High Dynamic Range Scanning Technique

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ABSTRACT

Measuring objects with high surface reflectivity variations (i.e., high dynamic range) is challenging for any optical method. This paper addresses a high dynamic range scanning (HDRS) technique that can measure this type of objects. It takes advantage of one merit of a phase-shifting algorithm: pixel-by-pixel phase retrieval. For each measurement, multiple shots of fringe images with different exposures are taken. And a sequence of fringe images with different overall brightness are captured: the brightest fringe images have good fringe quality for darker areas although the brighter areas may be saturated; while the darkest fringe images have good fringe quality in brighter areas although the fringes in the darker areas may be invisible. The sequence of fringe images is arranged from brighter to darker, i.e., from higher exposure to lower exposure. The final fringe images, used for phase retrieval, are produced pixel-by-pixel by choosing the brightest but the unsaturated corresponding pixel from one shot. A phase-shifting algorithm is employed to compute the phase, which can be further converted to coordinates. Our experiments demonstrate that the proposed technique can successfully measure objects with high dynamic range of surface properties.

Keywords: Shiny surface; specular surface; three-dimensional measurement; range scanning; phase-shifting; high-dynamic range.

1. INTRODUCTION

Measuring objects with large surface reflectivity variations, such as shiny objects or surface with high-contrast, is crucial for diverse applications including manufacturing, biomedical imaging, and entertainment. However, because the optical signal cannot be properly retrieved, it is usually very difficult for a optical method to accurately measure this type of objects.

Acquiring three-dimensional (3D) information of objects is very important. In general, 3D shape measurement techniques can be classified into two categories: surface contact and surface non-contact. Coordinate measuring machine(CMM) is a typical system that uses surface contact method for 3D shape measurement method. CMM can almost accurately measure any type of objects with various scales. Because of its surface contact measurement nature, this technique is not sensitive to the surface optical properties. However, because it is a point-by-point measurement method, the measurement speed very slow. Moreover, it requires surface contact, and thus is very difficult to measure soft objects.

On the contrast, the surface non-contact 3D shape measurement methods can be used to measure soft objects. Among the surface non-contact 3D shape measurement techniques, optical methods are widely used. The optical methods include laser range scanning, stereo vision, and structured light methods. Although they have many advantages over CMM, the optical methods suffer if the object does not have good surface optical properties. The optical methods usually require the surface to be diffuse and with low reflectivity variations from point to point. Therefore, if the object surface is specular (shiny) or with very large reflectivity variations, it is very challenging for any optical method to perform the measurement.

A variety of optical methods have been proposed to deal with shiny surfaces.[1–3] All these proposed methods are able to alleviate the errors due to surface specular properties to a various degree. However, the method introduced in[1] uses polarizers, which drastically reduces the output light intensity of projector and the incoming light of the camera, which may make it difficult to measure darker objects. The method proposed by Hu et al. [2] requires find the corresponding specular areas on the projected fringe image, which usually involves a complicated time-consuming procedure. Moreover, this method also involves a difficult and complicated registration issues for the area measured from two viewing angles. The template based approach using feature extraction[3] suffers if the object does not have strong features or the features are

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too complicated to track. On the other hand, shiny surfaces typically have good optical properties across the surfaces, thus relatively easier to measure. However, for objects with very high dynamic range of surface reflectivity, all these proposed methods will be potentially problematic.

This paper addresses a high dynamic range scanning (HDRS) technique to measure this type of objects. This method takes advantage of one merit of a phase-shifting algorithm: pixel-by-pixel phase retrieval. For each measurement, multiple shots of fringe images with different exposures are taken. And a sequence of fringe images with different overall brightness are captured: the brightest fringe images have good fringe quality in darker areas, although the brighter areas might be saturated; and the darkest ones have good fringe quality in brighter area although the fringes in the darker area may be invisible. The sequence of fringe images is arranged from bright to dark, i.e., from higher exposure to lower exposure. The final fringe images, used for phase retrieval, are produced pixel-by-pixel by choosing the brightest but unsaturated corresponding pixel from one shot. A phase-shifting algorithm is employed to compute the phase which can be further converted to 3D coordinates.

