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# Simultaneous geometry and color texture acquisition using a single-chip color camera

## Abstract

Capturing 3-D geometry and the perfectly aligned color texture simultaneously is crucial for diverse fields including entertainment, target recognition, and computer graphics. However, it is very challenging for a conventional technique because of a number of problems related to color. Previous researchers rely heavily on using two cameras: a black-and-white (B/W) camera to measure the geometry, and a color camera to capture the color texture. However, aligning the color image with the 3-D geometry point by point remains difficult. In this research, we propose a novel technique that uses a single-chip color camera to capture both geometry and color texture simultaneously. A projector projects B/W fringe patterns onto the object, and a color camera captures the raw fringe images with Bayer mosaic patterns. A phase-shifting algorithm is used for our system because of one of its merits: retrieving phase pixel-by-pixel. Therefore, the intensity variations between neighboring pixels do not significantly affect the measurement. Moreover, the same set of fringe images is also used to calculate the B/W texture image, which is further converted into a color image using a demosaicing algorithm. Therefore, the same set of fringe images are used to generate the 3-D geometry as well as the color texture image simultaneously. A hardware system was developed to verify the performance of the proposed technique. Experiments demonstrated that this technique can successfully measure both geometry and color texture of the color objects.

## Keywords

3-D shape measurement, phase-shifting, color texture, Bayer-filter, scanner, mosaic, demosaicing

## Disciplines

Computer-Aided Engineering and Design | Graphics and Human Computer Interfaces

## Comments

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# Simultaneous geometry and color texture acquisition using a single-chip color camera

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## ABSTRACT

Capturing 3-D geometry and the perfectly aligned color texture simultaneously is crucial for diverse fields including entertainment, target recognition, and computer graphics. However, it is very challenging for a conventional technique because of a number of problems related to color. Previous researchers rely heavily on using two cameras: a black-and-white(B/W) camera to measure the geometry, and a color camera to capture the color texture. However, aligning the color image with the 3-D geometry point by point remains difficult. In this research, we propose a novel technique that uses a single-chip color camera to capture both geometry and color texture simultaneously. A projector projects B/W fringe patterns onto the object, and a color camera captures the raw fringe images with Bayer mosaic patterns. A phase-shifting algorithm is used for our system because of one of its merits: retrieving phase pixel-by-pixel. Therefore, the intensity variations between neighboring pixels do not significantly affect the measurement. Moreover, the same set of fringe images is also used to calculate the B/W texture image, which is further converted into a color image using a demosaicing algorithm. Therefore, the same set of fringe images are used to generate the 3-D geometry as well as the color texture image simultaneously. A hardware system was developed to verify the performance of the proposed technique. Experiments demonstrated that this technique can successfully measure both geometry and color texture of the color objects.

**Keywords:** 3-D shape measurement; phase-shifting; color texture; Bayer filter; scanner; mosaic; demosaicing.

## 1. INTRODUCTION

3-D range scanning technique is increasingly expanding its applications to a variety of fields. In the conventional optical metrology field, obtaining the geometric shape information is the major concern, thus the measurement accuracy plays a key role, and not many people pay much attention to the texture, the photograph of the object surface. However, with the application of the 3-D range scanning extends to other areas, such as entertainment, medical imaging, target recognition, etc, the texture, especially color texture, becomes increasingly important. For example, in medical imaging field, the color texture also conveys vital information for medical diagnosis. However, simultaneously obtaining the perfectly aligned high-quality color texture with 3-D geometry remains challenging.

Over the past decades, a number of 3-D shape measurement systems using color have been developed.<sup>1-5</sup> All these methods could successfully measure objects without significant surface color variations. Their accuracies are affected, to a various degree, by the object surface color. A number of problems caused by using color, among which probably the most significantly one is the color coupling problem, i.e., the red and green, and the green and blue spectra are overlapping with each other. The color coupling problem is very difficult to be avoided, and significantly affects the measurement accuracy.<sup>6</sup> Besides, using color fringe images may not measure the surface profile properly. For example, for a red object, the green and blue light will be absorbed, the information carried on by these color channels will be lost. Therefore, for a structured light system, to measure object's 3-D geometry correctly, a black-and-white (B/W) camera and the white light is normally used.

