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High-resolution, high-speed three-dimensional shape measurement using projector defocusing

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Abstract. We present a high-resolution, high-speed three-dimensional (3-D) shape measurement technique that can reach the speed limit of a digital fringe projection system without significantly increasing the system cost. Instead of generating sinusoidal fringe patterns by a computer directly, they are produced by defocusing binary ones. By this means, with a relatively inexpensive camera, the 3-D shape measurement system can double the previously maximum achievable speed and reach the refreshing rate of a digital-light-processing projector: 120 Hz. *© 2011 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.3534798]

Subject terms: phase shifting; real time; three-dimensional; defocusing.

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1 Introduction

With the advancement of computational geometry for shape analysis, high-resolution, high-speed three-dimensional (3-D) shape measurement is increasingly important, with broad applications ranging from homeland security to great human health. However, it remains challenging to develop inexpensive systems. In this research, we are tackling this problem via an alternative route.

Real-time 3-D shape measurement can be classified into two categories, passive and active methods. A typical passive system is stereo vision; in this method, two cameras, viewing from different angles, capture the images in real time. The data acquisition speed can be as high as the camera reaches; thus, is easy to realize real-time 3-D data acquisition with low cost. However, hinging on identifying the corresponding pairs between two camera images, its accuracy is usually not high if the object surface does not have very strong reflectivity variations.

A active system uses an active device, such as a laser or a projector, to project pre-defined structured patterns onto the object surface to assist the correspondence identifications. Among the active methods, the camera-projector systems are widely used because of its low costs. To reach real-time 3-D shape measurement, methods based on color patterns[1,2] have been developed. However, the measurement accuracy is affected, to a various degree, by the surface color. For example, for a red object, the information carried by green and blue channels are all lost.

To circumvent the color-related problems, gray-scale structured patterns are used. To reach real time, the structured patterns must be switched rapidly and captured with a short period of time. Rusinwiski et al.[3] developed a real-time 3-D model acquisition system based on stripe boundary code.[4] Davis et al. has developed a real-time 3-D shape measurement system based on a Spacetime stereo vision method.[5] However, for all binary-structured pattern-based methods, it is difficult for them to reach pixel level resolution because the stripe width must be lager than one projector pixel.[6]

Digital fringe projection and phase-shifting methods have the advantage of spatial resolution because more gray-scale values are used. Over the years, we have developed a real-time 3-D shape measurement system using a modified digital-light-processing (DLP) projector. We have reached simultaneous data acquisition, reconstruction, and display in realtime.[7,8] Conventionally, a real-time 3-D shape measurement technique based on a digital fringe projection and phase-shifting method requires sinusoidal fringe patterns to be sent to a focused projector. However, due to its digital fringe-generation nature, the camera and the projector must be precisely synchronized. In other words, the camera must start capturing when the projector starts projection and must stop when the projector stops projection. Modern projectors usually have no time gap between channels; therefore, in order to reach the projection speed, the camera must be able to readout the data simultaneously under external control mode. However, when an external trigger is used, a relative inexpensive camera usually takes a long time, typically one per maximum frame rate (MFR), to readout the image captured before taking another one. Moreover, a typical DLP projector has different time durations for different color channels to balance its output color. This means that the camera must be able to change its exposure time from frame to frame. In reality, it is very difficult to do so especially when the external trigger mode is in use. Therefore, it is usually very difficult for an ordinary system to achieve the maximum 3-D shape measurement speed: the projector's refreshing rate. As a result, we only achieved 60 Hz with a 120-Hz projector.[9] In order to solve for this problem, a typical approach is to employ a high-end camera so that it can capture images when data are readout, and it allows for precise timing changes from frame to frame. However, this type of camera is usually extremely expensive.