The proposed method was implemented and tested in our previously developed 3D shape measurement system. Because this method does not require the change of the relative position between the system and the object, the measurement can be done rapidly, and the computation cost does not increase significantly. Moreover, since this method only requires take more images with different exposures, it does not increase the cost of the hardware system. The exposure time can be controlled by software (controlling the exposure time of the camera) or by hand (adjusting the aperture of the camera lens). Our experiments demonstrate that the proposed technique can successfully measure objects with high dynamic range of surface properties. The same approach can also be used to measure shiny/specular objects, since these objects also have larger surface surfaces reflectivity variations.

Section 2 explains the principles of the proposed method. Section 3 describes the hardware system. Section 4 shows some experimental results. Section 5 discusses the advantages and the disadvantages of the proposed approach, and Sec. 6 summarizes the paper.

2. PRINCIPLE

Phase-shifting algorithms are widely adopted in optical metrology due to its measurement speed and non-surface-contact nature.[4] There are a variety of phase shifting algorithms have been developed, including three-step, four step, double three-step, etc. One of the advantages of a phase shifting algorithm is its point-by-point computation, hence, the measurement can be done point-by-point. This proposed method takes full advantage of this merit: retrieving the phase value of different pixel from different shot of fringe images. Therefore, for phase computation, the saturated pixels in a higher exposure are replaced by the corresponding pixels in a lower exposure, while the rest pixels remain unaltered.

2.1 Three-step phase-shifting algorithm

In this research, a three-step phase-shifting algorithm is used. The fringe image intensities with a phase-shift of $2\pi/3$ are written as,

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

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

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

where $I'(x,y)$ is the average intensity, $I''(x,y)$ the intensity modulation, and $\phi(x,y)$ the phase to be solved for. Solving previous three equations simultaneously, we can obtain the phase $\phi(x,y)$,

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

and the intensity modulation $\gamma(x,y)$,

$$\gamma(x,y) = \frac{\sqrt{3(I_1 - I_3)^2 + (2I_2 - I_1 - I_3)^2}}{I_1 + I_2 + I_3}, \quad (5)$$

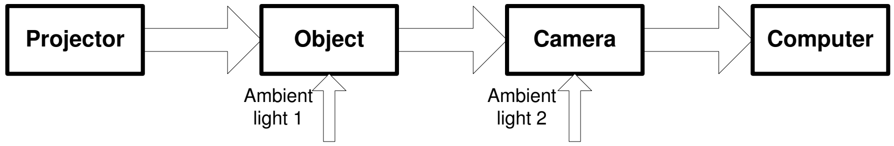


Fig. 1. The procedures of fringe image formation.

where $\gamma(x,y)$ is the intensity modulation, which indicates the quality of the point, with 1 being the best. 3D information is carried on by the phase $\phi(x,y)$. The value of phase $\phi(x,y)$ obtained from Eq. (4) ranges from $-\pi$ to $+\pi$. If multiple fringes are used, a phase unwrapping algorithm[5] is required to obtain a continuous phase map, which can be further converted to 3D coordinates once the system is calibrated.[6]

2.2 Fringe image analysis

For the object with large range of surface reflectivity (r) variations, some points have very low reflectivity values: $r \to 0$, while other points have large values $r \to \infty$, such as shiny areas. As shown in Fig. 1, the captured fringe images are formed through the following procedures:

1. *Fringe projection*. The computer generated fringe images are projected through a projector onto the object. The output light is the projected fringe images by the projector.
2. *Fringe reflection*. The projected fringe images are distorted and reflected by the object point by point. The reflected light includes that comes from the projector as well as the ambient light 1 ($a_1(x,y)$).
3. *Fringe acquisition*. The camera captures the distorted fringe images point by point. The captured light includes the light reflected by the object as well as the ambient light 2 ($a_2(x,y)$)entering directly into the camera.

