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Simultaneous three-dimensional geometry and color texture acquisition using a single color camera

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Abstract. A novel technique that uses a single color camera to capture high-resolution three-dimensional (3-D) geometry and the perfectly aligned color texture simultaneously is discussed. A projector projects three phase-shifted black-and-white fringe patterns onto the object, and a color camera captures the fringe images reflected by the object. From these three fringe images, both 3-D shape and the color texture are obtained. Moreover, since only three fringe images are required, this proposed technique permits real-time 3-D shape measurement. Experiments are presented to demonstrate the success of this technique.
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1 Introduction

The 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, measurement accuracy plays a key role, and not many people pay much attention to the texture, the photograph of the object surface. With recent advancements of real-time 3-D shape measurement technologies, the application of 3-D range scanning extends to other areas, such as entertainment, medical imaging, target recognition, etc., and the texture, especially color texture, becomes increasingly important. For example, in the medical imaging field, the color texture also conveys vital information for diagnosis. However, simultaneously obtaining perfectly aligned, high-quality color texture with 3-D geometry remains challenging.

Our research endeavors to develop techniques for real-time 3-D shape measurement. In our recent efforts, we have developed a real-time 3-D shape measurement system that could perform simultaneous data acquisition, reconstruction, and display at 30 frames/s[1] by utilizing a fast three-step phase-shifting algorithm.[2] We recently developed techniques to do real-time 3-D absolute coordinate measurement by employing a graphics processing unit (GPU) to assist with the processing.[3,4] Over the past few years, we have been constantly requested to develop a simultaneous 3-D geometry and color texture acquisition technique for our real-time system. They all required that the color texture be precisely aligned with 3-D geometry point by point for each frame, meanwhile keeping cost increases low.

Over the past decades, a number of 3-D shape measurement systems using color have been developed.[5–9] All these methods could successfully measure objects without significant surface color variations. However, their accuracies are affected, to various degrees, by the object surface color. A number of problems caused by using color, among which probably the most significant one is the color-coupling problem, i.e., the red and green, and the green and blue spectra overlap each other. The color-coupling problem is very difficult to avoid and significantly affects measurement accuracy.[10] Zhang et al. proposed a technique to alleviate the color coupling problems of the system.[11–13] This technique utilized a 3×3 matrix to represent the color-coupling effect of the system, which was a pretty nice approach to deal with the color-coupling problem. However, calibrating the color-coupling matrix could be a complicated issue, since each pixel might have slightly different responses if the lens chromatic aberration is considered. In 2008, Zhang et al. proposed another approach to deal with color bleeding (or coupling) by projecting red, green, and blue channel fringes separately and finding which color channel to use for each point.[14] This method, to some extent, can measure color objects but requires use of 36 color fringe patterns. All the above-mentioned papers by Zhang, Towers, and Towers tried to solve the problem of measuring color and geometry simultaneously by utilizing 3-CCD color cameras. However, none of them is suitable for real-time 3-D shape measurement, since more than three fringe images are utilized to deal with color-related issues. In general, all the techniques using color fringe images suffer from the following problem: they may not measure the surface profile properly. For example, for a red object, the green and blue light will be absorbed, and the information carried on by these color fringes will be lost. Therefore, for a structured light system, to measure an object's 3-D geom-

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etry correctly, a black-and-white (B/W) camera and a white light is usually desirable. Notni et al. proposed a technique that is able to acquire 3-D geometry and color texture simultaneously by utilizing unstructured red, green, and blue light, respectively, to obtain color while projecting regular fringe images to obtain 3-D geometry.[15] However, since this technique requires more images to be projected, it is unsuitable for real-time 3-D shape measurement.

In summary, previous efforts to measure colorful objects by utilizing a single color camera either reduce measurement speed or sacrifice measurement quality drastically. In contrast, 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.[16–18] However, using another color camera involves a complicated registration problem. The registration is to establish a one-to-one mapping between the color camera image 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.[1] By adding a beam splitter, the registration problem is simplified because theoretically, both cameras are viewing the same scene. However, precise alignment of two cameras pixel-by-pixel is still very challenging.

The goals of this research are to develop a system that

1. reaches pixel-level measurement resolution,
2. acquires 3-D geometry and color texture simultaneously,
3. has the potential for implementation into our real-time system,
4. realizes precisely aligned color texture and 3-D geometry, and
5. does not significantly increase costs.

