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High-speed three-dimensional shape measurement for dynamic scenes using bi-frequency tripolar pulse-width-modulation fringe projection

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A B S T R A C T

This paper introduces a high-speed three-dimensional (3-D) shape measurement technique for dynamic scenes by using bi-frequency tripolar pulse-width-modulation (TPWM) fringe projection. Two wrapped phase maps with different wavelengths can be obtained simultaneously by our bi-frequency phase-shifting algorithm. Then the two phase maps are unwrapped using a simple look-up-table based number-theoretical approach. To guarantee the robustness of phase unwrapping as well as the high sinusoidality of projected patterns, TPWM technique is employed to generate ideal fringe patterns with slight defocus. We detailed our technique, including its principle, pattern design, and system setup. Several experiments on dynamic scenes were performed, verifying that our method can achieve a speed of 1250 frames per second for fast, dense, and accurate 3-D measurements.

1. Introduction

The three-dimensional (3-D) scene acquisition is becoming increasingly crucial in practical application fields such as machine design, industrial inspection, prototyping, machine vision, robotics, 3-D imaging, game industry, culture heritage protection, advertising, information exchange and other fields of modern information technologies [1]. Fringe projection methods have been considered one of the most reliable techniques for recovering the shape of objects because of their accuracy and efficiency [2]. Recent advance in image sensors and digital projection technology becomes a powerful vehicle that motivates the rapid progress in reconstructing the 3-D shapes of dynamic scenes such as high-speed moving objects and rotating or vibrating non-rigid bodies [3,4]. High-speed 3-D dynamic shape measurement is essential and can be widely applied in such application fields as biomedical investigation, fluid dynamics, solid mechanics, deformation analysis under stress, impact and tension, where precise, accurate high-speed recordings are a must [3–8]. It is desirable that the 3-D information can be acquired at such a high speed that the details of shape changes in an instant can be captured, which can provide in-depth visual insights into events that happen during accidents [9].

Over the years, a number of fringe projection techniques have been developed by modifying the off-the-shelf digital projectors for high-speed applications [10–13]. Considering the resolution and the accuracy of measurements, most of these techniques use multiply sequentially sinusoidal patterns. In order to reliably determine the range information at each position, the scene must be almost static while each frame of the pattern is projected. However, most digital light processing (DLP) projectors are only capable of projecting patterns at a rate of 120 frames per second (fps) [4]. So it is difficult to use these projectors to capture fast moving dynamic scenes. On the other hand, today's high-speed camera, although relatively expensive, have a much higher frame rate (kHz) with a sufficient image resolution for most applications. To match the high recording speed of the camera, some researchers employed the DLP Discovery kit to control and program each mirror in the digital micromirror device (DMD) at a rather high speed so that the incident illumination could be precisely controlled [5,7,14,15]. However, since the DMD is a binary digital device: the DMD mirrors can be just switched between two orientations. In one orientation, incident light is reflected by the mirror toward the outside scene and in the other, light is reflected onto a black surface within the projector. This means only two illumination intensities can be generated at one moment within one switching cycle of DMD. To generate a gray-scale sinusoidal pattern, it must integral the illumination by

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binary temporal pulse width modulation [5,16], and the intensity level is reproduced by controlling the amount of time the mirror is on/off. For example, a 1-bit binary image just need one working cycles while an 8-bit gray-scales image needs 256 working cycles. So it is preferable that the pattern can be generated using as fewer gray-scales as possible so that it can be reproduced by DMD at a higher switching speed. For this purpose, Lei and Zhang [17] proposed a technique called squared binary defocusing method (SBM) that is to generate sinusoidal fringe patterns by properly defocusing squared binary structured ones. Ayubi et al. [18] presented methods for generating the binary pattern by the sinusoidal pulse-width-modulation (SPWM) technique of electrical engineering. Wang and Zhang proposed a binary pattern generation technique called optimal pulse-width-modulation (OPWM) [14] and conducted a comparative study on SBM, SPWM, and OPWM [19]. With these binary defocused patterns, the dynamic 3-D shape measurement can be achieved using either phase-shifting profilometry or Fourier transform profilometry. However, the boost in projection speed has been accompanied by a number of challenging issues: (1) The contradiction between the measurement accuracy with depth of field of the measurement: although SPWM and OPWM method can greatly improve the sinusoidality of the binary pattern, when the defocusing level is insufficient or the projector is nearly focused, the phase error caused by some unwanted high order harmonics of the generated patterns of SPWM and OPWM methods is still nonnegligible [16]. Conversely, an ideal sinusoidal pattern can be generated with a larger degree of defocusing, while the pattern contrast will be reduced by the effect of defocus. Therefore the close-to-be-ideally sinusoidal fringe pattern can be generated within a small depth range. (2) Efficient high-speed multi-object measurement: For measuring multiple objects simultaneously, the absolute phase should be recovered without ambiguity. To achieve this, Wang and Zhang [20] proposed a superfast phase-shifting technique for 3-D measurement using defocused binary patterns. Combining with the multi-frequency temporal unwrapping [21] and Gray-coding [15], the phase ambiguity problem can be solved. However, to unwrap a high-frequency phase, the minimum number of binary patterns is $\mathrm{INT}(\log_2 F)+1$, where F is the total number of periods in the field and INT is the 'integer part' function [22]. Besides, the phase unwrapping will easily fall into an error, when an improper value of Gray-coding is caused by mistake at the partial boundary of two adjacent binary words [15,23]. Temporal phase unwrapping is a well-established technique to retrieve the absolute phase [24,25]. However, at least six frames are needed for a two-frequency unwrapping and nine frames are needed for a three frequency method. Due to the relatedly higher phase error of the defocus pattern, usually a three frequency method is mandatory [21]. Obviously, the increased number of required patterns is undesirable under dynamic conditions, where it is preferable to minimize acquisition time to avoid the effect of motion.