Assume a projected fringe image is

$$I^p(x,y) = b + a\cos(x,y).$$

The image is reflected by the object with reflectivity of $r(x,y)$ and the ambient light of $a_1(x,y)$, the reflected image therefore has intensity of

$$I^o(x,y) = r(x,y)[b + a\cos(x,y) + a_1(x,y)].$$

The reflected image is then captured by the camera. Assume the ambient light entering directly to the camera is $a_2(x,y)$, and the camera sensitivity is α. Therefore, the fringe image actually captured by the camera is

$$I(x,y) = \alpha\{r(x,y)[b + a\cos(x,y) + a_1(x,y)] + a_2(x,y)\}. \tag{6}$$

For this fringe image, the data modulation is

$$I''(x,y) = \alpha r(x,y)a, \tag{7}$$

the average intensity is

$$I'(x,y) = \alpha r(x,y)[a_1(x,y) + b] + \alpha a_2(x,y), \tag{8}$$

and the intensity modulation is

$$\gamma(x,y) = \frac{I''(x,y)}{I'(x,y)} = \frac{r(x,y)a}{r(x,y)[a_1(x,y) + b] + a_2(x,y)} \tag{9}$$

From Eq. (7), if the surface reflectivity is small (i.e., $r(x,y)$ is small), in order to obtain large data modulation value, camera sensitivity value, α, has to be a large value. That is, in order to obtain good fringe images, it can increase the camera exposure time or aperture. However, the quality of data is determined by the intensity modulation $\gamma(x,y)$. To achieve high-quality measurement, $\gamma(x,y)$ must be close to 1. From Eq.(9), in order to have good fringe contrast, the ambient light, $a_2(x,y)$, entering directly to the camera has to be negligible. If reflectivity value is large, i.e., $r(x,y)$ is sufficient large, $a_2(x,y)$ is relative small and can be neglected. This is the case for shiny objects when $r(x,y)$ is always large, measuring them only requires to adjust the camera sensitivity. However, for very small value of $r(x,y)$, ambient light will play an important role, where the measurement environment requires to be *dark* to eliminate the effect of ambient light.

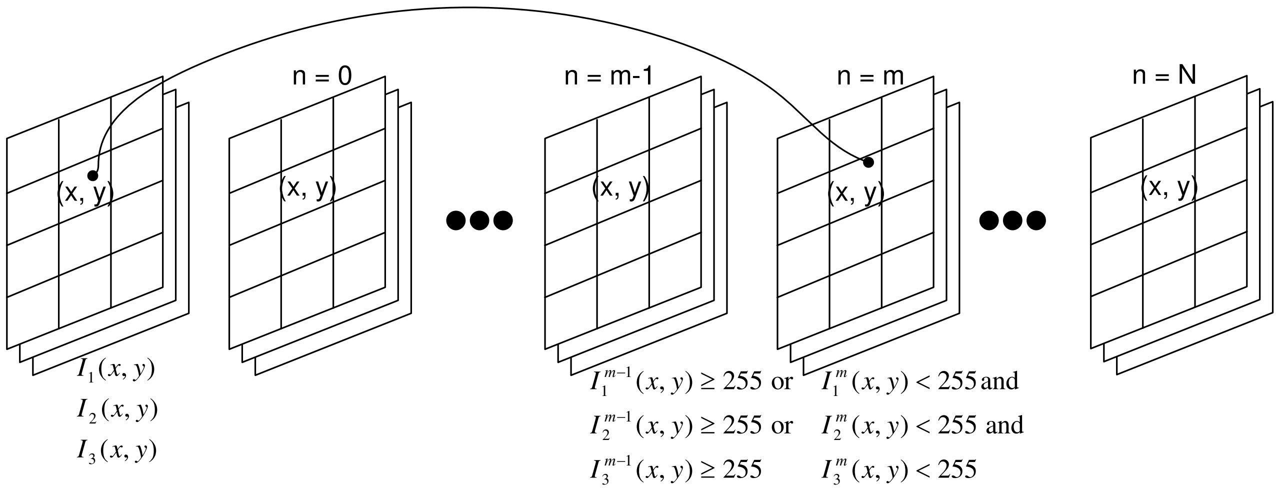


Fig. 2. The formation of each fringe image pixel from a sequence of fringe images with different exposures.

