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Digital micromirror transient response influence on superfast 3D shape measurement

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ABSTRACT

Nowadays, the high speed (e.g., kilo-Hertz) refreshing rate of the digital micro-mirror device (DMD) has enabled superfast 3D shape measurement using the binary defocusing technique. This research finds that when the system reaches its extreme binary pattern refreshing rate, the transient response of the DMD induces a coupling effect (i.e., two neighboring patterns blend together) that may cause substantial measurement error. Since this transient response repeats itself, this systematic measurement error is substantially reduced to a negligible level when the timing between the projector and the camera is properly adjusted. Experimental results are presented to demonstrate the observed phenomena, and the success of utilizing the proposed method to overcome the problems associated with the transient response of the DMD.

1. Introduction

The capture of 3D geometric motion of rapidly changing events is used considerably in academia. This new process started to impact the industry by enabling the acquisition of a new type of data that is vital to the development of new products. For instance, capturing the motion of a live beating heart is vital to understanding its mechanics and physiology [1]. Capturing quantitative measured data of debris flying around agricultural machinery while operating in the field is critical to the development of robust designs. Real-time 3D shape measurement has been realized by adopting the digital fringe projection (DFP) method facilitated by digital light processing (DLP) projectors [2,3]. However, it is extremely difficult for conventional DFP techniques to achieve rates higher than 120 Hz (which is the maximum refresh rate of a digital video projector). Therefore, it is difficult for such techniques to achieve high speed motion capture.

Recent advances in superfast 3D shape measurement have allowed high speed (in the order of kHz or higher) measurement rates by utilizing coherent laser interference and rotating mirrors [4], LED projection arrays [5], and digital binary pattern projection by the digital light processing (DLP) projectors [6]. All these technologies have utilized phase-shifting algorithms to achieve high-spatial resolution. The laser interference based technology [4] has the issue associated with the coherent lasers: speckle noise, albeit they partially reduced this problem by adding a second camera. The LED projection system [5] could reach 100 kilo-Hertz (kHz), yet the system they developed only reached 47 Hz due to the camera they used, and possibly the brightness of the projectors and some transient response of the LED light used. We have successfully developed a system [6] that could achieve 32 kHz using the DLP Discovery platform and the binary defocusing technique [7]. However, the core of the DLP technology is the digital micro-mirror device (DMD) that is inherently a mechanical device that toggles the pixel ON or OFF by mechanically flipping the micro-mirrors from one position to the other. This transient response of the digital micro-mirrors could influence the measurement quality as well if its speed limit is reached.

The binary defocusing technique has enabled us to achieve high speed (in the order of tens of kHz) 3D shape measurement because it requires only 1-bit structured patterns rather than 8-bit grayscale patterns [6]. However, the measurement error is large if the projector is not properly defocused [8]. Techniques based on 1-D pulse width modulation (PWM) [9–14], 2D area modulation [15,16], and binary dithering [17] as well as the optimized dithering techniques [18,19] have been developed to improve the binary defocusing technique. They proved successful in attaining high-quality 3D shape measurement even if the projector is nearly focused; and if the projector is slightly defocused, the phase quality obtained from the binary patterns could be the same as that

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obtained from the traditional sinusoidal fringe patterns. Our prior knowledge tells us on how to reduce the phase measurement error to a negligible level caused by the binary defocusing itself. Therefore, the phase measurement error discussed in this paper is mainly caused by sources other than the defocused binary patterns.

This paper presents a new phenomena that we have never observed before for superfast 3D shape measurement. Our experiments find that even if the binary patterns are properly selected and defocused, significant phase measurement error still occurs if the high-speed projectors (e.g., DLP LightCommander and DLP LightCrafter) operate under the structured light mode and pattern switching rate is at its maximum with the maximum illumination time. We discover that the transient response of the DMD causes pattern coupling (i.e., two neighboring patterns blend together) when the projector operates under the aforementioned conditions. Further experiments find that the transient response is a systematic error (i.e., an error caused independent of the projection speed), and thus its influence on phase measurement error could be reduced if the proper method is developed. This paper presents a method that we have developed to mitigate this problem by changing the timing of the system: the exposure time of the projector, the starting time and exposure time of the camera. We will demonstrate that this method can reduce the phase measurement error to a negligible level.

