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Iterative two-step temporal phase-unwrapping applied to high sensitivity three-dimensional profilometry

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A B S T R A C T

Although temporal phase unwrapping method can be applied to solve some problems to measure an object with steep shapes, isolated parts or fringe undersampling in three-dimensional (3D) shape measurement, it needs to acquire and process a sequence of fringe pattern images which would take much time. Servin et al. proposed a 2-step temporal phase unwrapping algorithm, which only needs the 2 extreme phase-maps to achieve exactly the same results as standard temporal unwrapping method. But this method is only validated by computer simulation, shortage of experimental demonstration, its sensitivity coefficient G is limited, and it cannot be used when the G value is larger. We proposed an iterative two-step temporal phase-unwrapping algorithm which is an extension of Servin's method. First, add a fringe pattern with an intermediate sensitivity, project the fringe patterns of different sensitivity onto the tested object's surface, and collect deformed fringe patterns with a CCD camera. Then we obtain the unwrapped phase with larger sensitivity coefficient G by cascading the sensitivity coefficients. And we derive the initial phase conditions of the 2-step temporal phase unwrapping algorithm. Finally, the experimental evaluation is conducted to prove the validity of the proposed method. The results are analyzed and compared with Servin's method. The experimental results show that the proposed method can achieve higher sensitivity and more accurate measurement, and it can overcome the main disadvantages encountered by Servin's method.

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1. Introduction

Phase measuring profilometry is an important method in three-dimensional (3D) shape measurement. It has been extensively investigated and widely used in numerical fields for its simple device and higher accuracy [1–4]. To unwrap the wrapping phase in 3D surface measurement, many spatial and temporal phase retrieval methods have been presented. However, spatial phase retrieval method often leads to errors because of discontinuous morphology, noise and fringe undersampling [5–7]. Temporal phase retrieval method [8,9] can solve this problem. But the method needs multiple frames of fringe images which would take much time. To solve this problem, Xi et.al [10–12] proposed a temporal shift unwrapping technique based on projection of patterns of two selected frequencies. Chen [13] proposed a method making use of the three primary color channels associated with digital projectors. Fu [14] proposed a modified temporal phase unwrapping algorithm with the exponent of 4 and changing phase-shifting step. Goldstein [15] proposed a smart temporal unwrapping that temporally unwraps the phase data such that small motion between frames is accounted for and phase data are unwrapped consistently between frames. Song [16] proposed a multi-sensitivity temporal phase unwrapping algorithm that does not need to calculate the equivalent wavelengths and the equivalent phases. Liu [17] proposed tri-Frequency Heterodyne Method. Liu [18] proposed a phase retrieval method using a composite fringe with multi-frequency. These methods make great progress in phase unwrapping.

Recently, Manuel Servin proposed a 2-step temporal phase unwrapping algorithm [19], which only needs the 2 extreme phase-maps to achieve exactly the same results as standard temporal unwrapping method. However, according to our own experience with the method, Servin's method has the following disadvantages: (1) It is only validated by computer simulation, shortage of experimental demonstration; (2) The sensitivity coefficient G is limited, and it is difficult to process when the G is becoming larger; (3) It does not provide the initial phase conditions.

Here, we present an iterative two-step temporal phase unwrapping algorithm which is an extension of Servin's method.

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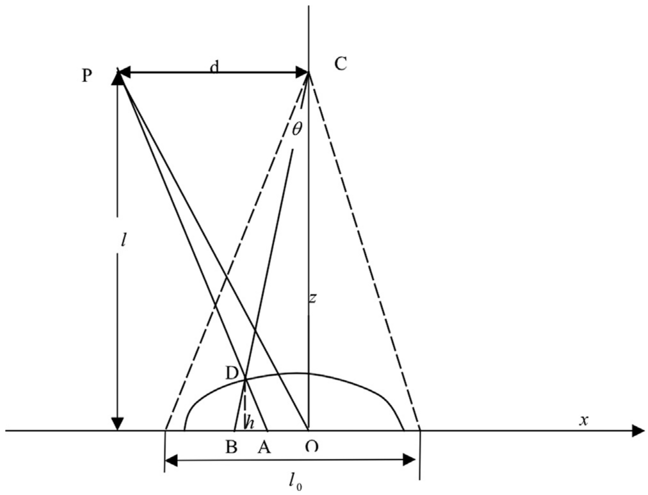

Fig. 1. Optical path of phase measuring profilometry.

In our method, the sensitivity coefficient G can take as larger value as possible only if the hardware conditions such as CCD and projector can permit. We test the proposed method on many experiments, and compare our results with Servin's method. In all cases, our method can give desired results.

The paper is organized as follows. Section 2 introduces the principle of the system. Section 3 presents the experimental results and discusses the different results. Section 4 summarizes this paper.

2. Theory

2.1. Two-step temporal phase unwrapping algorithm

The temporal phase unwrapping method is made in the temporal domain, a sequence of maps is acquired while the fringe pitch is changed. Then the phase at each pixel is unwrapped along the time axis. This method can be used to realize the 3-D shape measurement of complex object surface with steep shapes or isolated parts and fringe undersampling [8,9]. Servin proposed a 2-step temporal phase unwrapping algorithm based on temporal phase unwrapping method. The details for Servin's method can be found in [19]. What follows is a brief synopsis of the method.

