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Abstract. A recent study found that it is very difficult to use the squared binary defocusing technique to eliminate the influence of third-order harmonics without compromising fringe quality, and thus it is challenging to utilize Fourier transform profilometry to achieve high-quality three-dimensional measurement. A novel approach is presented to effectively eliminate the third-order harmonics by modulating the squared binary structured patterns. Both simulation and experiments are presented to verify the performance of the proposed technique. [DOI: 10.1117/1.OE.51.11.113602]

Subject terms: fringe analysis; binary defocusing; 3-D shape measurement; Fourier transform profilometry.

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1 Introduction

Fourier transform profilometry (FTP) has been extensively employed in high-speed three-dimensional (3-D) shape measurement because it only requires a single fringe pattern to recover a 3-D shape.[1] However, compared with a phase-shifting based method, the FTP method is more sensitive to the fringe quality.[2] In other words, a perfect sinusoidal pattern is usually required to perform high-quality 3-D shape measurement and this is usually challenging.

It is well known that digital video projectors can produce grayscale/color images easily, and it appears that it is not difficult for such a projector to generate perfect sinusoidal fringe patterns. However, it is very difficult to generate ideal sinusoidal fringe patterns with such a device because 1. the commercially available digital video projectors usually respond nonlinearly to input grayscale values (i.e., nonlinear gamma effect), 2. the nonlinear response of the projector varies from one to the other even with the same model, and 3. the computer graphics video card is usually a nonlinear device as well. Though numerous methods have been proposed to calibrate the nonlinear influence,[3–7] it remains challenging to find a universal method that works for every single model of projector due to the complexity of this problem. Since the binary structured patterns only require two grayscale values, the aforementioned nonlinear response of the system does not have any influence. Besides, since it perfectly fits the grayscale image generation nature of the digital-light-processing (DLP) technology, the binary defocusing method has also had many other merits over the conventional sinusoidal fringe projection method if a DLP projector is used (e.g., speed breakthrough[8] and less sensitivity to exposure time[9]).

Instead of utilizing a mechanical grating,[10] we recently developed a digital binary defocusing technique[11] for sinusoidal fringe pattern generation. The defocusing technique has numerous advantages over the conventional sinusoidal method if a DLP projector is used to generate fringe patterns.[9,12] For example, we have developed an unprecedented high-speed 3-D shape measurement system by employing the FTP method with an off-the-shelf DLP projector.[13] However, we found that it is difficult for such a technique to achieve high-quality 3-D shape measurement because of the influences of the third-order harmonics, as the second-order harmonics are not naturally present. This is because the defocusing technique, after all, is intended to suppress high-order harmonics rather than completely eliminate them. However, because in frequency domain, the location of the third-order harmonic component is close to that of the fundamental harmonic component, it is difficult to suppress their influence to a negligible level without substantially compromising fringe quality.

To alleviate the problems of the squared binary method (SBM), Ayubi et al. proposed the sinusoidal pulse width modulation (SPWM) technique to improve the fringe sinusoidality by shifting the high-order harmonics to higher frequencies so that they can more easily be suppressed by defocusing.[14] However, due to the nature of discrete fringe generation, when the fringe is dense (i.e., the fringe period is small), this technique actually deteriorates the fringe quality.[15] We have proposed the optimum pulse width modulation (OPWM) technique to improve the SPWM method by selectively eliminating the undesired harmonics.[16] However, we also found that this technique does not have any merit over the squared binary method when the fringe is dense.[15] This is because there are not sufficient pixels to manipulate for a discrete fringe projection technique. It is well known that for the FTP, the denser the fringe pattern, the better the 3-D measurement quality that can be achieved. This dilemma presents a challenge to adopt the binary defocusing technique for high-quality 3-D shape measurement when an FTP method is necessary. It is interesting to note that the SBM, SPWM, and OPWM are all one-dimensional (1-D) optimizations since the pattern only varies along one direction. To further improve the SBM, we proposed an area-modulation method to convert squared binary patterns to triangular patterns,[17] and by this means, the influence of the third-order harmonics is substantially reduced. For a phase-shifting method, the triangular pattern offers superior measurement quality. However, the third-order harmonics

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are still present in an emulated triangle pattern even though their influence is significantly diminished compared with a squared binary pattern, and unlike a phase-shifting method, the FTP method is mostly influenced by the third-order harmonics when the second-order harmonics naturally are not present in a squared binary pattern. Therefore, a method of eliminating third-order harmonics becomes crucial when the FTP method is adopted.

