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Absolute three-dimensional shape measurement combining digital image correlation and phase-shifting methods

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ABSTRACT

Phase-shifting methods have been extensively employed in high-resolution and high-speed absolute three-dimensional (3D) measurements. In the process of 3D reconstruction, one of the important tasks is to recover the absolute phase pixel by pixel. In this paper, we propose an absolute 3D shape measurement method that combines the digital image correlation (DIC) algorithm with the phase-shifting method on a one-camera and one-projector structure light system. Comparing to the conventional multi-wavelength unwrapping method, the proposed method only needs one random binary pattern for phase unwrapping. Experimental results demonstrated the proposed method can successfully measure complex scenes with high quality.

Keywords: Digital image correlation, phase shifting, 3D shape measurement, fringe projection, phase unwrapping, fringe analysis, absolute phase

1. INTRODUCTION

Among all of the 3D shape measurement methods, phase-based methods have the advantage over intensity methods because they are more robust to the sensor noise and surface reflection and they can achieve high spatial resolutions and provide denser 3D points.[1] However, these phase-based methods only provide phase information ranging from $-\pi$ to π with 2π discontinuities between each period. Thus, a phase unwrapping algorithm has to be applied to eliminate the 2π discontinuities.

Over the years, researchers have come up with several temporal phase unwrapping methods, including gray-coding method,[2] multi-wavelength phase unwrapping[3–5] and phase encoding method.[6] Yet, they required capturing multiple additional images. Given this, temporal phase unwrapping methods substantially slow down the measuring process, which is not desirable in high-speed 3D measuring applications.

In view of this, An et al.[7] developed a temporal phase unwrapping method that utilizes the geometric constraints of the structure light system without requiring additional camera and fringe images. Nevertheless, this phase unwrapping method has the limitation that we need to have prior knowledge of the depth and geometry variation. An and Zhang[8] combine the binary statistical pattern matching with the phase-shifting method. This method requires only projecting one additional pattern and doesn't depend on the prior knowledge of the object. But the difference between the camera and the projector needs to be further addressed. To deal with this, both images in our proposed matching process are captured by the same camera. In addition, the digital image correlation (DIC) is adopted for accounting for the distortion issue in the matching process.

In this research, we proposed a phase unwrapping method that combines DIC[9–12] with the phase-shifting method. The approximate absolute phase map is first found by performing DIC matching between the original projected image and the deformed image. Then the approximate absolute phase map is used to unwrap the wrapped phase of the deformed image. Finally, the high accuracy 3D geometry can be reconstructed. The proposed method has the merit of requiring only one additional binary random image to be projected, the prior knowledge of the depth of the measuring object is not needed and the measuring range is not limited by the geometry setting of the camera and the projector.

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2. PRINCIPLE

2.1 Three-step phase-shifting algorithm

Three phase-shifted fringe images with equal phase shifts can be mathematically written as

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

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

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

where $I'(x,y)$ is the average intensity, $I''(x,y)$ is the intensity modulation, and $\phi(x,y)$ is the phase to be solved. Solving equation simultaneously leads to the result,

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

Due to the arctangent operation, the phase ϕ obtained from the equation range only from $-\pi$ to π with 2π discontinuity between each period, which we called the wrapped phase. The mathematical relationship between the wrapped phase ϕ and the unwrapped phase Φ can be expressed as

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

where K is often referred to as fringe order. Therefore, we want to use the phase unwrapping algorithms to find the integer fringe order K of each pixel.

2.2 Phase unwrapping using DIC

In this research, we propose a temporal phase unwrapping method that incorporates the geometry constraint of a single camera and single projector structure light system and the DIC method[9–13] to unwrap the phase pixel by pixel without requiring additional fringe images and a second camera. In this method, we use the DIC to find the approximate absolute phase Φ_r of each pixel automatically. Then this approximate absolute phase map Φ_r can unwrap the wrapped phase map ϕ pixel by pixel to obtain high accuracy absolute phase map using equation

