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Optimized dithering technique for three-dimensional shape measurement with projector defocusing

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ABSTRACT

There have been active studies on optimized dithering techniques to improve 3D shape measurement quality with image sensor and defocusing projector. These techniques can be classified into intensity-based optimization technology and phase-based optimization technology. However, those phase-based optimization methods are sensitive to the amount of defocusing while intensity-based optimization methods cannot reduce phase errors efficiently. This paper presents an optimization framework. This framework combines structural similarity index measurement and intensity residual error optimization. By applying this optimization framework to patches and tiling the best patch, high quality fringe pattern can be generated for three-dimensional measurement. Both simulation and experimental results show that this proposed algorithm can achieve phase quality improvements and it is robust to various defocusing levels.

1. Introduction

Digital fringe projection (DFP) techniques based on sinusoidal fringe patterns have been widely used for high quality 3D shape measurement due to their flexibility and speed [1]. However, there are major limitations of the conventional DFP technique: high speed measurement (i.e., typically 120 Hz) and projection nonlinearity, which make it difficult to be applied to high speed measurement [2].

To overcome these limitations, binary pattern is proposed to increase the measurement speed. However, binary pattern could bring phase error into measurement results. To reduce this phase error, several techniques called squared binary method (SBM) [3], sinusoidal pulse width modulation (SPWM) [4] and optimal pulse width modulation (OPWM) [5] are proposed and developed which generate sinusoidal fringe patterns by proper defocusing. But these techniques also have defects: (1) when the fringe stripes are wide, the improvements have been limited, (2) these techniques cannot fully take advantage of two-dimension of binary defocusing pattern [6].

Dithering technology is developed to take advantage two-dimensional information of binary images so it could improve fringe quality for wide fringe stripes [7]. These techniques maintain low-frequency information such that the overall image is similar to be the original pattern when a low-pass filter is used. However, if the fringe stripes are narrow, the improvement is rather small, because high-frequency sinusoidal fringe patterns are usually desirable since they provide better measurement quality when the period of fringe pattern is small [8].

Taking advantages of the two-dimensional (2D) nature of the structured patterns, dithering optimization methods are developed for phase-based DFP systems [9]. According to their objective functions, these optimization methods can be classified into two categories: intensity-based optimization [10,11] and phase-based optimization [12,13]. The former is to approximate the dithered pattern to ideal sinusoidal line after defocusing. They are robust to projector defocusing levels but it cannot reduce the phase error efficiently [14]. Since the ultimate goal of optimization is to generate high-quality phase, it is natural to optimize the pattern in the phase domain [15]. The latter is to make the phase close to the desired linear phase after defocusing. However, the phase-based optimization method is sensitive to different amounts of defocusing [16].

In order to get high quality measurement results under various defocusing levels, this paper proposes an optimization framework which includes the structural similarity index measurement and intensity residual error optimization. The structural similarity index measurement belongs to pre-intensity similarity optimization and intensity residual error function belongs to further intensity optimization [17]. Because the existence of $(3l)$th harmonics does not bring any phase errors into the three-step phase-shifting algorithm [18], the intensity residual

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error function removes $(3l)$th harmonics out of the total intensity error between two patterns. The goal of optimization is to minimize the intensity residual error function. By applying the framework into patches, the best patch is selected and tilted to generate the full size pattern utilizing periodicity structure of the sinusoidal pattern. Both simulation and experiments demonstrate that the proposed method can achieve higher phase quality when the projector is at different amounts of defocusing.

This paper is organized as follows: Section 2 explains the principles concerned in this technique. Section 3 presents the optimization framework and the process of fringe pattern generation. Section 4 shows simulation results. The experimental results and analysis are presented in Section 5. Finally Section 6 summarizes this paper.

2. Principle

2.1. Three-step phase-shifting algorithm

A simple three-step phase-shifting algorithm with phase shift of $2\pi/3$ is used to evaluate the proposed optimization algorithm. The intensity of three images can be described as:

$$I_1(x,y) = I_a + I_m \cos\left[\phi(x,y) - 2\pi/3\right] \tag{1}$$

$$I_2(x,y) = I_a + I_m \cos\left[\phi(x,y)\right] \tag{2}$$

$$I_3(x,y) = I_a + I_m \cos\left[\phi(x,y) + 2\pi/3\right] \tag{3}$$

where I_a is the average intensity. I_m is the intensity modulation. $\phi(x,y)$ is the phase to be solved:

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

This equation 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 use the temporal phase unwrapping method with three frequency phase-shifting algorithm.

2.2. Bayer-dithering technique

Dithering technology has been developed to convert a higher bit depth into a lower bit depth, and this is analogous to the halftone technique used in printing. To approximate a sinusoidal pattern with a binary pattern, various dithering techniques can be used, such as the simple thresholding, the random dithering and the ordered dithering [19]. Among these dithering methods, the Bayer-dithering technique has been extensively used due to its simplicity and its potential for parallel processing [15].