This paper presents a novel approach to drastically enhance the 3-D shape measurement quality for the FTP with the binary defocusing technique. Unlike the SPWM or the OPWM method but similar to the area-modulation method,[17] this proposed technique modulates the binary structured patterns in both x and y dimensions. Because it has another dimension to control, we will demonstrate that this technique can completely eliminate the third-order harmonics even when the fringe is very dense (i.e., fringe period of 12 pixels). We will demonstrate that all higher order harmonics can be easily suppressed by slightly defocusing since the fringe is very dense.

Section 2 explains the principle of the proposed technique, Sec. 3 shows some experimental and simulation results, and Sec. 4 summarizes this paper.

2 Principle

2.1 *Fourier Transform Profilometry*

The FTP method was proposed by Takeda and Mutoh[18] and has been extensively adopted and utilized.[1] This technique has the merit of measuring rapidly changing scenes because only a single fringe image is required to recover one 3-D shape. For the FTP method, the phase is obtained by applying the Fourier transform to the fringe image, followed by applying a band-pass filter to preserve the carrier frequency component for phase calculation. Mathematically, a typical fringe pattern can be described as

$$I = a(x,y) + b(x,y)\cos[\phi(x,y)], \tag{1}$$

where $a(x,y)$ is the average intensity, $b(x,y)$ the intensity modulation or the amplitude of the carrier fringes, and $\phi(x,y)$ the phase to be solved for.

Equation (1) can be rewritten in complex form as

$$I = a(x,y) + \frac{b(x,y)}{2}[e^{j\phi(x,y)} + e^{-j\phi(x,y)}]. \tag{2}$$

If a band-pass filter is applied in the Fourier domain so that only one of the complex frequency components is preserved, we will have

$$I_f(x,y) = \frac{b(x,y)}{2}e^{j\phi(x,y)}. \tag{3}$$

From this equation, the phase can be calculated by

$$\phi(x,y) = \arctan\left\{\frac{\Im[I_f(x,y)]}{\Re[I_f(x,y)]}\right\}. \tag{4}$$

Here $\Im(X)$ represents the imaginary part of the complex number X, and $\Re(X)$ represents the real part of the complex value X. The phase obtained from Eq. (4) ranges from $-\pi$ to $+\pi$. The continuous phase map can be obtained by applying a spatial phase unwrapping algorithm.[19] Finally, 3-D coordinates can be obtained from the phase if the system is properly calibrated.[20]

In this research, we use a reference-plane-based approximation approach to convert the phase to depth.[21] This technique is basically to measure a known height object to obtain a scaling constant (K_z) between the phase changes and the true height of the object. The x and y are also scaled (K_x, K_y) to match the real dimensions. Even though this is an approximation, it is sufficient to verify the effectiveness of the proposed technique.

2.2 *Third-Order Harmonics Elimination for Binary Defocusing*

The success of the aforementioned FTP method heavily relies on the carrier fringes: if the carrier fringes are nonsinusoidal, the measurement will be erratic. In other words, if the carrier fringe has higher order harmonics, the measurement will show high-frequency noise. This becomes challenging if the sinusoidal fringe patterns are generated by naturally defocusing the squared binary patterns. This is because it is extremely difficult to completely suppress the third-order harmonics without radically compromising the fringe quality (contrast).