$$K(x,y) = ceil\left[\frac{\Phi_r - \phi}{2\pi}\right]. \tag{6}$$

Where $ceil()$ is the ceiling operator that obtains the closest integer that is larger than or equal to the value. In total, only four patterns are required for each measurement: one set of three-step phase-shifted fringe patterns and one random binary pattern. The phase-shifted fringe patterns are used to generate a wrapped phase map using Equation 4. We generate the approximate absolute phase map by applying DIC between the deformed image and the original projected image. The corresponding absolute phase map of the original image has been pre-computed using multi-wavelength phase-shifting algorithm[4] before we start doing the 3D measurement so that if the correspondence between the original image and the deformed image is established, the approximate absolute phase of each pixel on the deformed image can be obtained. Next, we use the approximate absolute phase map to unwrap the wrapped phase map using the geometric constraint based approach. Finally, the high accuracy 3D geometry can be reconstructed from the accurate absolute phase map. This unwrapping method has the advantage of enabling high-speed measurements since comparing to conventional temporal phase unwrapping algorithm where additional fringe patterns are needed, it only requires to project one random pattern.

3. EXPERIMENTS

To verify the proposed method, we developed a structure light system, Fig. 1, which includes one camera (FLIR Grasshopper3 GS3-U3-23S6C) attached with a 16 mm focal length lens (Computar M1614-MP2) and one projector (Texas Instrument LightCrafter 4500). The full resolution of the camera is 1920×1200 pixels. The resolution of the projector is 912×1140 pixels. The system was calibrated using the method proposed by Zhang and Huang[14] and the camera coordinate is chosen to be the world coordinate.

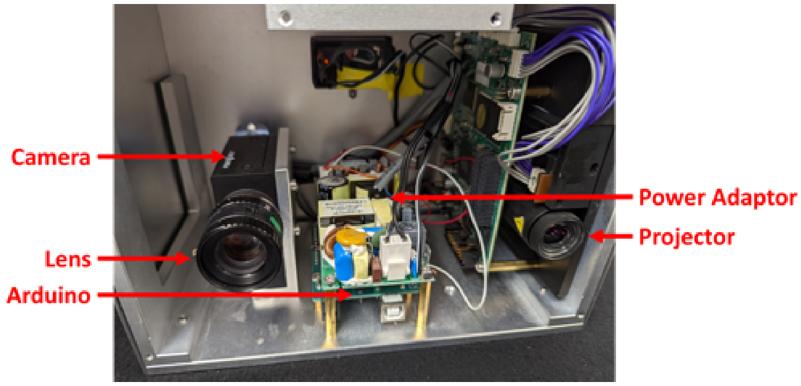

Figure 1. Experimental hardware system.

Prior to any 3D measurements, we obtain the original image by sequentially projecting 15 multi-wavelength phase-shifting patterns and the designed random binary pattern onto a white flat plane and capture it with the camera. We save the original image and its absolute phase for later use. Fig. 2 shows the ideal random binary pattern, the original image, and its corresponding absolute phase map. With the original image on hand,

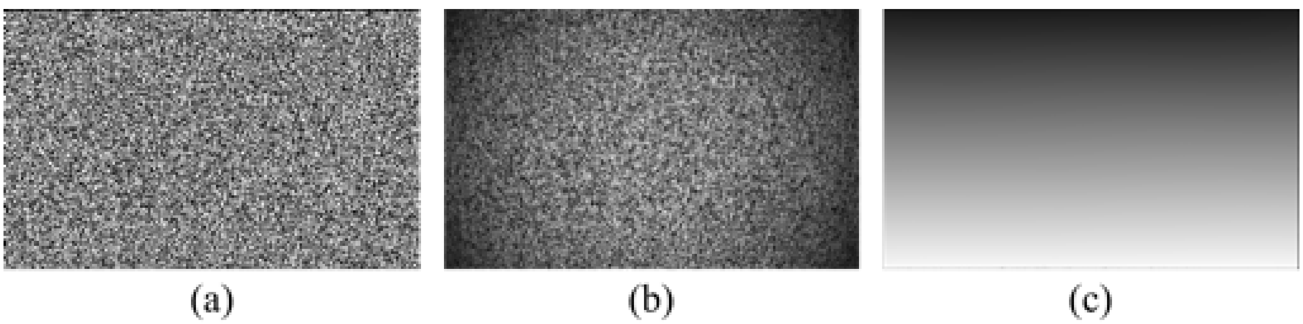

Figure 2. (a) Ideal random binary pattern. (b) Original image. (c) Corresponding absolute phase map of the original image.

