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A new method for fringe order error correction in fringe projection profilometry

Abstract

© 2019 SPIE. Phase unwrapping is an essential step for 3D shape measurement based on fringe projection. Temporal phase unwrapping methods can be implemented by analyzing the multiple patterns that encode the fringe order information. They can retrieve the fringe orders on a pixel-by-pixel basis and are less prone to error propagation compared with spatial methods. However, fringe orders errors may still occur due to noise, reflectivity fluctuation and discontinuity of the object surface. Such errors may exhibit an impulsive nature and result in significant error to the recovered absolute phase map. This has been exploited by several methods to correct the fringe order errors, e.g., by filtering the fringe order sequences in a line-by-line manner. In this paper, a new method is proposed to correct the errors associated with fringe orders for the temporal phase unwrapping. The scheme first makes use of the low-rankness property of the fringe order map and sparse nature of the impulsive fringe order errors to more effectively remove the impulsive errors by applying robust principal component analysis (RPCA) algorithm. Then the smoothness of the two-dimensional unwrapped phase map is examined and the residual fringe order errors are detected based on a discontinuity measure of the phase map and corrected by comparing phase difference between two adjacent pixels in the unwrapped phase. The effectiveness of the proposed method is demonstrated via numerical experiments.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Y. Zhang, C. Duan, J. Xi, J. Tong, Y. Yu & Q. Guo, "A new method for fringe order error correction in fringe projection profilometry," *Proceedings of SPIE - The International Society for Optical Engineering*, vol. 11189, pp. 11890X-1-11890X-8, 2019.

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A New Method for Fringe Order Error Correction in Fringe Projection Profilometry

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ABSTRACT

Phase unwrapping is an essential step for 3D shape measurement based on fringe projection. Temporal phase unwrapping methods can be implemented by analyzing the multiple patterns that encode the fringe order information. They can retrieve the fringe orders on a pixel-by-pixel basis and are less prone to error propagation compared with spatial methods. However, fringe orders errors may still occur due to noise, reflectivity fluctuation and discontinuity of the object surface. Such errors may exhibit an impulsive nature and result in significant error to the recovered absolute phase map. This has been exploited by several methods to correct the fringe order errors, e.g., by filtering the fringe order sequences in a line-by-line manner. In this paper, a new method is proposed to correct the errors associated with fringe orders for the temporal phase unwrapping. The scheme first makes use of the low-rankness property of the fringe order map and sparse nature of the impulsive fringe order errors to more effectively remove the impulsive errors by applying robust principal component analysis (RPCA) algorithm. Then the smoothness of the two-dimensional unwrapped phase map is examined and the residual fringe order errors are detected based on a discontinuity measure of the phase map and corrected by comparing phase difference between two adjacent pixels in the unwrapped phase. The effectiveness of the proposed method is demonstrated via numerical experiments.

Keywords: Phase unwrapping; fringe order error; robust principal component analysis

1. INTRODUCTION

Fringe projection profilometry (FPP) has been extensively studied for its high accuracy and high resolution in retrieving three-dimensional (3D) information in various applications [1-2]. With FPP, a set of fringe patterns are projected on the object surface by a digital projector, and then a camera captures the corresponding deformed fringe patterns which contains the height information of the object. By analyzing these patterns, the 3D profile can be obtained accordingly. However, the phase map retrieved by typical FPP techniques are wrapped into the range of $(-\pi, \pi]$, introducing phase ambiguity. In order to eliminate the phase ambiguity, phase unwrapping is required to recover the absolute phase maps (which are continuous). Among many phase unwrapping methods, temporal phase unwrapping is commonly used, especially for applications with noise and discontinuities [3-6].

