Optics Communications 438 (2019) 61–66

Contents lists available at ScienceDirect

Optics Communications

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

Reconstruction of isolated moving objects with high 3D frame rate based on phase shifting profilometry

Lei Lu [a,*], Zhaoyi Jia [a], Yinsen Luan [a], Jiangtao Xi [b]

[a] College of Information Science and Engineering, Henan University of Technology, Zhengzhou, 450001, China
[b] School of Electrical Computer and Telecommunications Engineering, University of Wollongong, Wollongong, NSW, 2522, Australia

ARTICLE INFO

Keywords:
Surface measurements
Phase measurement
Fringe analysis
Phase shift

ABSTRACT

Recently, moving object reconstruction based on PSP has been attracted intensive research. The errors caused by the inner movement of PSP have been addressed successfully. However, when the object with discontinuities or isolated surface is measured and the temporal phase unwrapping method is applied, additional fringe patterns are required to unwrap the phase map. The object movement between the PSP fringe patterns and additional fringe patterns will cause unwrapping errors. This paper proposes a new method to reconstruct the moving object with discontinuous or isolated surface. The object movement is tracked and the influence on the phase map caused by the movement is analyzed. Then, the phase variation caused by the movement is obtained. The phase map of the object before movement is obtained by compensating the phase map of the object after movement based on the phase variations. Finally, the object is reconstructed by dual-frequency phase unwrapping method. A new projection strategy increasing the efficiency of the 3D frame rate is also presented in this paper. The 3D frame rate achieves half of the camera capture speed. The proposed method has high potential to be applied in industrial applications for real-time measurement of moving objects. Experiments are presented to verify the effectiveness.

1. Introduction

Phase shifting profilometry (PSP) is one of the most popular techniques for 3D shape reconstruction because of its advantages such as high accuracy, robust and non-contact [1–6]. Multiple sinusoidal fringe patterns (normally at least three) are projected and the phase information is employed to reconstruct the object. However, as an arctangent function is used during the phase calculation, the obtained phase values are wrapped to the principle values ranging from $-\pi$ to π, leading to the ambiguous issue among different periods of the fringe pattern. The phase unwrapping is introduced to remove the discontinuities from the principle values and a monotonous phase map can be obtained. According to the unwrapping strategy, the phase unwrapping algorithms can be classified as spatial phase unwrapping and temporal phase unwrapping [7]. Spatial phase unwrapping methods (such as Goldstein's method [8] and quality-guided method [9] etc.) unwrap the phase value according to their neighbor pixels. The algorithm works well when the object surface is smooth and continuous but fails in the case of the object containing discontinuous or isolated surface. In the other hand, temporal phase unwrapping methods has the ability to unwrap the phase with large discontinuities and separations [10,11]. Compared with the spatial phase unwrapping methods, addition fringe patterns are required in the temporal phase unwrapping methods (such as multiple-frequency method and multiple-wavelength method etc.) and the point on the object is unwrapped independently [11,12].

Recently, intensive research has been focused on the moving object reconstruction based on PSP [13–18]. The errors caused by the inner movement of PSP are removed and correct phase map is obtained. However, when the object with discontinuities and isolated surface is reconstructed, temporal phase unwrapping method with additional fringe patterns is required to retrieve the unwrapped phase map. The movement between the PSP fringe patterns and additional fringe patterns will cause the failure of the unwrapping if the capture speed is not high enough.

In this paper, a new method is proposed to reconstruct the isolated moving objects with dual-frequency phase unwrapping method based on PSP. A new projection strategy is also given to increase the 3D frame rate. The wrapped phase map of the moving object is obtained by the method described in [18]. In order to unwrap the isolated objects by dual-frequency phase unwrapping method, the movement of the object is tracked during the measurement and the influence on the phase map caused by the movement is analyzed; then, the wrapped phase map after movement is compensated to remove the influence caused by the movement; at last, the traditional dual-frequency phase unwrapping method is applied to unwrap the phase map. Different from the static object reconstruction, high 3D frame rate is desired to obtain the continuously 3D data of the moving object. A new strategy is proposed to increase the efficiency of the 3D frame rate based on PSP.