However, if only a single B/W camera is used, the color information cannot be acquired simultaneously. Thus, previous researchers rely on using two cameras to measure color objects: a B/W camera is used to acquire the 3-D shape information, and a color camera is used to capture the color texture information.<sup>7-9</sup> However, using another color camera involves complicated registration problem. The registration is to establish a one-to-one mapping between the color camera image

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and the B/W camera image. It is usually very difficult without the assistance of an additional hardware component. For example, Zhang and Huang used a beam splitter in their system.<sup>10</sup> By adding a beam splitter, the registration problem is simplified since, theoretically, both cameras are viewing the same scene. However, aligning two camera pixel-by-pixel precisely is still very challenging.

In this research, we propose a method that utilizes a single-chip color camera to capture the 3-D geometry and the color texture simultaneously. The color camera has a single imaging sensor using a Bayer mosaic filter. Bayer mosaic filter is broadly employed to generate color images for the single-chip imaging devices, such as digital cameras and video cameras. The raw image acquired by such a sensor has a pixel-by-pixel grayscale value, with each pixel represents one of three primary colors (RGB). The raw mosaic image can be converted to color by employing a demosaicing algorithm, which will be discussed in detail in Subsec. 2.1.

For our system, a digital-light-processing (DLP) projector is used to project the computer generated B/W fringe images onto the object, and a single-chip color camera is used to acquire the scattered fringe images in raw format with Bayer mosaic patterns. A phase-shifting algorithm is used because of one of its merits: pixel-by-pixel measurement. For a raw image with Bayer mosaic patterns, a  $2 \times 2$  grid represents a color pixel. Each pixel only represents one of the three primary color components. The raw image of a color object may have significant intensity variations in this  $2 \times 2$  grid. Therefore, if the 3-D measurement technique requires the image to be smooth locally, it is very difficult to use such a camera to perform the measurement. A phase-shifting algorithm, on the other hand, does not have such a requirement, because it retrieves the phase pixel by pixel. Therefore, the grid pixel intensity variations will not significantly affect the measurement. Moreover, the same set of fringe images can also be used to generate a B/W texture image with Bayer mosaic patterns, which can be converted to color image using a demosaicing algorithm. Therefore, the same set of fringe images can simultaneously retrieve the 3-D geometry and the color information. Experiments are presented to verify the performance of this technique.

Section 2 introduces the principle of the system. Section 3 describes the hardware system. Section 4 shows some experimental results. Section 5 discusses the advantages and shortcomings of the proposed method, and Sec. 6 summarizes this paper.

## 2. PRINCIPLE

### 2.1 Bayer filter

A Bayer mosaic filter is a color filter array for arranging red, green, and blue (RGB) color filters on a square grid of photosensors. The term derives from the name of its inventor, Dr. Bryce E. Bayer of Eastman Kodak, and refers to a particular arrangement of color filters used in most single-chip digital image sensors used in digital cameras, camcorders, and scanners to create a color image. The filter pattern is 50% green, 25% red and 25% blue, hence is also called RGBG or GRGB.<sup>11</sup>

Figure 1 shows the diagram of a Bayer filter. The filter layer is mounted on top of the imaging sensor pixel-by-pixel. Only one primary color light can enter into one pixel of the image sensor to form the raw image with Bayer mosaic patterns. This raw image can be converted into a color image using a demosaicing algorithm. Various demosaicing algorithms have been developed, including simple interpolation,<sup>12</sup> adaptive approaches based on features of the area surrounding the pixel of interest,<sup>13</sup> and video super-resolution/demosaicing.<sup>14</sup>

In this research, a simple neighbor linear interpolation approach is used. For example, for a RGBG filter pattern, pixel  $(2i, 2j)$  represents red,  $(2i, 2j + 1)$  and  $(2i + 1, 2j)$  represent green, and  $(2i + 1, 2j + 1)$  represents blue. The color image can be generated using Table 1. In this table,  $I(i, j)$  is the intensity of the raw image for pixel  $(i, j)$ , and  $\alpha_r$ ,  $\alpha_g$  and  $\alpha_b$  are the coefficients used to balance three primary color channels, respectively. These coefficients are obtained from a step called *white balance*.

Table 1. Color pixel generation from a RGBG filter pattern.

