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High-quality fringe pattern generation using binary pattern optimization through symmetry and periodicity

Junfei Dai [a], Beiwen Li [b], Song Zhang [b,*]

[a] Mathematics Department, Zhejiang University, Zhejiang 310027, China
[b] Mechanical Engineering Department, Iowa State University, Ames, IA 50011, United States

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ABSTRACT

This paper presents a novel method to construct binary patterns for high-quality 3D shape measurement. The algorithm generates small patches using symmetry and periodicity, randomly initializes each pixels, optimizes the small patches through mutations, and finally tiles the optimized patches into full size patterns using again symmetry and periodicity. We will demonstrate that the proposed method can achieve substantial phase quality improvements over the dithering techniques for different amounts of defocusing.

1. Introduction

In the past decade, digital fringe projection (DFP) techniques have been increasingly used for high-quality 3D shape measurement due to its flexibility [1], but have the major limitations of speed bottleneck (typically 120 Hz) and projection nonlinearity. Our recently proposed binary defocusing technique [2,3] has demonstrated the great promise of overcoming the limitations of conventional DFP technique. Yet, the high-frequency harmonics substantially influence the measurement quality if the measurement depth range is large and the required measurement speed is high [4]. Xu et al. [4] proposed a passive error compensation method to alleviate the high-frequency harmonic influences. This technique has demonstrated its success if high-quality calibration is performed pixel by pixel. However, the improvement is rather limited if the fringe stripes are wide.

Actively modulating the squared binary patterns has been extensively studied and shows even greater improvements. Among these methods, the pulse width modulation (PWM) techniques [5–8] change the squared binary patterns in one dimension. These techniques either shift the high-order harmonics further away from fundamentally frequency such that they are easier to be suppressed by defocusing [5], or theoretically eliminate those most influential harmonics [6–8]. These techniques indeed could improve measurement quality. However, due to the discrete nature of fringe generation, the PWM techniques can only generate high-quality sinusoidal fringe patterns when the fringe stripes are narrow [9]. PWM techniques only modulate the patterns in 1D, and thus their ultimate enhancements are rather limited. 2D area modulation techniques [10] could further improve the quality. However, it is difficult for all these techniques to generate high quality fringe pattern when fringe stripes are wide.

It turns out that the dithering techniques [11–16], developed to represent high-bit number images with binary images, could improve fringe quality for wider fringe stripes [17]. These techniques endeavor to maintain low-frequency information such that the overall image appears to be the original once a low-pass filter is applied. However, we found that if the fringe stripes are narrow, the improvement was rather small. Unfortunately, for 3D shape measurement, high-frequency sinusoidal fringe patterns are usually desirable since they provide better measurement quality. Optimizing dithered patterns could improve the fringe quality. We have recently developed a genetic algorithm to drastically improve the phase quality when fringe stripes are narrow [18]. However, this technique is very time consuming (taking hours), and sometimes the algorithm does not converge if the initial genes are not good.

The objective of all these optimization techniques is to obtain the best fit of the binary patterns to the ideal sinusoidal pattern. In other words, the optimized binary patterns should be as close as possible to the ideal sinusoidal patterns after applying Gaussian smoothing. Mathematically, we are minimizing the functional

$$\min_{B,G} \| I(x,y) - G(x,y) \otimes B(x,y) \|_F \quad (1)$$

* Corresponding author. Tel.: +1 515 294 0723; fax: +1 515 294 3261.
E-mail address: song@iastate.edu (S. Zhang).

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where $\|\cdot\|_F$ is the Frobenius norm, $I(x,y)$ is the ideal sinusoidal intensity pattern, $G(x,y)$ is a 2D Gaussian kernel, $B(x,y)$ is the desired 2D binary pattern, and $\otimes$ represents convolution. Unfortunately, the problem is Non-deterministic Polynomial-time (NP) hard, making it impractical to solve the problem mathematically. Furthermore, the desired pattern should perform well for different amounts of defocusing (i.e., varying $G(x,y)$), making the problem even more complex.

This paper presents a method to conquer these challenges. This technique comes from our two observations: (1) the binary patterns should be symmetric for one fringe stripe since the resultant sinusoidal patterns are symmetric, and (2) the binary pattern should be periodical in both x and y directions since the desired sinusoidal patterns are periodical in both directions (with a period of 1 pixel for one direction). The optimization is to minimize the error between the defocused (or blurred) binary pattern and the desired ideal sinusoidal pattern. Since the ultimate goal is to generate high-quality phase for a large depth range, the proposed technique selects the fringe patterns that consistently perform well with different amounts of defocusing.

Section 2 explains the principle of the phase-shifting algorithm and the dithering technique. Section 3 presents the proposed framework for constructing binary patterns. Section 4 shows simulation results. Section 5 presents the experimental results. Section 6 discusses the merits and shortcomings of the proposed technique, and finally Section 7 summarizes this paper.