* Corresponding author.
E-mail address: lulei@haut.edu.cn (L. Lu).

https://doi.org/10.1016/j.optcom.2018.12.092
Received 19 October 2018; Received in revised form 27 December 2018; Accepted 29 December 2018
Available online 3 January 2019

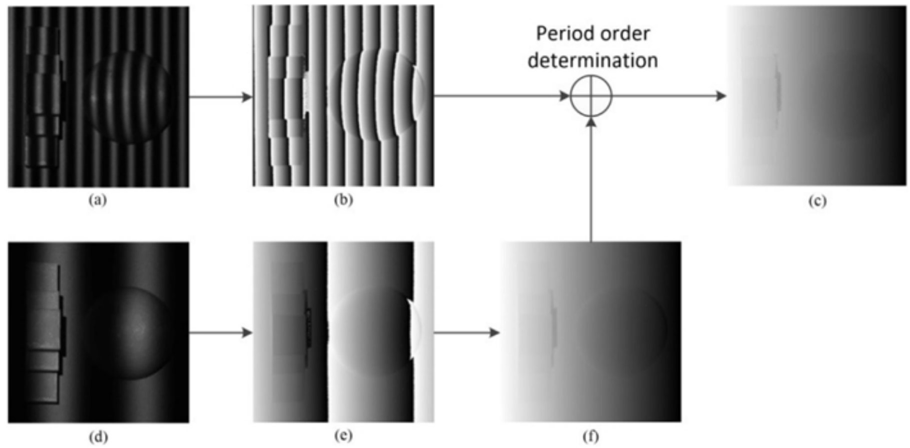

Fig. 1. The procedure of the dual-frequency phase unwrapping method. (a)–(c): the captured fringe pattern, the wrapped phase map and the unwrapped phase map of high frequency fringe pattern; (d)–(f): the captured fringe pattern, the wrapped phase map and the unwrapped phase map of low frequency fringe pattern.

With the dual-frequency phase unwrapping method, the fringe patterns of high frequency and low frequency are projected alternately and the 3D information of the object in each high frequency fringe pattern is reconstructed. The 3D frame rate can reach half of the camera capture speed with the new strategy.

This paper is organized as follows. In Section 2, the principle of the dual-frequency phase unwrapping method is described. The influence on the phase value caused by the object movement between the fringe patterns of low frequency and high frequency is analyzed and the phase map before movement is obtained by compensation. The new strategy increasing the 3D frame rate is given in Section 3. Section 4 shows the experimental results. Section 5 concludes this paper.

2. The proposed method

As a typical temporal phase unwrapping method, dual-frequency phase unwrapping method is employed in this paper to unwrap the moving object with discontinuous or isolated surface [19,20]. The basic principle of the traditional dual-frequency phase unwrapping method is described firstly. As the unwrapping errors will be introduced when the moving objects are reconstructed, the influence caused by the movement between the high frequency and low frequency fringe pattern is analyzed. Then, the phase map of the object before movement is obtained by compensating the phase variation to the phase map of the object after movement. At last, based on the traditional dual-frequency phase unwrapping method, the phase value is unwrapped by using the obtained phase map of the object before movement.

2.1. Principle of the dual-frequency phase unwrapping method

The procedure of the dual-frequency phase unwrapping method described in [20] is shown in Fig. 1. The fringe patterns with low frequency and high frequency are projected to the object surface firstly (as shown in Figs. 1(a) and 1(d)). The high frequency fringe patterns are used for object reconstruction and the low frequency ones are used for the period index determination of the high frequency fringe pattern. Then, the wrapped phase map is obtained respectively as shown in Figs. 1(b) and 1(e). As the low frequency fringe pattern is not sensitive to the height jump of the object, the spatial phase unwrapping method is applied to obtain the unwrapped phase map of low frequency (shown in Fig. 1(f)). At last, with the designed relationship between the unwrapped phase of low frequency and the wrapped phase of high frequency, the period order of the high frequency fringe pattern can be determined and the corresponding unwrapped phase map can be obtained as shown in Fig. 1(c).