Pixel	Red	Green	Blue
$(2i, 2j)$	$\alpha_r I(2i, 2j)$	$\alpha_g [I(2i + 1, 2j) + I(2i, 2j + 1)]/2$	$\alpha_b I(2i + 1, 2j + 1)$
$(2i+1, 2j)$	$\alpha_r I(2i, 2j)$	$\alpha_g I(2i + 1, 2j)$	$\alpha_b I(2i + 1, 2j + 1)$
$(2i, 2j+1)$	$\alpha_r I(2i, 2j)$	$\alpha_g I(2i, 2j + 1)$	$\alpha_b I(2i + 1, 2j + 1)$
$(2i+1, 2j+1)$	$\alpha_r I(2i, 2j)$	$\alpha_g [I(2i + 1, 2j) + I(2i, 2j + 1)]/2$	$\alpha_b I(2i + 1, 2j + 1)$

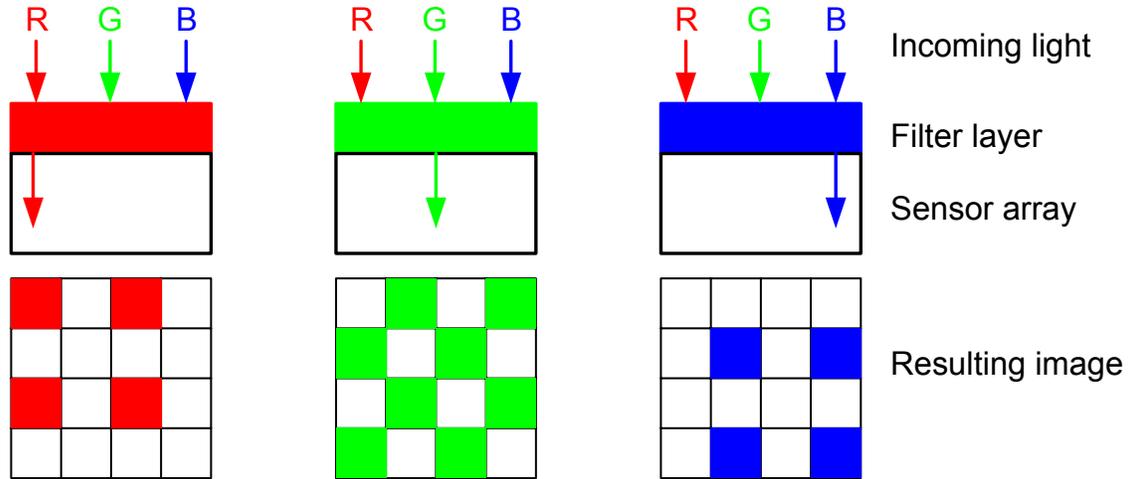


Fig. 1. Bayer filter.

## 2.2 Three-step phase-shifting algorithm

Phase-shifting algorithms are widely adopted in optical metrology because of their speed and non-surface-contact nature.<sup>15</sup> Over the years, a variety of phase shifting algorithms have been proposed, including three-step, four step, and five step. One of the advantages of a phase shifting algorithm is its point-by-point phase computation.

In this research, we used a three-step phase-shifting algorithm with a phase shift of  $2\pi/3$ . The fringe image intensities can be 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. From previous three equations, we obtain the phase  $\phi(x,y)$ ,

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

and the average intensity  $I'(x,y)$ ,

$$I'(x,y) = [I_1(x,y) + I_2(x,y) + I_3(x,y)]/3. \quad (5)$$

Here the average intensity can be used as texture since it does not contain any fringe stripes. The value of the phase  $\phi(x,y)$  in Eq. (4) ranges from  $-\pi$  to  $+\pi$ . If multiple fringe stripes are used, a phase unwrapping algorithm<sup>16</sup> is required to obtain a continuous phase map, that can be further converted into 3-D coordinates once the system is calibrated.<sup>17</sup>

## 3. SYSTEM SETUP

Figure 2 shows the layout of our system. The fringe images are generated by a computer and sent by a graphics card to a digital-light-processing (DLP) projector. A color camera viewing from another angle is used to acquire the raw fringe images scattered from the object, from which the phase can be retrieved. Finally, 3-D coordinates of the object are converted from the phase once the system is calibrated. Three phase-shifted raw fringe images acquired by the camera are used to calculate the wrapped phase map using Eq. (4), which is further processed to generate a continuous unwrapped phase map by employing a phase unwrapping algorithm.<sup>16</sup> In the meantime, the same set of fringe images can also produce a B/W texture image using Eq. (5). Because the B/W image contains the mosaic patterns, it can be converted to a color image by adopting a demosaicing algorithm. In this research, we use a very simple demosaicing algorithm as illustrated in Table 1.