Although the temporal phase unwrapping algorithms are generally effective for phase unwrapping, fringe order errors may still occur [4], which bring errors to the ultimate 3D measurement results. In order to improve the accuracy of the recovered fringe orders, Huntley and Saldner [7, 8] propose a temporal phase unwrapping algorithm, which works by recording the phase at different times and accumulating the phase variation. However, this approach is not suitable for real-time applications due to the requirement of a large number of extra patterns. To improve the efficiency, Zhao *et al* [9] propose a dual-frequency algorithm by employing two sets of fringe patterns. The high frequency pattern is used to reconstruct the object and the low frequency fringe pattern is used to unwrap the phase map of high frequency. Similarly, Liu *et al* [10] propose a novel multi-frequency schemes to improve the measurement speed by embedding low and high frequency components into a single pattern. However, fringe order errors may occur when the gap between two spatial frequencies exceeds a certain limit. Ding *et al* [11, 12] propose a temporal phase unwrapping method by using two fringe patterns with selected spatial frequencies to improve the robustness. However, noise in the wrapped phase would exceed the phase error bound in many practical applications [11, 15]. To increase the anti-error capability, an approach based on three fringe patterns with selected spatial frequencies is presented by Ding *et al* [13].

Typically, fringe order errors may appear when using those temporal phase unwrapping due to noise. In order to improve the reliability of fringe order recovery, it is desired to develop effective fringe order error correction schemes. Huang *et al* [14] propose a phase error identification framework based on the monotonicity of the phase map. However, it

may not work well for correcting multiple successive errors. Zhang *et al* [15] propose a method to eliminate phase errors caused by fringe order errors. This method is based on the smoothness of the absolute phase map, which requires the calculation of the quality map of the fringe patterns. Based on the step-wise increasing property of fringe order, Ding *et al* [16] propose a voting method that counts the number of pixels with different fringe order values in each step. However, this method may only reduce the fringe order errors to a certain degree for some cases. Li [17] presents to apply median filter to remove the impulsive errors associated with fringe orders row-by-row. However, this method may also fail when multiple successive fringe order errors are present.

In this paper, a new fringe order correction scheme is proposed. Different from the previous methods, which process the fringe order sequences in one-dimensional lines, we jointly correct the two-dimensional fringe order map. To achieve this, we first exploit the low-rank property of the fringe order maps and sparse nature of the impulsive fringe order errors. We apply robust principal component analysis (RPCA) to effectively separate the two components and thus remove the fringe order errors. Then the residual fringe order errors are detected based on the smoothly increasing property of the unwrapped phase map and corrected by minimizing the variation in the unwrapped phase. The proposed method features two-dimensional processing of the fringe order map and also the aid from the unwrapped phase map. Simulation results verify the effectiveness of the proposed method.

2. PRINCIPLE

2.1 Example of temporal phase unwrapping

In this paper, we assume that phase shifting profilometry (PSP) is used to obtain the wrapped phase value in a pixel-by-pixel manner due to its high accuracy and high resolution. Then temporal phase unwrapping is employed to recover the continuous absolute phase. With the PSP, a set of sinusoidal fringe patterns with equal phase shift are projected onto the object surface. The deformed fringe images captured by the camera can be modelled as:

$$I_n(x, y) = A(x, y) + B(x, y) \cos \left[\phi(x, y) + \frac{2\pi n}{N} \right], \quad n = 0, 1, \dots, N-1 \quad (1)$$

where $I_n(x, y)$ is the intensity value for the n -th fringe pattern on the object surface, $A(x, y)$ is the average intensity relating to the background illumination, $B(x, y)$ is the intensity modulation relating to the contrast of the pattern and surface reflectivity, and $\phi(x, y)$ is the phase distribution of the measured object. The wrapped phase can be extracted by

$$\phi(x, y) = \tan^{-1} \frac{\sum_{n=0}^{N-1} I_n(x, y) \sin(2\pi n/N)}{\sum_{n=0}^{N-1} I_n(x, y) \cos(2\pi n/N)}. \quad (2)$$

The wrapped phase extracted by the phase shifting algorithm falls into $(-\pi, \pi]$, and so phase unwrapping is required to obtain the absolute continuous phase map as:

$$\Phi(x, y) = \phi(x, y) + 2\pi k(x, y) \quad (3)$$

where $\Phi(x, y)$ is the unwrapped phase map and $k(x, y)$ is the integer number representing the fringe order.