Let us take a look at the cross-section of the binary pattern illustrated in Fig. 1(a), when the fringe period is 12 pixels. The ideal sinusoidal pattern is generated by suppressing the high-order harmonics through lens defocusing. As explained earlier, third-order harmonics are significant contributor to the total error in FTP and are the most difficult to suppress by defocusing because of their proximity to the fundamental frequency. In contrast, it might be easier to generate high-quality sinusoidal fringe patterns by increasing the effective grayscale value used, such as the one shown in Fig. 1(b). Their frequency spectra are shown in Fig. 1(c) and 1(d), respectively. It can be seen that the third-order harmonics are completely eliminated by adding another grayscale value to the binary pattern. This finding motivates the development of this proposed approach to eliminate third-order harmonics.

Existing defocused techniques[11,14,16] are limited because they assign to each column (or row) either a black (0) or white (1) value, as shown in Fig. 1(a). These patterns have third- and fifth-order harmonics, as shown in the 1-D fast Fourier transform (FFT) in Fig. 1(c). A closer approximation to the sinusoidal wave can be achieved by introducing a term halfway between the black and white, as shown in Fig. 1(b). The associated 1-D FFT [shown in Fig. 1(d)] for this pattern demonstrates that it completely eliminates the third-order harmonics, which causes the greatest error when calculating phase using the FTP method.

While the pattern given in Fig. 1(b) more closely resembles a sinusoidal wave, it is not directly physically realizable through binary defocusing since pixels can only either be black or white for the binary technique. Previous methods such as SBM,[11] SPWM,[14] and OPWM[16] assign the same value to every cell in a column. A column composed of only black cells would have intensity of 0; and a column composed of only white cells would have intensity of 1. If, instead, each cell in a column alternated between black and white, then the value for that column could be considered

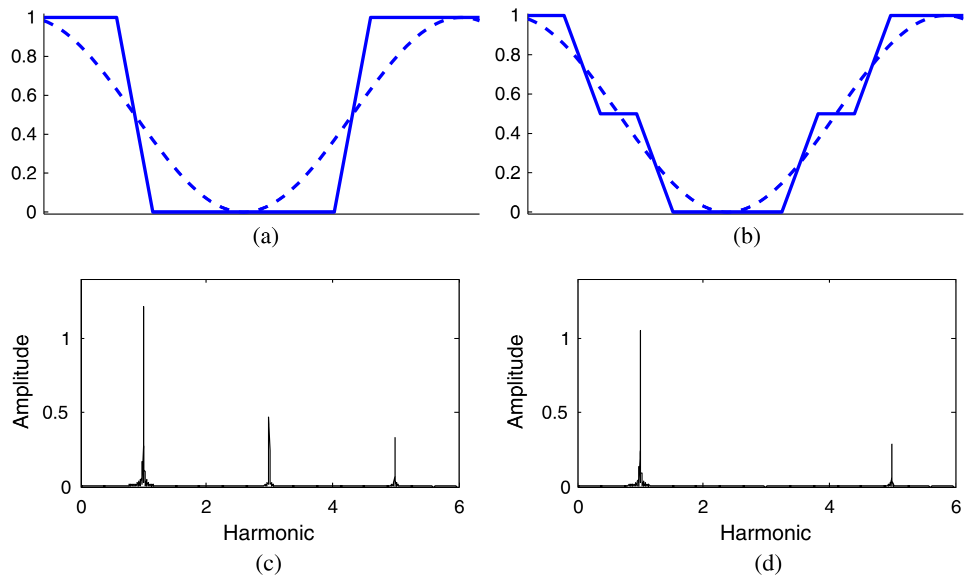


Fig. 1 Influence of grayscale levels on high-order harmonics. (a) 1-D squared binary waveform (solid line shows the binary waveform, and dashed line shows the approximated sinusoidal waveform); (b) 1-D modulated waveform with three intensity levels (solid line shows the waveform, and dashed line shows the approximated sinusoidal waveform); (c) Frequency spectrum of the waveform shown in (a); (d) Frequency spectrum of the waveform shown in (b).

