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Abstract

Our recent study found that it is very difficult to use the binary defocusing technique to completely suppress the 3rd-order harmonics, and thus it is challenging to achieve high-quality three-dimensional (3-D) measurement with the Fourier transformation method. This paper presents a novel approach to effectively eliminate the 3rd order harmonics by modulating the binary structured patterns in both x and y directions. Both simulation and experimental results will be presented to verify the performance of the proposed technique.

Keywords

Fringe analysis, binary defocusing, 3-D shape measurement, Fourier transform profilometry

Disciplines

Computer-Aided Engineering and Design | Graphics and Human Computer Interfaces

Comments

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Improve Fourier transform profilometry by locally area modulating squared binary structured pattern

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ABSTRACT

Our recent study found that it is very difficult to use the binary defocusing technique to completely suppress the 3rd-order harmonics, and thus it is challenging to achieve high-quality three-dimensional (3-D) measurement with the Fourier transformation method. This paper presents a novel approach to effectively eliminate the 3rd order harmonics by modulating the binary structured patterns in both x and y directions. Both simulation and experimental results will be presented to verify the performance of the proposed technique.

Keywords: Fringe analysis, binary defocusing, 3-D shape measurement, Fourier transform profilometry

1. INTRODUCTION

Fourier transform profilometry (FTP) has been extensively utilized in high-speed 3-D shape measurement because it only requires a single fringe pattern.¹ However, compared with a phase-shifting based method, the FTP method is more sensitive to the fringe pattern quality. Therefore, it is extremely vital to generate a perfect sinusoidal fringe pattern to obtain high-quality 3-D shape measurement.

Instead of utilizing a mechanical grating,² we recently developed a digital binary defocusing technique for sinusoidal fringe pattern generation. We have successfully achieved unprecedentedly high-speed 3-D shape measurement with an off-the-shelf DLP projector by employing the binary defocusing technique and the FTP method.³ However, we found that it is difficult for such a technique to achieve high-quality 3-D shape measurement because of the existence of 3rd-order harmonics when the projector is sufficiently defocused.

Ayubi et al. has proposed the sinusoidal pulse width modulation (SPWM) technique to improve the sinusoidality of the defocused fringe pattern by shifting the high-order harmonics to higher frequencies so that they can be easier to be suppressed by defocusing.⁴ However, due to the discrete fringe generation nature, when the fringe is dense (i.e., the fringe period is small) and the defocusing amount is not significant, this technique actually deteriorates the fringe quality.⁵ Wang and Zhang have proposed an optimum pulse width modulation (OPWM) to improve the SPWM method.⁶ However, we also found that this technique does not have any merit over a squared binary method when the fringe is dense.⁵ This is because there are not sufficient pixels to manipulate for a discrete fringe projection technique. It is well known that for FTP, the denser the fringe pattern is, 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.

This paper presents a novel approach to drastically enhance the 3-D shape measurement quality for FTP with the binary defocusing technique. Unlike the SPWM or the OPWM method, this proposed technique modulates the binary structured patterns in both x and y directions. Because it has another dimension to control, we will demonstrate that this technique can effectively eliminate the 3rd-order harmonics when the fringe is very dense (e.g., fringe period = 12 pixels). The other harmonics can be easily suppressed by defocusing since the fringe is very dense.

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

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2. PRINCIPLE

2.1 Fourier transform profilometry

Fourier transform profilometry (FTP) method for 3-D shape measurement was proposed by Takeda and Mutoh,⁷ and has been extensively adopted and utilized.¹ This technique has the merit of measuring rapidly changing scenes because only one 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

$$I = a(x, y) + b(x, y) \cos(\phi(x, y)), \quad (1)$$

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

Re-writing equation (1) in complex form as

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

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

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

Then the phase can be calculated by

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

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 (4) ranges from $-\pi$ to $+\pi$. The continuous phase map can be obtained by applying a spatial phase unwrapping algorithm.⁸ Finally, 3-D coordinates can be obtained from the phase if the system is properly calibrated.⁹

In this research, we use a reference-plane-based approximation approach to convert the phase to depth, as described in Reference.¹⁰ 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 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: Because the carrier fringes are non-sinusoidal, the measurement will be directly 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 Fig. 1(a), when the fringe period is 12 pixels. The ideal sinusoidal to be generated by suppressing the high-order harmonics through lens defocusing. As explained earlier, a significant contributor to the total error in FTP is the third-order harmonic, which is the most difficult to be suppressed by defocusing because of its absolute binary structures. In contrast, it might be easier to generate high-quality sinusoidal fringe patterns by increasing the effective grayscale value used, such as the on show in Fig. 1(b). Their frequency spectra are shown in Fig. 1(c) and Fig. 1(d), respectively. It can be seen that the third-order harmonics completely disappeared by adding another grayscale value to the binary pattern. This finding motivates the development of this proposed approach to eliminate the 3rd-order harmonics.