In this paper, the multi-frequency method of [11] is considered to realize temporal phase unwrapping. Following [11], two sets of fringe patterns with coprime frequencies f_1 and f_2 are projected onto the object surface. Then we have:

$$\begin{cases} \Phi_1(x, y) = \phi_1(x, y) + 2\pi k_1(x, y) \\ \Phi_2(x, y) = \phi_2(x, y) + 2\pi k_2(x, y) \end{cases} \quad (4)$$

where $\phi_1(x, y)$ and $\phi_2(x, y)$ are the wrapped phase, $\Phi_1(x, y)$ and $\Phi_2(x, y)$ are the corresponding absolute phase. The fringe orders $k_1(x, y)$ and $k_2(x, y)$ are determined using the one-one unique mapping from $[f_2\phi_1(x, y) - f_1\phi_2(x, y)]/2\pi$ to $(k_1(x, y), k_2(x, y))$. However, if the phase noise exceeds a certain level, fringe order errors may occur [16].

2.2 Fringe order errors in temporal phase unwrapping

Ideally, the fringe order should exhibit step-wise increase along the direction perpendicular to the fringes (i.e., x -axis) and the step size should be always one. However, if noise exists, the recovered fringe order can suffer from errors. Fig. 1 shows an example of the fringe orders recovered using the method of [11]. In general, the fringe order errors may occur in the following different forms:

- Fringe order error occurs on a single pixel and appears as one-pixel impulse.
- Multiple successive pixels are contaminated by the fringe order errors. The fringe order values of these pixels may have the same wrong value or change randomly.
- Fringe order errors occur on the boundary of adjacent fringes and the fringe order error coincides with the step-wise increase.

A significant portion of the fringe order errors are impulsive and distributed sparsely on the fringe order map. This is because, with temporal phase unwrapping, the fringe orders are recovered independently for each pixel, and thus the fringe order errors do not propagate and are restricted to small regions [16-17]. In the following, we introduce a novel scheme to correct such errors.

Fig 1. Fringe order with impulsive errors.

2.3 Impulsive fringe order error correction based on RPCA

An estimated fringe order $\hat{k}(x, y)$ for a point (x, y) can be modelled as:

$$\hat{k}(x, y) = k(x, y) + e(x, y), \quad (5)$$

where $k(x, y)$ is the true fringe order and $e(x, y)$ is the fringe order error. Both $k(x, y)$ and $e(x, y)$ are integer values. Since fringe order errors occur in almost all temporal phase unwrapping schemes, it is necessary to develop a robust method to correct this type of error.

From (5), the recovered fringe order map $\hat{\mathbf{K}}$ (with entries $\hat{k}(x, y)$) is the superposition of the true order map $\mathbf{K}$ (with entries $k(x, y)$) and the errors $\mathbf{E}$ (with entries $e(x, y)$). We propose to separate these two components so that we are able to recover the correct fringe order map. According to the above analysis of the fringe order error, the fringe order errors $\mathbf{E}$ have a sparse nature [3, 16, 17]. Furthermore, we notice that for many applications, the true fringe order map $\mathbf{K}$ is low-rank. This is demonstrated in Fig. 2, where the singular values of the true fringe order map of an example of size 1000×1000 (with a simulated hemisphere) are shown. It can be observed that only a small number, e.g., 10, of singular values are dominant. This suggests that the true fringe order map has a low-rank representation.

Figure 2. Singular value distribution of a simulated fringe order map with size 1000×1000

Exploiting the low-rankness of $\mathbf{K}$ and the sparsity of $\mathbf{E}$, it is possible to eliminate the fringe order errors from the recovered fringe order map by using RPCA. However, since the original RPCA problem is NP-hard, directly solving this is difficult [18, 19]. Following [18, 19], the nuclear norm and l_1 -norm can be used to promote the low-rankness and sparsity, respectively. We can thus formulate the following low-rank plus sparse recovery problem:

$$\min_{\mathbf{E}, \mathbf{K}} \gamma \|\mathbf{E}\|_{l_1} + \|\mathbf{K}\|_*, \quad \text{s.t.} \quad \mathbf{E} + \mathbf{K} = \hat{\mathbf{K}}, \quad (6)$$

