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Abstract

Phase unwrapping is an important step for the phase shifting profilometry. The dual-frequency phase unwrapping method can unwrap the object with discontinues when the object is static by employing more fringe patterns. However, errors will occur when moving object is reconstructed. In this paper, a new phase unwrapping method with dual-frequency phase unwrapping method for the moving object measurement is proposed. The fringe pattern with low fringe pattern and high frequency are projected onto the moving object surface. Then, the phase values are retrieved for the two frequencies respectively. The relationship between the movement and phase value is analyzed and the phase variations caused by the movement is compensated. At last, the phase value is unwrapped by the traditional dual-frequency phase unwrapping method. The effectiveness of the proposed method is verified by simulations.

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A new phase unwrapping method for phase shifting profilometry with object in motion

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ABSTRACT

Phase unwrapping is an important step for the phase shifting profilometry. The dual-frequency phase unwrapping method can unwrap the object with discontinues when the object is static by employing more fringe patterns. However, errors will occur when moving object is reconstructed. In this paper, a new phase unwrapping method with dual-frequency phase unwrapping method for the moving object measurement is proposed. The fringe pattern with low fringe pattern and high frequency are projected onto the moving object surface. Then, the phase values are retrieved for the two frequencies respectively. The relationship between the movement and phase value is analyzed and the phase variations caused by the movement is compensated. At last, the phase value is unwrapped by the traditional dual-frequency phase unwrapping method. The effectiveness of the proposed method is verified by simulations.

Keywords: Phase unwrapping, Phase measurement, Fringe analysis, Phase shift

1. Introduction

Phase shifting profilometry (PSP) is one of the most popular techniques for 3D shape reconstruction [1-3]. It has the advantages such as high accuracy, robust to the ambient light and reflectivity variation etc. The sinusoidal fringe patterns are employed and the phase information is utilized to reconstruct the object. However, as an arctangent function is used during the phase calculation, the phase value is wrapped into the range of $-\pi$ to π, making the ambiguity exists in the fringes. In order to clear the ambiguity, phase unwrapping is required to remove the discontinuities and obtain a monotonous phase map. Among many phase unwrapping methods [4], dual-frequency phase unwrapping method [5] is one of the most used methods and it has the ability to unwrap the phase with large discontinuous or separations. During the unwrapping, the fringe patterns with high frequency and low frequency are projected onto the object surface and the wrapped phase map is calculated. The high frequency fringe pattern is used to reconstruct the object and the low frequency fringe pattern is used to unwrap the phase map of high frequency. Then, based on the designed relationship between the two phase maps, the phase period index of the phase map on high frequency is determined correctly.

However, the dual-frequency phase unwrapping method only can be used for static object measurement as more fringe patterns are projected. Errors will be introduced when the moving object is reconstructed. When the object is stable, the phase period index is obtained by the relationship between the phase map of low frequency and high frequency retrieving from the captured fringe patterns. In the other hand, when the object is moved during the projection of the fringe patterns, the two phase maps of the object will be mismatched and the designed relationship will be violated.

This paper proposes a new algorithm to unwrap the phase map by the dual-frequency phase unwrapping method for the moving object reconstruction. The movement of the object is tracked firstly and the wrapped phase maps of low frequency and high frequency are retrieved respectively; then, the relationship among the movement, the phase maps of low frequency and high frequency is analyzed and the phase variation caused by the movement is obtained; at last, the unwrapped phase map of high frequency is obtained by the traditional dual-frequency phase unwrapping algorithm and the phase variation values.

This paper is organized as follows. Section 2 describes the principle of the dual-frequency phase unwrapping method.

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In Section 3, the influence caused by the movement on the phase map is analyzed and the steps of the proposed method are given. Section 4 shows the simulation results to verify the effectiveness of the proposed algorithm. Section 5 concludes this paper.

2. Principle of the dual-frequency phase unwrapping method

The traditional dual-frequency phase unwrapping method described in [5] is employed in this paper. The low frequency and high frequency fringe patterns are projected on the object surface and they can described as

$$\begin{cases} d_l^n(x,y) = a + b\cos(\phi_l(x,y) + 2\pi n/N) \\ d_h^n(x,y) = a + b\cos(\phi_h(u,v) + 2\pi n/N) \end{cases} \tag{1}$$

where N is the step number of PSP; $d_l^n(x,y)$ and $d_h^n(x,y)$ are the fringe patterns of low frequency and high frequency respectively; a is the background light, b is the reflective modulation; $\phi_l(x,y)$ and $\phi_h(u,v)$ are the wrapped phase map of low frequency and high frequency fringe patterns.

