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Color fringe projection profilometry using geometric constraints

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A B S T R A C T

A recently proposed phase unwrapping method using geometric constraints performs well without requiring additional camera, more patterns or global search. The major limitation of this technique is the confined measurement depth range (MDR) within 2π in phase domain. To enlarge the MDR, this paper proposes using color fringes for three-dimensional (3D) shape measurement. Each six fringe periods encoded with six different colors are treated as one group. The local order within one group can be identified with reference to the color distribution. Then the phase wrapped period-by-period is converted into the phase wrapped group-by-group. The geometric constraints of the fringe projection system are used to determine the group order. Such that the MDR is extended from 2π to 12π by six times. Experiment results demonstrate the success of the proposed method to measure two isolated objects with large MDR.

1. Introduction

Optical 3D shape measurement has widely applied in many fields such as industrial inspection, reverse engineering and digital entertainment [1–3]. Among various techniques developed, fringe projection profilometry (FPP) has been an intense research subject due to its merits of non-contact, low-cost, full-field acquisition, fast data processing and high-resolution [4–6]. The 3D reconstruction from the modulated fringes on the measured objects is often referred as fringe analysis [7]. Until now, several algorithms including Fourier transform [8], wavelet transform [9] and phase-shift [10] have been proposed to analyze the fringe patterns. In general, phase-shift methods acquiring more than three frames calculate the phase pixel-by-pixel and are more accurate than transform methods. However, phase-shift methods involve the arctangent operation that will result in phase values ranging from [-π, +π] with 2π jumps. Therefore, phase unwrapping should be carried out for the absolute phase map.

Numerous methods have been presented for phase unwrapping during past decades which are generally classified into two categories: spatial methods and temporal methods [11]. Spatial phase unwrapping is a natural way that detects and removes 2π jumps from the wrapped phase directly. However, spatial methods tend to fail if abrupt shapes introduce more than 2π phase changes from one pixel to its neighboring pixels. To avoid the error transferring between pixels, temporal phase unwrapping finds the fringe order using additional information [12]. The common temporal methods include two-wavelength [13,14], multiple-wavelength [15,16], gray-coding [17,18], color-coding [19,20] and phase-coding [21,22], and these methods all require additional patterns. Overall, spatial methods are limited to smooth and continuous phase reconstruction, and temporal methods are more general but time consuming. Instead of requiring additional patterns, some researchers attempted to employ additional camera for phase unwrapping [23–25]. However, these methods usually require global search for correct corresponding point that will slow down the processing speed. Furthermore, accurate calibration of stereo cameras and the projector are also necessary. And some flexible methods have been developed for FPP system calibration, then the absolute phase can be converted into the depth data [26,27].

Some recent studies using the geometric constraints of the FPP system for phase unwrapping have been conducted, without requiring additional camera, more patterns, or global search [28–31]. This method has the following advantages: high-speed 3D shape measurement, high-speed processing, simple system setup, simultaneous multiple objects measurement, robustness in fringe order determination. However, the maximum MDR this method can handle is up to 2π in phase domain. If the MDR of measured objects is larger than 2π, the method will fail to determine the correct fringe order. Combined with the phase-coding method, the MDR can be significantly enlarged, yet two additional binary patterns are needed [32].

To address the above problems, this paper presents a method that uses color fringes for 3D shape measurement. Each six fringe periods encoded with six typical colors (red, yellow, green, cyan, blue and magenta) are treated as one group. The local order within one group can be determined with reference to the color distribution, and

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wrapped phase ranging from [0, 2π] can be converted into wrapped phase ranging from [0, 12π]. The group order is determined by using the geometric constraints of the FPP system. Then the fringe order can be obtained by combining the local order and the group order. Such that the maximum MDR can be extended from 2π to 12π by six times. The paper is organized as follows. Section 2 introduces the related works. Section 3 explains the principles of the proposed method. Section 4 presents experiment results of two isolated objects to validate the proposed method. Finally, Section 5 summarizes this paper.

2. Related work

2.1. Three-step phase-shift algorithm

Phase-shift methods are widely used in optical metrology because of their speed and accuracy [33]. Without loss of generality, the three-step phase-shift algorithm that requires the least number of patterns is chosen for the proposed method [34]. Three captured fringes can be mathematically described as:

$$\begin{cases} I_1(x, y) = a(x, y) + b(x, y)cos[\phi(x, y) - 2\pi/3] \\ I_2(x, y) = a(x, y) + b(x, y)cos[\phi(x, y)] \\ I_3(x, y) = a(x, y) + b(x, y)cos[\phi(x, y) + 2\pi/3] \end{cases} \quad (1)$$

where $a(x, y)$ is the average intensity that relates to the fringe brightness and background illumination, $b(x, y)$ is the intensity modulation that relates to the fringe contrast and surface reflectivity, and $\phi(x, y)$ denotes the wrapped phase which can be extracted by simultaneously solving the above equations:

$$\phi(x, y) = tan^{-1}\left(\sqrt{3}\frac{I_1 - I_3}{2I_2 - I_1 - I_3}\right) \quad (2)$$

The principal component analysis also provides an alternative method for the wrapped phase calculation [35,36]. Because of the arctangent operation, Eq. (2) produces the wrapped phase ranging from [-π, +π] with 2π jumps. Therefore, phase unwrapping should be carried out to recover the absolute phase map. The fringe order K determination is the most critical step in phase unwrapping [37]. Once K determined, the unwrapped phase map Φ can be obtained using the following equation:

