Optics and Lasers in Engineering 90 (2017) 139–145

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Removing harmonic distortion of measurements of a defocusing three-step phase-shifting digital fringe projection system

Zi-Xin XU, Yuk-Hee Chan*

Center for Multimedia Signal Processing, Dept. of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hong Kong

A R T I C L E I N F O

Keywords:
Fringe analysis
3D shape measurement
Dithering
Binary defocusing
Optimization

A B S T R A C T

Binary defocusing method was adopted in 3D profilometry as it allows real-time measurement and does not need to handle the luminance nonlinearity of a projector. Current patch-based binary fringe patterns are periodic and carry strong harmonic distortion as compared with the ideal sinusoidal fringe patterns, which affects the measuring performance remarkably. In this paper, we propose a framework for generating aperiodic fringe patterns based on optimized patches. The produced fringe patterns can significantly lower the noise floor and suppress the harmonic distortion in the constructed phase map. Accordingly, the achieved depth measuring performance can be significantly improved. Special care is also taken during the optimization of the patches in our framework such that the depth measuring performance is robust to fringe period and defocusing extent.

1. Introduction

Digital fringe projection technique [1] has been widely used in commercial 3D depth map acquisition in the past decades due to its simplicity, reliability and flexibility. When it is used, the projected fringe patterns impact the measurement quality directly. Phase-shifting sinusoidal patterns [2] are popular patterns used in digital fringe projection as they can provide pixel resolution measurement with reliable resistance to environmental noise. However, the measurement speed of the systems developed based on this technique is subject to the frame rates of a projector (typically <120 Hz). To release the speed bottleneck, square binary fringe patterns (SBM) were introduced by Su et al. [3] and Lei et al. [4] to produce sinusoidal-like fringe patterns with a properly defocused projector. These binary fringe patterns can be generated by simply toggling the mirrors of a digital micromirror device (DMD) and hence the frame rate can be increased dramatically. Another advantage of using binary fringe patterns is that they are not affected by the luminance nonlinearity of a projector, which eliminates one of the most annoying noise sources in 3D measurement. However, measurements based on SBM still suffer from their sensitivity to the extent of defocusing and the noise contributed by the high frequency harmonics of a binary square fringe pattern.

Various solutions have been proposed to reduce the unwanted high frequency harmonics induced by a square binary pattern. Early-stage proposals are mainly based on pulse width modulation (PWM) [5–11]. Recently, halftoning techniques have been extensively applied to produce high quality binary halftone patterns that can approximate the ideal sinusoidal patterns more closely after defocusing [12–19]. Their superiority over PWM-based solutions is due to the fact that halftoning is a two-dimensional process that can manipulate the noise more flexibly [20–22].

The optimization of the halftone patterns can be carried out in either intensity or phase domain. The former approach [13–15,17–19] tries to minimize the error between the defocused halftone and a sinusoidal fringe pattern while the latter approach [16] tries to minimize the phase error achieved with the defocused halftone patterns. Since the quality of the depth measurement is determined by the phase error, the phase-based optimization tends to optimize the measurement quality directly while the intensity-based optimization does not. However, the performance of current phase-based optimization methods is more sensitive to the extent of defocusing which may not be controlled precisely in practical situations [15].

Sinusoidal fringe patterns are periodic. To provide flexibility and reduce the optimization effort, the optimization processes of recent proposals are generally patch-based [14,17–19]. In general, they optimize one single halftone patch of size $N_y \times (T/2)$ such that its defocused output is close to a patch of a sinusoidal fringe pattern, where T is the fringe period (in number of pixels) and N_y is an integer value. By tiling the patches and shifting the tiling results by $\pm 2T/3$ pixels, three full-size halftone patterns can be generated to approximate the ideal sinusoidal fringe patterns after being defocused. We have three observations on this common strategy as follows: (1) The tiling result must be periodic and hence it contains periodic noise with respect to the ideal sinusoidal fringe pattern. Consequently, the phase

* Corresponding author.
E-mail addresses: ben.x.xu@connect.polyu.hk (Z.-X. XU), enyhchan@polyu.edu.hk (Y.-H. Chan).

http://dx.doi.org/10.1016/j.optlaseng.2016.10.002
Received 5 July 2016; Received in revised form 6 September 2016; Accepted 3 October 2016
Available online 15 October 2016

error contains harmonic distortion, which can mix with the phase variation contributed by the surface texture and reduce the measurement quality accordingly. (2) The shift must be an integer and hence the fringe period is bound to be an integer multiple of 3. (3) The phase error at a specific pixel, say (x,y), depends on three patch pixels, namely (x,y) and $(x, \mathrm{mod}(y+T\pm 2T/3,T))$, instead of patch pixel (x,y) itself, which introduces more constraint for the optimization process.

Although state-of-the-art researches have already reduced the phase error achieved by defocused binary patterns sharply, there still leave room for improvement, especially when fringe patterns of large period are applied during the measurement. It is obvious that the quality of a quantized fringe pattern can be improved by increasing its quantization levels. We have introduced multilevel fringe patterns in [19] and demonstrated how they can improve the measurement efficiently. However, the defocused fringe patterns still suffer from the aforementioned problems due to the patch-based optimization process exploited to produce them.

To get an optimized halftone pattern the performance of which is robust to the amount of defocusing, conventional methods optimize halftone patterns under different conditions (e.g. different patch sizes [14,17–19] and different defocusing extent [14]) and then, from the optimized results, pick the one which is the most robust to defocusing conditions. This pick-the-best-from-the-available approach is passive to some extent and makes the optimization effort grow in multiples.

