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High-dynamic-range 3D shape measurement utilizing the transitioning state of digital micromirror device

Vignesh Suresh [a], Yajun Wang [b], Beiwen Li [a,*]

[a] Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, USA
[b] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China

A R T I C L E I N F O

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A B S T R A C T

This paper introduces a novel method for 3D shape measurement of high-contrast surfaces in real-time by taking advantage of the transitioning state of digital micromirror device. We propose to project defocused 1-bit binary patterns for sinusoidal generation to bypass the rigid camera-projector synchronization requirement. Each pattern is capture twice in one projection cycle to obtain two fringe images with different brightness: the first fringe is captured when the camera is totally exposed within the projector's bright period; the second fringe is captured when part of the projector's dark period is within the camera exposure. The two fringes will be combined to alleviate the saturation problem. Experiments demonstrate the success of the proposed method by showing the real-time 3D shape measurement capability (image acquisition rate: 166 Hz; 3D frame rate: 14 Hz). Moreover, since 1-bit binary patterns are used, it is potentially applicable to high-speed measurements.

1. Introduction

Non-contact 3D shape measurement of high-contrast surfaces is of significant importance to a variety of applications such as manufacturing, medical imaging and entertainment [1]. Such task, however, has long been challenging for the optical community due to the difficulty of achieving high-quality measurements across an entire surface with high reflectivity variations. Therefore, developing novel measurement techniques for high-contrast surfaces is crucial in broadening the application of optical 3D shape measurement.

There are basically four different approaches developed to address the aforementioned problem: 1) using polarizing filters [2–5]; 2) performing multi-view measurements [6]; 3) performing textural analysis [7]; 4) developing high-dynamic-range (HDR) 3D shape measurement techniques [8]. The methods using polarizing filters can effectively reduce specular reflections, yet it is at the cost of reducing the overall light intensities which makes it difficult to measure the dark areas. The method performing multi-view measurement alleviates the problem associated with specular areas by referring to corresponding areas in another view. However, 3D data fusion from different perspectives is a non-trivial problem which involves complicated post-processing after data capture. The method performing textural analysis is well functioned when imaging a scene with rich textural variations. However, it could be problematic if the scene does not exhibit features that are strong enough to be tracked.

To address the limitations of the aforementioned high-contrast surface measurement methods, researchers developed HDR 3D shape measurement techniques. Conventional HDR methods typically take multiple shots of each fringe image with variable camera exposures, which can be essentially classified into two categories: 1) performing measurements with multiple different camera exposure times [8,9]; 2) identifying the optimal camera exposure time [10–13]. In the first method, the camera captures a series of fringe images with different exposures. The final fringe images for 3D reconstruction are then created by pixelwise choosing the brightest unsaturated intensity among captured fringe sequence. The second method also involves capturing many images with the different exposures and then the optimal exposure time is picked by performing pre-analysis among the entire fringe sequence. The fringe images captured under the optimal exposure time is then used for 3D reconstruction. In general, the first approach is more robust to local high surface reflectance, yet the second approach has the merit of algorithm simplicity. Though both methods are successful, they involve capturing fringe images with varying camera exposures, which tends to reduce the level of automation and thus is undesirable for real-time or high-speed applications.

To address the limitations of conventional HDR methods, researchers are seeking solutions without varying camera exposures. Jiang et al. [14] proposed a method using three-step phase shifted inverted/complementary patterns that realizes real-time HDR 3D shape measurement, and was later generalized to arbitrary phase shifting steps [15]. Then, Chen and Zhang [16] discovered that saturated fringe

* Corresponding author.
E-mail address: beiwen@iastate.edu (B. Li).

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patterns with its number of phase shifting steps $N = P/2$ pixels (P denotes pixels per period of fringe) in fact produces high quality 3D reconstruction for shiny surfaces. Furthermore, another special type of research was carried out which adaptively modifies the projector's intensity levels [17–22] or color information [23] based on the feedback from previously captured data. Overall, all these state-of-art HDR methods have achieved great successes when measuring high-contrast or shiny surfaces with different speeds, flexibilities and complexities. However, these methods typically hinges on the analysis of 8-bit sinusoidally varying intensities. The usage of multiple gray levels limits the potential for high-speed applications in that a digital video projector is typically subject to a refreshing limit of 120 Hz for 8-bit patterns.

In 2009, Lei and Zhang [24] developed a technology call the binary defocusing method which approximates sinusoidal fringe projection through 1-bit binary patterns with projector defocusing. The usage of 1-bit binary patterns, together with the advances of the high-speed digital-light-processing (DLP) technologies, have drastically boosted the measurement speeds up to Kilo-Hertz (kHz) level [25]. Moreover, this bit-wise technology also has the following advantages: 1) no requirement for gamma correction; and 2) no requirement for precise camera-projector synchronization.