The fringe order of the high frequency fringe pattern is determined by

$$n(x,y) = INT\left[\frac{k\Phi_l(x,y) - \phi_h(x,y)}{2\pi}\right] \tag{1}$$

where $\Phi_l(x,y)$ is the unwrapped phase map of low frequency; $\phi_h(x,y)$ is the wrapped phase map of high frequency; $n(x,y)$ is the fringe order of the high frequency; k is the ratio of high frequency to low frequency; $INT[\cdot]$ denotes rounding to the nearest integer.

The unwrapped phase map of the high frequency $\Phi_h(x,y)$ can be obtained by

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

When the object is stable, $n(x,y)$ can be calculated correctly by Eq. (1) with the help of the designed relationship between the phase maps of high frequency and low frequency. However, when the object is moved during the projection of the fringe patterns, the wrapped phase map of high frequency $\phi_h(x,y)$ and the unwrapped phase map of low frequency $\Phi_l(x,y)$ will be mismatched and the designed relationship will be violated, leading to the errors in the $n(x,y)$. Please note that, the correct unwrapped phase map of low frequency (obtained by spatial phase unwrapping method) is required when the dual-frequency phase unwrapping method is implemented. When the spatial phase unwrapping method failed due to the challenge of the object shape, decreasing the frequency can alleviate the issue (such as when only one period is projected, the phase unwrapping is not required).

2.2. The influence analysis and compensation method

The influence on the phase value caused by the movement is analyzed firstly. The measurement system is shown in Fig. 2. It includes one projector, one camera and one reference plane. Only the 2D (two-dimensional) movement is considered in this paper. Compared with the reference plane, the height of the object does not change with the movement.

Assume the parallel light is projected and the phase varies along the x direction. One ray of the fringe pattern is emitted to point C on reference plane and point A on the object surface. The camera captures point A of the object and point B of the reference plane. The point A and B have the same coordinate in the captured images of object and reference plane. The following relationship of the phase value can be obtained

$$\begin{cases} \Phi(A) = \Phi(C) \\ \Phi(A) - \Phi(B) = \Phi(C) - \Phi(B) \end{cases} \tag{3}$$

where $\Phi(\cdot)$ is the phase value on point $(\cdot)$. As point A and C are emitted by the same ray of the fringe pattern, their phase values equal to each

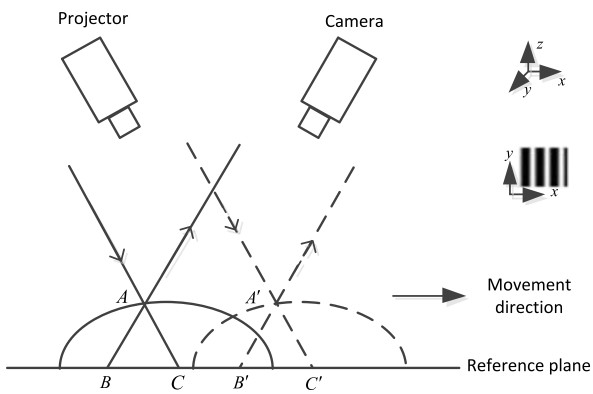

Fig. 2. The measurement system with moving object.

other. The point B and A have the same coordinate in the captured image. The phase difference between point A and point B equals to the phase difference between point C and point B.

When the object has the translation movement as shown in Fig. 2 and point$A$ is moved to A'. Similar relationship can be obtained:

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

Since only 2D movement is considered, the height of the object does not change with the movement, resulting to the phase difference caused by the height of the object also keeps constant between the object before movement and after movement:

$$\Phi(A) - \Phi(B) = \Phi(A') - \Phi(B') \tag{5}$$

From Eq. (5) the phase difference for the same point of the object before movement and after movement can be obtained by

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

Eq. (6) transfers the movement influence from the object to the reference plane. Therefore, when the translation movement of the object is tracked, the phase variation on the object caused by the movement equals to the phase variation on the reference plane caused by the same movement.

Compensate the above phase variation to the phase value after movement, the phase value of the object before movement can be obtained by

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

The above relationship in Eq. (7) also can be extended to the object with 2D rotation movement. With the 2D rotation movement, a specific point on the object only has translation movement as the height is not changed with the movement. Different from the translation movement in Fig. 2, the movement distance is not same for different points on the object.