In this paper, we propose to use the projector defocusing technique that we developed recently to circumvent the problems caused the a traditional phase-shifting technique.[10] The defocusing technique to generate sinusoidal fringe patterns was not new. In 1992, Su et al. introduced a technique to defocus square waves for sinusoidal fringe wave generation and implemented it with the Ronchi grating for 3-D shape measurement.[11] However, because a mechanical

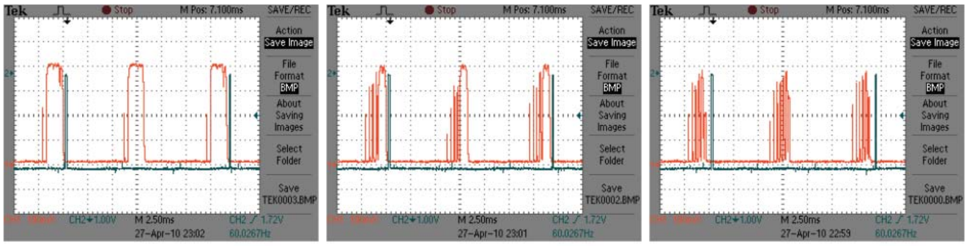
(a) (b) (c)

Fig. 1 Example of the projected timing signal if the projector is fed with different gray-scale values of the blue image: (a) 255, (b) 128, and (c) 64.

grating is used, it is very difficult to precisely keep phase-shifted fringe patterns at a very high speed, and the error caused by phase shift is usually the dominant one. In contrast, the digital fringe projection technique does not have the phase-shift error because the fringe patterns are generated digitally. The single dominant error source is the nonsinusoidality of the fringe patterns; thus, how to generate ideally sinusoidal fringe pattern is the major concern. The digital projector defocusing technique we[10] recently proposed intended to solve the nonsinusoidal fringe pattern problem caused a digital video projector for real-time measurement purposes.

We use this defocusing technique to improve our real-time 3-D shape measurement system speed. We will demonstrate that this technique does not require the camera to capture the full channel projection and allows for the use of a low-cost camera to reach the maximum speed. Specifically, we send binary patterns instead of sinusoidal fringe patterns to the DLP projector to avoid the strict synchronization requirement. Because only binary levels of fringe patterns are used, the capture can happen any time and with any exposure time during the image projection. For high-quality 3-D shape measurement, sinusoidal fringe patterns are desirable; thus, the defocusing technique is applied here to generate sinusoidal pattern. The projector is defocused to a degree so that the binary patterns become good-quality sinusoidal ones. By this means, with a relatively inexpensive camera, the 3-D shape measurement system can double the previously maximum achievable speed and reaches the refreshing speed of a DLP projector: 120 Hz. Experiments will be presented to demonstrate that real-time 3-D shape measurement quality does not significantly drop even though the exposure time is reduced to $\sim 36\%$ of the projection time.

Section 2 introduces the principle of the system, Sec. 3 shows some experimental results, and Sec. 4 summarizes this paper.

2 Principle

2.1 *Synchronization between the Projector and Camera*

For a DLP projector, the gray-scale values of an image are generated digitally by time modulation.[12] A simple test was performed for a DLP projector, PLUS U5-632H. The output light was sensed by a photodiode, and the photocurrent was converted to the voltage signal that is monitored by an oscilloscope. Figure 1 shows some typical results when it was fed with different grays-cale images. The projector usually uses the video signal VSync to synchronize the computer's video signal. A new projection cycle usually starts as the VSync signal arrives, and the duration time of each channel is controlled by the electronics of the projector. If 60-Hz input video frequency is used, then the DLP projector used in this research actually refreshes twice within one period of the video signal. If the pure blue, RGB = (0, 0, 255), is supplied, then there are two periods of signal output for each VSync period. This clearly shows that if the supplied signal is reduced to other grayscale values, then the output signal becomes irregular. Therefore, if a sinusoidal fringe pattern (which varies from 0 to 255) is supplied, then the whole projection period must be captured to correctly capture the fringe image projected from the projector. This is not desirable for high-speed 3-D shape measurement. This is because, in many real-time applications, the exposure time must remain short to capture the motion.