we can perform 3D measurements. We measured a sculpture that has arbitrary geometry. Fig. 3 shows the 3D reconstruction process of the sculpture. Fig. 3(a) shows the photograph of the object. Fig. 3(b) shows the random pattern for DIC. Fig. 3(c) shows the wrapped phase map from three phase-shifted fringe patterns. From the random pattern, approximate absolute phase was obtained, and a 3D shape was reconstructed shown in Fig. 3(e). We then used the approximate absolute phase shown in Fig. 3(d) to unwrap the wrapped phase shown in Fig. 3(c). The unwrapped phase was further used to to reconstruct the 3D geometry shown in Fig. 3(f). Compare to the 3D reconstruction result shown in Fig. 3(e) with the approximate absolute phase, Fig. 3(f) has much higher accuracy and higher resolution. This demonstrates that our proposed method can successfully unwrap the wrapped phase and reconstruct the high accuracy 3D geometry of the sculpture.

4. SUMMARY

This paper presented a 3D shape measuring method that combines the DIC algorithm and the phase-shifting method. Three phase-shifted fringe patterns and one random binary pattern are projected onto the measuring object. Then the camera captures the scene as the deformed image. The deformed image is matched with the original image using the DIC algorithm for approximate absolute phase retrieval. Then the retrieved approximate absolute phase is used to unwrap the wrapped phase. Finally, we use the high accuracy absolute phase to reconstruct high accuracy 3D geometry. The proposed method can deal with the optical difference between the projector and the camera and has the advantage of not requiring additional cameras for high-speed 3D measurements.