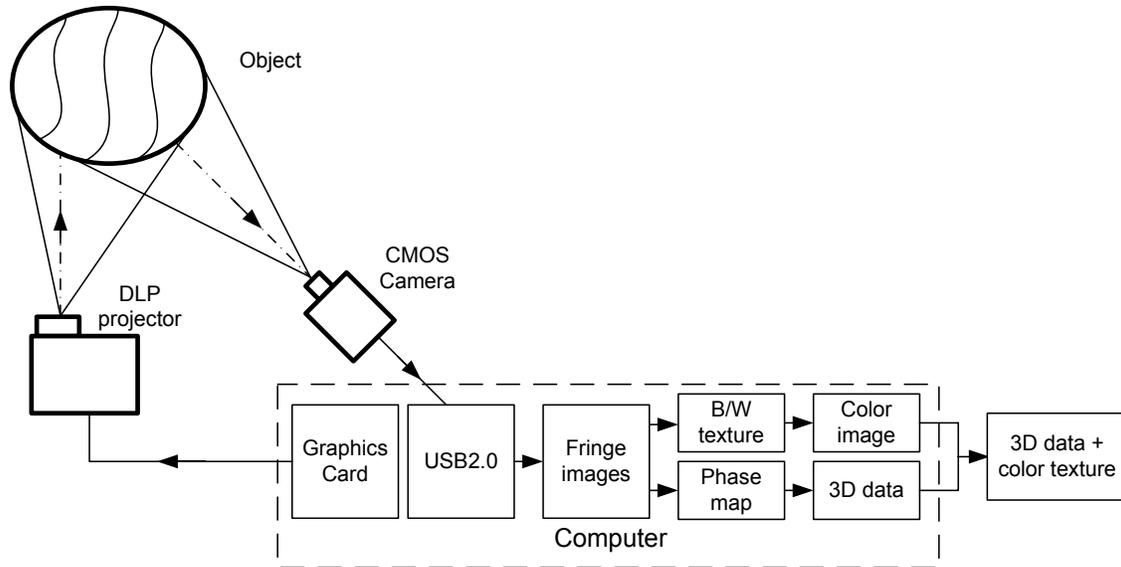


Fig. 2. Layout of the system.

The DLP projector used in this system is Optoma EP739, with a resolution of  $1024 \times 768$ ; the camera is a CMOS digital camera (Mightex MCN-C013-U) that has  $1280 \times 1024$  image resolution, 8-bit image depth, and USB2.0 interface. Its maximum speed under full resolution is 22fps. In this research, we set the camera resolution as  $640 \times 480$  for the sake of data acquisition speed (at such a resolution, the maximum data acquisition speed is 70 fps).

It should be noted that we use the projector to project B/W fringe patterns instead of color fringe patterns to avoid the problem of the interference between the object surface color and the structured light color. The B/W fringe patterns are generated by a computer by equalizing three primary color channels. They are projected by the color projector, and the output image should be B/W assuming that the projector's color channels are balanced.

#### 4. EXPERIMENTS

To verify the performance of the proposed technique, we first measured a flat checkerboard comprising of red/blue checker squares. Figure 3 shows the measurement result. Figure 3(a)-Figure 3(c) show the phase-shifted fringe images acquired by the camera. Figure 3(d) shows the wrapped phase map. Since three  $2\pi/3$  phase-shifted fringe images are used, averaging these three fringe images will give us the B/W image, that is shown in Fig. 3(e). This B/W image is then converted to be a color image using the demosaicing algorithm illustrated in Table 1. The color image is shown in Fig 3(f).

The phase shown in Fig. 3(d) is unwrapped to obtain a continuous phase map that is further converted to coordinates using the calibrated system parameters. Figure 4 shows the measurement result. Figure 4(a) shows the 3-D result rendered in shaded mode. This figure shows that the surface is smooth, as expected, albeit the object has red/blue color checker squares. The reason is that although the object surface color varies from area to area, the projected structured light is B/W, and the camera can still see good fringe images scattered from the checkerboard. Figure 4(b) shows the 3-D measurement result rendered with color texture mapping, and Fig. 4(c) shows its cross section of the object. The 3-D data are smoothed by a  $3 \times 3$  Gaussian filter to reduce the most significant random noises. This experiment demonstrated that our proposed technique can measure color object successfully.

