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Recovering the absolute phase maps of three selected spatial-frequency fringes with multi-color channels

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ABSTRACT

In a recent published work, we developed the technique to enhance the reliability of absolute phase maps by using the fringes of three spatial frequencies. However, it is time-consuming to capture the fringe images of three spatial frequencies with single channel in time sequence. To increase the efficiency of our proposed three-frequency technology, in this paper we propose a method to capture the fringe images of three spatial frequencies with multi-color channels and 3CCD camera. The projected spatial frequencies can be selected to guarantee the correctness of recovered fringe orders and avoid the chromatic aberration effect on frequency distortion. The cross talk among color channels can be eliminated effectively and the measured object can be reconstructed with high accuracy. The effectiveness of this method is verified by experimental results.

1. Introduction

Fringe projection profilometry (FPP) has become one of the most promising technologies for non-contact 3D shape measurement. The methods based on the phase maps of fringe patterns are the most widely utilized. A challenging task associated with existing phase measurement technique in FPP is phase unwrapping operation, which aims to recover the absolute phase maps from the wrapped phase maps. Existing phase unwrapping methods include spatial [1], temporal [2], and period coding [3]. However, recovery of absolute phase maps is still a challenging task when the wrapped phase maps contain noise, sharp changes or discontinuities.

To achieve reliable and accurate phase unwrapping for FPP, a variety of temporal phase unwrapping approaches have been proposed. Huntley and Saldner [2] employ the multiple fringe patterns which are projected onto the object in time sequence, phase unwrapping can be carried out by comparing the wrapped phases of adjacent frequencies in order to avoid noise or boundaries and thus achieving correct recovery of the absolute phase map. While the method proposed in [2] is demonstrated to be effective for accurate phase unwrapping, it also suffers from the drawback of requiring many intermediate phase patterns, which is obviously not suitable for fast or real-time measurement. In order to increase the efficiency, Zhao, et al. [4] propose to use two image patterns, one of which has a very low spatial frequency in contrast to the other. In particular, the low spatial frequency pattern only has a single fringe. Such a pattern has its absolute phase value falling within the range $(-\pi, \pi)$, and hence can be used as a reference to calculate the fringe number of the other fringe pattern, thus yielding its absolute phase map. Li, et al. [5] also employ the phase map of single fringe pattern as reference to unwrap high spatial frequency fringe patterns, and it is shown that the spatial frequency of the pattern to be unwrapped is determined by the level of noise. Following the same method in [4], Liu, et al. [6] project a single fringe pattern and a high frequency pattern in one shot to accelerate the speed of 3D measurement. These method works well in principle, but the gap between two spatial frequencies should be restricted within a range based on the noise level or steps in the low frequency phase maps. As the accuracy performance of FPP requires the use of high frequency fringe patterns, these methods may not work well when the phase maps are noisy. Consequently, multiple intermediate image patterns are still required in order to reduce the frequency gaps among adjacent patterns. Saldner and Huntley [7,8] study the multiple intermediate image patterns, showing that to unwrap a phase map of frequency f, $\log_2 f + 1$ sets of fringe patterns are required. A similar result is also reached by Zhang [9,10], indicating that the spatial frequency can be increased by a factor of 2 between two adjacent patterns.

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Taking a typical FPP arrangement as an example where the image pattern has 16 fringes, 5 image patterns are still required with this approach. To reduce the frequencies used for temporal phase unwrapping, Zhong, et al. [11] also constructed a look-up table to unwrap the absolute phase maps for multiple-spatial-frequency fringes. This look-up table denotes the corresponding relationship from a pair of fringe orders at two spatial frequencies (f_1, f_2) to $[f_2\phi_1(x) - f_1\phi_2(x)]/2\pi$. However, when the spatial frequencies f_1 and f_2 are large values, one value in $[f_2\phi_1(x) - f_1\phi_2(x)]/2\pi$ may correspond to two or more pairs of fringe orders, thus the fringe orders cannot be determined uniquely. To make sure the values of $[f_2\phi_1(x) - f_1\phi_2(x)]/2\pi$ unique, Zhong [12] proposed to generate the two relatively irrational spatial frequencies fringes by changing the projection angle of the grating. However, the minimal value gap of $[f_2\phi_1(x) - f_1\phi_2(x)]/2\pi$ of two irrational frequencies is always smaller than the two rational frequencies [11,12], which may yield mistakes in determining fringe order pairs.

In order to guarantee the uniqueness of recovered fringe orders, we have developed a temporal phase unwrapping technique based on the use of two fringe images with two selected frequencies [13]. When the two normalized spatial frequencies f_1 and f_2 are co-prime, there exists a one-to-one map from $[f_2\phi_1(x) - f_1\phi_2(x)]/2\pi$ to their fringe orders, where $\phi_1(x)$, $\phi_2(x)$ are the wrapped phase maps. The performance of the proposed method in [13] is limited by phase error tolerance bound, $\pi/(f_1 + f_2)$ [14]. If the phase error of wrapped phase maps is larger than the phase error bound, errors may occur in the recovery of the absolute phase maps. In order to enhance the reliability of the recovered absolute phase maps, we propose to increase the phase error tolerance bound by the use of three fringe patterns with selected frequencies. The minimal value gap concerning the values of $[f_2\phi_1(x) - f_1\phi_2(x)]/2\pi$ is increased significantly, resulting in a higher phase error tolerance bound [15]. The case of employing multiple spatial-frequency fringes is generalized for high accurate reconstruction [16]. However, the experiments in [15,16] are implemented by monochrome fringe patterns, at least 18 images are needed if we employ the six-step PSP (Phase-Shifting-Profilometry) to obtain the wrapped phase of three spatial-frequency fringes, which is not time-efficient for various applications.

