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High-quality fringe pattern generation using binary pattern optimization based on a novel objective function

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ABSTRACT

The recently proposed optimized dithering techniques can improve measurement quality. However, the objective function in these optimization methods just qualifies the global similarity of the pattern while the global optimization methods ignore the influences of local structure. To complete the phase-based optimization for high-quality three-dimension (3D) shape measurement, this paper presents a novel objective function which consists of global intensity term and local texture term, as well as a novel framework. Then, both simulation and experimental results show that the proposed method is able to improve quality and speed of 3D reconstruction for optimized dithering techniques.

1. Introduction

The development of the digital fringe projection (DFP) technique has been made in high-quality three-dimension (3D) reconstruction thanks to the flexibility and simplicity of its system [1]. A series of sinusoidal fringe patterns generated by the computer are projected on an object by the project. Then, a camera captures the fringe patterns distorted by the object surface geometry. Finally, the 3D shape of the object is reconstructed by the fringe analysis algorithms. According to the recent trends of 3D reconstruction, the real-time demand is growing [2]. We inevitably require a high measurement speed to achieve real-time. However, it is a challenge for the conventional DFP technique. Because of the limitation of typical projector refresh rate, the maximum measurement speed of 8 bits sinusoidal pattern is generally limited to 120 Hz [3]. Recently, with the development of projector technique, the refresh rate of binary pattern of special projector is able to exceed 104 frame/s. For example, DLP Discovery D4100 projector developed by Texas Instruments can catch 3.255×104 frame/s with the resolution of 1024 pixels wide by 768 pixels high [4]. Thus, in recent years, many researchers have combined binary defocusing technique with DLP to improve the measurement speed.

In 2009, Lei and Zhang developed the technique about flexible 3D shape measurement using projector defocusing, which has successfully made rate breakthroughs [5]. However, the quality of its result is far worse than DFP technique due to the high-frequency harmonics influences. In 2010, some researchers introduced the pulse width modulate (PWM) techniques developed in power electronics field into binary defocusing technique [6,7]. The high frequency harmonics can be easier to be eliminated by the PWM techniques, after defocusing. Yet, the technique also has the defects: (1) when the fringe stripes are wide, the improvements have been limited [8], and (2) the PWM technique is one-dimension, and cannot fully take advantage of the two-dimension of binary defocusing technique [9]. Xian and Su [10] proposed the area-modulation technique, which can generate high-quality sinusoidal fringe patterns with precise micro manufacturing. The technique requires a 1 μm cell. However, the 1 μm cell was not able to be provided by the DLP projector. Therefore, the application space and the development prospect are limited. In 2012, Lohry and Zhang [11] proposed a technique to approximate the triangular waveform by modifying 2×2 pixels so that the result in patterns is better for the defocusing technique. However, if the fringe stripes are wide, it is difficult to achieve high-quality patterns.

Since the 1960s, researchers have been developing methods to represent gray-scale images with binary images for printing and processing. The dithering technique is among these methods. Over the past years, some researchers have developed the dithering techniques to make significant improvement of fringe pattern quality. These studies include: Bayer method [12], error diffusion method [13] and genetic method [14]. The quality of the pattern based on optimization method is higher than that of other methods, and the genetic method improve the phase drastically. However, the optimization method such as genetic method also has some shortcomings: (1) the objective function of these optimization just fit

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the global intensity similarity while ignore the influences of local structure. (2) The global intelligent optimization method is very time-consuming, and may be not convergence or local convergence.

In this paper, a method is proposed to conquer the two challenges. The method includes two observations: (1) the optimization objective function proposed needs to make sure global and local similarity between the ideal pattern and the defocused dithering pattern, and (2) through the subset optimization ideas, the Non-deterministic Polynomial-time (NP) problem is overcome. We proposed the novel objective function named structure aware function (SAF), which weighted combines normalized mean squared error (NMSE) and structural similarity index measure (SSIM). The NMSE and SSIM respectively represent the global similarity and the local similarity. The optimization is to minimize the SAF between the defocused (or blurred) binary pattern and its corresponding ideal sinusoidal pattern. Besides, instead of the optimizing the whole patter, our method is optimizing pixel in a subset and achieve the best patches, and then tiling the patch to generate the full-size pattern utilizing symmetry and periodicity of the sinusoidal pattern. Both simulations and experiments are presented to prove the effectiveness and accuracy of the proposed technique.

This paper is organized as follows: Section 2 explains the principle including the three-step phase-shifting algorithm, objective function and optimization steps. Section 3 shows simulation results. Section 4 shows experimental results, and finally Section 5 concludes the paper.