In this research, we propose a method that utilizes a single color camera to capture 3-D geometry and color texture simultaneously. A projector projects three phase-shifted B/W fringe patterns onto the object, and a color camera captures the fringe images from which the 3-D geometry can be obtained. The same set of fringe images can also be used to calculate the B/W texture image, which can be further converted to color. Therefore, three fringe images are sufficient to measure the 3-D geometry and the color texture simultaneously. Moreover, because only three fringe images are required, this technique is suitable for real-time 3-D shape measurement. The color camera used in this research has a single imaging sensor with a Bayer mosaic filter. The Bayer mosaic filter is broadly employed to generate color images for 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 representing one of three primary colors (RGB). The raw mosaic image can be converted to color by employing a demosaicing algorithm, which is discussed in detail in Sec. 2.1. Experiments are presented to demonstrate the performance of the proposed 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.

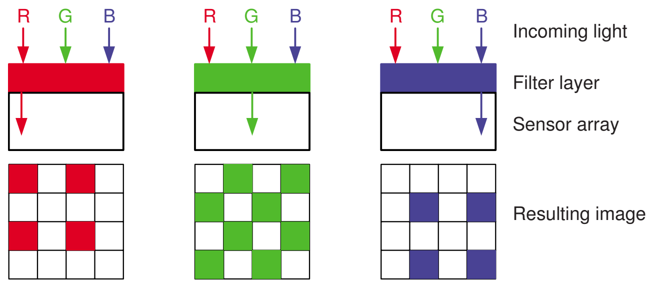


Fig. 1 Bayer filter. (Color online only.)

2 Principle

2.1 *Bayer Filter*

A Bayer mosaic filter is a color filter array for arranging RGB color filters on a square grid of photosensors. The term is derived 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 and, hence, is also called RGBG or GRGB.[19]

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,[20] adaptive approaches based on features of the area surrounding the pixel of interest,[21] and video superresolution/demosaicing.[22]

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 the pixel (i,j), and α_r, α_g,

Table 1 Color pixel generation from a RGBG filter pattern.

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

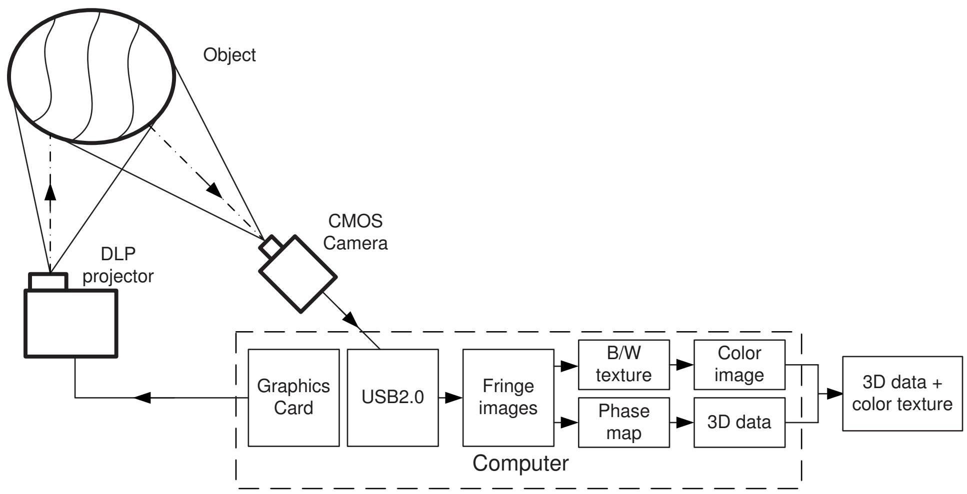


Fig. 2 Layout of the system.

and α_b are the coefficients used to balance the three primary color channels, respectively. These coefficients are obtained from a step called white balance.

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. Over the years, a variety of phase-shifting algorithms have been proposed, including three-step, four-step, and least-squares.[23] 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 the previous three equations, we obtain the phase $\phi(x,y)$,

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

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[24] is required to obtain a continuous phase map. If B/W fringe images are used, because the surface color affects each B/W fringe image in exactly the same manner and the captured fringe images used for phase calculation are also affected by the surface color to the same degree, the problem induced by the surface color for each point is avoided.

In this research we adapted the calibration approach introduced by Zhang and Huang to calibrate our system.[25] Because the camera is a color camera, the color image of the red/blue checkerboard can be acquired. Hence, unlike the system using a B/W camera, this system does not require use of a red or blue light to illuminate the checkerboard in order to obtain the regular B/W checkerboard image. For this system, the regular B/W checkerboard image can be retrieved by taking either the red or blue channel of the color image. Therefore, the calibration is simpler. Once the system is calibrated, the intrinsic and the extrinsic parameters of the system can be estimated and the absolute phase can be converted to coordinates with these calibrated system parameters. Once the system is calibrated, the phase can be used to convert the coordinates point-by-point.