Figure 2 shows the timing of a typical CCD camera when the external trigger mode is used. It indicates that it takes sometime to transfer the image buffer before capturing the next frame capture. Typically, the maximum achievable speed of a CCD camera is

$$\text{FrameRate} = 1/(t_\text{r} + t_\text{e}).$$

Here $t_r = 1/MFR$ (in seconds) is the readout time, which is one over the maximum frame rate it can achieve. For example, if a camera states that its maximum frame rate is MFR = 30 Hz, and an exposure time of $t_r = 1/30$ (in seconds) is used, the maximum data capturing speed is 15 Hz. Figure 3 shows a typical timing of the DLP projection; it does not have any gap between different channels. Therefore, our real-time 3-D shape measurement system usually skips one channel before the next frame is captured.[7] Hence, the maximum data acquisition speed is one-half of the projection speed. If one wants to reach the maximum measurement speed, then a very high-speed CCD camera is usually required. However, this will significantly increase the cost of the system.

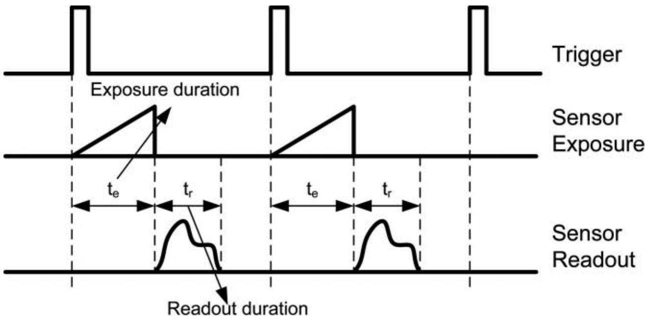

Fig. 2 Typical timing chart for a CCD camera operation under external trigger mode.

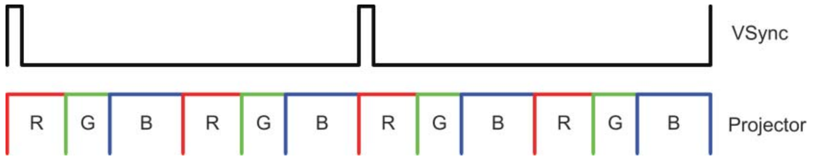

Fig. 3 Typical timing chart for a single-chip DLP projector.

In the meantime, one should note that if the full gray-scale value of 255 is used, any time period can be used to represent the signal and thus allows for shorter exposure time than its channel projection time. Similarly, if the grayscale value of 0 is used, it also allows any shorter exposure time. Therefore, if only 0 and 255 gray-sale values are used, then it would be essentially feasible to perform the measurement with very short exposure time, which thus allows for the camera to readout the data captured. Figure 4 shows the possible timing of the camera and the projector. By this means, it is easier to reach maximum measurement speed with an ordinary camera.

2.2 *Sinusoidal Fringe Pattern Generation by Defocusing Binary Pattern*

For high-resolution 3-D shape measurement, sinusoidal fringe patterns are desirable. However, from our previous discussion, in order to reach maximum measurement speed, only binary structured patterns can be used. To resolve this dilemma, we use a method that we recently proposed: generating sinusoidal fringe patterns by properly defocusing binary ones.[10]

Figure 5 shows some typical fringe images when the projector is defocused to different degrees while the camera is in focus. It shows that if the projector is defocused to different degrees, then the binary structured patterns are deformed differently. Figure 5(a) shows the fringe pattern when the projector is in focus. There are clear binary structures on the image. If the degree of defocusing increases, then the binary structures become less and less clear and they become more and more sinusoidal. However, if the defocusing degree is too much, then sinusoidal structures start diminishing, as indicated in Fig. 5(f). This experiment indicates that seemingly sinusoidal fringe patterns can be generated by defocusing the projected binary structured patterns.