Then, we have the following relationship,

$$\Phi_h(x,y) = \phi_h(x,y) + 2\pi n(x,y) \tag{2}$$

$$n(x,y) = INT\left[\frac{k\Phi_l(x,y) - \phi_h(x,y)}{2\pi}\right] \tag{3}$$

Where $\Phi_h(x,y)$ and $\Phi_l(x,y)$ are the unwrapped phase of high frequency fringe and low frequency respectively; $n(x,y)$ is the fringe order of the high frequency fringe pattern; k is the ratio of high frequency to low frequency; $INT[\cdot]$ denotes rounding to the nearest integer. When the shift of the low frequency fringe is less than half of the high frequency fringe period and $\Phi_l(x,y)$ is correct, the unwrapped phase of high frequency is obtained by Eq. (2) and Eq. (3).

Eq. (3) utilizes the relationship between the phase maps of high frequency and low frequency and $n(x,y)$ can be calculated correctly when the object is stable. When the object is moved between the high frequency and low frequency, not only $\Phi_l(x,y)$ and $\phi_h(x,y)$ is mismatched, the designed relationship is also violated, resulting errors in the retrieved fringe order $n(x,y)$.

3. The proposed method

In order to unwrap the phase value correctly, the influence on the phase value of the movement is analyzed firstly. The measurement system of the PSP shown in Fig. 1 includes one projector, one camera and one reference plane. Assume the projector emits one ray of the fringe pattern to the A on the object (point C on reference plane) and point A is captured by the camera (point B on the reference plane). Therefore the phase value on point A equals the phase value on point C, then we have

$$\begin{cases} \Phi(A) = \Phi(C) \\ \Phi(A) - \Phi(B) = \Phi(C) - \Phi(B) \end{cases} \tag{4}$$

When the object is moved in two-dimensional and point A is moved to A'. Similar relationship can be obtained as

$$\begin{cases} \Phi(A') = \Phi(C') \\ \Phi(A') - \Phi(B') = \Phi(C') - \Phi(B') \end{cases} \tag{5}$$

Only 2D movement is considered in this paper, the height of the object does not change, which means the phase difference between the object and reference plane before movement and after movement is same,

$$\Phi(A) - \Phi(B) = \Phi(A') - \Phi(B') \tag{6}$$

From Eq. (6), we can found the following,

$$\Phi(A) - \Phi(A') = \Phi(B) - \Phi(B') \tag{7}$$

From the view of camera, A and B have the same coordinate, A' and B' also have the same coordinate. Therefore, Eq. (7) means that, when the object movement is tracked, the phase variation on the object caused by the movement equals to the phase variation on the reference caused by the same movement.

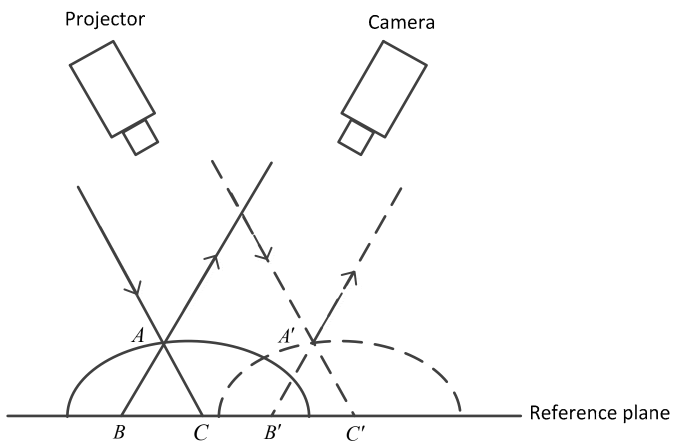


Fig. 1 The analyze of the influence caused by movement

Based on the phase variation obtained by Eq. (7), the phase map of high frequency before movement can be retrieved with the phase value after movement and the phase variation. Then, the object can be unwrapped by the traditional phase unwrapping method. The movement tracking method and the wrapped phase maps of low frequency and high frequency can be obtained by the method described in the author's recent publications [6, 7]. Figure 2 shows the steps of the proposed method.