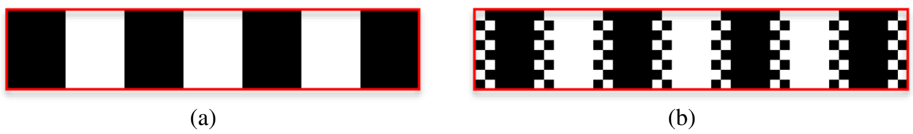


Fig. 2 Influence of random noise on phase errors. (a) Example of added noise to a conventional squared binary pattern; (b) Example of added noise to a 2-D area-modulated binary pattern; (c) Phase error with difference noise levels.

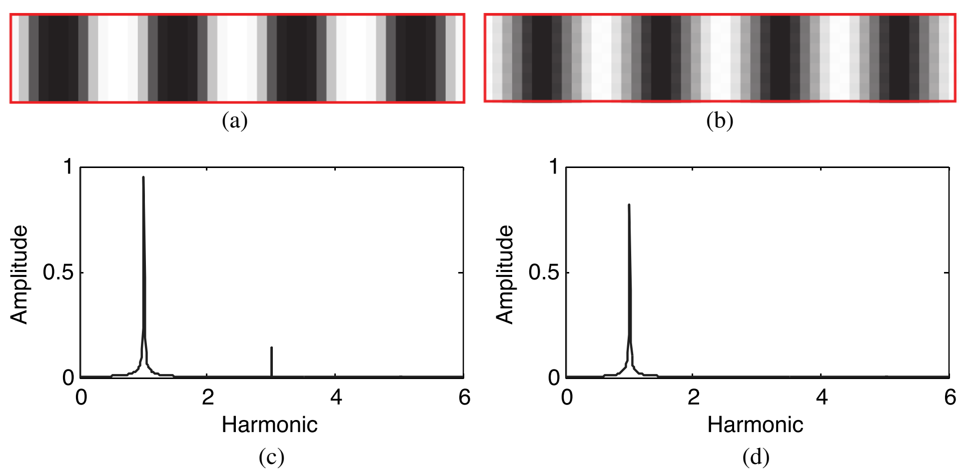


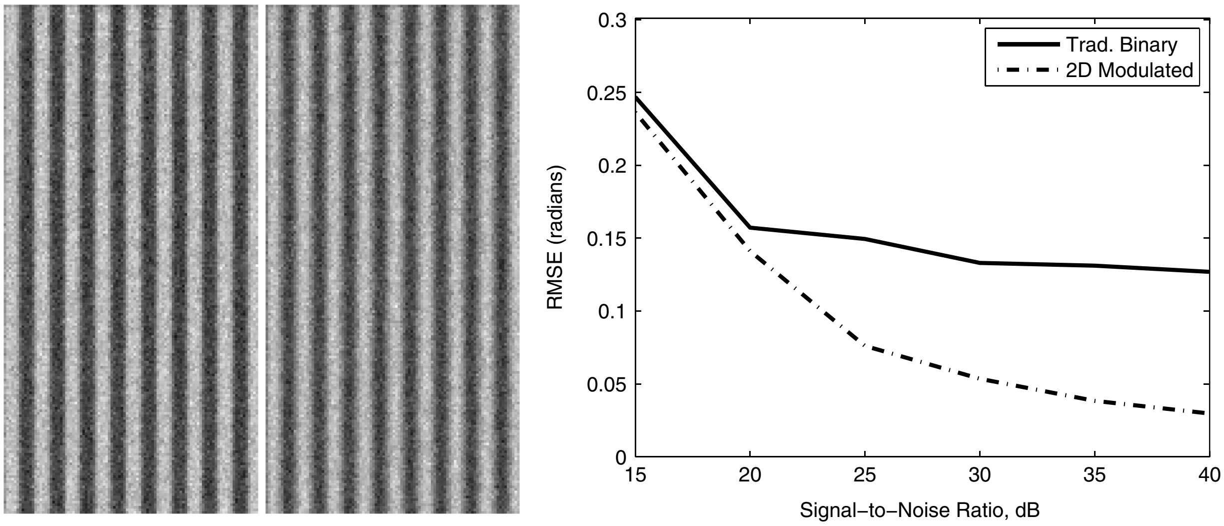
Fig. 3 Comparison of slightly defocused results using the conventional squared binary pattern and the modified pattern. (a) Resultant pattern shown in Fig. 2(a) after applying a Gaussian smoothing filter; (b) Resultant pattern shown in Fig. 2(b) after applying a Gaussian smoothing filter; (c) Frequency-amplitude spectrum of a cross-section of the pattern shown in (a); (d) Frequency-amplitude spectrum of a cross-section of the pattern shown in (b).