where $\|\cdot\|_{l_1}$ is the l_1 norm, defined as the sum of the absolute values of the elements in $\mathbf{E}$, $\|\cdot\|_*$ is the nuclear norm, defined as the sum of all the singular values of $\mathbf{K}$, and $\gamma > 0$ is a constant to balance low-rankness and sparsity. Different algorithms can be applied to approximately solve (6). We here adopt the alternating direction method (ADM), which minimizes the following augmented Lagrangian function:

$$L(\mathbf{E}, \mathbf{K}, \mathbf{Z}) = \gamma \|\mathbf{E}\|_{l_1} + \|\mathbf{K}\|_* - \langle \mathbf{Z}, \mathbf{E} + \mathbf{K} - \hat{\mathbf{K}} \rangle + \frac{\beta}{2} \|\mathbf{E} + \mathbf{K} - \hat{\mathbf{K}}\|^2 \quad (7)$$

where $\mathbf{Z} \in \mathcal{R}^{M \times N}$ is the multiplier of the linear constraint of (6), $\beta > 0$ is the penalty parameter for the violation of linear constraint and $\langle \cdot \rangle$ represents the standard trace inner product. The solution can be found iteratively. Let $P_{\Omega_{\infty}^{\gamma/\beta}}$ denote the Euclidean projection onto $\Omega_{\infty}^{\gamma/\beta} = \{\mathbf{X} \in \mathbf{R}^{N \times N} | -\gamma/\beta \leq X_{ij} \leq \gamma/\beta\}$, n the number of iteration, and $(\mathbf{E}^n, \mathbf{K}^n, \mathbf{Z}^n)$ the current solution. The ADM updates the solution using the following steps [19]:

1. Generate $\mathbf{E}^{n+1} = \left(\frac{1}{\beta} \mathbf{Z}^n - \mathbf{K}^n + \hat{\mathbf{K}}\right) - P_{\Omega_{\infty}^{\gamma/\beta}} \left(\frac{1}{\beta} \mathbf{Z}^n - \mathbf{K}^n + \hat{\mathbf{K}}\right)$
2. Generate $\mathbf{K}^{n+1} = \mathbf{U}^{n+1} \text{diag} \left(\max \left\{ \sigma_i^{n+1} - \frac{1}{\beta}, 0 \right\} \right) (\mathbf{V}^{n+1})^T$, where $\mathbf{U}^{n+1}$, $\mathbf{V}^{n+1}$ and $\{\sigma_i^{n+1}\}$ are the left singular vector, right singular vector and singular value matrices of $\hat{\mathbf{K}} - \mathbf{E}^{n+1} + \frac{1}{\beta} \mathbf{Z}^n$
3. Update the multiplier $\mathbf{Z}^{n+1} = \mathbf{Z}^n - \beta(\mathbf{E}^{n+1} + \mathbf{K}^{n+1} - \hat{\mathbf{K}})$

We can terminate ADM by setting an appropriate stopping criterion. In our study, the iteration stops when $\frac{\|(\mathbf{E}^{n+1}, \mathbf{K}^{n+1}) - (\mathbf{E}^n, \mathbf{K}^n)\|_F}{\|(\mathbf{E}^n, \mathbf{K}^n)\|_F + 1} \leq 10^{-6}$.

After applying the above algorithm to the estimated fringe order map, we will obtain the sparse component associated with impulsive fringe order errors and the low-rank component associated with the fringe order map with the impulsive errors eliminated. By rounding the entries of the output low-rank matrix to integers, we obtain the corrected fringe order sequences $\tilde{k}(x, y)$.

2.4 Residual fringe order error correction

With the above algorithm, the impulsive fringe order errors can be suppressed. However, residual fringe order errors may still exist and influence the absolute phase. In general, the difference of the absolute phases of two adjacent pixels in each row is smaller than π . This means the absolute phase should exhibit a smooth increase. Thus, by comparing the phase difference between two adjacent pixels to a certain threshold, we can possibly identify whether fringe order errors still exist or not. We thus propose the following procedure for fringe order correction:

1. Apply RPCA on the fringe order map recovered from temporal phase unwrapping to obtain the corrected fringe order sequence $\tilde{k}(x, y)$ with impulsive errors eliminated.
2. Calculate the unwrapped phase $\tilde{\Phi}(x, y)$ similarly to (3) using $\tilde{k}(x, y)$.
3. Calculate the phase difference between two adjacent pixels row by row as:

$$\Delta\tilde{\Phi}(x, y) = \tilde{\Phi}(x + 1, y) - \tilde{\Phi}(x, y), \forall x$$