Bayer-dithering technique compares the original image with a *2D* grid of Bayer kernel, and then the original image is quantized according to the corresponding pixels in the Bayer kernel: if the grayscale value is larger than the kernel, the pixel is turned to 1 (or 255 grayscale value), otherwise to 0. Neighboring pixels do not affect each other. Different kernels can generate different dithering effects. A low-pass filter can suppress high-frequency noises. The Bayer kernel can be obtained by:

$$M_1 = \begin{bmatrix} 0 & 2 \\ 3 & 1 \end{bmatrix} \tag{5}$$

where M_1 is the smallest base and other larger patterns can be obtained by:

$$M_{n+1} = \begin{bmatrix} 4M_n & 4M_n + 2U_n \\ 4M_n + 3U_n & 4M_n + U_n \end{bmatrix} \tag{6}$$

where U_n is n-dimensional unit matrix (all elements are 1). In this research, we found that the Bayer kernel 8×8 produces the best result for all tested fringe stripes.

3. Optimization framework

3.1. Structural similarity index measurement

Local structure is one of the important information in the defocusing binary pattern. It contains particular high-frequency components. In order to contain local similarity, we design the structural similarity index measurement (*SSIM*) as pre-intensity optimization function to evaluate the local structure similarity between the differing pattern and the corresponding ideal pattern. Based on the theory of references [20,21], the comparison between the ideal pattern and dither pattern focuses on three parts: luminance, contrast and structure. Local structure function (*LSF*) should be generated and the structural intensity error is calculated by comparing the *LSF* between $I(x,y)$ and $I_d(x,y)$.

We set $I(x,y)$ as an example and the calculation process of $LSF(x,y)$ is shown as following:

Luminance: Luminance function can be designed as $l(x,y)$, as shown in Eq. (7):

$$l(x,y) = \frac{2S_x S_y + c_1}{S_x^2 + S_y^2 + c_1} \tag{7}$$

where c_1 is a constant (here $c_1 = 1$) to avoid singularity. Every S_x and S_y can respectively be calculated by using formula: $S_x = \sum_{i=1}^{W} y_i$ and $S_y = \sum_{i=1}^{H} y_i$, where x_i is the intensity of every row and y_i is the intensity of every column. In every part, W is the width and H is the height.

Contrast: Contrast function can be designed as $c(x,y)$. It is similar to Eq. (7) but it uses σ_x and σ_y to express estimation of the contrast, as shown in Eq. (8):

$$c(x,y) = \frac{2\sigma_x\sigma_y + c_2}{\sigma_x^2 + \sigma_y^2 + c_2} \tag{8}$$

where c_2 is also constant (here $c_2 = 1$) to avoid singularity. The standard deviation σ_x can be calculated by using formula: $\sigma_x = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - S_i\right)}$ and σ_y can be gotten with the same form.

Structure: Structural function can be designed as $s(x,y)$. It uses the correlation between the ideal pattern and dithering pattern to measure the structural similarity, as shown in Eq. (9):

$$s(x,y) = \frac{\sigma_{xy} + c_3}{\sigma_x + \sigma_y + c_3} \tag{9}$$

where c_3 is similar to c_1 and c_2 (here $c_3 = 1$) and the standard deviation σ_{xy} is solved for $\sigma_{xy} = \frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - S_x\right)\left(y_i - S_y\right)$.

The local weighted function (*LWF*) is generated by combining the luminance function, contrast function and structural function, as shown in Eq. (10):

$$LSF(x,y) = l(x,y)^{\alpha}\cdot c(x,y)^{\beta}\cdot s(x,y)^{\gamma} \tag{10}$$

where α, β and γ are used as weighted factor between luminance function, contrast function and structural function. Usually α, β and γ are set to 1.

The ideal sinusoidal fringe pattern $I(x,y)$ and dithering pattern $I_d(x,y)$ have the same process to calculate the *LSF* and LSF_d, and finally the function $SSIM(I, I_d)$ can be calculated as shown in Eq. (11):

$$SSIM\left(I, I_d\right) = \sqrt{\sum_{x=1}^{N}\sum_{y=1}^{M}\left(LSF(x,y) - LSF_d(x,y)\right)^2} \tag{11}$$

where $I(x,y)$ is the pixel intensity of desired ideal sinusoidal fringe and $I_d(x,y)$ is the pixel intensity of the Gaussian filtered dithering fringe.

3.2. Intensity residual error function

Because the existence of the third harmonics does not induce any phase errors for three-step phase-shifting algorithm [18], it can be proved that if the intensity error varies periodically at the frequency which is multiple of $3f_0$(f_0 is the fundamental frequency of the desired