Existing defocused techniques (e.g. those discussed in ^{4,6,11}) are limited because they assign to each column (or row) either a black (0) or white (1) value, as shown in Fig. 1(a). This causes third- and fifth-order harmonics, as shown in the one-dimensional FFT in Fig. 1(c). A closer approximation to the sinusoidal wave can be achieved by introducing a term

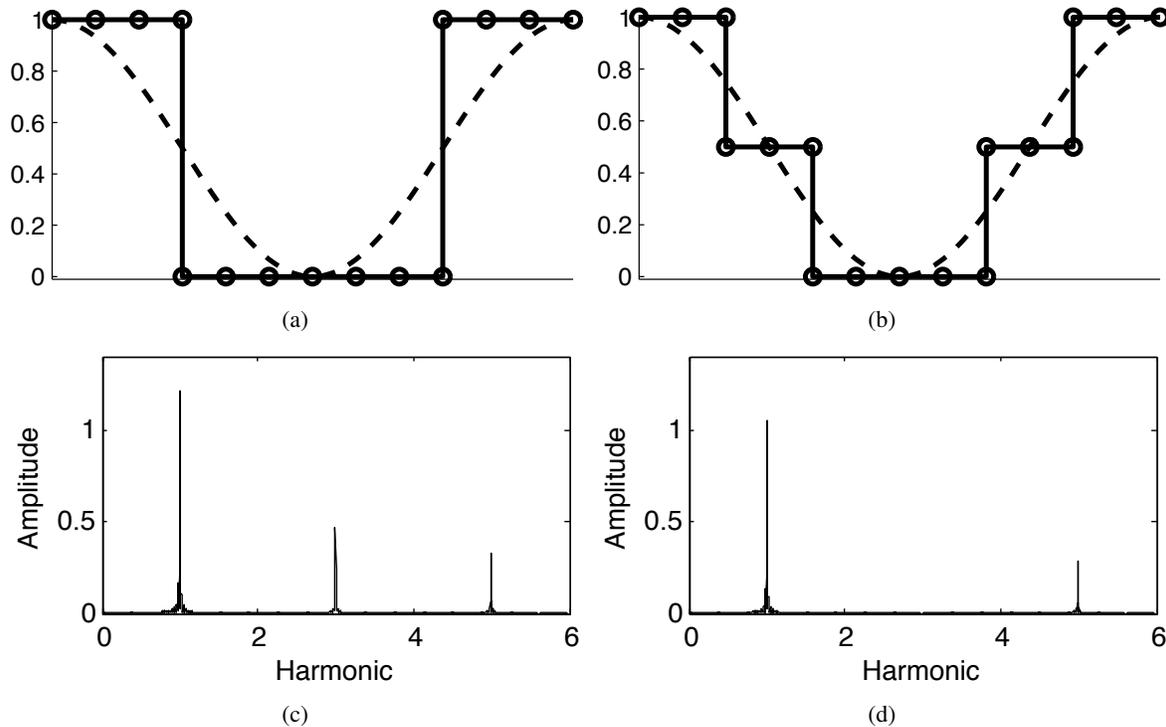


Figure 1. Influence of grayscale levels on high-order harmonics. (a) 1-D squared binary waveform (solid line shows the binary waveform and dashed-line shows the approximated sinusoidal waveform); (b) 1-D modulated waveform with three intensity levels (solid line shows the waveform and dashed-line shows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



Figure 2. Example of conventional squared binary pattern and the modified pattern. (a) traditional squared binary pattern; (b) 2D area-modulated binary pattern.

halfway between the black and white, as shown in Fig. 1(b). The associated one-dimensional FFT (shown in Fig. 1(d)) for this pattern demonstrates that it completely eliminates the third-order harmonic, which causes the greatest error when calculating phase using the Fourier 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 be white. Previous methods such as the traditional squared binary method,¹¹ SPWM,⁴ and OPWM⁶ 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 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 realizing 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. Figures 3(a) and 3(b) shows the result. It can be seen that even