The core of the DLP technology is an array of digital micromirrors called the digital micromirror device (DMD). Each mirror corresponds to a single projector pixel which is switched to ON or OFF states to produce a bright or dark pixel. To use such a device for pattern projection, Wang et al. [26] discovered that it is important to put at least some dark times in one projection period to avoid coupling or cross-talk between two consecutively projected patterns. This dark period can be actually utilized to alleviate saturation problem in highly reflective surface measurements.

In this research, we propose a novel HDR method with defocused 1-bit binary patterns for high-contrast surface measurements. The proposed technology will take advantage of 1) the non-rigid camera-projector synchronization requirement for the binary defocusing technology, and 2) the transitioning state between the DMD's bright and dark times. We capture images twice in each pattern projection cycle: the first fringe image is captured with the entire camera exposure within the DMD's bright period; yet the second fringe is captured with part of the camera exposure within the DMD's dark time. The two captured fringe images with different brightness will be combined to alleviate saturation problem in high-contrast surface measurement. We performed real-time 3D shape measurement of a deforming shiny metal surface under an image acquisition rate of 166 Hz and a 3D frame rate of 14 Hz. Since the 1-bit binary patterns are used, such technology can be potentially applicable to high-speed measurements.

2. Principles

2.1. Three-step phase shifting algorithm

Many phase shifting algorithms have been developed over the period of the past few decades. Among them, the three-step phase shifting algorithm requires the minimum number of fringe patterns for phase calculation. A three-step phase shifting algorithm with equal phase shifts is mathematically described as,

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

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

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

where $I'(x, y)$ is the average intensity, $I''(x, y)$ represents the intensity modulation, and $\phi(x, y)$ is the phase to be solved for. Simultaneously solving the above three equations will lead to,

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

An arctangent function is used so that the phase value obtained from Eq. (4) will range from $-\pi$ to π with a 2π modulus. Spatial or temporal phase unwrapping algorithms could be used to unwrap the phase so that we can get a continuous phase map. The unwrapping process essentially estimates the 2π discontinuous locations and removes the 2π jumps by adding or subtracting $k(x, y)$ multiples of 2π.

$$\Phi(x, y) = \phi(x, y) + k(x, y) \times 2\pi. \tag{5}$$

In this research, we used an enhanced two-frequency phase shifting method [27] for phase unwrapping. Essentially such method uses an additional set of three-step phase shifted low-frequency patterns to find cues for identifying $k(x, y)$. The calibration method described in [28] is used to finally reconstruct the 3D geometry.

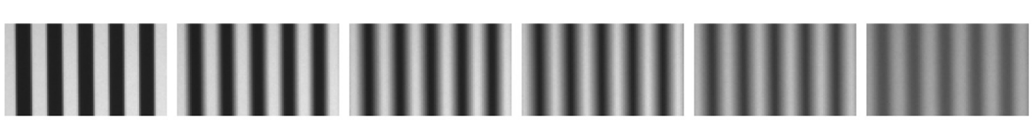
2.2. Revisit of the binary defocusing technique

A conventional digital fringe projection system uses sinusoidal patterns for extracting 3D information. But the use of sinusoidal patterns typically limits the speed capacity of the projector (e.g. 120 Hz for DLP LightCrafter 4500). The binary defocusing technique which generates quasi-sinusoidal profiles with 1-bit square binary patterns overcomes such limitation. A squared binary structure is essentially composed of its first order harmonic sinusoidal signal and higher order harmonics. The projector defocusing which emulates a Gaussian filter is to suppress the higher order signal to make the first order harmonic sinusoidal signal predominant. Fig. 1(a)–(f) show the camera captured squared binary patterns with different levels of projector defocusing, from which one can see that at the mid-range levels of projector defocusing, quasi-sinusoidal profiles can be approximated with squared binary patterns. Given that a bit-wise binary pattern is less expensive to produce by hardware, the image refreshing rate can be boosted up to over kHz using the advanced DLP projection devices (e.g. 4,225 Hz for DLP LightCrafter 4500).

2.3. Revisit of digital-light-processing (DLP) technology

The digital light processing (DLP) technology is based on an optical semiconductor called a digital micromirror device (DMD). DMD is a precision light switch which modulates the light digitally with the help of an array of microscopic mirrors. Each mirror corresponds to a pixel in a projected image. A digital video signal is to activate the tiny electrode below DMD causing the mirror to tilt either towards or away from the light source as shown in Fig. 2. When the mirror is tilted toward (or away) the light source, the pixel is switched to ON (or OFF) status.

Different brightness or grayscale values are produced by time integration: i.e. the percentage of ON time versus OFF time. Therefore,



(a) (b) (c) (d) (e) (f)

Fig. 1. Binary structured patterns projected with a projector at different defocusing levels, where (a) is in focus and (f) is severely defocused.