We also measured an object with a variety of colors on its surface: a painting. Figure 5 shows the measurement results. Figures 5(a) shows the measurement result rendered in shaded mode. Figure 5(b) shows the 3-D result rendered with color texture mapping, and Fig. 5(c) shows the textured result viewing from another angle. This measurement result is also smoothed by a  $3 \times 3$  Gaussian filter to reduce the most significant random noises. This experiments shows that the proposed method can also measure the 3-D geometry and color texture simultaneously for the object with drastic surface color variations.

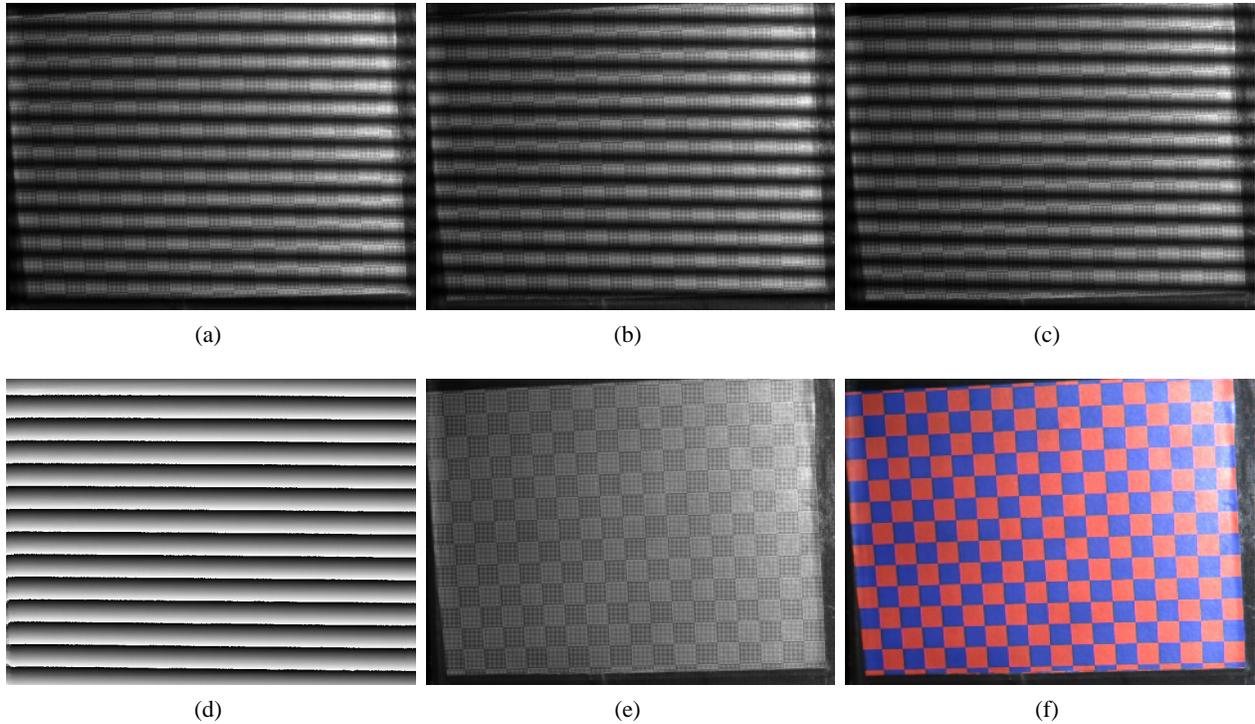


Fig. 3. Measurement result of a color object. (a)-(c) Three fringe images with a phase shift of  $2\pi/3$ ; (d) The wrapped phase map; (e) The average image of the fringe images in (a)-(c); (f) The color texture by demosaicing the image in (e).