2.3 Multi-exposure principle

For any phase-shifting algorithms, in order to measure 3D objects with high quality, the acquired fringe images must have good quality of fringes (larger signal to noise ratio (SNR)). From the analysis in Subsec. 2.2, for an object with high surface reflectivity (i.e., large $r(x,y)$) and small range of variations, it is very easy to be measured with high quality. However, it is very challenging to measure an object with some areas having very low surface reflectivity and some areas having very high surface reflectivity. This research will address a novel multi-exposure method to measure this type of objects, this technique is called high dynamic range scanning (HDRS).

For the multi-exposure technique, a sequence of fringe images ($I_k^n(x,y)$, with $k = 1,2,3$ and $n = 1,2,3,...,N$) are acquired for the measurement. For each set n, three fringe images with a phase-shift of $2\pi/3$ are captured under the same exposure. In other words, each set of fringe images can be used to independently reconstruct 3D shape for good points. Assume the brightness of the fringe image sets decreases from one exposure to the next, i.e.,

$$I_k^n(x,y) >= I_k^{(n+1)}(x,y),$$

then the final fringe images used for 3D measurement are,

$$I_k^f(x,y) = I_k^m(x,y), m = \min(n), \quad (10)$$

with $I_1^m < 255, I_2^m < 255$, and $I_3^m < 255$, while $I_1^{m-1} \geq 255$, or $I_2^{m-1} \geq 255$, or $I_3^{m-1} \geq 255$. Here, $m = \min(n)$ is the minimum function of n. That is, each pixel of the fringe images is generated by selecting the brightest but unsaturated corresponding pixel from one set of fringe images, namely,

$$I_1^f(x,y) = \max\{I_1^n(x,y)|I_1(x,y) < 255, I_2(x,y) < 255, I_3(x,y) < 255\}, \quad (11)$$

$$I_2^f(x,y) = \max\{I_2^n(x,y)|I_1(x,y) < 255, I_2(x,y) < 255, I_3(x,y) < 255\}, \quad (12)$$

$$I_3^f(x,y) = \max\{I_3^n(x,y)|I_1(x,y) < 255, I_2(x,y) < 255, I_3(x,y) < 255\}. \quad (13)$$

Figure 2 illustrates how to form the final fringe images pixel by pixel. For an arbitrary point on the image, its intensity values of three fringe images use the of exposure m, so that all intensity values of this pixel are not saturated while the same pixel of the previous set images with higher exposure is saturated for at least one fringe image.

Since the phase-shifting algorithm computes the phase point-by-point, the fringe images obtained in Eq. (10) can be substituted into Eq. (4) to obtain the phase pixel-by-pixel that can be further converted into 3D coordinates.

