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Abstract. To circumvent the problems induced by nonlinear gamma of the commercial video projector, we recently developed a flexible method for 3-D shape measurement that generates sinusoidal fringe patterns for 3-D shape measurement by defocusing binary structured patterns. However, it can only measure “smooth” objects. In this paper, we propose a technique to generalize this technique for arbitrary step height measurement. In particular, the binary coding method is combined with this technique for point-by-point phase unwrapping. Experiments have verified the success of the proposed approach.

Keywords: Step height; Phase shifting; Defocusing; Framework.

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INTRODUCTION

3-D shape measurement is very important to numerous disciplines, over the years, a number of techniques have been developed including stereo vision, structured light, and digital fringe projection and phase-shifting method [1]. Among existing techniques, digital sinusoidal fringe projection techniques are rapidly expanding because of its accuracy and speed. However, developing a system with an off-the-shelf projector for high-quality 3-D shape measurement remains challenging. One of the major issues is the nonlinear gamma effect of the projector.

Our recent study demonstrated the success of generating sinusoidal fringe patterns by defocusing binary structured patterns, and thus avoid the problems induced by nonlinear gamma effect [2]. Comparing with the conventional method when the sinusoidal fringe patterns are directly generated by the computer, this technique has a number of advantages if a DLP projector is used [3]: (1) It is less sensitive to the synchronization between the projector and the camera; (2) Its measurement accuracy is not affected by the projector’s nonlinear gamma; and (3) Its exposure time can be shorter than one projection channel time. However, because this technique uses a single-wavelength phase-shifting algorithm, it cannot measure step-height objects, and cannot measure discontinuous surfaces.

Conventionally, the step-height objects are measured by using more fringe images with different wavelengths, such as two-wavelength [4] and multiple-wavelength [5] techniques. Among these techniques, the ultimate goal is the same: increase the equivalent wavelength. If the equivalent wavelength is long enough, arbitrary step height can be measured [6]. However, all fringe patterns with different wavelength must be sinusoidal. This is certainly not feasible for this flexible 3-D shape measurement technique, because given a degree of defocusing, it is impossible to generate the same high-quality sinusoidal fringe images for different spatial wavelength.

This paper will introduce a technique to solve this problem. In particular, we combine binary coding method with this flexible 3-D shape measurement technique. A sequence of binary structured patterns with different spatial wavelength are sent to an defocused projector that is defocused to a degree so that the narrowest binary patterns become high-quality sinusoidal while the longer ones are deformed to different degrees. The narrowest binary patterns are spatially shifted so that a sinusoidal phase shifting algorithm can be adopted to compute the phase. The rest fringe patterns are binarized to generate the codeword that is designed to be the same as the integer numbers for phase unwrapping. Because the phase can be unwrapped point by point without using neighboring phase information, it can be used to measure arbitrary step height objects. Experiments will be presented to verify the viability of the proposed approach.

PRINCIPLE

Phase-shifting methods are widely used in optical metrology because of their speed and accuracy [7]. Three-step phase-shifting algorithm is the advantageous when the measurement speed is the key. We use a three-step phase-shifting...
algorithm with a phase shift of $2\pi/3$. The intensity of three fringe images can be written as:

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

\[
I_2(x,y) = I'(x,y) + I''(x,y) \cos(\phi),
\]

\[
I_3(x,y) = I'(x,y) + I''(x,y) \cos(\phi + 2\pi/3).
\]

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 Eq. (1)-(3), the phase can be obtained

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

Equation (4) provides phase values ranging from $-\pi$ to $+\pi$ with $2\pi$ phase discontinuities. Conventionally, a spatial phase unwrapping algorithm can be applied to remove the $2\pi$ discontinuities and obtain the continuous phase [8]. In general, the phase unwrapping is to detect the $2\pi$ jumps and remove them by adding or subtracting multiple times of $2\pi$. In other words, the phase unwrapping is to find integer number $k(x,y)$ so that

\[
\Phi(x,y) = \phi(x,y) + k(x,y) \times 2\pi.
\]

Here, $\Phi(x,y)$ denotes the unwrapped phase.

Instead of using a conventional phase unwrapping algorithm, some other alternative route can be used. One of the approach is to use the gray coding method [9]. For this method, a sequence of binary images ($B_k(x,y)$) is used to uniquely determine $k(x,y)$ in Eq. (5) point by point. By this means, $k(x,y)$ is so called codeword as a convention in a gray coding method. The codeword is essentially an unique value determined from a binary sequence, for example 1000 is 8, and 1100 is 12.

