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Composited color-coded sinusoidal fringe pattern for absolute phase measurement

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ABSTRACT

A novel color-coded sinusoidal fringe pattern for absolute phase measurement is proposed in this letter. We used composited color sinusoidal fringe to calculate the wrapped phases and fringe orders without other assistant gratings. A novel algorithm was used to map wrapped phase to absolute phase. Three different colors were employed to mark to fringe orders, and then 27 fringes could be encoded by 4-bits codeword in three gratings with a phase shift of $2\pi/3$. Gray values of the color-coded sinusoidal fringe are employed to calculate the wrapped phases by phase shift method, and then we used wrapped phases to obtain the lowest bit of codewords. Color information were used to decide three high bits of codewords. With codewords of 4 bits, the fringe orders can be found from a lookup table, and then the wrapped phased could be mapped to absolute phase. Moreover, shortcomings of channels coupling in color grating measurement are also circumvented. The experimental results showed the validity of our algorithm.

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1. Introduction

Phase measurement has been widely used in many scientific, industrial and entertainment fields, however, the problems caused by the complexity of phase unwrapping process still lead to fast and stable measuring 3D objects restricted. There have been many methods proposed that do not need unwrapping process, such as gray-coding method [1], phase-coding method [2], color-coding methods [3] and we call them absolute phase measurement in this letter. The gray-coding technique is limited to 2^M (M is the number of binary patterns used) [2]. Phase-coding method was proposed recently to improve this problem, which needs three extra images to mark the fringe orders. Color-coding method marks the fringe orders by designing color codewords series and only one extra image is needed. However, those absolute phase measurements always need extra marking gratings which will obviously decrease the speed of data acquisition for phase measurement. Also, there have been absolute phase measurement methods by one-shot composite grating in Fourier transform profilometry [4–6], unfortunately, all those methods cannot be transplanted directly to phase-shift measurement because the intensities of the color gratings captured by the CCD camera always have large errors when the colors changes abruptly.

In this letter, a novel color-coded sinusoidal fringe method, with three color gratings, is proposed. Unlike the traditional color phase-shifting technique [7,8], our method does not need complex compensation and special camera to deal with the channel-imbalance and color coupling. What we need is to balance the intensities of three different color strips, which is easy in practice. The intensities of the gratings are used for wrapped phase calculation, and with the color information are used to decode the fringe orders and map the wrapped phase to absolute phase. Three different colors are employed to mark to fringe orders, and then 27 fringes could be encoded in three gratings with a phase shift of $2\pi/3$. In order to minimize the phase error caused from sharp color transitions, color changes only happened in the weakest intensity of the color gratings. Gray values of the color-coded sinusoidal fringe were employed to calculate the wrapped phases by phase shift method, and then wrapped phases were used to obtain the lowest bit of codewords. Color information is used to decide 3 high bits of codewords. With 4 bits codewords, the fringe orders could be retrieved from a lookup table, and then the wrapped phased could be mapped to absolute phase. This algorithm could be faster because of no need of unwrapped phase processing. Moreover, shortcomings of channels coupling in color grating measurement are also circumvented.

2. Theoretical background

Phase shift measurement was used to test our algorithm. A three step phase shift measurement with a phase shift of $2\pi/3$ is widely

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Table 1
Definition of bit values of codewords.

Phase	$[0, 2\pi/3]$	$[2\pi/3, 4\pi/3]$	$[4\pi/3, 2\pi]$
Bit (1)	1	2	3
Color	Red	Green	Blue
Bit (2–4)	1	2	3

used because of the least need for image frames, which can be described as

$$g1(x, y) = A(x, y) + B(x, y)\cos(\phi(x, y)) \quad (1)$$

$$g2(x, y) = A(x, y) + B(x, y)\cos(\phi(x, y) + 2\pi/3) \quad (2)$$

$$g3(x, y) = A(x, y) + B(x, y)\cos(\phi(x, y) + 4\pi/3) \quad (3)$$

where $A(x, y)$ is the average intensity, $B(x, y)$ is the intensity modulation, and $\phi(x, y)$ is the phase to be solved. Through solving Eqs. (1)–(3), we can obtain

$$\phi(x, y) = \arctan(\sqrt{3} * (g3 - g2)/(2 * g1 - g2 - g3)) \quad (4)$$

The arctangent function will result a value range $[0, 2\pi]$ with 2π discontinuities. While many unwrapping algorithms can be used to remove 2π discontinuities [9], when there are abrupt surface changes needed to be simultaneously measured, those unwrapping algorithms all have some problems. Thereby, the absolute phase techniques proposed to improve this problem without spatial phase unwrapping.

