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Single-shot real-time three dimensional measurement based on hue-height mapping

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A B S T R A C T

A single-shot three-dimensional (3D) measurement based on hue-height mapping is proposed. The color fringe pattern is encoded by three sinusoidal fringes with the same frequency but different shifting phase into red (R), green (G) and blue (B) color channels, respectively. It is found that the hue of the captured color fringe pattern on the reference plane maintains monotonic in one period even it has the color crosstalk. Thus, unlike the traditional color phase shifting technique, the hue information is utilized to decode the color fringe pattern and map to the pixels of the fringe displacement in the proposed method. Because the monotonicity of the hue is limited within one period, displacement unwrapping is proposed to obtain the continuous displacement that is finally used to map to the height distribution. This method directly utilizes the hue under the effect of color crosstalk for mapping the height so that no color calibration is involved. Also, as it requires only single shot deformed color fringe pattern, this method can be applied into the real-time or dynamic 3D measurements.

1. Introduction

Three-dimensional (3D) measurement based on the structured light projection [1–4] has been well developed with the advances of the digital light projection technology and imaging sensor technology. Owing to its simplicity, non-contact and high accuracy, it is widely used in enormous fields including mechanical manufacture, heritage security, face recognition and biomedical engineering.

Over the past few years, applications of real-time reconstructions have been increased rapidly due to the demand for dealing with dynamic objects [5–9]. Among the existing real-time 3D measurement techniques, single-shot projection is one possible approach since it is insensitive to vibration with only one image captured. Fourier-transform profilometry (FTP) firstly proposed by Takeda et al. [10] is one popular single-shot method due to its merits of high speed and full-field analysis, and it has successfully been applied to dynamic 3D shape measurement [8,9]. But the process of effectively filtering the first-order spectrum from the other order spectrums is a challenge and may reduce the accuracy of the FTP method to some extent. Guan et al. proposed a composite structured light pattern for real-time 3D measurement based on phase measuring profilometry (PMP) [11]. In this method, phase shifting fringe patterns are spatially modulated along the orthogonal direction by different carrier frequencies and then summed into a composite grayscale image, which overcomes the limitations of PMP for measuring dynamic objects. Then, each individual pattern can be obtained by demodulation based on communications theory. This technique is pretty robust, but the resolution could be insufficient to obtain high accuracy details [12–14]. Color phase shifting technique (CPST) [15,16] is another single-shot method relying on PMP with a composite color image by encoding the phase shifting patterns into the color channels. However, it has a major problem, the color crosstalk, which is caused by the overlapped spectrum of the cameras and projectors. To address this problem, some studies have been researched [17–22], but most of them will implement a color pre-calibration process or complex algorithm. The color calibration has the drawback that it has to be performed again if the measured object or the condition of the system changes. Thus, an easier algorithm without color calibration is expected for color phase shifting technique, which can be applied in real-time 3D measurements.

In this study, a single-shot method based on hue-height mapping is proposed for real-time 3D measurements. The method of hue-height mapping has been studied recently [23]. In this method, a color composite fringe pattern composed by three phase shifting sinusoidal fringe patterns is firstly projected, which is similar to that in traditional CPST [15]. The hue of the captured color fringe pattern is found to maintain monotonic in a period even it has the color crosstalk, thus it is taken as the fringe identification label to decode the deformed color fringe pattern and map to the pixels of the fringe displacement, finally to the height distribution. However, because the fringe deformation is

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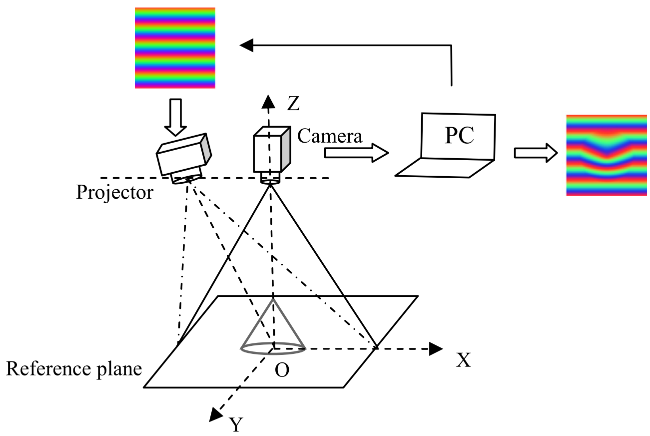

Fig. 1. Schematic diagram of the proposed 3D shape measurement.

limited in one period of the fringe, the method of hue-height mapping is only suitable for measuring thin objects. To make it as a general method applicable for thicker objects, this study proposes a technique of displacement unwrapping. When the fringe deformation is greater than one period, the continuous displacement can be obtained using displacement unwrapping, and then used to map to the height distribution. As a result, the proposed method is more general than the previously proposed method by directly utilizing the hue under color crosstalk and avoiding the color calibration. In addition, it requires only one deformed color fringe pattern, thus, this method has the potential application in real-time 3D measurements.

