need to gather a background pattern, besides two phase-shift figures. Zhai [13] embedded the three two-plus-one phase-shifting figures in orthogonal composite grating. Jia [14] used triangle wave projection to replace sinusoidal grating fringes. Kang [15] calculated the background by the π phase shift,and used the arccosine to calculate phase. Zhu [16] use the Fourier transform method to eliminate background,Yang [17] eliminated background with gradient method, and the phase shift is π. In these algorithms, phase-shift value should be set and known in advance. However, if we project the patterns by the LCD or DLP projector, phase step can be achieved accurately. But if the interference fringe projection profilometry is used [18], due to the nonlinear phase-shift, it is difficult to achieve precise phase-shift, and it's easy to result in differences betwen the setting phase-shift and the actual phase-shift. In addition, when measuring the dynamic topography, phase step is generally difficult to control even with projector [19]. Meng [20] proposed generalized phase-shift method to solve the uncertain problem for phase step in the digital holography. Deng et al. [21] put forward phase-shift extraction algorithm based on Euclidean matrix norm. Qian [22] presented phase extraction from arbitrary phase-shifted fringe patterns with noise suppression. In Deng and Qian's methods, they need a large number of phase-shifting-fringe patterns. It is not suitable for dynamic measurement. To resolve the random phase-shift problem, we propose an improved method of two-step phase-shift projection profilometry. The algorithm uses the statistical properties of the fringe pattern to determine the amount of phase shift after the normalization. The amount of phase shifts between the two projection grating images can be any value except π, which is similar to Ref. [16]. In the proposed method, the amount of phase shift can be random and unknown, and it is suitable for the measurement without strictly controlling phase shift.

2. Theory

Sinusoidal gratings are projected to the surface of the object via optical projection device, and they are deformed. The deformed gratings contain the shape information of the tested object. We take a picture of the deformed gratings, and we can obtain the phase values by the deformed gratings through image processing. The

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light intensity distribution of the deformed fringe pattern modulated by object height can be expressed by:

$$I(x,y) = A(x,y) + B(x,y)\cos[2\pi f_0 x + \varphi(x,y)] \quad (1)$$

where, $f_0 = \frac{1}{p}$ is the spatial frequency of optical grating on cardinal plane. In the two-step phase shifting projection, the light intensity of the two deformed fringe pattern, which has a phase shift of δ, expressed by:

$$I_1(x,y) = A(x,y) + B(x,y)\cos[2\pi f_0 x + \varphi(x,y)] \quad (2)$$

$$I_2(x,y) = A(x,y) + B(x,y)\cos[2\pi f_0 x + \varphi(x,y) + \delta] \quad (3)$$

Usually, $\delta = \pi$ or $\delta = \pi/2$ In the two-step phase-shifting method. A more universal condition is that the δ is unknown but $\delta \in (0, 2\pi)$

2.1. Stripe normalization

The key to normalize the stripes is to obtain the background $A(x,y)$ and the contrast respectively $B(x,y)$. Therefore many scholars have studied them [23–28]. Each has advantages and disadvantages on the speed and accuracy. After comprehensive consideration, the normalization method was based on Ref. [29]. First we obtain the background and contrast respectively by the least square method, and then we normalize the patterns as in the following expression:

$$I' = \mathrm{sat}(\tfrac{I-A}{B}) \quad (4)$$

$\mathrm{sat}(\frac{I-A}{B})$ is the saturation function and it's condition is $[-1, +1]$. then:

$$I'_1(x,y) = \cos[2\pi f_0 x + \varphi(x,y)] \quad (5)$$

$$I'_2(x,y) = \cos[2\pi f_0 x + \varphi(x,y) + \delta] \quad (6)$$

2.2. Determination of the amount of phase shift

Multiplying Eqs. (5) by (6), we can obtain:

$$I'_3(x,y) = I'_1(x,y) \cdot I'_2(x,y) = \tfrac{1}{2}\left\{\cos[2\cdot(2\pi f_0 x) + \delta] + \cos(\delta)\right\} \quad (7)$$