Summarily, the phase value of the object before movement can be obtained by compensating the phase value of the object after movement as described in Eq. (7). Please note that, $\Phi(B)$ and $\Phi(B')$ should be the unwrapped phase value of the reference plane. Eq. (7) can be applied directly when $\Phi(A)$ and $\Phi(A')$ are also the unwrapped phase values. When $\Phi(A')$ is the wrapped phase value, adjustment should be applied to keep the phase value of $\Phi(A)$ in the range of $(-\pi, \pi)$. When $\Phi(A)$ is bigger thanπor smaller than $-\pi$ after the compensation, the adjustment described in Eq. (8) can be applied. The mod() means the modulo operation and $abs()$ is the absolute value operation.

$$\Phi(A) = \begin{cases} \Phi(A) & -\pi \le \Phi(A) \le \pi \\ \mathrm{mod}[\Phi(A) + \pi, 2\pi] - \pi & \Phi(A) > \pi \\ \pi - \mathrm{mod}[abs(\Phi(A) + \pi), 2\pi] & \Phi(A) < -\pi \end{cases} \tag{8}$$

Please note that, the above derivation is based on the assumption that the parallel light is projected during the measurement (as shown in Fig. 2). Eq. (5) will be violated if the divergent light is employed. In practice, the parallel light can be achieved when the distance between the projector and object is much larger than the height of the object or the special equipment is used (such as telecentric lens).

3. The projection strategy increasing the 3D frame rate

High 3D frame rate is essential for moving object measurement. When the 3D frame rate is low, information of the object will be lost. Assume the 3-step PSP is used and the dual-frequency phase unwrapping method is employed, the reconstructed 3D frame rate will be $FR/6$ as shown in Fig. 3(a). FR is the number of the fringe patterns captured by the camera in one second. The L1, L2 … L6 are the captured image of the low frequency; H1, H2 … H6 are the captured image of high frequency. Every six captured fringe patterns reconstruct one 3D frame. The information of the object in L1, L2, L3, H2 and H3 are lost.

In order to increase the 3D frame rate, a new strategy for the fringe pattern projection is proposed based on the phase retrieval method described in [18] and phase unwrapping method described in Section 2. Different from the traditional PSP assumes the object is static during the fringe pattern projection, the method described in [18] utilizes the movement information to retrieve the phase. This results more flexible for the fringe pattern projection and phase retrieval. As shown in Fig. 3(b), the high frequency and low frequency fringe patterns are projected alternately. The object movement is tracked among the fringe patterns. The frame1 is generated by L1, L2, L3, H1, H2 and H3 at the position of H3. Then, frame2 is reconstructed by L2, L3, L4, H2, H3 and H4 at position of H4. Similar operations are applied for frame3 and frame4. By this strategy, the 3D frame is reconstructed with every two new fringe patterns (one high frequency and one low frequency). The 3D frame rate can reach $FR/2$ after the first 3D frame is reconstructed. More information of the object can be obtained and real-time measurement can be achieved.

In summary, the procedure of the proposed method can be described as follows.

Step 1: project and capture the low frequency and high frequency fringe patterns alternately with the proposed strategy described in Fig. 3(b);
Step 2: track the object movement in each fringe pattern and calculate the object wrapped phase map of the low frequency and high frequency by the method in [18]; obtain the object unwrapped phase map of low frequency and reference plane;
Step 3: use the position of the object in high frequency phase map as the reference, move the object in unwrapped phase map of low frequency to the reference position;
Step 4: compensate the object unwrapped phase map of low frequency (obtained in Step 3) by Eq. (7);
Step 5: unwrap the object wrapped phase map of high frequency with the traditional dual-frequency phase unwrapping method and the object unwrapped phase map obtained by Step 4;
Step 6: reconstruct the object with the unwrapped phase map of high frequency;
Step 7: repeat Step 2 to Step 6 with the new captured fringe patterns of low frequency and high frequency.

