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An improved stair phase encoding method for absolute phase retrieval

Canlin Zhou [a,*], Tongchuan Liu [a], Shuchun Si [a], Jianqiang Xu [a], Yepeng Liu [a], Zhenkun Lei [b]

[a] School of Physics, Shandong University, Jinan 250100, China
[b] Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China

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ABSTRACT

An improved phase unwrapping method is proposed to reduce the projection fringes in three-dimensional (3D) surface measurement. Color fringe patterns are generated by encoding with sinusoidal fringe and stair phase fringe patterns in red and blue channels. These color fringe patterns are projected onto the tested objects and then captured by a color CCD camera. The recorded fringe patterns are separated into their RGB components. Two groups of four-step phase-shifting fringe patterns are obtained. One group of the stripes are four sinusoidal patterns, which are used to determine the wrapped phase. The other group of stripes are four sinusoidal patterns with the codeword embedded into stair phase, whose stair changes are perfectly aligned with the 2π discontinuities of sinusoidal fringe phase, which are used to determine the fringe order for the phase unwrapping. The experimental results are analyzed and compared with those of the method in Zheng and Da (2012. Opt Express 20(22):24139–24150). The results show that the proposed method needs only four fringe patterns while having less error. It can effectively reduce the number of projection fringes and improve the measuring speed.

1. Introduction

Many spatial and temporal phase retrieval methods have been presented for phase unwrapping [1–3]. They have made great progress in 3D surface measurement. However, spatial phase retrieval method can hardly measure an object with complex shapes or isolated parts. Temporal phase retrieval method can solve this problem, but it needs multiple frames of fringe images which would take much time [4]. In order to work out this problem, Han proposed a color structured light technology [5]; Hu proposed a color fringe projection method [6]; Chen proposed a color-coding and phase-shift method which is similar to Han's [7]; Lu needed three gray scale coding [8]; Zhang used the stair gray scale [9]; Xu used the gray coding [10]; Zuo realized phase unwrapping by only four fringes [11]. However, these methods would reduce efficiency when there are complex surface reflectances. Zhang proposed a stair phase coding technology [12]. The codeword is embedded into the phase and then used to determine the fringe order. It is robust to the surface contrast, ambient light, and camera noise. Basing on it, Fu measured a blade with complex surface [13]. However, its accuracy would reduce when dealing with a large number of codewords. To solve this problem, Zheng proposed a technology using two groups of stair phases [14]. The experiments performed well. But Zuo found that four-step phase-shifting algorithm is less sensitive to the high order harmonics [15]. To avoid the complex gamma correction, we often use four-step phase-shifting algorithm [16]. If we use Zheng's method, we would need twelve fringe patterns which would make the measurement slow. It becomes a problem to determine the fringe order by the temporal phase retrieval methods with less fringe patterns.

We propose an improved phase unwrapping method based on Zheng's stair phase coding method. Two groups of phases are used, but they are put into different channels of RGB color fringe patterns. The method only needs four fringe patterns while retrieving the absolute phase well. It has the advantage of speed and suits for fast 3D surface measurement.

The paper is organized as follows. Section 2 introduces the principle of the system. Section 3 presents the experimental results and discusses the different results. Section 4 summarizes this paper.

2. Theory

2.1. Four-step phase-shifting algorithm

Phase-shifting algorithms are widely used in surface measurement because of their speed and accuracy. A four-step phase-shifting algorithm with a phase shift of $\pi/2$ can be shown as

$$I_1(x,y) = A(x,y) + B(x,y)\cos[\varphi(x,y)] \quad (1)$$

* Corresponding author. Tel.: +86 13256153609.
E-mail address: canlinzhou@sdu.edu.cn (C. Zhou).

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$$I_2(x,y) = A(x,y) + B(x,y)\cos\left[\varphi(x,y) + \pi/2\right] \quad (2)$$

$$I_3(x,y) = A(x,y) + B(x,y)\cos\left[\varphi(x,y) + \pi\right] \quad (3)$$

$$I_4(x,y) = A(x,y) + B(x,y)\cos\left[\varphi(x,y) + 3\pi/2\right] \quad (4)$$

where $A(x,y)$ is the background illumination, $B(x,y)$ and $\varphi(x,y)$ are the modulation and phase maps.

Based on Eqs. (1)–(4), we can obtain

$$\varphi(x,y) = \arctan\left(\frac{I_4 - I_2}{I_1 - I_3}\right) \quad (5)$$

The arctangent function will result a value range of $(-\pi, +\pi)$ with 2π discontinuities. We should unwrap the phases.