In the meantime, by solving Eqs. (1)–(3) simultaneously, we can also obtain an image with the following intensity:

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

$I_{\max}(x,y)$ does not have fringe stripes and thus can be used as texture. If it is captured by a single-chip color camera (our case), the captured image will contain mosaic patterns, allowing conversion to a color image by employing a demosaicing algorithm. Because the same set of fringe images is used to obtain 3-D geometry and the color texture simultaneously, they are perfectly aligned with each other. Moreover, since the phase-shifting algorithm allows point-by-point 3-D shape measurement, we can therefore reach pixel-level resolution. In addition, since only three fringe images are utilized, this technique permits real-time 3-D shape measurement.

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 view 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

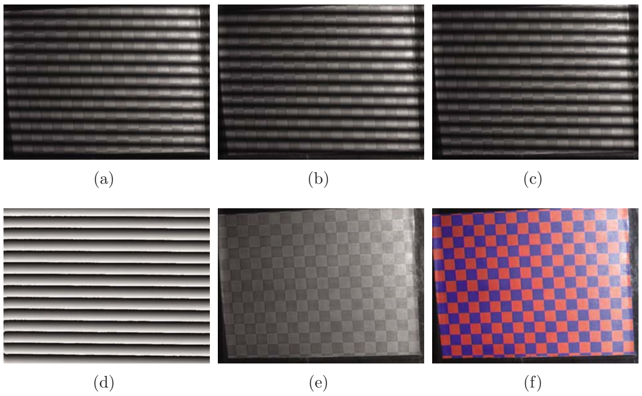


Fig. 3 Measurement result of a color object. (a)–(c) Three fringe images with a phase shift of $2\pi/3$. (d) The wrapped phase map. (e) The average image of the fringe images in (a)–(c). (f) The color texture by demosaicing the image in (e). (Color online only.)

Eq. (4), which is further processed to generate a continuous unwrapped phase map by employing a phase unwrapping algorithm.[24] 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 mosaic patterns, it is 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.

The DLP projector used in this system is Optoma EP739 with a resolution of 1024×768; the camera is a complementary metal-oxide semiconductor (CMOS) digital camera (Mightex MCN-C013-U) that has 1280×1024 image resolution, 8-bit image depth, and a USB 2.0 interface. The camera uses a roll-shuttering mechanism and exposes each line of pixels sequentially. Its maximum speed under full resolution is 22 fps. In this research we set the camera resolution as 640×480 for the sake of data acquisition speed (at such a resolution, the maximum data acquisition speed is 70 fps). We want to emphasize that that the camera we used is a CMOS camera of very low cost (only U.S. $190), and the projector is also very cheap, having a cost of only U.S. $700 in 2005. The noise of the system is much larger than that of the system using a better camera and a better projector. We use this low-cost system to verify the performance of the proposed approach. The exposure time used for data acquisition is 16.67 ms to avoid the roll-shuttering problem of the camera and the synchronization between the camera and the projector. Unlike our real-time system that switches the fringe patterns naturally by the projector, this system switches the B/W fringe images by software. Therefore, the data acquisition speed is drastically reduced.

We use a projector to project B/W fringe patterns instead of color fringe patterns to avoid the problem of interference between the object surface color and the structured light color. If the color wheel of a DLP projector is removed, as in our previous system,[1] the B/W fringe images will be projected directly. However, for an ordinary color projector, to generate the ideal B/W fringe images, the color calibration procedure is required to balance three color channels of the whole system. For this research, since precisely ideally balanced color channels are not required to successfully perform the measurement, we simply generate fringe images with R=G=B and adjust the color balance of the projector manually and visually.

4 Experiments

To verify the performance of the proposed technique, we first measured a flat checkerboard comprised of red/blue checker squares. Figure 3 shows the measurement result. Figures 3(a)–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, which is shown in Fig. 3(e). This B/W image is then converted to a color image using the demosaicing algorithm illustrated in Table 1, which 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 3×3 Gaussian filter to reduce the most significant random noises. This experiment demonstrates that our proposed technique can measure color objects successfully.