4. Experiments

The effectiveness of the proposed method is verified by the experiments. Two isolated objects (a 3D printing stairs and a tape) shown in Fig. 4(a) are reconstructed. The object is moved randomly in two-dimension. 3-step PSP is used and the dual-frequency phase unwrapping method is employed. In order to obtain the phase information and the movement information simultaneously, the fringe patterns in red color are projected and a color camera is used to capture the reflected images (as shown in Fig. 4(b)). In the red channel of the captured image, the

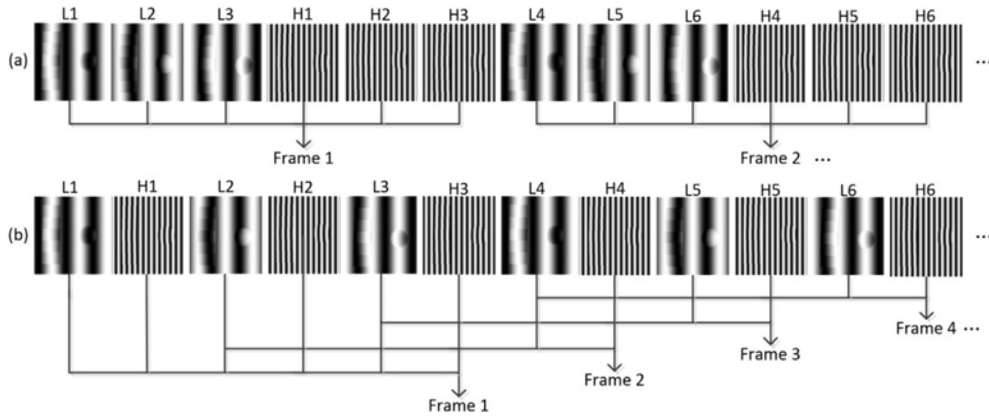

Fig. 3. The strategy of the fringe pattern projection. (a) The frame rate of the traditional PSP with dual-frequency phase unwrapping method; (b) The frame rate of the proposed strategy with dual-frequency phase unwrapping method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

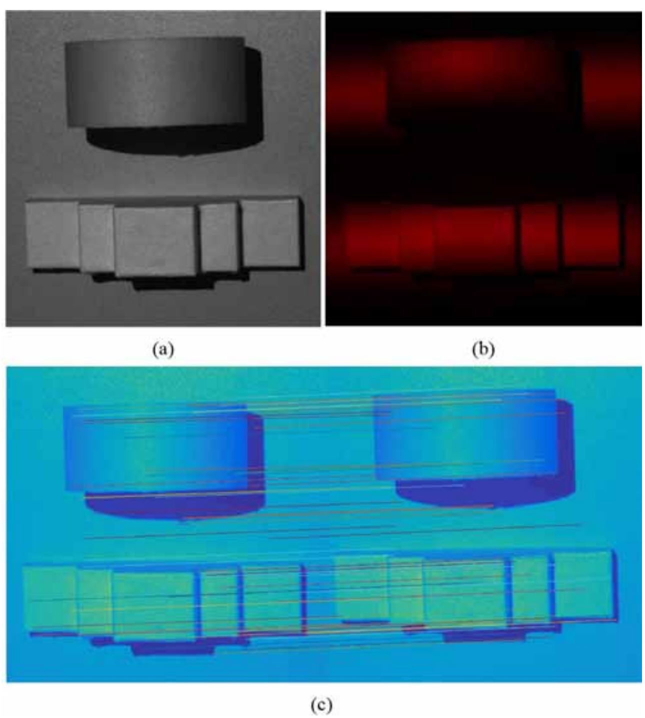

Fig. 4. Two isolated objects used in the experiment. (a) The two isolated objects used in the experiment; (b) The captured object image in red fringe pattern; (c) The movement tracking result with SURF algorithm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fringe pattern information is used to retrieve the phase value; in the other hand, the pure object image without fringes can be found in the blue channel of the captured image [18]. Then the SURF (Speeded up robust features) algorithm is employed to track the object movement with the pure object image as shown in Fig. 4(c). As the proposed method is not sensitive to the movement, the capture speed of the system is set at 1 frame/second.

With the method in [18], the wrapped phase map of low frequency and high frequency fringe patterns are retrieved as shown in Fig. 5. It is apparent that the position is mismatched by the movement.

