Optics and Lasers in Engineering 74 (2015) 22–27

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

3D shape from phase errors by using binary fringe with multi-step phase-shift technique

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A R T I C L E I N F O

Article history:
Received 1 December 2014
Received in revised form
1 April 2015
Accepted 23 April 2015
Available online 27 May 2015

Keywords:
Fringe analysis
Uniaxial
Binary defocusing
Three-dimensional sensing
Phase error

A B S T R A C T

A three-dimensional shape measurement method is presented, which is a uniaxial measurement by measuring phase errors instead of the well-known phase, modulation or contrast. A sequence of exposures are captured by using a multi-step phase-shift technique with the binary fringes. Then the high-accuracy phases can be obtained by using all the exposures, meanwhile, a set of low-accuracy phases can be calculated by dividing those exposures into a set of four-step phase-shift measurements. For each pixel there will be a set of phase errors by subtracting low-accuracy phases from the high-accuracy ones. And the weighted phase error of every pixel can be calculated. Meanwhile the phase error caused by the improperly defocused binary fringes has a unique relationship with the depth z. Therefore, the 3D information of every pixel can be obtained by analyzing the phase errors. It will be promising for a uniaxial measurement, such as deep holes.

1. Introduction

Three-dimensional shape measurement based on sinusoidal fringe projection techniques has been widely used. Principally there are two categories of 3D shape measurement methods, one is to form a triangle for depth recovery [1], therefore the depth accuracy is based on the angle between the projection line and the camera imaging line as well as the phase accuracy, and it is not easy to measure the holes with the influence of occlusions. The other is to measure the steep object by setting the angle to be zero, which is called the uniaxial measurement by measuring modulation or contrast [2–4]. Because the modulation or contrast has a unique relationship with the depth z. Therefore by z-direction scanning, the modulation or contrast curve will give the depth.

Recently Xu and Zhang [5] introduced a novel method, which is to use the phase errors as the signals to retrieve the 3D information. Because the phase error caused by the improperly defocused binary fringes has a unique relationship with the depth z. As a matter of fact the phase errors come from the high-order harmonics, whose magnitudes decrease with the increase of the defocused degree. In Ying's method, they used the three-step phase-shift technique to obtain the low accuracy phases from the binary fringes and the ideal phases from the perfect sinusoidal fringes. Then the phase error can be calculated by the two measurements. There are six waves in the phase error map. They found the locations of the peaks and valleys of the six waves, then the 3D information of those peaks and valleys can be restored from the relationship between the phase errors and depth z. However, by using the three-step phase-shift technique, the highest magnitude high-order harmonic, i.e. the third-order harmonic was eliminated. Only those certain pixels, whose ideal phases are around $\pm(2*k+1)\pi/12$, $k=1,\ldots,5$, can get the 3D information. The perfect sinusoidal fringes need the projector to cast the gray level patterns, which may reduce the ability of high speed and need to calibrate the systematic gamma.

In this paper, we employ the multi-step phase-shift technique with projecting binary fringes. The perfect phases can be obtained by all exposures with the multi-step phase-shift technique. In order to use the third-order harmonic, we choose four-step phase-shift technique to calculate the low accuracy phases. The multi-step phase-shift exposures will form a set of four-step phase-shift measurements, then a set of low accuracy phases will be obtained, i.e., for each pixel, there will be a set of phase errors, therefore we can calculate a phase error for every pixel, finally, the 3D information can be restored pixel by pixel with the known relationship between phase errors and depth z.

The paper is organized as follows. In Section 2, the principle of the proposed technique is introduced. The experimental results

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http://dx.doi.org/10.1016/j.optlaseng.2015.04.014
0143-8166/

of the setup are presented in Section 3. Summary is shown in Section 4.

2. Principle

2.1. Multi-step phase-shift technique with binary fringes

In phase-shifting technique, when projecting the binary fringes, the solution to achieve high accuracy phases is to increase the amount of exposures, which could not only reduce the random noise but also reduce the systematic errors including the high-order harmonics. In extreme case, one-pixel phase-shift can be used. The deformed binary fringes can be expressed as a Fourier cosine series by [6]

$$\mathrm{I}(x,y)=A(x,y)+B(x,y)\sum_{k=2m-1}^{\infty}C_j\cos(k2\pi f_0x+\phi_{k0}) \tag{1}$$

where $A(x,y)$ is the background intensity, $B(x,y)$ is the fringe modulation, C_j is the magnitude of every component. Noted that there are only odd-order harmonics. Let's assume $\phi=2\pi f_0x+\phi_0$, then the each particular measurement intensity I_n can be rewritten by [7]

$$I_n(x,y)=a_0+\sum_{k=2m-1}^{\infty}a_k\cos[k(\phi(x,y)+\delta_n)] \tag{2}$$

It is known that a multi-step phase-shift technique will reduce almost all high-order harmonics, e.g. the period of the grating is 36 pixels, then a 36-step phase-shift technique will be used to decipher the perfect phase.