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

2.2. Phase unwrapping using geometric constraints

As recently proposed by An et al. [28], wrapped phase can be unwrapped by using geometric constraints of the FPP system. Fig. 1 illustrates the fundamental principle of this method. If a flat surface is precisely placed at $z^w = z_{min}$ that coincides with the closest depth plane of interest, one can establish the geometric mapping between the camera sensor (e.g., charge-coupled device, or CCD) and the projector sensor (e.g., digital micro-mirror device, or DMD). Therefore, the

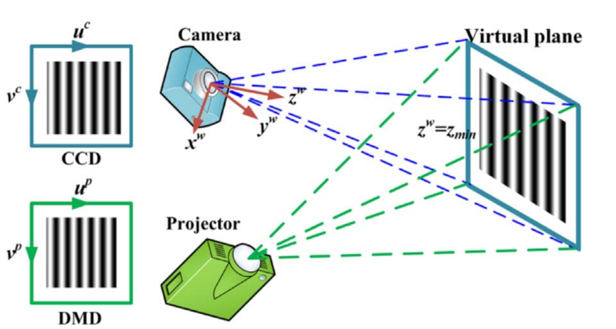

Fig. 1. Geometric mapping between the camera sensor and the projector sensor for a virtual z_{min} plane.

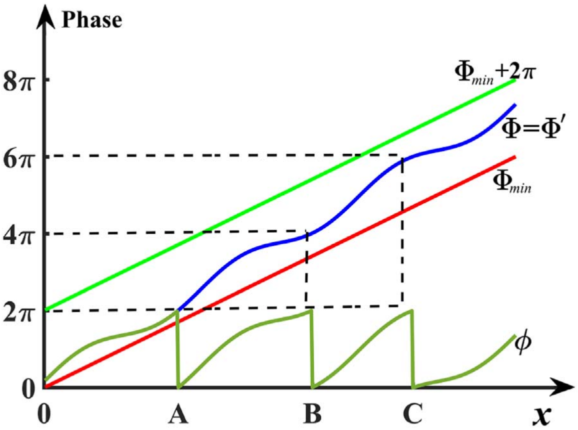

Fig. 2. Cross sections of wrapped phase ϕ, the actual unwrapped phase Φ, and the reovered phase Φ' using the minimum phase map Φ_{min} when $max(\Phi - \Phi_{min}) < 2\pi$.

minimum phase map Φ_{min} corresponding to the virtual z_{min} plane can be precisely created. Then phase unwrapping can be performed pixel-to-pixel with reference to Φ_{min}. The details of z_{min} determination and Φ_{min} generation can be referred to [28].

Fig. 2 illustrates the phase unwrapping when $max(\Phi - \Phi_{min}) < 2\pi$. If the wrapped phase ϕ captured at $z^w > z_{min}$ is below Φ_{min}, K times of 2π should be added to ϕ for unwrapped phase Φ. For cases shown in Fig. 2, below A, $\Phi_{min} < \phi$ and $\Phi = \phi$; between A and B, $0 < \Phi_{min} - \phi < 2\pi$ and $\Phi = \phi + 2\pi$; between B and C,$2\pi < \Phi_{min} - \phi < 4\pi$ and $\Phi = \phi + 4\pi$; beyond C, $4\pi < \Phi_{min} - \phi < 6\pi$ and $\Phi = \phi + 6\pi$. Based on the difference $\Phi_{min} - \phi$, the fringe order K can be determined as:

$$K(x, y) = ceil\left(\frac{\Phi_{min} - \phi}{2\pi}\right) \quad (4)$$

where function $ceil(x)$ returns the closest integer larger than input x. Nevertheless, there is an essential prerequisite for Eq. (4) that can be expressed as:

$$2\pi * (K - 1) < \Phi_{min} - \phi < 2\pi * K \quad (5)$$

It means that the maximum MDR from the measured surface to the virtual z_{min} plane should be less that 2π in phase domain. If the MDR is larger than 2π, this method could produce the incorrect fringe order. Fig. 3 illustrates the phase unwrapping when $max(\Phi - \Phi_{min}) > 2\pi$. At points $\Phi - \Phi_{min} > 2\pi$, the recovered Φ' diverges from the actual unwrapped phase Φ. For example, between D and E, $\Phi - \Phi_{min} < 2\pi$ and $\Phi = \Phi'$; but between F and G, $\Phi - \Phi_{min} > 2\pi$ and $\Phi \neq \Phi'$. The confined MDR will limit the applications of this method.

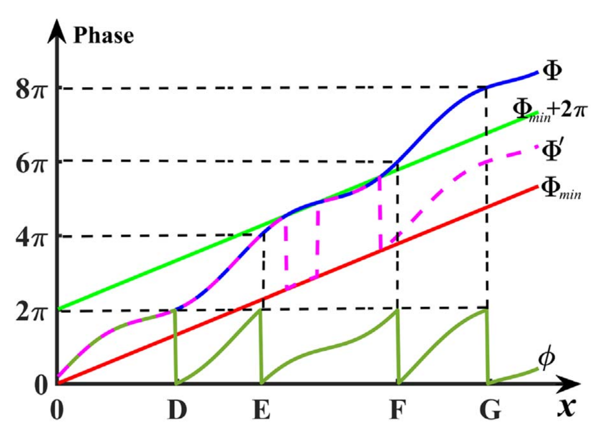

Fig. 3. Cross sections of wrapped phase ϕ, the actual unwrapped phase Φ, and the reovered phase Φ' using the minimum phase map Φ_{min} when $max(\Phi - \Phi_{min}) > 2\pi$.