the average of the column. This column would have intensity of 0.5 for optimization in the sine coefficients. By this means, three instead of two intensity values can be realized using binary images. An example of an optimized pattern using these coefficients is shown in Fig. 2(b), and Fig. 2(a) shows the conventional squared binary pattern.

3 Results

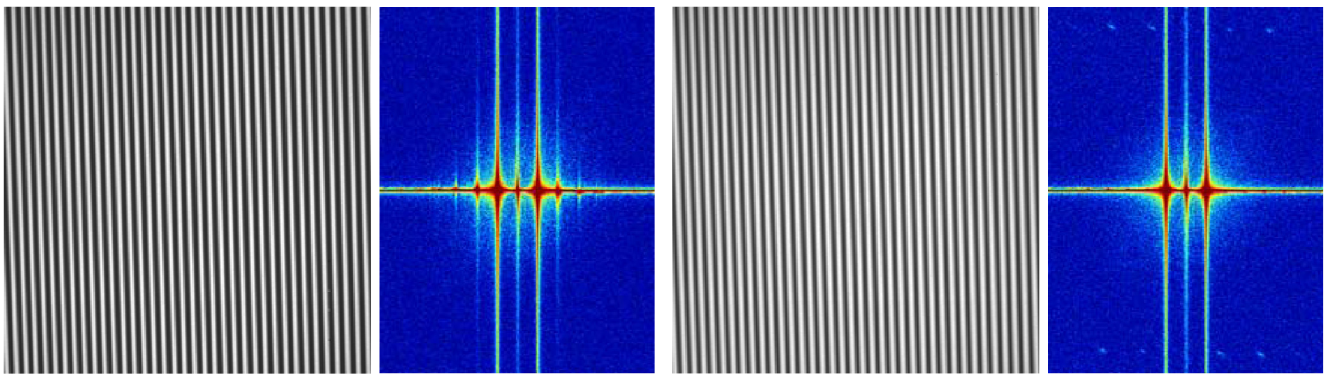
3.1 *Simulation Results*

Simulation was used to verify the effectiveness of this method. A 2-D Gaussian filter of size 5 pixels and standard deviation 0.83 pixels was applied to both patterns shown in Fig. 2. Figure 3(a) and 3(b) shows the result. It can be seen



(a) (b) (c)

Fig. 4 Examples of noise added to (a) a binary pattern and (b) a 2-D modulated pattern, and (c) their respective error at different added noise levels.



(a) (b) (c) (d)

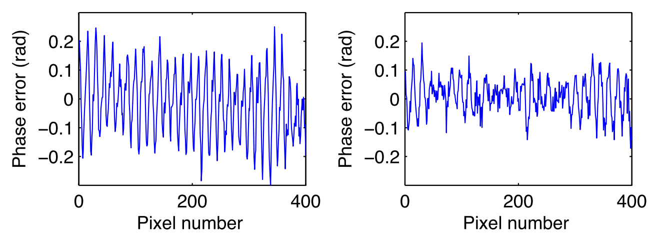
Fig. 5 Comparison results of measuring white flat board. (a) 2-D captured pattern using the square binary method; (b) Frequency spectrum of pattern shown in (a); (c) 2-D captured pattern using the modulated binary method; (d) Frequency spectrum of pattern shown in (b).

that even before the modulated pattern indeed appears better sinusoidal. Figure 3(c) and 3(d) shows their frequency-amplitude spectrum. It clearly shows that the modulated pattern has no third-order harmonics, but the squared binary one clearly includes the third-order harmonic component.