As we wish to reconstruct the object from high frequency fringe pattern, the object position in high frequency fringe patterns is used as the reference. The object unwrapped phase map of low frequency is obtained by the spatial phase unwrapping method firstly. Then, the object position is moved back to the reference position and the unwrapped phase map compensated by the proposed algorithm. The result is shown in Fig. 6.

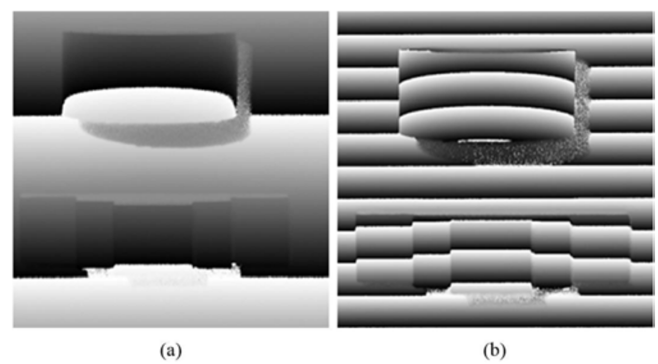

Fig. 5. The wrapped phase maps of the low frequency and high frequency. (a) The wrapped phase map of low frequency; (b) The wrapped phase map of high frequency.

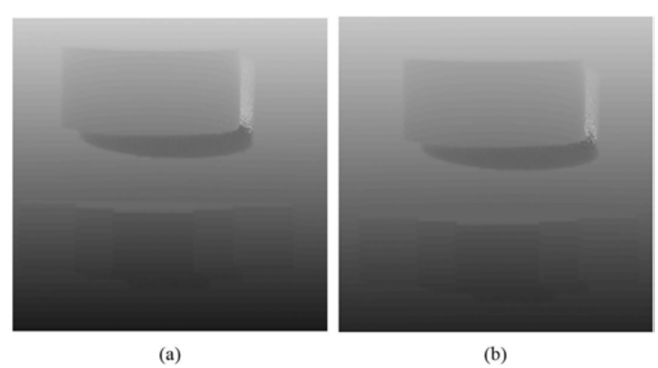

Fig. 6. The compensation of the phase map. (a) The unwrapped phase map of low frequency before compensation; (b) The unwrapped phase map of low frequency after compensation and position adjustment.

With the phase map in Figs. 6(b) and 5(b), the traditional dual-frequency phase unwrapping method is applied to reconstruct the object and the results are shown in Figs. 7(a)–7(b). The object is well reconstructed. In order to compare the results, the traditional dual-frequency phase unwrapping method without compensation is applied directly to the above experiment. The results are shown in Figs. 7(c)–7(d). Significant errors are caused by the movement.

The proposed projection strategy is also verified and high efficiency 3D frame rate is obtained. The low frequency and high frequency fringe patterns are projected alternately and the camera capture speed is set as

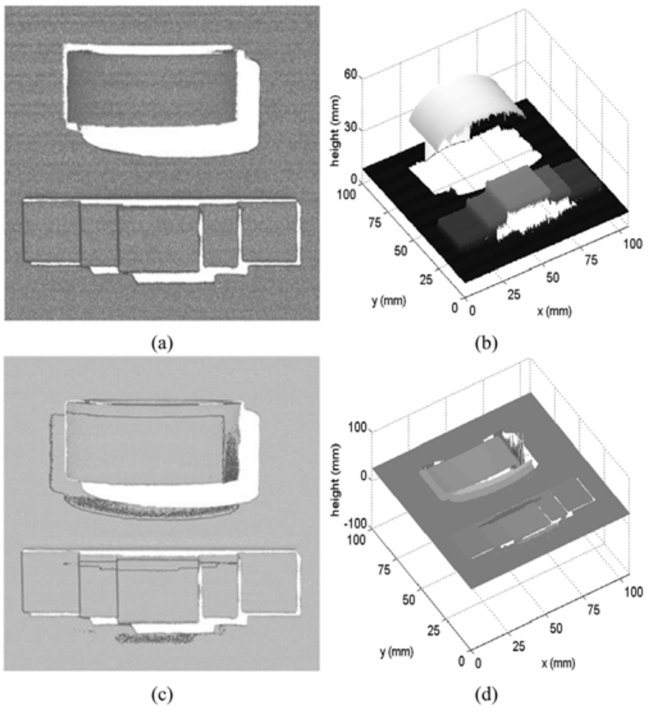

Fig. 7. The reconstructed result with the proposed method and traditional method. (a) The reconstructed result with the proposed method; (b) The mesh display for Fig. 7(a); (c) The reconstructed result with the traditional method; (d) The mesh display for Fig. 7(c).