Assuming that the intensity mathematical formula for two fringe patterns with different phase modulation sensitivities is as follows,

$$I1(x,y)=a(x,y)+b(x,y)\cos\,[\varphi(x,y)],\varphi(x,y)\in(-\pi,\pi),$$
$$I2(x,y)=a(x,y)+b(x,y)\cos\,[G\varphi(x,y)],(G>>1),G\in R. \quad (1)$$

where $\varphi(x,y)$ is a 1λ sensitive phase (λ is wavelength) and $G\,\varphi(x,y)$ is G-times more sensitive. We can use the phase demodulation algorithm [2,20] to obtain the 2 demodulated wrapped phase-maps as,

$$\varphi1(x,y)=W[\varphi(x,y)],\varphi(x,y)\in(-\pi,\pi)$$
$$\varphi2_w(x,y)=W[G\varphi(x,y)],(G>>1),G\in R. \quad (2)$$

where W is the wrapping phase operator. The first demodulation $\varphi1$(x,y) is not wrapped because it is less than 1λ. So, we have, $\varphi1(x,y)=\varphi(x,y)$.

Based on Ref. [19], we can obtain the unwrapped phase of $\varphi2_w(x,y)$,

$$\varphi2(x,y)=G\varphi1(x,y)+W[\varphi2_w(x,y)-G\varphi1(x,y)] \quad (3)$$

where $\varphi2(x,y)$ is the continuous phase of $\varphi2_w(x,y)$.

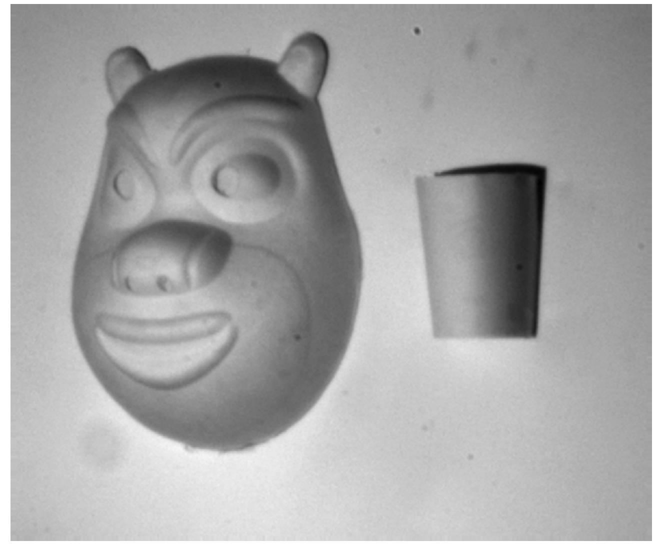

Fig. 2. The tested object.

Eq. (3) is effective, only when the following is satisfied,

$$[\varphi2(x,y)-G\varphi1(x,y)]\in(-\pi,\pi) \quad (4)$$

2.2. The iterative two-step temporal phase unwrapping algorithm

2.2.1. The initial phase

In Ref. [19], Eq. (1) says, $\varphi(x,y)$ is the modulation phase of the projected fringe whose frequency is 1; Eq. (13) says, $\varphi1(x,y)\in(-\pi,\pi)$. These two requirements seem to contradict each other. But we think that they are same in essence, that is, the initial modulation phase must be continuous phase distribution which needs not a phase unwrapping process. Here, we give a method for determining the initial phase according to Ref. [21].

Fig. 1 shows the optical path of phase measuring profilometry, where P is the projection center of the projector, C is the camera imaging center, and D is an arbitrary point on the tested object. Its modulation phase can be calculated by,

$$\phi_{BD}=\frac{dh}{(l-h)l_0}\phi_0 \quad (5)$$

where l_0 is the maximum width of field-of-view (FOV) observed by CCD camera, ϕ_0 is the corresponding phase values within l_0 ϕ_{BD} does not occur 2 π jump, that means, $\phi_{BD}<2\pi$. So we can determine the starting point (initial phase conditions) according to the phase value of ϕ_0. If there is no phase jump until $\phi_0=k\pi$, then the initial phase conditions should be $\phi_0=(k-1)\,\pi$.

2.2.2. The algorithm with larger sensitivity coefficient G

The method in Ref. [19] can unwrap the phase correctly when the value of G is not larger. But when G is too large to satisfy Eq. (4), the results are not accurate. By Eq. (4) in Ref. [19], the greater the sensitivity G is, the greater the SNR of the demodulation phase is. Therefore, in order to improve the measurement accuracy, the G value should be as large as possible if the hardware conditions such as CCD and projector permit.

So, we propose an algorithm with larger G. The basic idea of the method is that we can obtain the larger sensitivity coefficient G by adding an intermediate sensitivity fringe pattern and cascading the sensitivity coefficients.

Assuming that the intensity mathematical formula for three fringe patterns with different phase modulation sensitivities is as follows,

$$I1(x,y)=a(x,y)+b(x,y)\cos\,[\varphi(x,y)],\varphi(x,y)\in(-\pi,\pi),$$

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