With N-phase-shifts, the algorithm for the perfect phase $\phi(x,y)$ deciphering has a form of

$$\phi(x,y)=-\arctan\left[\frac{\sum_{n=0}^{N-1}I_n\sin(2\pi n/N)}{\sum_{n=0}^{N-1}I_n\cos(2\pi n/N)}\right] \tag{3}$$

2.2. Four-step phase-shift technique to decipher the phase errors

A defocusing optical system can act as a low-pass filter system, which can dump the higher harmonic components. But if the projector is not properly defocused, there are still binary structures on the resultant fringe patterns, and the phase error is significant. It is known that there are only the 3*2m ± 1th order harmonics in three-step phase-shift technique and only the 5*2 m ± 1th order harmonics in five-step method, but all harmonics remain by using the four-step method, as shown in Table 1.

For the binary structured pattern, in the Fourier cosine series, the amounts of the third and fifth harmonics are 1/3 and 1/5 of the fundamental component. Therefore, the phase errors will become larger by using the four-step phase-shift technique. From Eq. 3 by using four-step technique we get

$$\phi'(x,y)=-\arctan\left[\frac{\sum_{n=0}^{3}\{a_0+\sum_{k=2m-1}^{\infty}a_k\cos[k(\phi(x,y)+\delta_n)]\}\sin(2\pi n/4)}{\sum_{n=0}^{3}\{a_0+\sum_{k=2m-1}^{\infty}a_k\cos[k(\phi(x,y)+\delta_n)]\}\cos(2\pi n/4)}\right] \tag{4}$$

Then the phase error will be

$$\Delta\phi=\phi'(x,y)-\phi(x,y)$$
$$=-\arctan\left[\frac{(a_3-a_5)\sin[4\phi(x,y)]+(a_7-a_9)\sin[8\phi(x,y)]+\cdots}{a_1+(a_3+a_5)\cos[4\phi(x,y)]+(a_7+a_9)\cos[8\phi(x,y)]+\cdots}\right] \tag{5}$$

Because the amounts of the third and fifth harmonics are much larger than the rest harmonics, therefore four waves are expected within the phase errors. The phase errors with the three-step technique will demonstrate six waves in the phase errors, because the lowest harmonic is the fifth one. The results are shown in Fig. 1 by using the three-step and four-step phase-shift techniques with the ideal binary structured patterns. The curve is the phase errors versus the wrapped ideal phases. Obviously the four-step phase-shift technique contains more phase errors.

2.3. Phase error determination pixel by pixel

In Fig. 1, it shows that there are some pixels in the phase map, whose phase errors are at peaks or valleys. In Ying's work they used these pixels to restore the depth z by using the relationships between phase errors, ideal phases and depth z. Obviously there are always some pixels, whose phase errors are always small or even zero. Then it is difficult to get the 3D information of these pixels. As a matter of fact, with the multi-step exposures, a set of

Table 1
Sensitivity of different phase-shifting algorithms to harmonics.

Number of steps	Harmonics													
	2	3	4	5	6	7	8	9	10	11	12	13	14	15
3				×		×				×		×		
4		×		×		×		×		×		×		×
5								×		×				
6				×		×				×		×		
7												×		×
8						×		×						×

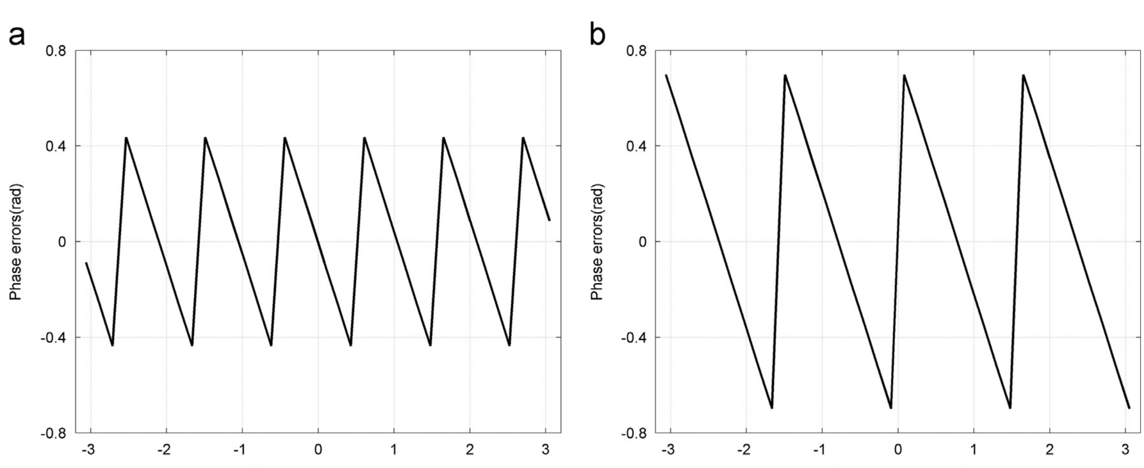

Fig. 1. The phase errors versus wrapped phase, (a) three-step phase-shift, and (b) four-step phase-shift.