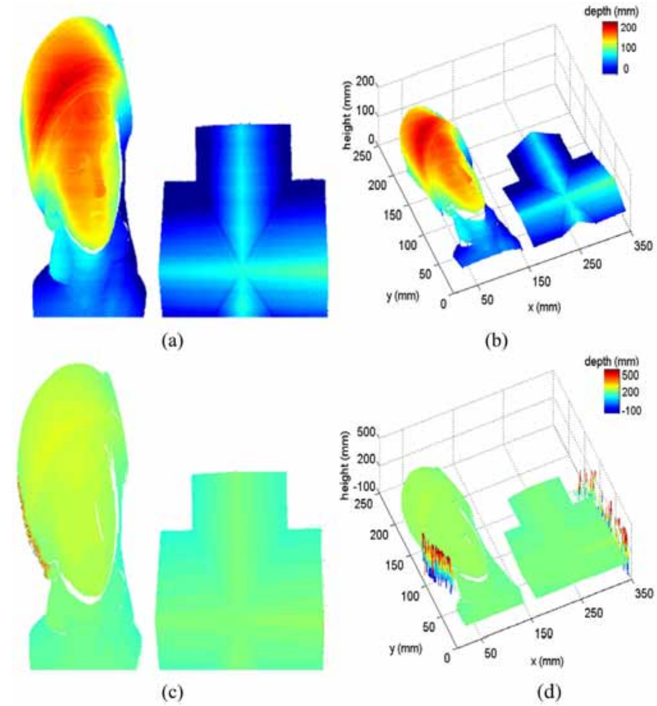

Fig. 8. The reconstructed results of the object with complex surface. (a) The reconstructed result with the proposed method; (b) The mesh display for Fig. 7(a); (c) The reconstructed result with the traditional method; (d) The mesh display for Fig. 7(c).

1 frame/s. The object is moved randomly in two-dimensional. The object is reconstructed in all the captured fringe pattern of high frequency. Visualization 1 shows all the captured fringe patterns and the 3D frames of the measurement.

In order to further verify the unwrapping performance of the proposed method, two sculptures with complex shape are reconstructed in the second experiment. The moving speed is increased to 80 mm/s and the capture speed is set to 10 frame/s. Fig. 8 shows the reconstructed results of the traditional dual-frequency phase unwrapping method and the proposed method. Fig. 8(a) shows the front view of the reconstructed result with the proposed method and Fig. 8(b) is the corresponding mesh display from another angle. The objects are unwrapped correctly. In contrast, with the traditional method, significant errors are introduced as shown in Figs. 8(c) and 8(d).

5. Conclusion

This paper proposes a new method reconstructing the moving isolated objects based on the dual-frequency phase unwrapping method. A projection strategy increasing the efficiency of the 3D frame rate is also presented. The object movement is tracked and the influence caused by the movement on the phase maps of the low frequency and high frequency is analyzed. Then, The phase map of the object before movement is obtained by compensating the phase map of the object after movement with the phase variations caused by the movement. At last, the dual-frequency phase unwrapping method is applied to reconstruct the object. During the measurement, the fringe patterns of high frequency and low frequency are projected alternately. With the multiplexing use of the captured fringe patterns, the 3D frame rate can reach to half of the camera capture speed. Please note that, except the dual-frequency phase unwrapping method described in this paper, the proposed method can be applied to other temporal unwrapping methods that employ the additional phase maps (rather than black and white pattern) to determine the fringe orders.

Funding Information

National Natural Science Foundation of China (NSFC) (61705060).

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.optcom.2018.12.092.