In this paper, we proposed a different optimization framework which generates multiple patches for tiling so that the periodicity of phase error can be effectively suppressed.

The contribution of this paper includes:

1) It is able to generate fringe patterns the produced phase error of which is close to aperiodic and carries almost no harmonic distortion.
2) It is capable to generate multilevel fringe patterns of arbitrary fringe period.
3) It releases a constraint for the optimization and theoretically it is able to achieve a better optimization result.
4) It takes proactive action to find optimized patches that are robust to defocusing extent.

The remainder of this paper is organized as follows. In Section 2, we briefly review the working principle of a three-step phase-shifting algorithm and the binary defocusing technique. In Section 3, we presented our idea of generating multi-level fringe patterns and our optimization procedures. Performance evaluation will be given in Section 4, and Section 5 presents the experimental results. Finally, a conclusion is provided in Section 6.

2. Review of binary defocusing three-step phase-shifting algorithm

Phase-shifting algorithms have been extensively used in 3D surface measurement because it can provide pixel-level accuracy and robustness. A simple three-step phase-shifting algorithm projects three sinusoidal fringe patterns, each of which has a phase shift of $2\pi/3$ from each other, onto the surface of the object to be measured. Accordingly, three phase-shifted fringe images, denoted as S_k for $k\in\{1,2,3\}$, can be captured with a high speed camera. Their intensity values at pixel (x, y) are given as:

$$S_1(x, y) = A + M\cos(\varphi(x, y) - 2\pi/3) \quad (1)$$

$$S_2(x, y) = A + M\cos(\varphi(x, y)) \quad (2)$$

$$S_3(x, y) = A + M\cos(\varphi(x, y) + 2\pi/3) \quad (3)$$

where A is the average intensity, M denotes the amplitude of intensity modulation, and $\varphi(x, y)$ symbolizes the pixel-wise phase to be solved. By solving the above three equations, we have:

$$\varphi(x, y) = \tan^{-1}\left(\sqrt{3}\,\frac{S_1(x, y) - S_3(x, y)}{2S_2(x, y) - S_1(x, y) - S_3(x, y)}\right) \quad (4)$$

Notably, the environmental noise can be eliminated by subtraction of different patterns. The solved phase from Eq. (4) is wrapped in range $[-\pi, \pi]$. After unwrapping $\varphi(x, y)$, one can obtain the depth information of the object.

A digital-light-processing (DLP) projector projects a gray level image with pulse width modulation (PWM) [23] and hence it takes time to project a gray-level pattern. To solve this problem, 8-bit sinusoidal patterns can be replaced with binary patterns such that the frame rate is only limited by the switching rate of the projection. Since switching can be super fast, it makes real-time 3D measurement feasible even though we still need to project 3 patterns onto the object being measured [24]. The issue is then how we can design a binary pattern that can approximate the original sinusoidal pattern well after being defocused under control.

Let B_k be the ideal binary pattern for approximating S_k for k={1,2,3}. In general, B_k can be obtained by minimizing the error in intensity domain as follows [15].

$$B_k = \min_B \|S_k - H \otimes B\|_2 \ \text{ for } k = \{1, 2, 3\} \quad (5)$$

where H is the blurring function that models the defocusing effect of the projector, B is a binary pattern having the same size of S_k, $\otimes$ denotes 2-D convolution, and $\|.\|_2$ symbolizes L2 norm. During the optimization process, H is generally modeled as a 2D Gaussian filter [12–19]. Patterns B_1, B_2 and B_3 can also be obtained by looking for three binary patterns that can minimize the L2 norm of the phase error resulted by replacing S_k with $H \otimes B_k$ in Eq. (4) [16].

As B_k is binary, optimizing B_k in either intensity or phase domain is a Non-deterministic Polynomial-time (NP) hard problem. Thus, optimization is usually realized by iteratively mutating pixels of B_k along raster scanning paths to find sub-optimal results [12–19].

3. Proposed fringe patterns and their generation

3.1. Octa-level fringe patterns

A full color image can be separated into three color channels (R, G and B). Since the color channels are handled independently by a projector, one can produce three different binary patterns, one for each channel, for the projector to project a color fringe image X. The luminance channel of X, say L, can be generally determined as

$$L = 0.299B_R + 0.587B_G + 0.114B_B \quad (6)$$

where B_R, B_G and B_B are, respectively, the binary patterns for channels R, G and B. Let $B_c(x, y)$, where $c\in\{R,G,B\}$, be the intensity value of pixel (x, y) of pattern B_c. Since $B_c(x, y)\in\{0,1\}$ for all c, there are altogether 2^3=8 possible intensity levels in L. In other words, if we project the color fringe image X onto the object and extract the luminance plane of the color image captured by the camera, it will be equivalent to projecting an octa-level fringe pattern onto the object directly.

Note that the actual luminance value associated with a particular color can vary among different projectors in practical situations. However, they can be acquired in the projector profile, or measured easily though a simple experiment before doing 3D measurements. Eq. (6) can then be adjusted accordingly.

Since the proposed octa-level fringe patterns are actually produced by manipulating binary patterns in individual channels, it enjoys the following advantages:

1. Super fast measurement is supported because the frame rate can be as high as in the case when binary defocusing technique is used.