2.2. The improved stair phase unwrapping algorithm

Zheng unwrapped the phases through coding two groups of phase information. The first group of coding phase has 32 fringe periods, each of which is 32 pixel and same as the wrapped phase. It is divided into four equal parts, each of which is quantized into eight levels. In the first eight periods, the coding phase decreases from $+\pi$ to $-\pi$ with a stair height of $2\pi/8$. For the second eight periods, the coding phase increases from $-\pi$ to $+\pi$ with a stair height of $2\pi/8$. The third eight periods, the coding phase distribution is the same as the first eight periods, and the fourth eight periods is the same as the second. The second group of coding phase has four phase periods, each of which is 256 pixel and eight times of the 32 pixel for the first group of coding phase. It is quantized into four levels which decreases from $+\pi$ to $-\pi$ with a stair height of $2\pi/4$.

One group of coding phase divides the measuring field into four parts, the other group divides every part more carefully. Every coding phase is corresponded to the period of the sinusoidal fringes. Each codeword can determine one fringe order for the phase unwrapping. A total of 32 unique codewords can retrieve the absolute phase. One thing to note here is that the adjacent stair phase jumps may result in adjacent gray level jumps.

However, the adjacent stair phase jumps can be used to divide the measuring field into four parts. In other words, we don't need

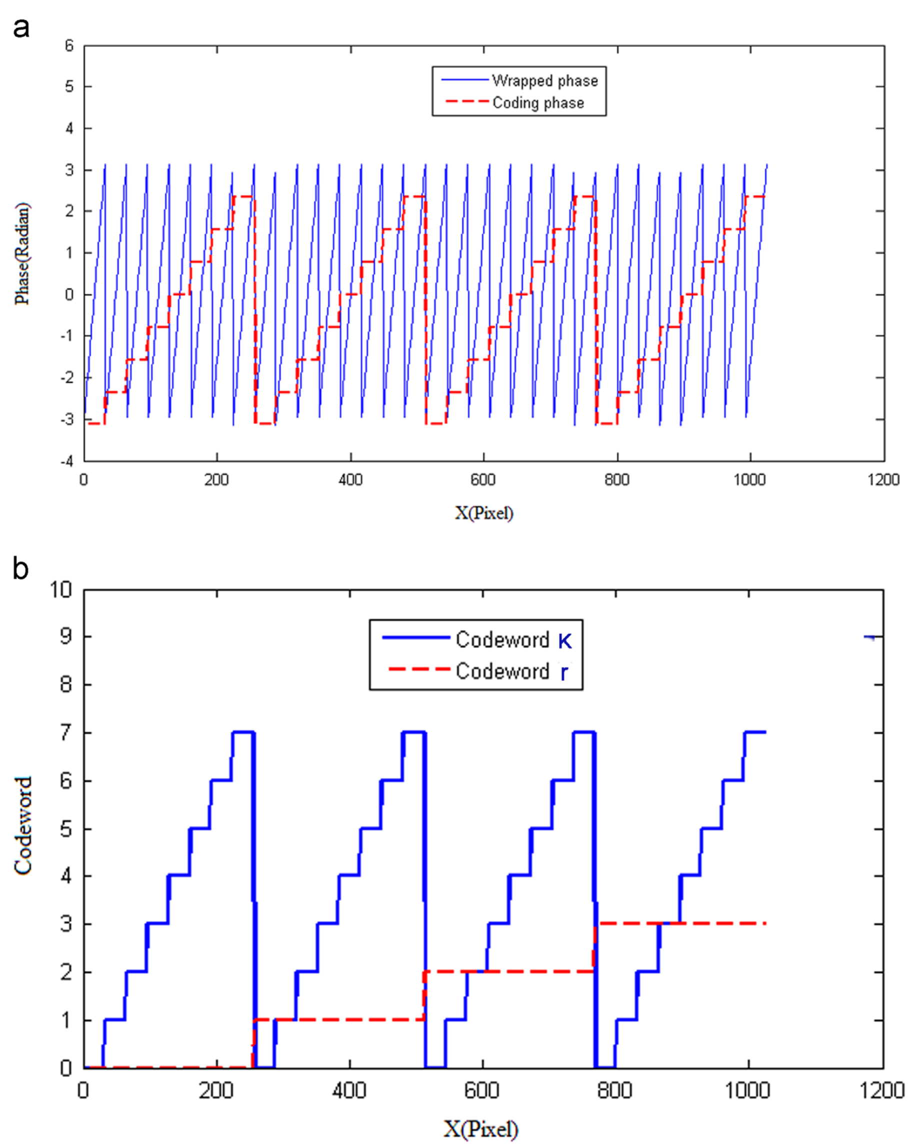

Fig. 1. One cross section (a) of the coding phase and wrapped phase; and (b) of the fringe codeword k and the sub-zone codeword r.