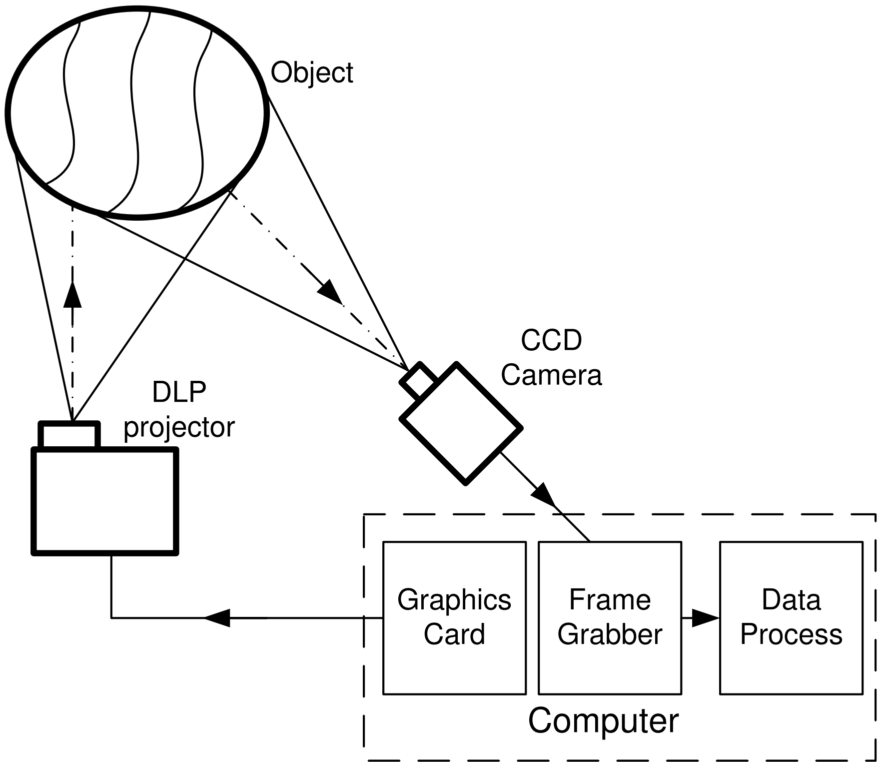


Fig. 3. System setup.

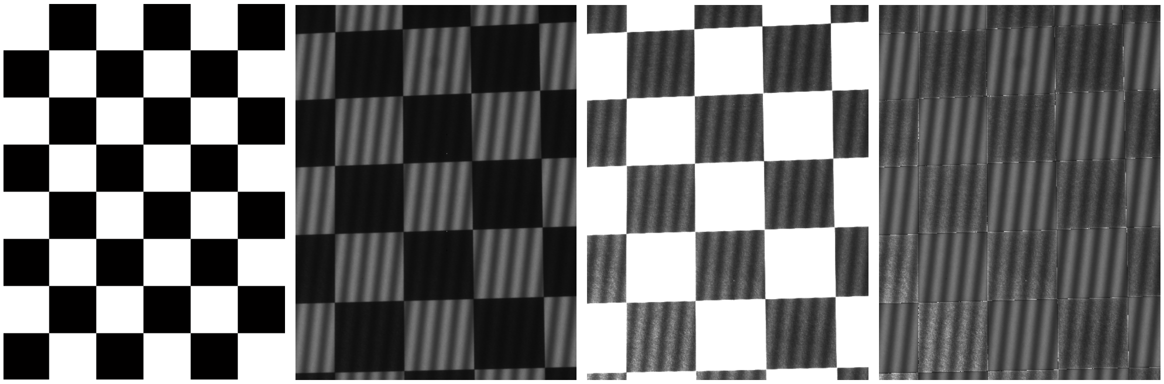
3. SYSTEM SETUP

In this research, we developed a 3D shape measurement system based on a digital fringe projection and phase-shifting method. As shown in Fig 3, computer graphics card send fringe image signals to a digital-light-processing (DLP) projector that projects them onto the object. The fringe images were reflected and sensed by a charge-coupled device (CCD) camera that were further converted to digital images by a frame grabber. In this research, the DLP projector used is PLUS U5-632h with a resolution of 1024×768, the camera is Jai Pulnix TM-6740CL with a resolution of 640×480 at a frame rate up to 200 frames/sec., the camera lens is Fujinon HF25SA-1 with a focal length of 25mm, and the frame grabber is Matrox Solios XCL that has a camera link interface. The digital fringe images acquired by the camera are then processed to retrieve the phase using a phase-shifting algorithm. The phase is further converted to 3D coordinates using the calibrated system parameters. The system was calibrated using our previous proposed method.[6]