With the development of digital fringe projection system, multi-color fringe patterns have been employed for shape measurement in FPP. Huang et al. [17] project the color fringe patterns in $2\pi/3$ phase shift at the same spatial frequencies onto the object and compensate the color channel coupling effect by intensity modulation parameter to obtain wrapped phase map. Skydan et al. [18] propose to use the colored fringe patterns at the same spatial frequencies from different angles to overcome the shadow problem of measured objects. Hu et al. [19] develop a blind approach to calculate the de-mixing matrix that no extra images are required for color calibration. However, these techniques only use the wrapped phase of single spatial frequency, which may lead to phase ambiguity for the objects with sharp changes or discontinuities. Pfortner et al. [20] use 3CCD camera to capture the interference patterns at three wavelengths generated by three laser sources simultaneously for distance measurement, while this method is more suitable to solve the problem of interferometry rather than fringe projection profilometry. Kinell [21] uses three color channels to carry three spatial frequencies to implement temporal phase unwrapping, in each channel the fringe images are projected and captured in phase shift sequences. The normalized three selected frequencies of three color channels are 14, 15, 16, errors occur in the recovered fringe orders due to the phase noise and spatial frequency selection. Zhang et al. [22] use the three color channels to carry the three normalized spatial frequencies 100, 99, 90 to implement temporal phase unwrapping. While these very high spatial frequencies will distort as the chromatic aberration effect, which will lead to the errors in recovered fringe orders. Thus the actual projected frequencies should be adjusted according to the application scenarios, the actual spatial frequencies used in [22] are 100.196, 99 and 89.846. The estimation of proper actual spatial frequencies should be implemented before object measurement, which is not convenient for various applications.

To accelerate the fringe image acquisition of our previous work in [15], in this paper we employ the color channels of projectors and 3CCD camera to capture the fringe patterns in a more time-efficient manner. Each channel carries the fringe pattern of one spatial frequency. Three spatial frequencies are selected based on the principles developed in [15], which yields high reliability for temporal phase unwrapping. Since the selected spatial frequencies are not very high, the frequency distortion caused by chromatic aberration is negligible, the actual projected frequencies need not to recalibrate before fringe projection. The experimental results validate the effectiveness of the proposed method, which enables our proposed three-frequency technology for time efficient applications.

This paper is organized as follows. In Section 2 we revisit the technique to recover the absolute phase maps with three selected spatial-frequency fringes. In Section 3, we describe the multi-color channel scheme and strategies to eliminate the cross talk. In Section 4, experiments are presented to show the effectiveness of proposed method. Section 5 concludes the whole paper.

2. Absolute phase maps recovery with three frequency fringe patterns

2.1. Three -frequency technique

Let us consider a FPP system, with which image patterns of three spatial frequencies are projected onto the object surface respectively. The image patterns are characterized by fringe structure where the light intensity is constant in y-axis and varies sinusoidally in x-axis. The normalized spatial frequencies of the multiple patterns are f_i (i=1,2,3) referring to the total number of fringes on the respective patterns. Let us use $\Phi_i(x)$ (i=1,2,3) and $\phi_i(x)$ (i=1,2,3) to denote respectively the absolute phase maps and the corresponding wrapped phase maps of the fringe patterns. Taking the central vertical line of images as the reference, the value of the wrapped phase map is limited by $-\pi \le \phi_i(x) \le \pi$ (i=1,2,3), and the value of the absolute phase maps should fall into the following:

$$-f_i\pi < \Phi_i(x) < f_i\pi \tag{1}$$

Hence the absolute and wrapped phase maps are related by the following:

$$\Phi_i(x) = 2\pi m_i(x) + \phi_i(x) \tag{2}$$

where $m_i(x)$ (i=1,2,3) are referred to as fringe numbers or indices. They are integers and $-f_i < m_i(x) < f_i$. Obviously, the absolute phases can be recovered if $m_i(x)$ are determined. In order to achieve this, the following relationships hold:

$$f_j\Phi_i(x) = f_i\Phi_j(x) \tag{3}$$

where $i \neq j$.

Combining Eqs. (2) and (3), we have:

$$\frac{f_j\phi_i(x) - f_i\phi_j(x)}{2\pi} = m_j(x)f_i - m_i(x)f_j \tag{4}$$

Similar to the method employed in [15], an intermediate variable $\Phi_0(x)$ is introduced, which increases monotonically from $-\pi$ to π with respect to x and defined as follows:

$$\Phi_0(x) = \frac{\Phi_1(x)}{f_1} = \frac{\Phi_2(x)}{f_2} = \frac{\Phi_3(x)}{f_3} \tag{5}$$