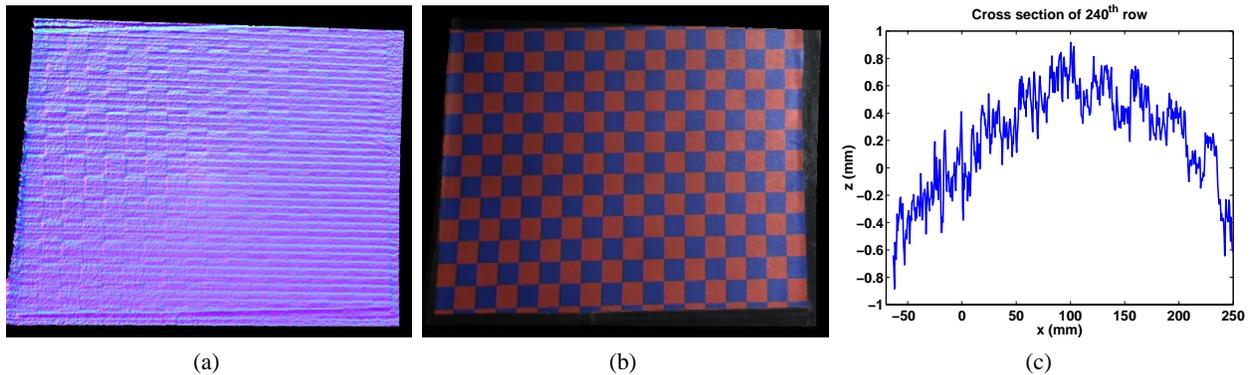


Fig. 4. Reconstruction result of the flat checkerboard shown in the previous figure. (a) 3-D data rendered in shaded mode; (b) 3-D data rendered with texture mapping; (c) 240-th row of the cross section.

Moreover, since only three fringe images are used to reconstruct the 3-D geometry, the data acquisition speed is fast. For our system, the total data acquisition time is approximately 250 ms. Therefore, it is possible to measure slowly moving object, such as a human face. Figure 6 shows the measurement result. Figure 6(a) shows the 3-D result rendered in shaded mode, from which we can see that the face is smooth without significant noises. Figure 6(b) shows the result with color texture mapping, the quality of the color texture is very good considering that it was taken under very strong projector light. Figure 6(c) shows the result rendered in wireframe mode. Since it is very difficult to let the subject hold the face still for 250 ms, the motion of the head results in some errors. The surface is smoothed by using a  $7 \times 7$  Gaussian filter to reduce the most significant random noise. This experiment demonstrated that the proposed approach can be used to measure human face with high quality. If this technique is applied to our previously developed real-time 3-D shape measurement system,<sup>10</sup> it can also do real-time 3-D shape measurement with color texture.

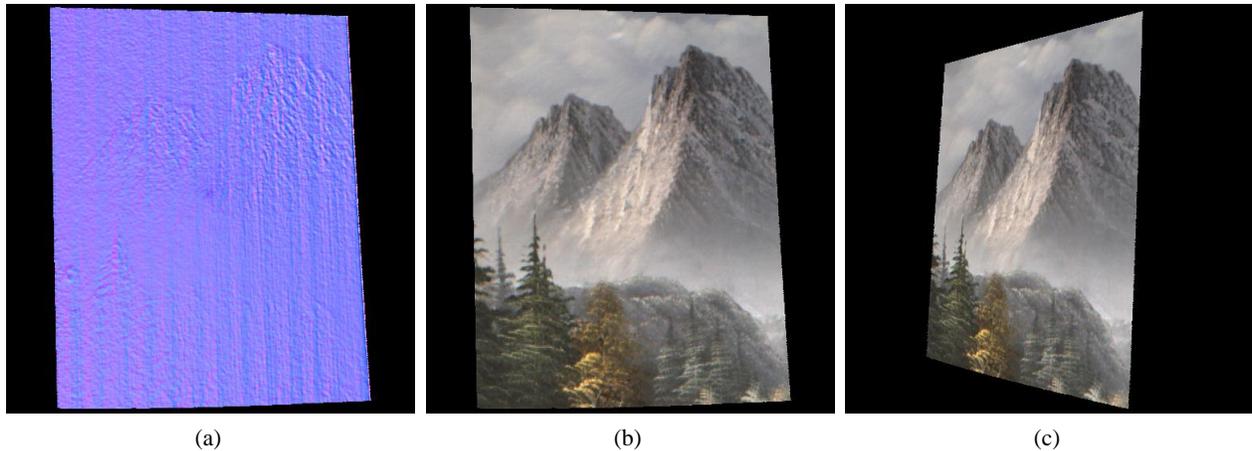


Fig. 5. Measurement result of a color paint. (a) 3-D result rendered in shaded mode; (b) 3-D result rendered with color texture image; (c) 3-D result rendered with color texture image viewing from another angle.