2. Principle

2.1. Three-step phase-shifting algorithm

Phase-shifting algorithms have been extensively used in optical metrology [19]. Typically, the more fringe patterns used, the better measurement quality can be achieved. For high-speed 3D shape measurement, a three-step phase-shifting algorithm is usually adopted since it requires the minimum number of patterns to solve for the phase uniquely point by point. Since our research focuses on high-speed 3D shape measurement, a simple three-step phase-shifting algorithm with a phase shift of $2\pi/3$ was used to test the generated patterns. Three fringe images can be described as

$$I_1(x,y) = I'(x,y) + I''(x,y)\cos[\phi - 2\pi/3], \quad (2)$$

$$I_2(x,y) = I'(x,y) + I''(x,y)\cos[\phi], \quad (3)$$

$$I_3(x,y) = I'(x,y) + I''(x,y)\cos[\phi + 2\pi/3]. \quad (4)$$

where $I'(x,y)$ is the average intensity, $I''(x,y)$ the intensity modulation, and $\phi(x,y)$ the phase to be solved for

$$\phi(x,y) = \tan^{-1}\frac{\sqrt{3}(I_1 - I_3)}{2I_2 - I_1 - I_3}. \quad (5)$$

This equation provides the wrapped phase ranging $[-\pi, +\pi)$ with 2π discontinuities. A continuous phase map can be obtained by adopting a spatial [20] or temporal phase unwrapping algorithm. In this research, we used the temporal phase unwrapping framework introduced in [21].

2.2. Error-diffusion dithering technique

Compared with the Bayer-ordered dithering technique, the error-diffusion dithering technique is more complicated but achieves higher quality. For an error-diffusion algorithm, the pixels are quantized in a specific order, and the quantization error for the current pixel is propagated forward to local unprocessed pixels through the following equation:

$$\tilde{f}(i,j) = f(i,j) + \sum_{k,l \in S} h(k,l)e(i-k, j-l). \quad (6)$$

Here, $f(i,j)$ is the original image, $\tilde{f}(i,j)$ the quantized image, and $e(i,j)$ the quantization error: the difference between the quantized image pixel and the diffused image pixel. $e(i,j)$ is further diffused to its neighboring pixels through a two-dimensional weighting function $h(i,j)$, known as the diffusion kernel. There are numerous error-diffusion dithering algorithms differing on the diffusion kernel selection. In this paper, we use one of the most accurate methods proposed by Floyd–Steinberg, with the following diffusion kernel:

$$h(i,j) = \frac{1}{16}\begin{bmatrix} - & * & 7 \\ 3 & 5 & 1 \end{bmatrix} \quad (7)$$

Here − represents the processed pixel, * represents the pixel in process. It should be noted that the kernel coefficients sum to one, and thus the local average value of the quantized image will be equal to the local average of the original one.

3. Binary pattern construction framework

As discussed earlier, the objective of all these optimization techniques is to obtain the best fit of the binary patterns to the ideal sinusoidal pattern. In other words, the optimized binary patterns should be as close as possible to the ideal sinusoidal patterns after applying Gaussian smoothing. Mathematically, we are minimizing the functional

$$\min_{B,G}\|I(x,y) - G(x,y) \otimes B(x,y)\|_F. \quad (8)$$

This problem is NP hard, making it impractical to solve the problem mathematically. Furthermore, the desired pattern should perform well for different amounts of defocusing (i.e., varying $G(x,y)$), making the problem even more complex.

Instead of optimizing the desired fringe pattern as a whole (e.g., 800×600) as our previously proposed [18,22], we propose to optimize a subset called *binary patch*, and then tile the patch to generate the full-size patterns using symmetry and periodicity. Unlike those PWM techniques, the proposed technique belongs to area modulation technique where the modulations occur in both x and y directions. Compared with the dithering techniques, the proposed technique strives to generate higher quality fringe patterns with narrow fringe stripes, and similar quality for broad fringe stripes. In addition, unlike the previously proposed method [18] where the optimization is performed under one defocusing level, the proposed method improves fringe quality for different amounts of defocusing.

Assume that the desired sinusoidal fringe patterns vary along x direction: the best-fit binary pattern should be symmetric along x direction for one fringe period (T); and it should be periodic along the y direction. *Row period*, S_y, is defined as the period along y direction. We believe that different breadths of fringe patterns require different optimization strategies, and thus we could utilize different row periods for different breadths of fringe patterns. Instead of directly solving the best-fit *NP*-hard problem, we propose to modulate a small binary patch for each fringe pattern, and then tile the patch together using symmetry and periodicity of the fringe pattern. The process of modulating a binary patch to generate the whole binary pattern can be divided into the following major steps:

*Step*1: *Patch formation*. This step initializes the S_y (2 to 10), and defines the number of pixels along x direction. The patch is formed as a dimension of $S_x \times S_y$, here $S_x = T/2$ is one half fringe period.