4. EXPERIMENTS

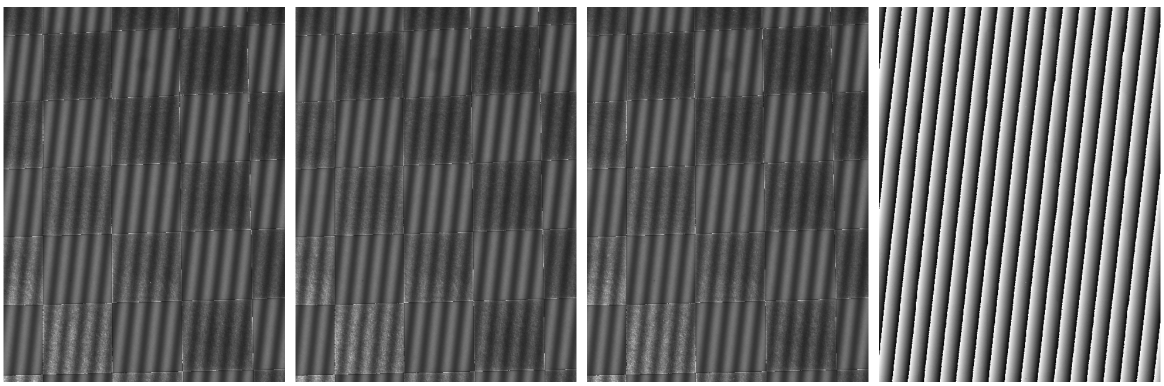
To verify the performance of the system, we measured a B/W checkerboard use the hardware system. The B/W checkerboard with pure black and white squares was printed using a B/W laser printer onto a fine paper, and then was glue onto a flat surface (a piece of glass). Figure 4(a) shows the B/W checkerboard. It is very easy to understand that such a checkerboard is very difficult to measure with a single exposure, because the contrast between the black and white squares are very large, albeit its surface is diffuse. Figure 4(b) shows that when the white checkers have good fringes, the fringes on those black ones are almost invisible. Figure 4(c) shows that the black checkers have good fringes while the white checkers are saturated. Hence, neither exposure is sufficient to correctly measure the whole surface. On the other hand, if the white areas use fringe pixels as shown in Fig. 4(b), and black areas use fringe pixels in Fig. 4(c). The whole surface can be measured.

Figure 5 shows the measurement result of the checkerboard. Figures 5(a)-5(c) shows three fringe images by combining these two exposure fringe images. Figures 5(d) shows the wrapped phase map. Although the fringe images are not seemingly regular fringe images, the phase map is very natural. Therefore, the measurement can be performed with good

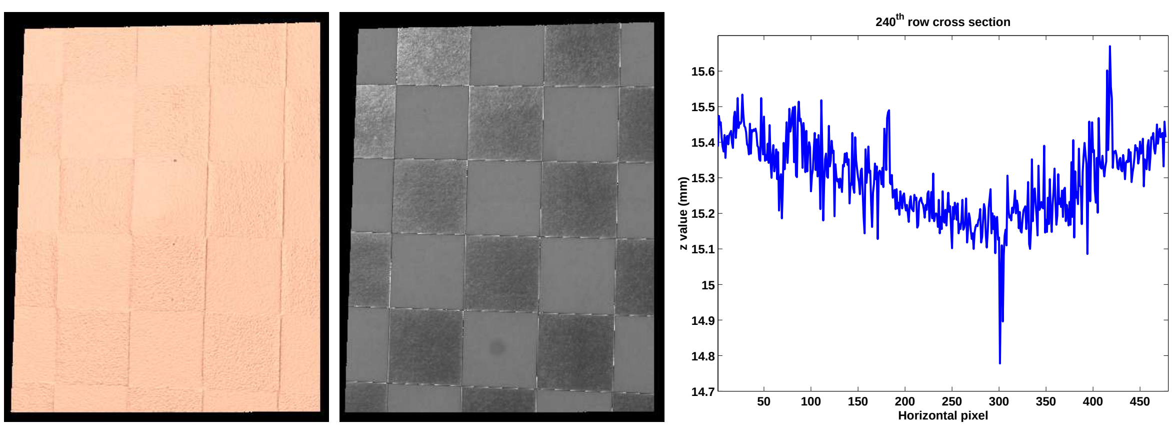


(a) (b) (c) (d)

Fig. 4. Fringe image formation of the checkerboard object. (a) The B/W checkerboard; (b) One fringe image with the white checker squares well illuminated. (b) One fringe image with the black checker squares well illuminated.