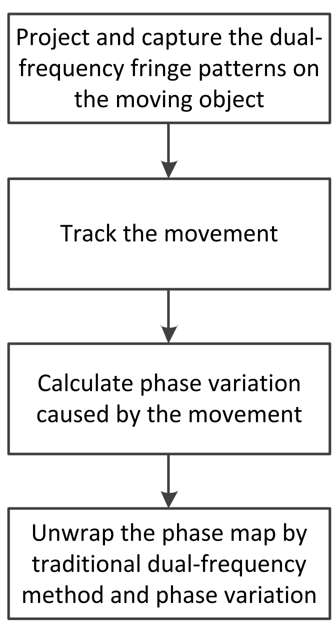
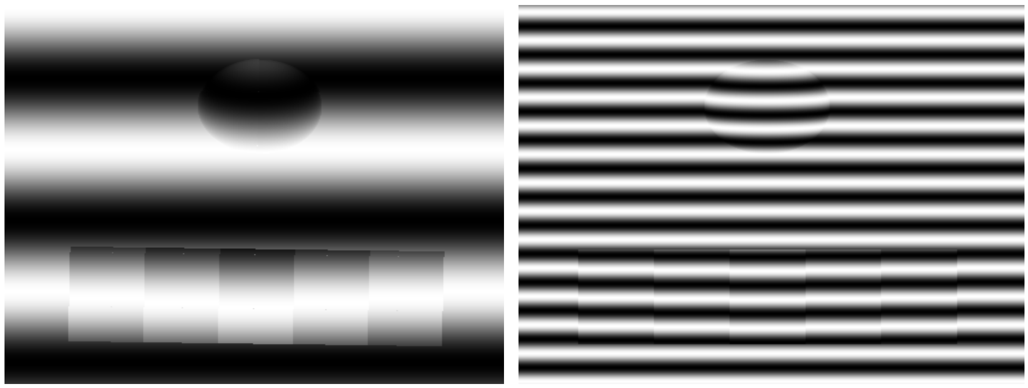


Fig. 2 The steps of the proposed method

4. Simulations

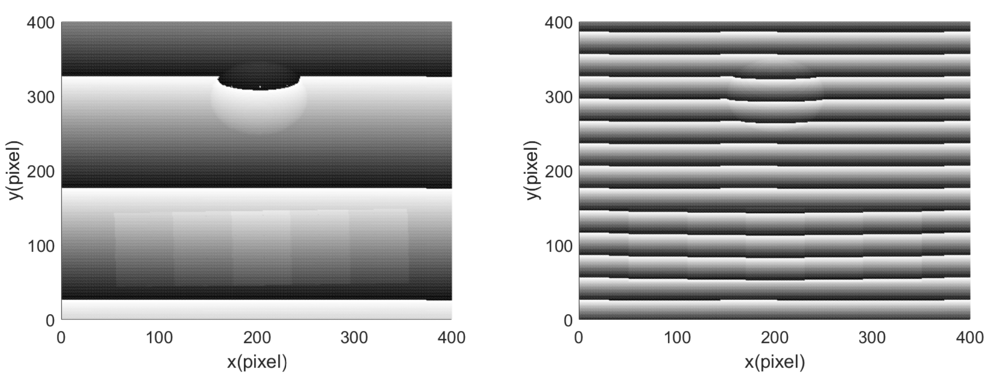


(a) (b)

Fig. 3 The first fringe patterns of the object. (a) the first object fringe pattern of low frequency; (b) the first object fringe pattern of high frequency.

Simulations are finished to verify the effectiveness of the proposed method. In order to clarify the advantages of the dual-frequency phase unwrapping method, two objects separating with each other shown in Fig.3 are employed. 3-step PSP is used and the object keeps moving during the whole measurement (including rotation movement and translation movement). For the low frequency fringe patterns, the object is moved to the left for 10 pixels between the first fringe pattern and second fringe pattern; rotate in the clock wise direction for 1 degree between the second fringe pattern and third fringe pattern. For the high frequency fringe patterns, the object is moved to the right for 10 pixels between the first fringe pattern and second fringe pattern; rotation in the clock wise direction for 2 degree between the second fringe pattern and third fringe pattern. Between the low frequency and high frequency fringe patterns, the object is moved in the upward direction for 10 pixels. Fig.4 shows the position difference between the low frequency and high frequency after the 2D movement.