4. Identify an interval with fringe order errors when a pair of pixels (x_1, y) and (x_2, y) with $|\Delta\tilde{\Phi}(x, y)| \geq \pi$ and $x_1 < x_2$ are detected; Correct the fringe order for $x_1 < x \leq x_2$ as follows:

$$\tilde{k}'(x, y) = \begin{cases} \tilde{k}(x, y) + 1, & \text{if } \Delta\tilde{\Phi}(x_1, y) < \Delta\tilde{\Phi}(x_2, y) \\ \tilde{k}(x, y) - 1, & \text{if } \Delta\tilde{\Phi}(x_1, y) > \Delta\tilde{\Phi}(x_2, y) \end{cases}$$

Using this procedure, we can detect and correct the fringe order errors resulting from temporal phase unwrapping.

3. SIMULATION RESULTS

In order to verify the feasibility of the proposed method, numerical simulations are carried out. We use a hemisphere as the measured object. In the simulations, two fringe patterns with frequencies $f_1 = 5$ and $f_2 = 8$ are projected onto the object surface, and the image size is 1000×1000 . In our simulations, we adopt the six-step phase shifting algorithm to obtain the corresponding wrapped phase maps. Based on [11], we can recover the absolute phase maps of the two fringes ($f_1 = 5, f_2 = 8$) in Fig 3(a) and 3(b). The fringe order of the recovered absolute phase maps at $f_1 = 5$ and $f_2 = 8$ are depicted in Fig 3(c) and 3(d)

Figure 3. The absolute phase maps. (a) Recovered absolute phase map at $f_1 = 5$. (b) Recovered absolute phase map at $f_2 = 8$. (c) Recovered fringe order map at $f_1 = 5$. (d) Recovered fringe order map at $f_2 = 8$.

In the ideal cases free of noise, the recovered fringe order maps have no errors. In order to make the simulate practical applications, we add random impulsive noise on the fringe order and the simulated fringe order of hemisphere is shown in Fig 4(a). The feasibility of applying RPCA method for removing the impulsive errors are shown in Fig 4(b). It is seen that we are able to remove the impulsive errors successfully. Fig. 4(c) and (d) also demonstrate the reconstruction results at $f_1 = 5$ without fringe order correction and with our proposed fringe order correction scheme. It is seen that the proposed method can effectively wipe off the fringe order errors.

Figure 4. (a) Simulated fringe order with impulsive errors. (b) Corrected fringe order after employing RPCA. (c) 3D reconstruction result with impulsive errors. (d) 3D reconstruction result with proposed fringe order correction scheme.

Fig. 5 compares the fringe order correction results obtained by median filter [17] and our proposed method. We still use a hemishpere as the measured object and add multiple successive errors on the recovered fringe orders (492 pixels with fringe order error). Fig 5(a) and (b) show the simulated fringe order map with multiple successive fringe order errors. Fig 5(c) and (d) show the fringe order correction results by using median filters in a row-by-row manner (with sliding window properly selected). Fig 5(e) and (f) demonstrate the correction results obtained by our proposed method. It is seen that the median filter method does not perform well if the fringe order contains a large cluster of fringe order errors, while our proposed method can still successfully correct the fringe order errors.

Figure 5. (a) Simulated fringe order with consecutive errors. (b) Cross section for Fig. 5(a) when $x=599$. (c) Fringe order correction results by using median filter. (d) Cross section for Fig. 5(c) when $x=599$. (e) Fringe order correction results by using our proposed method. (f) Cross section for Fig. 5(e) when $x=599$.

4. CONCLUSION

In this paper, we propose a novel approach to correct the fringe order errors for temporal phase unwrapping. RPCA is applied to effectively remove the impulsive errors from the recovered fringe order map. To further correct the residual fringe order errors, the smoothly increasing property of the absolute phase is utilized. The effectiveness of the proposed scheme has been verified by numerical simulations.

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