Since the projection stripes usually contain many periodic stripes,thus:

$$\left\langle \tfrac{1}{2}\left\{\cos[2\cdot(2\pi f_0 x)]\right\}\right\rangle_w \approx 0 \quad (8)$$

and then:

$$\left(I'_3\right)_{\mathrm{DC}} = \left\langle I'_3\right\rangle_w = \left\langle \tfrac{1}{2}\left\{\cos[2\cdot(2\pi f_0 x) + \delta] + \cos(\delta)\right\}\right\rangle_w = \tfrac{1}{2}\cos(\delta) \quad (9)$$

Eq. (7) shows that $\cos(\delta)$ is the dc component of I'_3. In Eq. (9), $\left(I'_3\right)_{DC}$ indicates the dc component of I'_3. $\left\langle \frac{1}{2}\left\{\cos[2\cdot(2\pi f_0 x) + \delta] + \cos(\delta)\right\}\right\rangle$ indicates average operator, w is the window size. The window size is about 6 – 8, or others, periodic widths in the vertical direction of projection fringes. In actual measurement, due to the noise and the nonuniformity of the modulation amplitude that exist in the fringe patterns, to reduce the error of phase-shift extraction effectively, we select the stripe regions with better quality and as many stripes as possible in the deformed fringes.

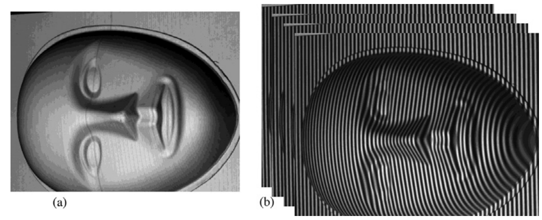

Fig. 1. Tested object and deformed fringe. (a) Tested mask and (b) four-step phase-shifting sinusoidal patterns are projected on the tested mask

Then, the amount of phase shift can be obtained from:

$$\delta = a\cos\{2 \cdot \left(I'_3\right)_{\mathrm{DC}}\} \quad (10)$$

2.3. Phase demodulation

Deduced by Eq. (5) and (6):

$$I'_4 = \frac{I'_1\cos(\delta) - I'_2}{\sin(\delta)} = \sin(2\pi f_0 x + \varphi(x,y)) \quad (11)$$

By Eqs. (5) and (11), we can obtain:

$$2\pi f_0 + \varphi(x,y) = \arctan(\tfrac{I'_4}{I'_1}) \quad (12)$$

where, $\arctan(\frac{I'_4}{I'_1})$ represents the function operator of arctangent.

3. Experiment

To verify the proposed algorithm, we develop a fringe projection measurement system, which consists of a CCD camera (DH-SV401FM) and a DLP projector (Optoma Ex762) driven by a computer. The surface measurement software is programmed by Matlab. First we take a picture of the object without Grating projection when the tested object is static, and then we project fringes and collect 4 deformed grating patterns (phase shifts are: 0, $\pi/2$, π and $3\pi/2$) according to the standard four-step phase-shifting method, what's more we project random phase-shifting gratings and collect the fifth grating pattern (phase shift is unknown, but the amount of phase shiftings are actually known in the laboratory. In order to validate the algorithm,first we regard them as a known amount by Ref.[16], then as an unknown treat according to the proposed method). Tested facial mask and deformed fringe are shown in Fig. 1.

We select first and fifth patterns from the captured 5 patterns. Firstly, using our method, we normalize the first and fifth deformed grating images. Fig. 2 shows the result of the normalization. Fig. 2 (a)

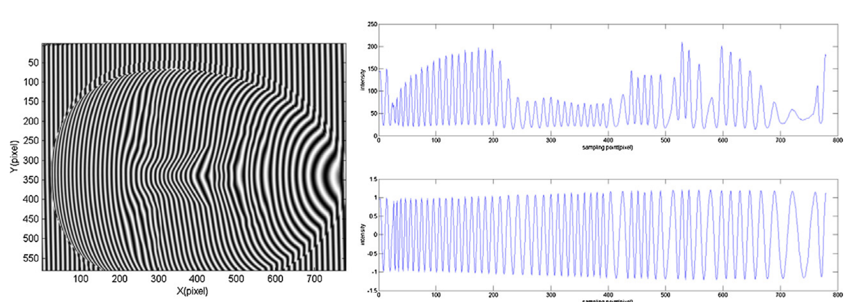

Fig. 2. (a) Deformed pattern after normalization and (b) comparison of the same cross section (j = 300) before and after normalization.