We also measured an object with a variety of colors on

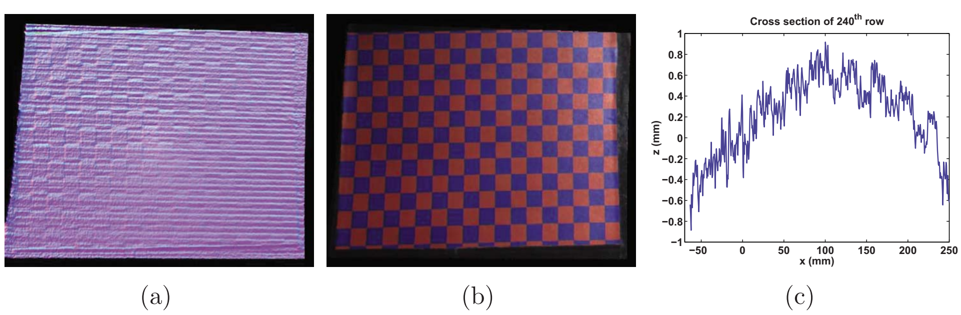


Fig. 4 Reconstruction result of the flat checkerboard shown in the previous figure: (a) 3-D data rendered in shaded mode, (b) 3-D data rendered with texture mapping, and (c) 240th row of the cross section. (Color online only.)

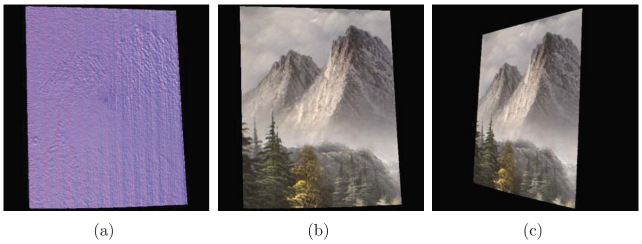


Fig. 5 Measurement result of a color paint: (a) 3-D result rendered in shaded mode, (b) 3-D result rendered with color texture image, and (c) 3-D result rendered with color texture image viewing from another angle. (Color online only.)

its surface: a painting. Figure 5 shows the measurement results. Figure 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 viewed from another angle. This measurement result is also smoothed by a 3×3 Gaussian filter to reduce the most significant random noises. This experiment shows that the proposed method can also measure the 3-D geometry and color texture simultaneously for the object with drastic surface color variations.

Moreover, because 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 a 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 a very strong projector light. Figure 6(c) shows the result rendered in wireframe mode. Video 1 shows the 3-D view of the reconstructed 3-D face. 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 7×7 Gaussian filter to reduce the most significant random noise. This experiment demonstrated that the proposed approach can be used to measure a human face with high quality. If this technique is applied to our previously developed real-time 3-D shape measurement system,[1] it can also do real-time 3-D shape measurement with color texture.

5 Discussion

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 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 the following:

1. *Simultaneous aligned geometry and color texture acquisition*. Because the color and the geometry come from the same sensor simultaneously, they are precisely aligned point-by-point. In contrast, it is very difficult to achieve such a precise alignment if multiple cameras are used.
2. *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, and neither does the captured fringe images. Therefore, 3-D measurement accuracy is not affected significantly.
3. *Low cost*. Camera companies usually provide the same price for a B/W camera and a color camera if the same type of sensor (with or without Bayer mo-

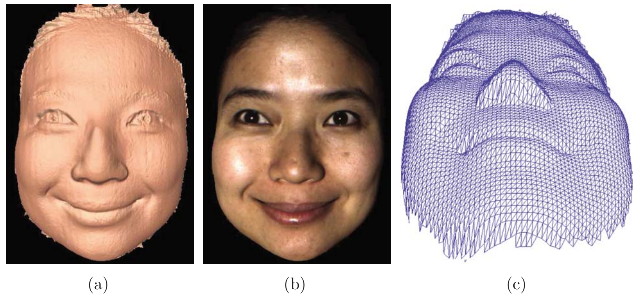
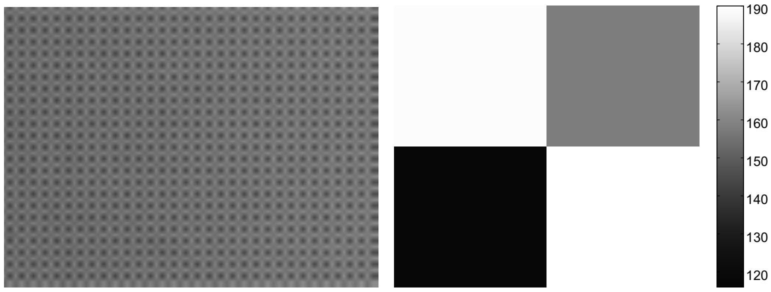


Fig. 6 Experimental result of a human face: (a) 3-D geometry rendered in shaded mode, (b) 3-D geometry rendered in with color texture mapping, and (c) 3-D geometry rendered in wireframe mode. (Color online only.)