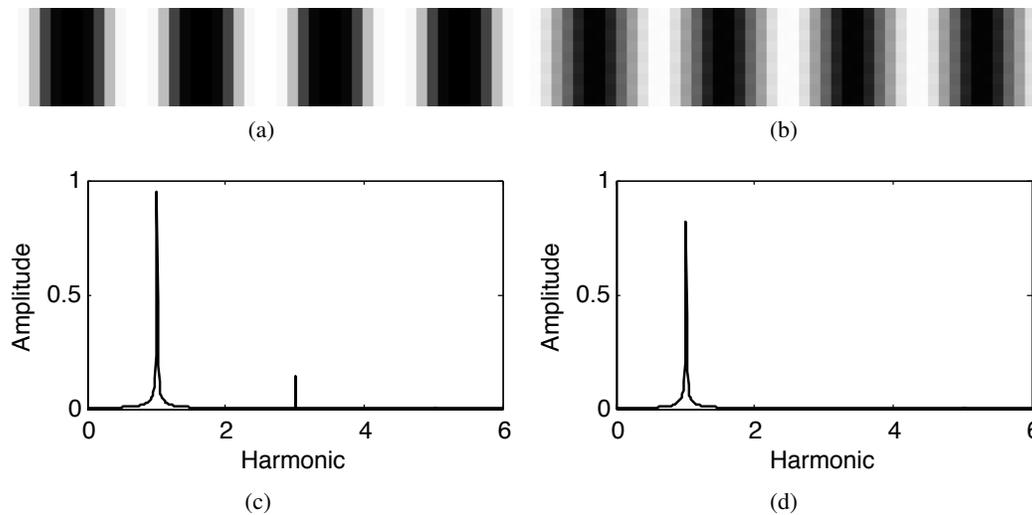


Figure 3. Comparison of slightly defocused results using the conventional squared binary pattern and the modified pattern. (a) Resultant pattern shown in Fig. 2(a) after applying a Gaussian smoothing filter; (b) Resultant pattern shown in Fig. 2(b) after applying a Gaussian smoothing filter; (c) Frequency-amplitude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

before the modulated pattern indeed appears better sinusoidal. Figures 3(c) and 3(d) show 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 component.

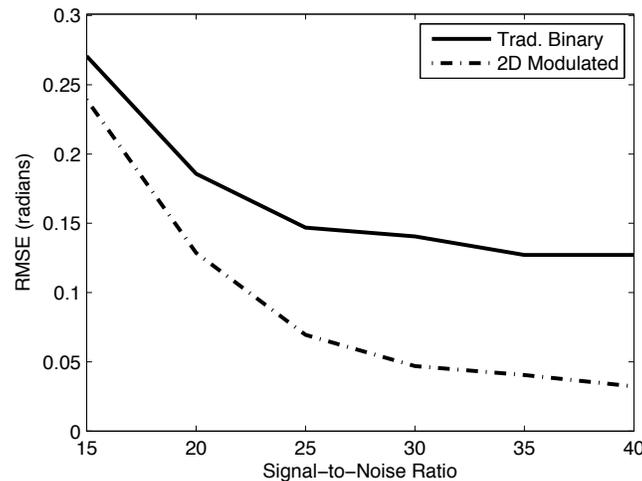


Figure 4. Effect of added noise on traditional binary (solid line) and 2D binary pattern (dashed line).

To further test the effectiveness of this proposed method, noise was introduced into the simulation to emulate the practical real measurement system. 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 5 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 modulated method outperforms the traditional squared binary method under all conditions.

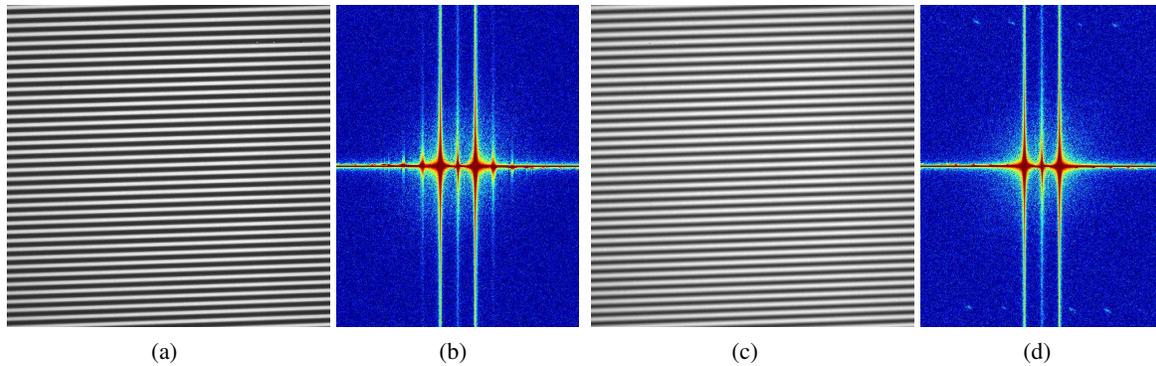


Figure 5. Comparison results of measuring white flat board. (a) 2D captured pattern using the square binary method; (b) Frequency spectrum of pattern shown in (a); (c) 2D captured pattern using the modulated binary method; (d) Frequency spectrum of pattern shown in (b).