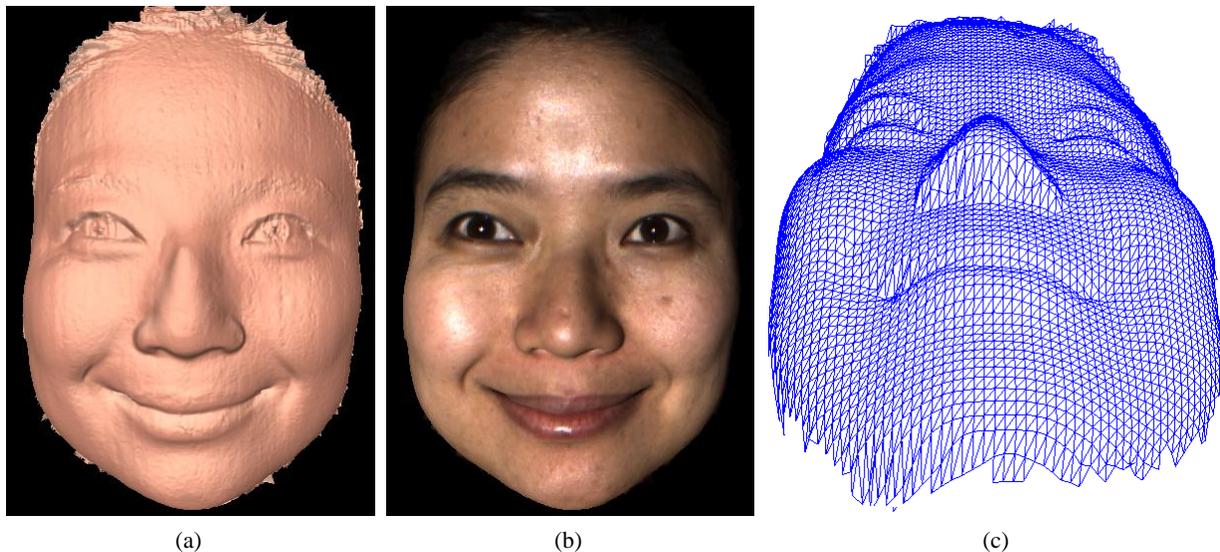


Fig. 6. Experimental result of a human face. (a) 3-D geometry rendered in shaded mode; (b) 3-D geometry rendered in with color texture mapping; (c) 3-D geometry rendered in wireframe mode.

## 5. DISCUSSIONS

As addressed above, by using a standard phase-shifting algorithm and a single-chip image sensor color camera with Bayer mosaic filters, our proposed method can acquire the 3-D geometry and color texture simultaneously. Our experiments have demonstrated that this technique can successfully measure objects with drastic surface color variations. The advantages of the proposed approach are obvious, which include

- *Simultaneous aligned geometry and color texture acquisition.* Since the color and the geometry come from the same sensor simultaneously, they are precisely aligned point by point. On the contrast, it is very difficult to achieve such a precise alignment if multiple cameras are used.
- *Less sensitive to surface color variation.* The proposed approach uses B/W fringe patterns, thus, the surface color does not significantly affect the coded structured patterns, neither does the captured fringe images. Therefore, the 3-D measurement accuracy is not affected significantly.
- *Low cost.* Camera companies usually provide the same price for the B/W camera and the color camera if the

same type of sensor (with or without Bayer mosaic filter) is used. Therefore, the cost of the system is not affected comparing with the system using a B/W camera.

- *High resolution.* Because the geometry calculation is pixel-by-pixel, the resolution of the measurement is as high as the camera resolution. However, for the color texture, as explained previously, each  $2 \times 2$  grid represents one color pixel. Therefore, the color texture resolution is 1/2 of the spatial resolution of the camera.
- *Fast speed.* Because only three fringe images are used for our measurement, this technique is also possible to be used for real-time 3-D shape measurement. If the B/W camera used in our previously developed real-time 3-D shape measurement system<sup>18</sup> is replaced with a single-chip color camera, simultaneous 3-D geometry and color texture acquisition can be reached in real time with a single high speed camera without the need of the second color camera.