References

[1] S. Zhang, Recent progresses on real-time 3-D shape measurement using digital fringe projection techniques, Opt. Lasers Eng 48 (4) (2010) 149–158.

[2] Y. Xing, C. Quan, C. Tay, A modified phase-coding method for absolute phase retrieval, Opt. Lasers Eng. 87 (1) (2016) 97–102.

[3] H. Cui, W. Liao, N. Dai, X. Cheng, Reliability-guided phase-unwrapping algorithm for the measurement of discontinuous three-dimensional objects, Opt. Eng. 50 (6) (2011) 063602.

[4] Y. Liu, Q. Zhang, X. Su, 3D shape from phase errors by using binary fringe with multi-step phase-shift technique, Opt. Lasers Eng. 74 (4) (2015) 22–27.

[5] D. Zheng, F. Da, K. Qian, H. Seah, Phase error analysis and compensation for phase shifting profilometry with projector defocusing, Appl. Opt. 55 (21) (2016) 5721–5728.

[6] Z. Zhang, S. Huang, S. Meng, F. Gao, X. Jiang, A simple flexible and automatic 3D calibration method for a phase calculation-based fringe projection imaging system, Opt. Express 21 (10) (2013) 12218–12227.

[7] C. Zuo, L. Huang, M. Zhang, Q. Chen, A. Asundi, Temporal phase unwrapping algorithms for fringe projection profilometry: A comparative review, Opt. Lasers Eng. 85 (4) (2016) 84–103.

[8] R. Goldstein, H. Zebker, C. Werner, Satellite radar interferometry: Two dimensional phase unwrapping, Radio Sci. 23 (4) (1988) 713–720.

[9] H. Lim, W. Xu, X. Huang, Two new practical methods for phase unwrapping, in: International Geoscience and Remote Sensing Symposium (IGARSS)-Quantitative Remote Sensing for Science and Applications, 1995, pp. 196–198.

[10] J. Huntley, H. Saldner, Temporal phase-unwrapping algorithm for automated interferogram analysis, Appl. Opt. 32 (17) (1993) 3047–3052.

[11] K. Creath, Step height measurement using two-wavelength phase-shifting interferometry, Appl. Opt. 26 (14) (1987) 2810–2816.

[12] H. Saldner, J. Huntley, Temporal phase unwrapping: Application to surface profiling of discontinuous objects, Appl. Opt. 36 (13) (1997) 2770–2775.

[13] J. Flores, G. Ayubi, J. Martino, O. Castillo, J. Ferrari, 3D-shape of objects with straight line-motion by simultaneous projection of color coded patterns, Opt. Commun. 414 (2) (2018) 185–190.

[14] Z. Liu, P. Zibley, S. Zhang, Motion-induced error compensation for phase shifting profilometry, Opt. Express 26 (10) (2018) 12632–12637.

[15] S. Feng, C. Zuo, T. Tao, Y. Hu, M. Zhang, Q. Chen, G. Gu, Robust dynamic 3-D measurements with motion-compensated phase-shifting profilometry, Opt. Lasers Eng. 103 (1) (2018) 127–138.

[16] L. Lu, J. Xi, Y. Yu, Q. Guo, New approach to improve the accuracy of 3-D shape measurement of moving object using phase shifting profilometry, Opt. Express 21 (25) (2013) 30610–30622.

[17] L. Lu, J. Xi, Y. Yu, Q. Guo, Improving the accuracy performance of phase-shifting profilometry for the measurement of objects in motion, Opt. Lett. 39 (23) (2014) 6715–6718.

[18] L. Lu, Y. Ding, Y. Sen, Y. Yin, Q. Liu, J. Xi, Automated approach for the surface profile measurement of moving objects based on PSP, Opt. Express 25 (25) (2017) 32120–32131.

[19] H. Zhao, W. Chen, Y. Tan, Phase-unwrapping algorithm for the measurement of three-dimensional object shapes, Appl. Opt. 33 (20) (1994) 4497–4500.

[20] M. Dai, F. Yang, C. Liu, X. He, A dual-frequency fringe projection three-dimensional shape measurement system using a DLP 3D projector, Opt. Commun. 382 (8) (2017) 294–301.