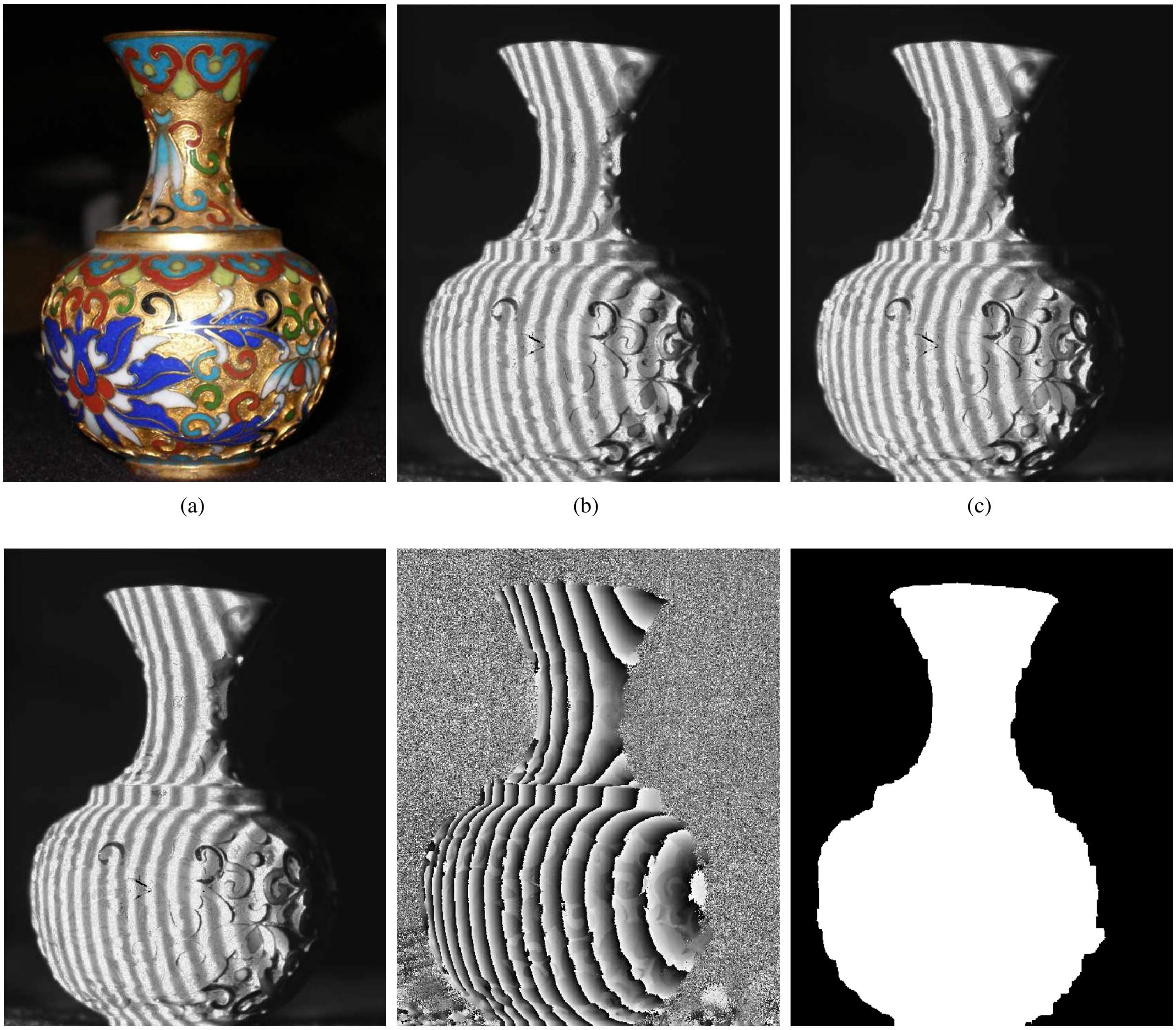
(a) (b) (c) (d)



(e) (f) (g)

Fig. 5. Experimental results of a shining object. (a)-(c) Three fringe images with a phase shift of $2\pi/3$; (d) The wrapped phase; (e) 3D reconstructed result rendered in shaded mode; (f)3D result with texture mapping; (g) Cross section plot of the 320-th row.

quality. Figure 5(e) shows the measurement result rendered in 3D shaded mode, while Fig. 5(f) shows the measurement result with texture mapping. It can be seen here that the checker squares are still clearly seen but the geometry are well captured. Figure 5(g) shows one cross section of the measurement, from which we can see that between the boundary of the black and white checker squares, the noises are larger, we do not know the cause of this phenomenon. It might be induced by the sampling of the camera in these transition areas. This example demonstrated that the proposed approach is



(a) (b) (c) (d) (e) (f)

Fig. 6. Experimental results of the vase. (a) Color photograph of the vase; (b) Fringe image I_1 $(-2\pi/3)$; (c) Fringe image I_2 (0); (d) Fringe image I_3 $(+2\pi/3)$; (e) The wrapped phase map; (e) The mask used to remove the background.

able to measure high contrast object with two exposures.