To further test the effectiveness of this proposed method, noise was introduced into the simulation to emulate the real measurement. In this simulation, white Gaussian noise with different intensity was added to the original patterns to simulate projector error. The defocusing effect was simulated by applying a Gaussian filter of size pixels and standard deviation 0.83 pixels. The defocused patterns had additional white Gaussian noise added to emulate camera noise. FTP method was used to compute the phase, and the phase error is calculated by comparing with the ideal phase value. Figure 4 shows the simulation results. This simulation, again, shows that the proposed method outperforms the SBM under all conditions.

3.2 *Experimental Results*

Real experiments were also carried out to further verify the performance of the proposed technique against the conventional squared binary method. In this experiment, a DLP projector (Model: Texas Instruments LightCommander) and a digital charge coupled device (CCD) camera (Model: Pulnix TM-6740CL) were used. A 50 mm focal length lens was used (Model: Nikon AF Nikkor) at $f/2.8$ for the projector and a 16 mm focal length lens was used (Model: Tamron 07A) at $f/8$ for the camera. The camera captured images of resolution 640×480 with 8-bit depth.



(a) (b)

Fig. 6 Cross-section error of flat board measurement. (a) Cross-section error of the squared binary pattern (rms 0.11 radians); (b) Cross-section error of the modified binary pattern (rms 0.05 radians).

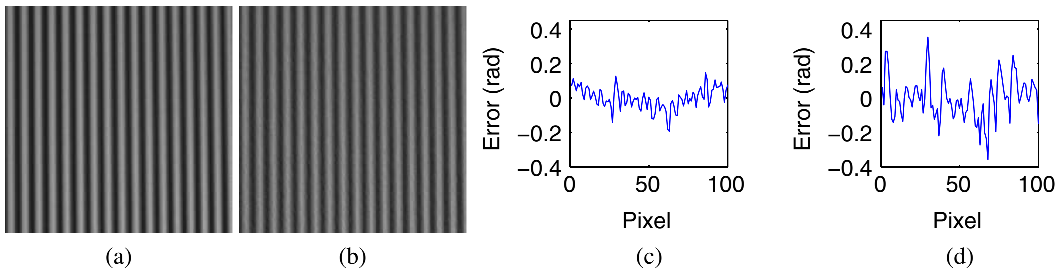


Fig. 7 Comparison between the proposed area modulation method and another method[17] when the FTP method is adopted. (a) The modulated pattern using the proposed method; (b) The modulated pattern using the other method;[17] (c) Cross-section of phase error for the pattern using our proposed method (rms 0.064 radians); (d) Cross-section of the phase error for the pattern using the other method[17] (rms 0.123 radians).