Video 1 Three-dimensional view of the reconstructed three-dimensional face (QuickTime, 4.8 MB).
[URL: http://dx.doi.org/10.1117/1.3046715.1]



(a) (b)

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 64×48 pixels). (b) Local 2×2 pixels intensity values. Here the *x*-axis goes right, and the *y*-axis goes up.

saic filter) is used. Therefore, the cost of the system is not affected in comparison with a system using a B/W camera.

4. *High resolution*. Because the geometry calculation is pixel-by-pixel, the resolution of the measurement is as high as the camera resolution. However, for color texture, as explained previously, each 2×2 grid represents one color pixel. Therefore, the color texture resolution is $1/2$ of the spatial resolution of the camera.
5. *Fast speed*. Because only three fringe images are used for our measurement, this technique can also 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[3] 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 a second color camera.

A phase-shifting algorithm is used due to one of its merits: pixel-by-pixel measurement. For a raw image with Bayer mosaic patterns, a 2×2 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 2×2 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 a color image using a demosaicing algorithm.

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

1. *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 a brighter light source. It should be noted that even if a more expensive 3-CCD color camera is used in such a system, the exposure time still needs to be significantly longer because only part of the light is passed onto each individual sensor to perform high-quality measurement.
2. *Larger local noise*. For the color camera with Bayer mosaic patterns, the response of the light differs from pixel to pixel for any 2×2 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 wavelengths 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 the whiteboard 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 been seen that the intensities of different pixels are different and are very significant for the pixels representing different color. It should be noted that for our very low cost camera, the local noise is significant. There are single-chip (generally more expensive) color cameras allowing for adjusting gain for each individual color pixels where the local intensity variations will not be as significant as the one we tested.
3. *Possible lower resolution*. For the extreme case, even though it might not happen in practice, the measurement resolution might be reduced. For example, for a purely red object that only reflects the red spectra of the light, and the green and blue filters of the camera completely eliminate the red spectra, only the red pixels can perform the measurement and the measurement resolution will be reduced to $1/4$.

In this research, we use a single-chip color camera instead of a 3-CCD camera. This does not mean the 3-CCD camera cannot be used for this proposed approach. On the contrary, 3-CCD cameras might be able to provide better image quality than single-chip cameras because local noise is smaller. The reasons for using a single-chip camera instead of a 3-CCD camera are the following:

1. 3-CCD cameras are generally much more expensive compared with single-sensor cameras, which is contrary to our research goals.
2. The phase calculation might be problematic since it is extremely difficult to guarantee that three CCDs in the color cameras are 100% accurately aligned pixel-by-pixel. This misalignment can cause the phase shift error, which might be significant for a low-cost camera.
3. From a 3-D shape measurement point of view, 3-CCD cameras suffer the same light loss as the single-chip color cameras, since each sensor captures only a partial spectra of light. Of course, 3-CCD cameras might provide better image quality than single-chip cameras because local noise is smaller.

For our system, a 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. If the color wheel of a DLP projector is removed, as in our previous system,[1] the B/W fringe images will be projected automatically. However, for an ordinary color projector, three major factors determine whether the output light is ideally B/W: (*i*) the fringe images generated by the computer, (*ii*) the computer graphics card that connects to the projector, and (*iii*) the white balance of the projector. Moreover, the color spectra response of the camera will also play an important role for such a system. In order to generate ideal B/W fringe images, the color calibration procedure is required to equalize the three color channels of the whole system. For this research, since the precisely ideally balanced color channels are not required to successfully perform the measurement, we simply generate fringe images with R=G=B and adjust the color balance of the projector manually and visually.

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

6 Conclusions

This paper presents 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 a 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 a 3-D image 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 a color texture image using a demosaicing algorithm. The advantages of this proposed method include: (*i*) simultaneous geometry and color texture acquisition using a single color camera and a projector; (*ii*) the shape measurement is less sensitive to object color in comparison with previous proposed methods using color cameras; (*iii*) the cost does not increase in comparison with a system using a B/W camera; 4. the resolution is high (pixel level), and 5. it is 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. 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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