The proposed technique has many advantages over the previously proposed approaches, but it also comes with its own drawbacks. From the metrology point of view, comparing with a 3-D geometric shape measurement system using a B/W camera, the proposed system has some shortcomings that include:

- *Longer exposure or brighter light.* Because only a part of the light (about 1/3 of the B/W camera) is entering into the image sensor, in order to obtain sufficient good fringe images, it requires longer exposure or brighter light source.
- *Larger local noise.* For the color camera with Bayer mosaic patterns, the response of the light differs from pixel to pixel for any  $2 \times 2$  neighboring pixels. Because each pixel has different filters mounted on the top of the imaging sensor, the projector light intensity over the white light spectrum range is not uniform, and the response of the sensor to different wavelength of light varies, it is very difficult to ensure that each color pixel has the same response to incoming light. Therefore, the signal to noise ratio varies from pixel to pixel, especially for different color pixels. Figure 7 shows the raw image of white board captured by the color camera. Figure 7(a) shows the whole image, and Fig. 7(b) shows a four pixel square of the image. It can be seen that the intensities of different pixels are different, and even are very significant for the pixels representing different color.

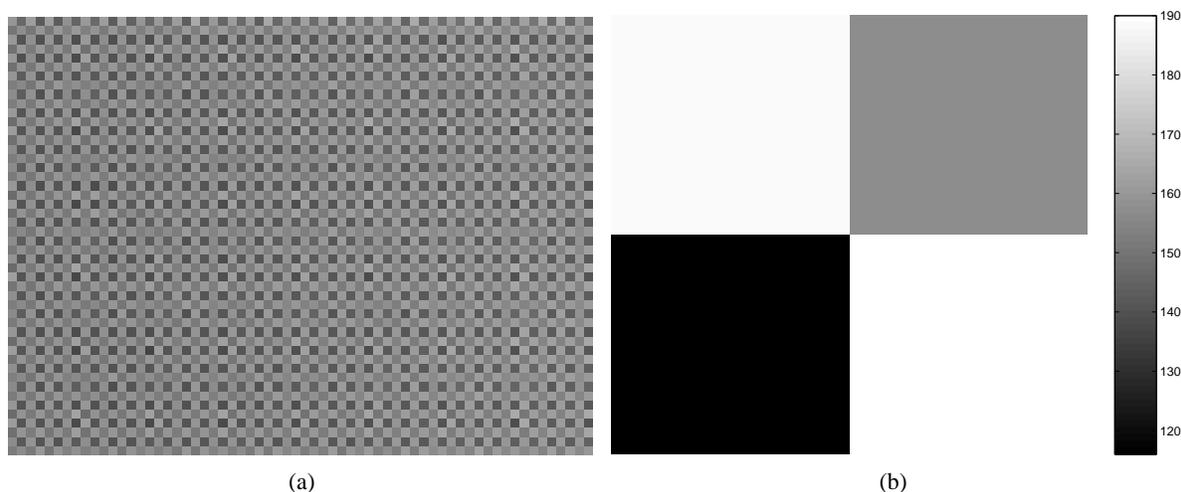


Fig. 7. Local intensity variation of the single chip color camera is larger than a B/W camera. (a) White board image captured by the color camera (this figure only shows  $64 \times 48$  pixels); (b) Local  $2 \times 2$  pixel intensity values. Here  $x$ -axis goes right,  $y$ -axis goes up.

Despite its shortcomings, the proposed technique is still very useful for many applications, especially where color texture plays an important role.

## 6. CONCLUSIONS

This paper has presented a technique that uses a single-chip color camera to capture 3-D geometry and color texture simultaneously. We used a DLP projector to project B/W phase-shifted fringe pattern, and a color camera to capture the

distorted fringe images scattered by the object. By utilizing one of the advantages of a phase-shifting algorithm, pixel-by-pixel phase retrieval, the raw fringe images with Bayer mosaic filters were used to obtain 3-D shape of the object pixel by pixel. Moreover, from the same set of fringe images, a B/W texture image was also computed, which was further converted to color texture image using a demosaicing algorithm. The advantages of this proposed method include: 1) simultaneous geometry and color texture acquisition using a single color camera and a projector; 2) the shape measurement is less sensitive to object color in comparison with previous proposed methods using color cameras; 3) the cost does not increase comparing the system using a B/W camera; 4) the resolution is high (pixel level), and 5) potentially feasible for real-time simultaneous shape and color texture measurement. However, in comparison with the system using a B/W camera, the noise is a little bit larger, and the response to the projector light is weaker. Even though, this technique is very useful for many potential applications where precisely aligned color texture and geometry is highly needed. Our experiments verified the success of this proposed technique. The applications of the proposed technique include entertainment, computer graphics, target recognition, and medical imaging and diagnosis.

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