The goal of this research is to present a new three-dimensional shape measurement technique for dynamic scenes combining our recently proposed Tripolar pulse-width-modulation (TPWM) [16] pattern strategy with a new bi-frequency phase-shifting algorithm. As we recently reported, the TPWM technique can generate ideal sinusoidal fringe pattern even with a nearly focused optical system, which greatly increases the measurement accuracy and depth range of the defocusing method. The newly introduced bi-frequency phase-shifting algorithm can retrieve two phase maps with different fringe frequencies with only five fringe images. By applying a number-theoretical phase-unwrapping, the absolute phase can be easily obtained by a look-up table (LUT) based implementation. We discuss three typical methods for two-frequency phase-unwrapping, and explained the advantages of the adopted number-theoretical phase-unwrapping for our defocusing TPWM pattern. We also discuss the design of TPWM pattern as well as the synchronization between the projector and the high-speed camera. Experiments on two dynamic scenes are preformed to verify the performance of the proposed technique.

2. Bi-frequency tripolar pulse-width-modulation fringe projection

In this section, we detail our technique in three aspects: first, we introduce the bi-frequency phase-shifting method in which two different wrapped phase maps can be obtained by analyzing only five fringe images. Then we review three most widely used two-frequency phase-unwrapping algorithms. Finally, we briefly introduce the TPWM pattern generation technique and explain the advantages and necessity of combining the number-theoretical phase-unwrapping with TPWM technique.

2.1. Bi-frequency phase-shifting method

Phase-shifting profilometry has become one of the most popular phase extraction approaches, because it completely eliminates interferences from ambient light and surface reflectivity. Requiring the least number of fringe patterns for 3-D shape recovery, the three-step phase-shifting algorithm has been used extensively in high-speed applications [4]. The fringe images of a three-step phase-shifting algorithm with equal phase-shift can be described as

$$I_1(x,y)=A(x,y)+B(x,y)\cos(\phi_1-2\pi/3), \tag{1}$$

$$I_2(x,y)=A(x,y)+B(x,y)\cos(\phi_1), \tag{2}$$

$$I_3(x,y)=A(x,y)+B(x,y)\cos(\phi_1+2\pi/3), \tag{3}$$

where $A(x,y)$ is the average intensity relating to the pattern brightness and background illumination, $B(x,y)$ is the intensity modulation relating to the pattern contrast and surface reflectivity. ϕ_1 is the corresponding wrapped phase map which can be extracted by the following equation:

$$\phi_1(x,y)=\tan^{-1}(\sqrt{3}(I_1-I_3)/(2I_2-I_1-I_3)). \tag{4}$$

Since the arctangent function only ranges from $-\pi$ to π, the phase value provided from Eq. (4) will have π phase discontinuities. To obtain an absolute phase distribution, a phase unwrapping algorithm is usually needed. The absolute phase distribution is necessary for 3-D shape measurement of isolated objects with complex shapes. Spatial phase unwrapping algorithms cannot resolve the phase ambiguity in discontinuous surfaces and large step height changes where the phase changes large than π [26]. In order to obtain the reliable absolute phase distribution of a deformed fringe pattern, another set of two fringe images with π phase-shift (the fringe pitch is different from I_1-I_3) are used

$$I_4(x,y)=A(x,y)+B(x,y)\sin(\phi_2), \tag{5}$$

$$I_5(x,y)=A(x,y)+B(x,y)\cos(\phi_2) \tag{6}$$

Assuming that both the camera and the projector have a fairly large depth-of-view and the reflection of the object surface is linear, the average intensity coefficients $A(x,y)$ should be constant for pixel (i,j) in all the five images. It can be calculated using the