As the object has movement among the 3-step PSP, the method described in Ref. [6] is used to retrieve the wrapped phase map for the low frequency fringe pattern and high frequency fringe pattern respectively.



(a) (b)

Fig. 4 The wrapped phase maps. (a) the wrapped phase map for low frequency; (b) the wrapped phase map of high frequency.

The object is reconstructed with the traditional dual-frequency phase unwrapping method firstly, the result is shown in Fig. 5(a) and Fig. 5(b). It is apparent that errors are introduced in the result. Fig. 5(c) and Fig. 5(d) shows the reconstructed result with the proposed method. The phase map is unwrapped correctly and the object is reconstructed successfully.

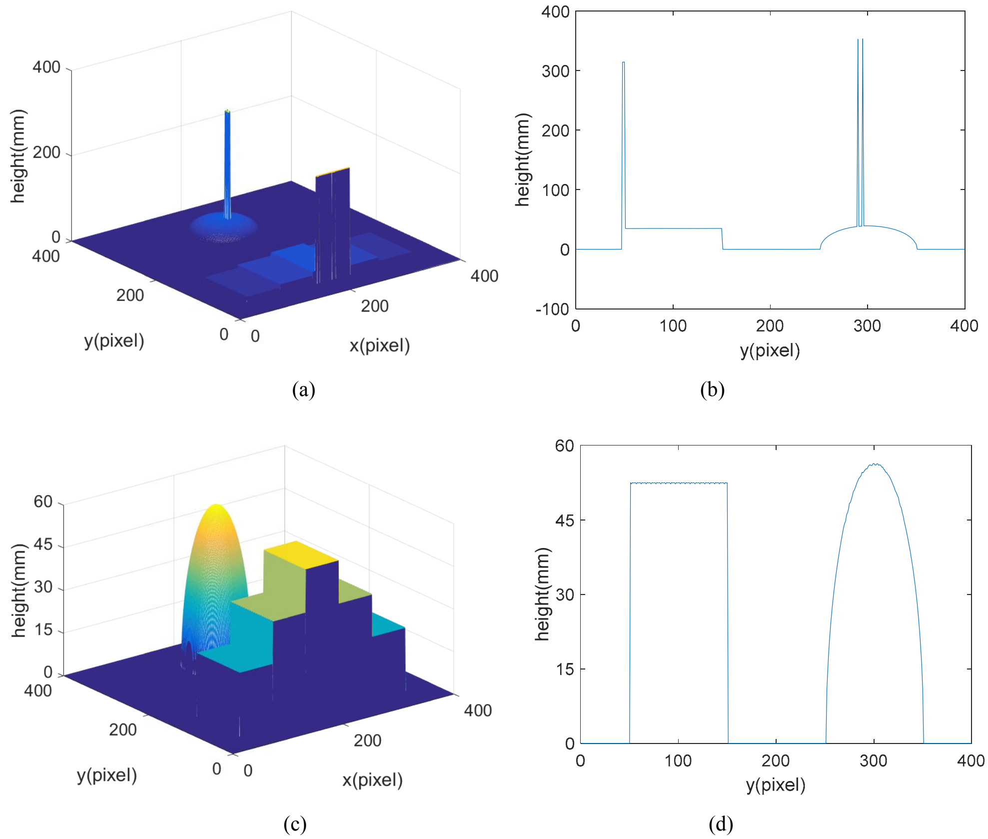


Fig. 5 The reconstructed result with the traditional method and the proposed method. (a) the reconstructed result with the traditional method; (b) the cross section for the result in Fig. 5(a) when x=200; (c) the reconstructed result with the proposed method; (d) the cross section for the result in Fig. 5(c) when x=200.

5. Conclusion

This paper proposes a new approach to unwrap the phase map with dual-frequency method for the moving object. The proposed algorithm has the ability to reconstruct the moving objects with discontinues. The object movement is tracked firstly; then, the influence caused by the movement on the phase maps is analyzed and the phase variation caused by the movement is retrieved. At last, the phase variation caused by the movement is compensated for the phase maps after movement and the traditional dual-frequency phase unwrapping method is used to unwrap the phase map correctly. The effectiveness of the proposed algorithm is verified by the simulations.

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