Unlike traditional binary methods by simply embedding the codewords to intensity image, both color information and intensity information are used to identify the fringe orders. Each period has a unique codewords consist of 4 bit. In order to simplify the follow-up analysis, we use 1 to denote red, 2 to green, 3 to blue. Three high bits are derived from the color information of three color gratings while the intensities of the gratings are used to derive the lowest bit. If the wrapped phases obtained from Eq. (4) locate in the area of $[0, 2\pi/3]$, the last bit equals 1, else if in $[2\pi/3\pi/3]$, the bit equals 2, else, the bit equals 3. You can also find the definition of bit values of codewords in Table 1, and 4-bit codewords used in this letter are showed in Table 2. After color pattern was projected, image obtained in CCD camera would be divided into many color strips. Then recognizing the color information, three high bits of each codewords will be obtained. Fig. 1 shows an example of the color-coding projection pattern used in this experiment. Here, we summarize the steps to generate the composite color gratings:

Step 1: Generate three gray gratings $g1$, $g2$ and $g3$ with phase shift of $2\pi/3$, which are showed in Fig. 1a.
Step 2: Generate three color strips gratings. As showed in Fig. 1b(1), first color strips are perfectly aligned with 2π discontinuities of the gray gratings in Fig. 1a(1). The second color strips, showed in Fig. 1b(2), mark three neighbor fringes as a group, in the same time, the edges of the color transition of the color strips align with 2π discontinuities of the gray gratings in Fig. 1a(2). The third color strips, showed in Fig. 1b(3), mark nine neighbor fringes as a group, the edges of the color transition align with 2π discontinuities of the gray gratings in Fig. 1a(3). Note that, we set the 2π discontinuities happen in the weakest intensity of gray gratings in this letter.
Step 3: The gratings in Fig. 1a and b are incorporated to generate the composited color-coded sinusoidal fringe pattern, as showed in Fig. 1c.

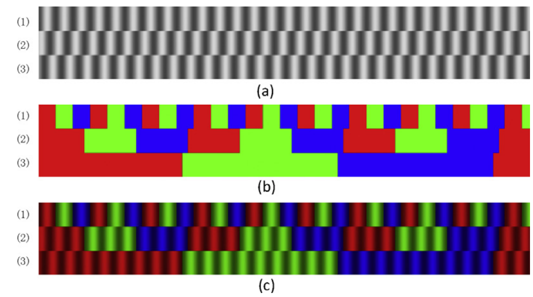

Fig. 1. Color-coding pattern used in the experiment. (For interpretation of the references to color in text, the reader is referred to the web version of the article.)

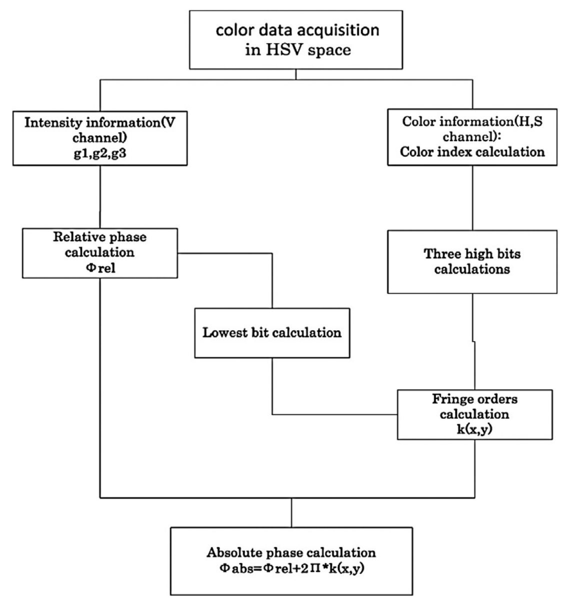

Fig. 2. The flowchart of our algorithm.

Traditional unwrapping methods remove the 2π discontinuities by analyzing the phase values of its neighboring pixels, then adding or subtracting multiple times of 2π assuming the surface smoothness. That is, the relationship between the wrapped phase and the unwrapped can be written as

$$\varphi(x, y) = \varphi(x, y) + k(x, y) * 2\pi \quad (5)$$

Table 2
Lookup table.

Codewords	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Order	1	1	1	2	2	2	3	3	27	4	4	4	5	5	5	6	6	3
Codewords	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Order	7	7	7	8	8	8	9	27	6	10	10	10	11	11	11	12	12	9
Codewords	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Order	13	13	13	14	14	14	15	15	12	16	16	16	17	17	17	18	9	15
Codewords	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
Order	19	19	19	20	20	20	21	21	18	22	22	22	23	23	23	24	24	21
Codewords	73	74	75	86	77	78	79	80	81									
Order	25	25	25	26	26	26	27	18	24									

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