Section 2 explains the principles of proposed techniques. Section 3 shows some experimental results, and Section 4 summarizes the paper.

2. Principle

2.1. Two-frequency phase-shifting technique for absolute phase retrieval

Phase-shifting methods have been extensively adopted in optical metrology because of their measurement speed and accuracy. Over the years, a variety of phase-shifting algorithms have been developed, that include three-step, four-step, and least-square algorithms [20]. For high-speed 3D shape measurement, a three-step phase-shifting algorithm with a phase shift of $2\pi/3$ is commonly used. The three fringe images 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. Simultaneously solving Eqs. (1)–(3), the phase can be obtained

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

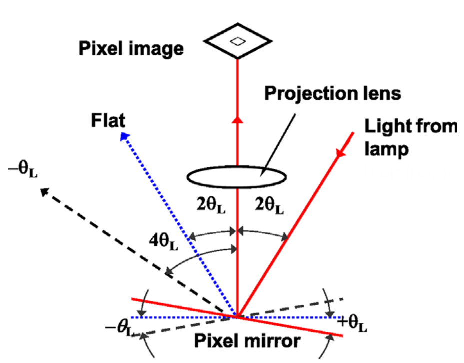

Fig. 1. Optical switching principle of a digital micro-mirror device (DMD).

This equation provides the wrapped phase with 2π discontinuities. A spatial or temporal phase unwrapping algorithm can be applied to obtain continuous phase.

We utilized a two-frequency temporal phase-unwrapping algorithm to unwrap the phase. Essentially, two wrapped phase maps, low frequency phase $\phi^l(x,y)$ and high-frequency $\phi^h(x,y)$ were used. $\phi^l(x,y)$ is obtained from wide fringe patterns with a single fringe covering the whole measuring range, such that no phase unwrapping is required. By referring to $\phi^l(x,y)$ point by point, $\phi^h(x,y)$ is unwrapped to obtain a continuous phase map, $\Phi(x,y)$. Because 3D information (i.e., the depth) is carried on by the phase, 3D shape can be reconstructed from the unwrapped phase $\Phi(x,y)$ using a phase-to-height conversion algorithm [8].

2.2. Fundamentals of the DLP technology

Digital light processing (DLP) concept originated from Texas Instruments (TI) in the later 1980s. TI began its commercialized DLP technology in 1996. At the heart of every DLP projection system is an optical semiconductor called the digital micro-mirror device (DMD), which functions as an extremely precise light switch. The DMD chip contains an array of hinged, microscopic mirrors, each of which corresponds to 1 pixel of light in a projection image.

Fig. 1 shows the working principle of the micro mirror. The micro mirror can be moved to $+\theta_L$ (ON) or $-\theta_L$ (OFF) , thereby modulating the output light corresponding to that cell. The rate of a mirror switching ON and OFF determines the brightness of the projected image pixel. Gray-scale values are produced by controlling the proportion ON and OFF times of the mirror during one projection period (black being 0% ON time and while white being 100% ON time).

2.3. Fundamentals of the binary defocusing technique

For a conventional DFP technique, sinusoidal patterns are projected and captured for 3D information extraction. Since it requires to project 8-bit sinusoidal patterns, the refresh rate of a digital video projector is typically limited to 120 Hz, which is not sufficient for high-speed motion measurement. The recently proposed binary defocusing technique is able to break the speed limitation for DFP technique. Instead of sending 8-bit sinusoidal patterns, 1-bit binary patterns are fed to the projector. By properly defocusing the projector, the projected patterns will be pseudo-sinusoidal. Fig. 2 shows the results with different defocusing levels. The first row of Fig. 2 shows the captured defocusing binary patterns, while the second row of Fig. 2 shows the corresponding cross sections.

Since only 1-bit binary patterns are used, there are some techniques which can be used for high-speed pattern projection. For example, the DLP LightCommander projector can switch binary patterns at 4 kHz, while it can only project sinusoidal patterns at about 700 Hz. By using the binary defocusing technique, we have demonstrated the feasibility for superfast motion capture [6]. However, when operating under high speed, there are limitations for some projectors, which may bring error to the final measurement result. In the following sections of this paper, we will demonstrate the limitation of a DLP LightCommander projector along with our proposed solution.

3. Experiments

3.1. Experimental system setup

The developed 3D shape measurement system is composed of a DLP LightCommander projector (model: LightCommander,