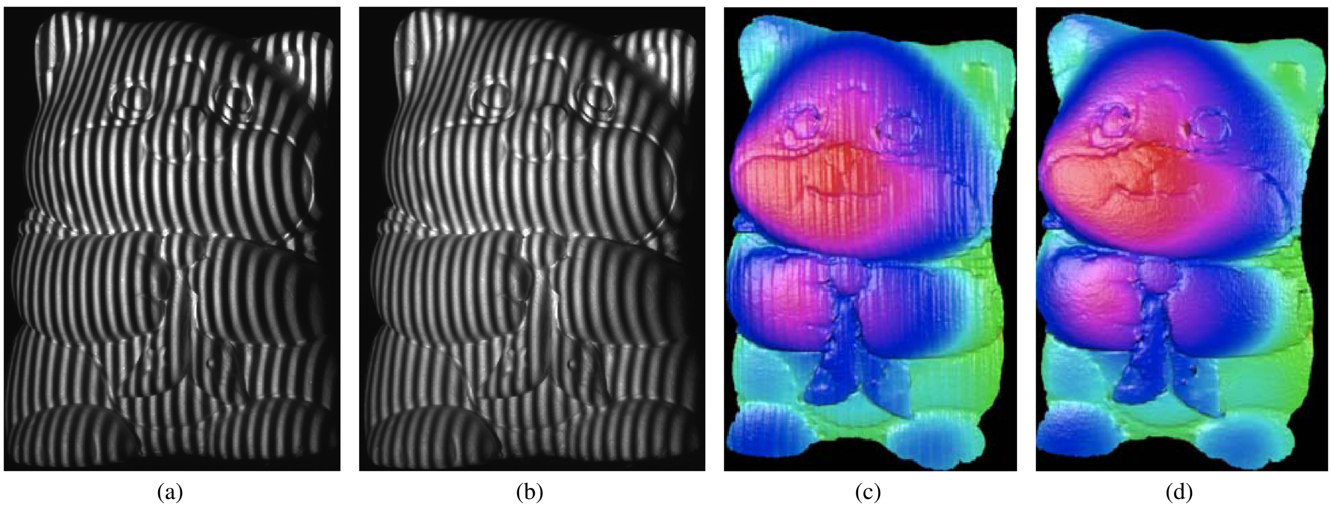


Fig. 8 Measurement results of more complex 3-D object. (a) Captured fringe pattern using the conventional squared binary pattern; (b) Captured pattern using the modified binary pattern; (c) 3-D result using the pattern shown in (a); (d) 3-D result using the pattern shown in (b).

During the experiment, the projector and the camera remained untouched.

We first measure a uniform white board. Figure 5 shows the results. Figure 5(a) shows the pattern with the conventional squared binary method when the projector is nearly focused. It clearly shows binary structures. Its frequency spectrum is shown in Fig. 5(b), and the third-order harmonic component clearly depicts in the image. In contrast, the area modulated pattern of Fig. 5(c) does not have the third-order harmonic component as in Fig. 5(d).

The measurement accuracy is then evaluated for this method. To determine the measurement error, the phase obtained using these methods was compared against the phase obtained using the conventional phase-shifting method with ideal sinusoidal patterns (i.e., the projector nonlinearity was calibrated and corrected). Figure 6 shows the cross-sections of the error maps. The root-mean-squared (rms) error for the SBM and the proposed method are 0.11 and 0.05 radians, respectively. This further demonstrates the superiority of the proposed method over the SBM.

We also measured a uniform white board using the method proposed in this paper, and another method[17] under exactly the same conditions. Figure 7 shows the results. Although the captured fringe images show no obvious difference except less random noise for the proposed method shown in Fig. 7(a), the recovered phase using the FTP methods shows drastic difference between these two area-modulation methods: the phase error resulting from the proposed method is approximately half that from the other method.[17]

Furthermore, we measured a more complex 3-D statue to further evaluate the proposed method. Figure 8 shows the measurement results. The high frequency stripes shown in Fig. 8(c) were introduced by the third-order harmonics. Figure 8(d) shows that the proposed method does not have this problem. This again demonstrates the success of the proposed method.

Both simulation and experimental results have demonstrated the merits of the proposed method over the existing methods. However, due to the discrete fringe generation nature and the small number of pixels to control per fringe period, we found that, for binary patterns with fringe periods up to 16 pixels, only patterns with a fringe period of 12 pixels (which we currently use) can completely eliminate the third-order harmonic.

4 Summary

This paper has presented a novel approach to fundamentally eliminate third-order harmonics with area (both x and y) modulation technique. Specifically, we treat local 2×2 pixels as a unit and increase the effective grayscale values by changing the ratio of 1s. For example, grayscale value

0.5 can be generated by setting two pixels to be 1s. Both simulation and experiments have found that this technique can completely eliminate the most significant error sources, third-order harmonics; and when the fringe pattern is quite dense (12 pixels per period), a much better measurement quality can be achieved when an FTP technique is adopted.

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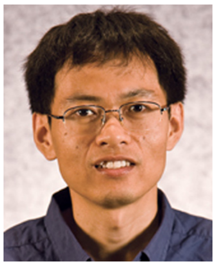
William Lohry is currently an undergraduate student of chemical engineering working with Dr. Zhang at Iowa State University. He joined Dr. Zhang's laboratory in 2009 as a freshman honor student. He is currently working on area modulation methods to improve the binary defocusing technique that was developed in Dr. Zhang's group.



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