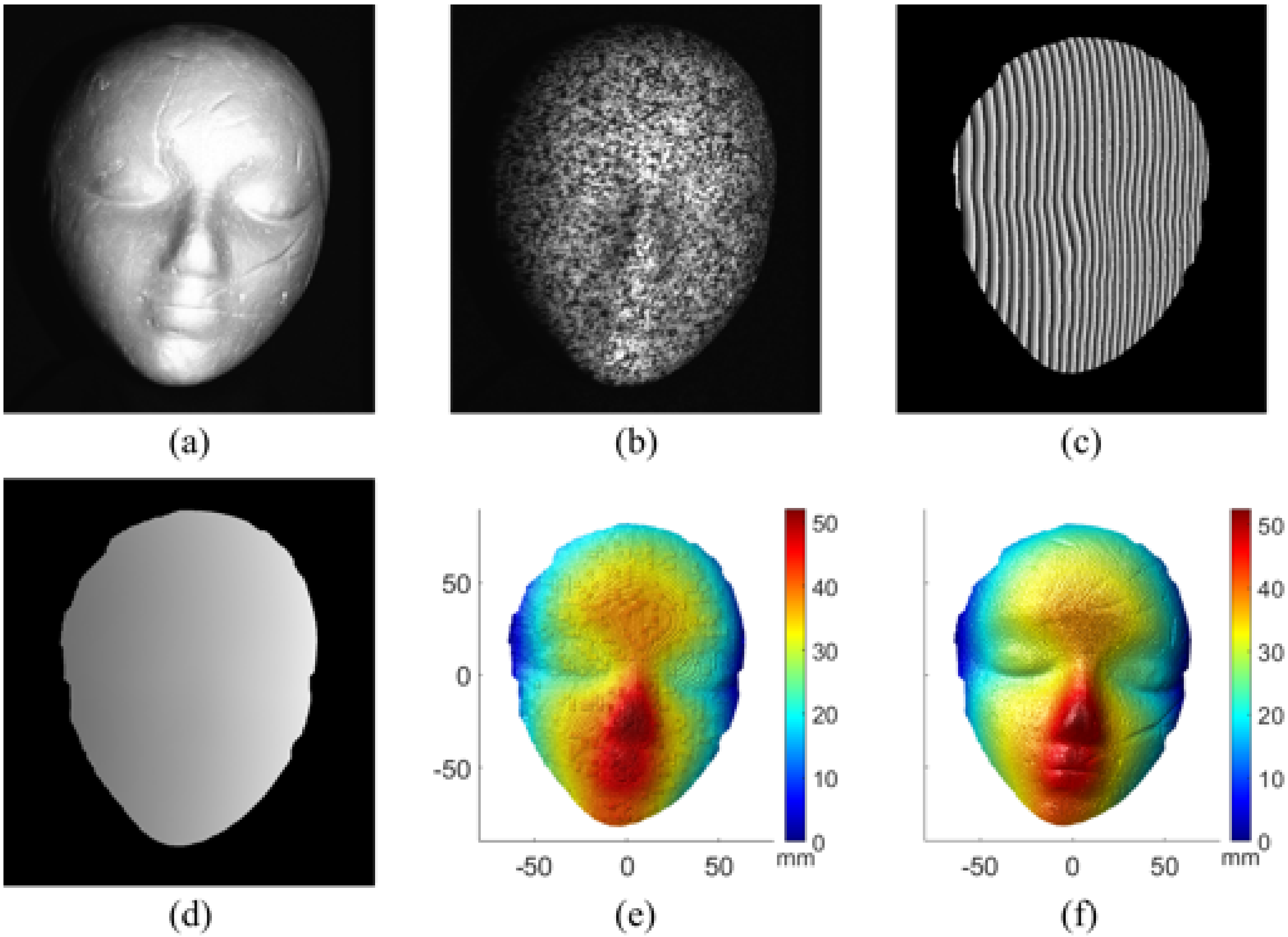

Figure 3. 3D reconstruction process of the sculpture. The units are all in mm. (a) The sculpture measured. (b) The sculpture projected with the random binary pattern. (c) Wrapped phase of the sculpture. (d) Approximate absolute phase of the sculpture. (e) 3D reconstruction of the sculpture using (d). (f) 3D reconstruction using the high accuracy absolute phase obtained from unwrapping (c).

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REFERENCES

[1] Zhang, S., "High-speed 3d shape measurement with structured light methods: A review," *Optics and Lasers in Engineering* **106**, 119–131 (2018).

[2] Sansoni, G., Carocci, M., and Rodella, R., "Three-dimensional vision based on a combination of gray-code and phase-shift light projection: analysis and compensation of the systematic errors," *Appl. Opt.* **38**, 6565–6573 (Nov 1999).

[3] Cheng, Y.-Y. and Wyant, J. C., "Two-wavelength phase shifting interferometry," *Appl. Opt.* **23**, 4539–4543 (Dec 1984).

[4] Cheng, Y.-Y. and Wyant, J. C., "Multiple-wavelength phase-shifting interferometry," *Appl. Opt.* **24**, 804–807 (Mar 1985).

[5] Towers, C. E., Towers, D. P., and Jones, J. D. C., "Optimum frequency selection in multifrequency interferometry," *Opt. Lett.* **28**, 887–889 (Jun 2003).

[6] Wang, Y. and Zhang, S., "Novel phase-coding method for absolute phase retrieval," *Opt. Lett.* **37**, 2067–2069 (Jun 2012).

[7] An, Y., Hyun, J.-S., and Zhang, S., "Pixel-wise absolute phase unwrapping using geometric constraints of structured light system," *Opt. Express* **24**, 18445–18459 (Aug 2016).

[8] An, Y. and Zhang, S., "Three-dimensional absolute shape measurement by combining binary statistical pattern matching with phase-shifting methods," *Appl. Opt.* **56**, 5418–5426 (Jul 2017).

[9] Cofaru, C., Philips, W., and Paepegem, W. V., "Pixel-level robust digital image correlation," *Opt. Express* **21**, 29979–29999 (Dec 2013).

[10] Shao, X., Dai, X., and He, X., "Noise robustness and parallel computation of the inverse compositional gauss–newton algorithm in digital image correlation," *Optics and Lasers in Engineering* **71**, 9–19 (2015).

[11] Pan, B., Li, K., and Tong, W., "Fast, robust and accurate digital image correlation calculation without redundant computations.," *Exp. Mech.* **53**, 1277–1289 (2013).

[12] Gao, Y., Cheng, T., Su, Y., Xu, X., Zhang, Y., and Zhang, Q., "High-efficiency and high-accuracy digital image correlation for three-dimensional measurement," *Optics and Lasers in Engineering* **65**, 73–80 (2015). Special Issue on Digital Image Correlation.

[13] Shao, X., Dai, X., Chen, Z., and He, X., "Real-time 3d digital image correlation method and its application in human pulse monitoring," *Appl. Opt.* **55**, 696–704 (Feb 2016).

[14] Zhang, S. and Huang, P. S., "Novel method for structured light system calibration," *Optical Engineering* **45**(8), 1 – 8 (2006).