Fig. 1 illustrate the schematic diagram for the proposed method. A computer generates a set of binary patterns with three narrowest ones being shifted spatially. These patterns are sent to a defocused projector. The projector is defocused to a degree so that the narrowest binary patterns become ideal sinusoidal, while the wider ones are deformed to a certain degree. Three sinusoidal fringe patterns are used to obtain the phase using Eq. (4), while the wider structured patterns are binarized to obtain the codeword $k(x,y)$ in Eq. (5) for phase unwrapping.

![Schematic diagram of proposed algorithm.](image)

**FIGURE 1.** Schematic diagram of proposed algorithm.

Because the object surface might not be uniform, normalizing the structured images is needed to generate codeword. The normalization procedure is actually straightforward because from Eq. (1)-(3), the maximum and minimum intensity for each pixel can be obtained,

\[
I_{\min}(x,y) = I'(x,y) - I''(x,y),
\]

\[
I_{\max}(x,y) = I'(x,y) + I''(x,y).
\]

Where $I'(x,y) = (I_1 + I_2 + I_3)/3$, and $I''(x,y) = \sqrt{3}I_1 - I_1^2 + (2I_2 - I_1 - I_3)^2/3$. The binary images $B_k(x,y)$ can be normalized by

\[
B_k(x,y) = [B_k - I_{\min}]/[I_{\max} - I_{\min}].
\]

The approach proposed in [9] performs well for an in-focused system, i.e., both the projector and the camera are all in focus. However, for our flexible measurement system, the projector is required to be defocused, and there are
some new problems to be solved for. In this research, we applied similar computation framework as that introduced in Reference [10] to tackle with these problems. In particular, we used the following three steps:

1. **Step 1**: During binarization stage, identify the binary codeword changing points, and compute the phase changes for these points. If the phase does not change over $\pi$, the point is marked as incorrect points that need to be post processed.
2. **Step 2**: Due to the configuration of this structured light system, the phase should monotonically change cross the fringe stripes. The points that do not satisfy this condition are marked them as incorrect points for further processing.
3. **Step 3**: For those marked points, an additional phase unwrapping is applied. This phase is unwrapped locally by satisfying the surface smoothness condition.

**EXPERIMENTS**

This proposed method is tested by a fringe projection system that includes a Dell LED projector (M109S), and The Imaging Source digital USB CCD camera (DMK 21BU04) with a Computar M3514-MP lens F/1.4 with $f = 8$ mm. The camera resolution is $640 \times 480$, with a maximum frame rate of 60 frames/sec. The projector resolution is $858 \times 600$, and the projection lens has F/2.0 and $f = 16.67$ mm.

We first measure a uniform white flat surface. Figure 2(a)- 2(e) show binary structured images, and Figure 2(f)-2(h) shows the phase-shifted sinusoidal fringe images. Using this set of structured images, the codeword map can be obtained. After applying the previously introduced computation framework, we can obtain the codeword map as shown in Fig. 2(i). The phase can be wrapped using the three phase-shifted fringe images, as shown in Fig. 2(j).

![Figure 2](image_url)

**FIGURE 2.** Experimental results of a flat white surface. (a)-(e) Binary structured patterns; (f)-(h) Sinusoidal phase-shifted fringe patterns; (i) Codeword map; (j) Wrapped phase map.

Figure 3(a) shows one cross section of the codeword map and the wrapped phase map. It clearly indicates the the $2\pi$ jumps are perfectly aligned with the codeword changes. Because the codeword is unique for each pixel, it can be applied to unwrap the phase point by point. Figure 3(b) shows the unwrapped phase map. This result shows that the phase map can be correctly unwrapped point by point without using a conventional spatial phase unwrapping approach.
FIGURE 3. Phase unwrapping using the codeword map (a) One cross section of codeword map and the wrapped phase map; (b) The unwrapped phase map.

Because this phase unwrapping approach is point by point, it can be used to measure step-height objects. The test object in the example is actually a step-height one. If the slope of the unwrapped phase is removed by a reference plane, the phase map is shown in Fig. 4. It clearly shows that the phase changes sharply on the surface.

FIGURE 4. 3-D shape measurement results. (a) Depth phase map shown as 2-D color map; (b) 3-D view of the depth phase map.

Fig. 5 shows one cross section of the unwrapped phase map. It clearly shows that the phase difference between the bottom surface and the top surface is more than $2\pi$.

**SUMMARY**

This paper has presented a technique to extend the measurement range (i.e., step-height objects and discontinuous surfaces) of the previously proposed flexible 3-D shape measurement technique based on projector defocusing effect. Experiments have verified the feasibility of the proposed approach and the computational framework to handle the phase unwrapping problems introduced by the projector defocusing.
FIGURE 5. Cross section of the phase map of the step-height object.

REFERENCES