2. Principle

2.1. Three-step phase-shifting algorithm

Phase-shifting algorithms have been extensively used in optical metrology. Especially, three-step phase-shifting algorithm could achieve rapid measurement since it requires the minimum number of patterns to reconstruct a 3D shape [15]. In this research, the three-step phase-shifting algorithm is used to verify the performance for the following works. For this algorithm with a phase shift of $2\pi/3$, the fringe patterns can be described as,

$$I_1(x, y) = I'(x, y) + I''(x, y)\cos[\phi - 2\pi/3] \quad (1)$$

$$I_2(x, y) = I'(x, y) + I''(x, y)\cos[\phi] \quad (2)$$

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

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

$$\phi(x, y) = \tan^{-1}\frac{\sqrt{3}(I_1 - I_3)}{2I_2 - I_1 - I_3} \quad (4)$$

Eq. (4) provides the phase ranging $[-\pi, +\pi]$ with 2π discontinuities. A continuous phase map can be obtained by adopting a spatial or temporal phase unwrapping algorithm. In this research, we used the exponential sequence temporal phase unwrapping framework introduced in [16].

2.2. Binary pattern construction framework

2.2.1. Objective function

Optimization method, designed to improve the dithering technique, has succeeded in reducing its overall phase error. The objective function of all these optimization techniques is to get the best fit of the binary patterns to the corresponding ideal sinusoidal pattern [17]. Mathematically, the optimization problem can be described as the norm function such as Frobenius norm function:

$$\min_{B,G} \left\| I(x, y) - G(x, y) * B(x, y)_F \right\| \quad (5)$$

where $||\cdot||_F$ represents the Frobenius norm, $I(x, y)$ the ideal sinusoidal intensity pattern, $G(x, y)$ a 2D Gaussian kernel, $B(x, y)$ the 2D binary pattern, and * convolution. Obviously, the function evaluates the global intensity similarity between the dithering pattern and its corresponding ideal pattern, but the similarity of the local detailed structure in an image has not been considered. In addition, the global optimization such as genetic method is a very time-consuming process and therefore the NP problem makes the objective function impractical to solve the problem mathematically [18].

Texture, which consists of particular high-frequency component and represents the local detailed structure, is one of the important information resources in an image. In order to contain the texture similarity in the objective function, we proposed a structure aware function (SAF), which borrows a little of Structure-aware halftoning (SAH) method [19]. The objective function combines two terms: a global intensity term and a local structure term. The global intensity measure is based on the normalized mean squared error (NMSE) to calculate the distance with ideal pattern. The local structure measure is based on the structural similarity index measure (SSIM) [20]. The SAF can be expressed as follows:

$$\mathrm{SAF} = w_n \mathrm{NMSE}(I, I_d) + w_s(1 - \mathrm{SSIM}(I, I_d)) \quad (6)$$

where $\mathrm{NMSE}(I, I_d)$ measures the global similarity and $\mathrm{SSIM}(I, I_d)$ measures the local similarity, respectively, between the ideal pattern I and the dithering pattern I_d. The w_n and w_s are the weighting factors limited by $w_n + w_s = 1$. Fig. 1 illustrates the phase RMS error values when NMSE weight $w_n = 0–1$. The lowest point of the broken line in Fig. 1 means the phase RMS error value is the smallest when w_n is 0.7. Thus, in this research, we set $w_n = 0.7$.

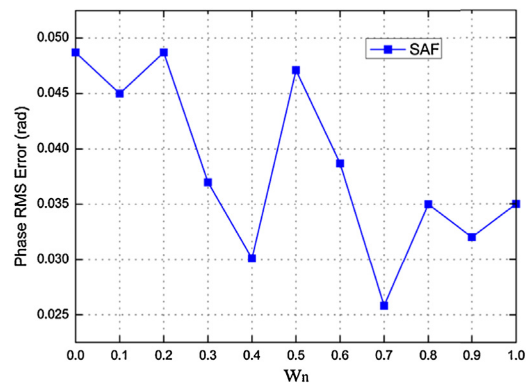

Fig. 1. The phase RMS error values of the different w_n values.

The details of SSIM and NMSE are described in the following sections.

2.2.1.1. SSIM. The SSIM can evaluate the local structure similarity between the differing pattern and the corresponding ideal pattern. The SSIM value measures the local structure similarity in a local neighborhood. In our case, we suppose the neighborhood window with the uncertain size since this size is limited by the calculation efficiency in the whole pattern. Then, the pattern I and I_d are divided into N elements by the neighborhood window. In a word, the basic idea of SSIM is to separate the structure similarity into three parts: luminance, contrast and structure.

Luminance: The luminance function is $l(x, y)$, as shown in Eq. (7).

$$l(x, y) = \frac{2\mu_x\mu_y + c_1}{\mu_x^2 + \mu_y^2 + c_1} \quad (7)$$