Moreover, we measured a more complex object, china vase, which has high dynamic range surface reflectivity variations. Figure 6 shows the measurement result. Figure 7(a) shows the color photograph of the measured object taken by a digital camera. Unlike the checkerboard shown in previous example, this object has larger surface reflectivity variation range, thus, two exposures are not sufficient. We used 23 exposures in order to obtain high-quality data. Figures 7(b)-6(d) show the resultant fringe images, Figure 6(e) shows the wrapped phase map, and Fig. 6(f) shows the mask used to remove the background.

Figure 7 shows the 3D result of the vase shown in Fig. 6, which is rendered in different modes. It can be seen that the small size of rings (approximately 1mm width) are well captured and details of the objects are properly measured. It should be noted that the results shown in this figure are all smoothed by a 3×3 Gaussian filter to remove the most significant random noises. This experiment demonstrated that the proposed method can successfully measure object with large dynamic surface reflectivity.

(a) (b) (c)

Fig. 7. Measurement result of the vase (size of the vase is approximately 75mm in height and 50mm in width). (a) Draw in wireframe mode; (d) Rendered in shaded mode, the details of the vase rings are well captured; (e) Zoom-in view of a mall region (ring width is approximately 1mm).

5. DISCUSSION

From the experimental results shown previously, it can be seen that the advantages of the proposed method are obvious:

- *Low cost*. This method does not requires the use of additional hardware. It only needs to adjust the exposure of the camera. Therefore, no additional cost of the hardware is necessary.
- *Simple*. The whole area can be measured once without changing the relative position of the object and the system, hence, no sophisticated registration and merging algorithms are required.
- *Fast*. In our case, for simple example as the checkerboard, only two exposures are needed. For an object with significantly large dynamic range of surface reflectivity variations, more exposures are needed to measure every level of the reflectivity areas. For the vase example, 23 exposures are need. However, since all the operations can be done automatically, adjusting the aperture or controlling the exposure time, the measurement can be done rapidly.
- *Generic*. The proposed method theoretically works for any surface reflectivity variations. The larger dynamic range the object has, the more exposures needed. Of course, the more exposure used, the better the result will be, although the slower the measurement process is.

In the meantime, because a phase-shifting algorithm is less sensitive to ambient light, it is less sensitive to surface reflectivity variations. Therefore, the phase shifting algorithm is robust to measure object with certain range of surface reflectivity variations. However, for large surface reflectivity variations, the signal-to-noise ratio (SNR) is very small for low reflectivity areas, the quality of measurement is hard to be ensured, where the ambient light requires be controlled to be at a very low level. Therefore, theoretically, the proposed method can be used to measure any object with any dynamic range of surface reflectivity.

6. SUMMARY

In summary, this paper has presented a novel method to measure specular surfaces. It utilizes a multi-exposure, phase-shifting method. For this method, a sequence of fringe images with different exposures are taken. For each exposure, a number of phase-shifted fringe images, required to retrieve the phase, are taken. We changed the exposure by adjusting the aperture of the camera lens which is similar to controlling the exposure time of the camera. The brightness of the fringe images ranges from bright to dark, so that the brightest fringe images are overall well illuminated although a large area of pixels are saturated. On the contrast, the darkest fringe images do not have any pixel saturated although most of areas of the fringes might not be visible. The final fringe images, used for 3D reconstruction, are formed by choosing the brightest but unsaturated corresponding pixel from the fringe image sequence. For this method, the saturated pixels in the higher exposure are covered by the corresponding pixels of the lower exposures. Therefore, measuring the bright area properly does not affect the rest areas. We implemented the proposed method into a 3D shape measurement system. Our experiments verified that the proposed method can be used to measure the objects with high surface reflectivity variations. It should be noted that a three-step phase-shifting algorithm is used for this research, but the proposed method is not limited to this algorithm, and any phase-shifting algorithms can be used.

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