This paper is organized as follows. Section 2 explains the principle of the proposed 3D measurement based on hue-height mapping. Section 3 illustrates the numerical simulation. Section 4 presents the experimental results and Section 5 concludes the paper.

2. 3D measurement based on hue-height mapping

The schematic diagram of the proposed 3D measurement is shown in Fig. 1, which is just the same as the typical CPST system.

A designed color-encoded fringe pattern is projected by a projector onto the measured object on the reference plane. Only one deformed color fringe pattern modulated by the height of the measured object is captured with a color camera and then is decoded using the hue information. At last, the 3D shape of the object will be reconstructed after the hue-height mapping. The process of the proposed method is described in the following sections.

2.1. Measurement principle

The optical geometry of the proposed measurement system is illustrated in Fig. 2. The X–Z axis is located in the figure plane that is normal to Y axis. The distance between the pupil center of the projector (point P) and that of the camera (point C) is defined as d. Points P and C are at the same distance L from the reference plane. The fringe deforms from point A to point B due to the height of the inspection point D; AB is the fringe displacement in world coordinates (X–Y). Let β (millimeters/pixel) be the camera pixel coordinate to world coordinate (X–Y) mapping coefficient, and p be the pixel of the corresponding fringe displacement. According to the triangulation principle [22–25], the height h of the point D relative to the reference plane can be expressed as

$$h = \frac{L}{d + AB} \times AB = \frac{L}{d + \beta \times p} \times \beta \times p \quad (1)$$

Because β, d and L are the optical setup parameters, they can be obtained by calibrations [26]. If p can be extracted from the captured deformed pattern, h can be calculated with Eq. (1). Then, the 3D shape of the measured object can be successfully reconstructed.

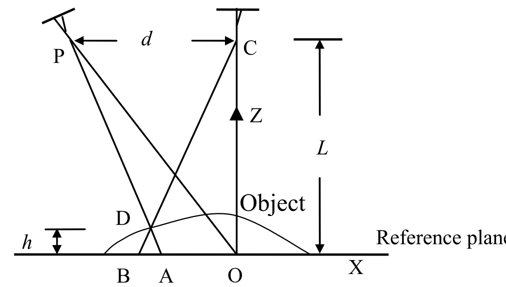

Fig. 2. Optical geometry of the measurement system.

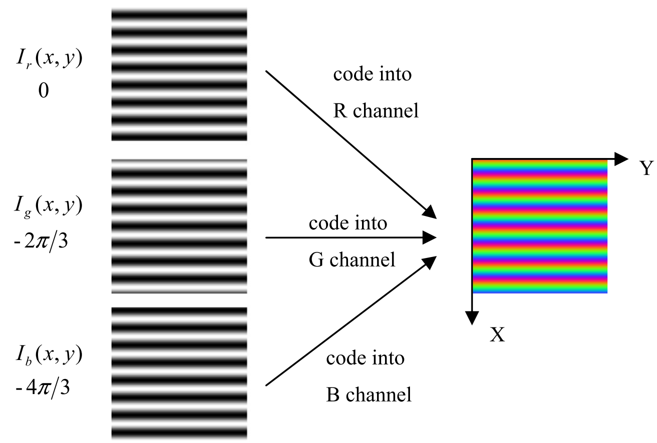

Fig. 3. Design of color-encoded fringe pattern.

2.2. Color-encoded method

Generally, the color-encoded fringe pattern in CPST is generated by coding three sinusoidal fringe patterns into RGB color channels as shown in Fig. 3. The three sinusoidal fringe patterns have the same period with $2\pi/3$ shift phase in between, and the phase shifting direction is parallel to X axis. The intensities of each grayscale pattern have a constant value in the Y direction and can be described as follows

$$I_r(x, y) = A_0 + B_0 \cos(2\pi x/T) \quad (2)$$

$$I_g(x, y) = A_0 + B_0 \cos(2\pi x/T - 2\pi/3) \quad (3)$$

$$I_b(x, y) = A_0 + B_0 \cos(2\pi x/T - 4\pi/3) \quad (4)$$

where (x, y) are the camera pixel coordinates, A_0 and B_0 are user defined constants, B_0/A_0 represents the fringe contrast, and T is the period of the fringe. When the designed color-encoded fringe pattern is projected onto the reference plane, a color fringe pattern is captured by a color camera. In traditional CPST, phase information will be calculated using the three grayscale sinusoidal fringe patterns extracted from the captured color fringe pattern. But, in practical, the extracted intensities will not be as ideal as Eq. (2) to Eq. (4) due to the color crosstalk, and measurement errors will be introduced in the next height calculation using these fringe patterns. Color calibrations are usually implemented to compensate the errors caused by color crosstalk, which restricts the application of CPST in real-time 3D measurements.

In this study, we calculate the height distribution using the fringe displacement instead of phase information to avoid the complex color calibrations. The hue value is used to encode each fringe of the color-encoded fringe pattern so that we can obtain pixels of fringe displacement by locating the hue values. The color fringe pattern is usually in RGB format and can be transformed into hue (H), saturation (S) and