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 digital-light-processing (DLP) projector (Model: Texas Instruments LightCommander) and a digital 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. During the experiment, the projector and the camera remained untouched.

We firstly 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 shown in Fig. 5(b), and the third-order harmonic component clearly depicts in the image. In contrast, the pattern 5(c) resulting from the modified method does not have third-order harmonic component 5(d).

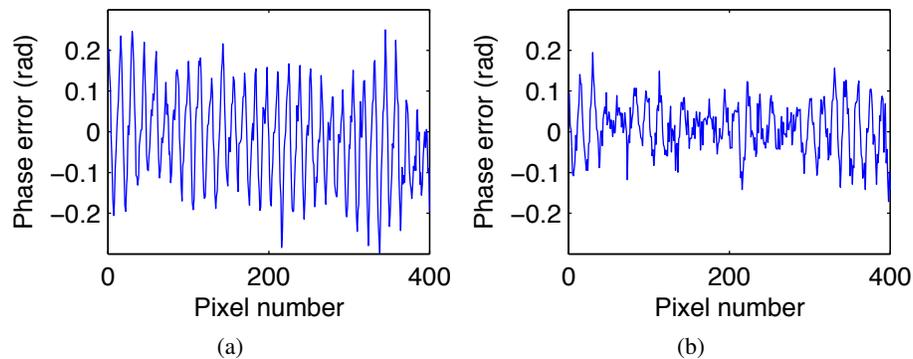


Figure 6. Cross section error of flat board measurement. (a) Cross section error of the squared binary pattern (rms 0.11 radians); (b) Cross section error of the modified binary pattern (rms 0.05 radians).

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. Figure 6 shows the cross sections of the error maps. The root-mean-squared (rms) error for the traditional method and the 2D-modulated method are 0.11 and 0.05 radians, respectively. This further demonstrates the superiority of the proposed method over the conventional squared binary method.

Furthermore, we measured a more complex 3-D statue to further evaluate the proposed method. Figure 7 shows the measurement result. The high frequency stripes shown in the result (Fig.7(c)) were introduced by the third order harmonics, on the contrast, the proposed method does not have this problem. This, again demonstrated the success of the proposed method.

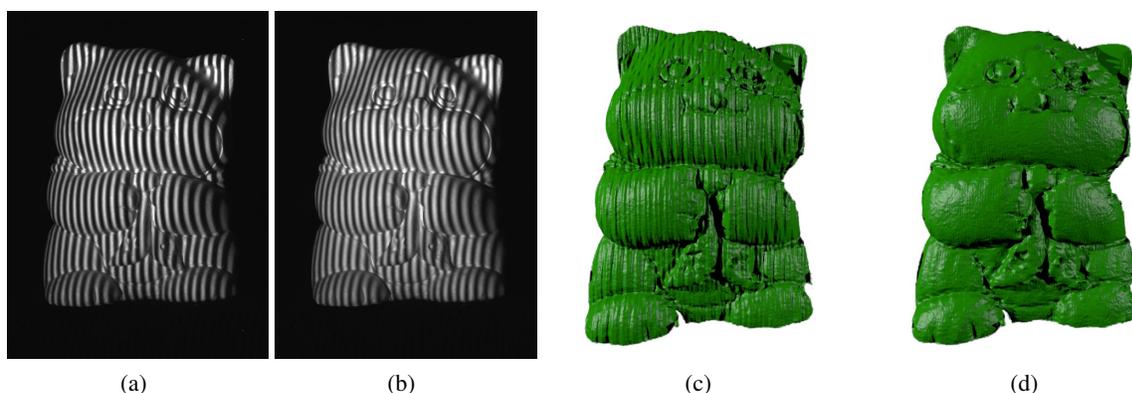


Figure 7. Measurement results of more complex 3-D object. (a) Captured fringe pattern using the conventional squared binary pattern; (b) Captured pattern using the modified binary pattern; (c) 3-D result using the pattern shown in (a); (d) 3-D result using the pattern shown in (b).

4. SUMMARY

This paper has presented a novel approach to fundamentally eliminate the third order harmonics with area (both x and y) modulation technique. Specifically, we treat local 2×2 pixels as a unit and to increase the effective grayscale values by changing the ratio of 1s. For example, grayscale value 0.5 can be generated by setting 2 pixels to be 1s. Both simulation and experiments have found that this technique can effectively eliminate the most significant error sources, 3rd-order harmonics, when the fringe pattern is quite dense (12 pixels per period), resulting in a much better measurement quality when an FTP technique is applied.

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