2.3 *Three-Step Phase-Shifting Algorithm*

Phase-shifting algorithms have been extensively utilized in optical metrology. Over the years, a number of phase-shifting algorithms have been developed, including three-step, four-step, double three-step, etc.[13] Although the number of fringe images used are different, they share the common features: (i) at least three fringe images are needed, (ii) fringe images are spatially shifted fringe frame to frame, (iii) the phase is retrieved point by point from the fringe images, and (iv) the coordinates (or depth) are retrieved from the phase point by point. To achieve high speed, a three-step phase-shifting algorithm is usually used. Three fringe images with a phase shift of $2\pi/3$ can be described as follows:

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

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

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

where $I'(x, y)$ is the average intensity, $I''(x, y)$ the intensity modulation, and $\phi(x, y)$ the phase to be solved for. Simultaneously solving Eqs. (1)–(3) will give the phase

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

Equation (4) only provides phase value with the range of $[-\pi, +\pi)$. If multiple fringe stripes are used, then a phase-unwrapping algorithm is necessary to obtain a continuous phase map.[14] The phase can be further converted to 3-D coordinates once the system is calibrated.[15]

In this proposed fringe generation technique, to generate phase shift, the original binary patterns will move spatially. For example, in order to generate $2\pi/3$ phase shift, the binary pattern will move 1/3 of a period from one to the other.

3 Experiments

We implemented this proposed method with our previously developed real-time 3-D shape measurement system.[8] Instead of using sinusoidal fringe patterns, we use binary patterns. Figure 6 shows the system layout. Three spatially shifted binary images are encoded as three primary color channels (RGB) of a color image. The color fringe pattern is sent to a single-chip DLP projector without color filters. The projector projects the RGB sequentially onto the object. The projector is properly defocused so that the binary-structured patterns become sinusoidal ones. A CCD camera, synchronized with the projector, is used to capture each color channel separately into the computer. Three phase-shifted fringe images are then used to reconstruct one 3-D geometry through phase-wrapping, phase-unwrapping, and phase-to-coordinate conversion steps.

In this system, the projector we used is a DLP projector (PLUS U5-632h), the cameras are digital CCD camera with a image resolution of 640×480 (Pulinx TM6740-CL), and the frame grabber is Matrox Solios XCL. It should be noted that this camera allows simultaneous data capture and readout

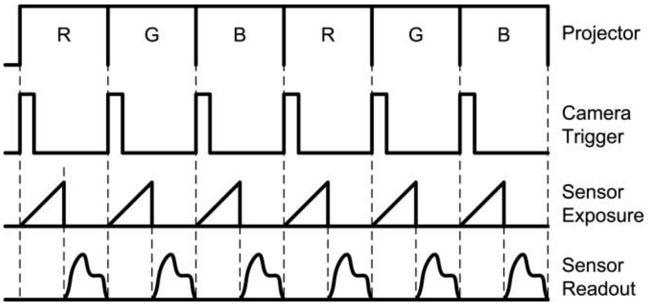

Fig. 4 Possible timing for an ordinary projector-camera system.

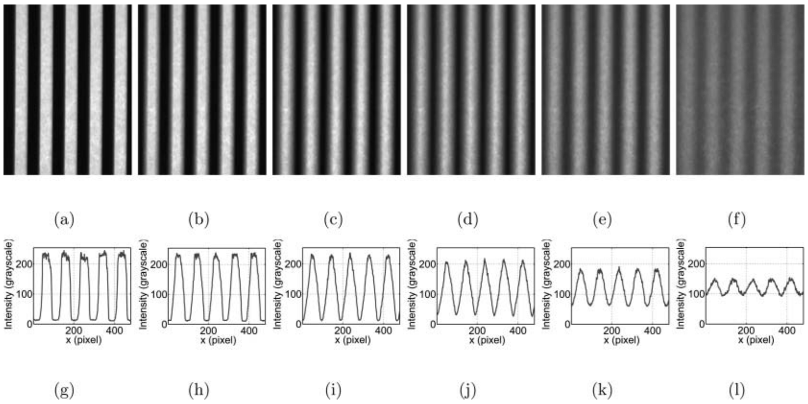

Fig. 5 Example of sinusoidal fringe generation by defocusing a binary structured patterns. (a–f) Fringe images when the projector is defocused to different degrees and (g–l) associated 320*th* row cross sections in (a–f).

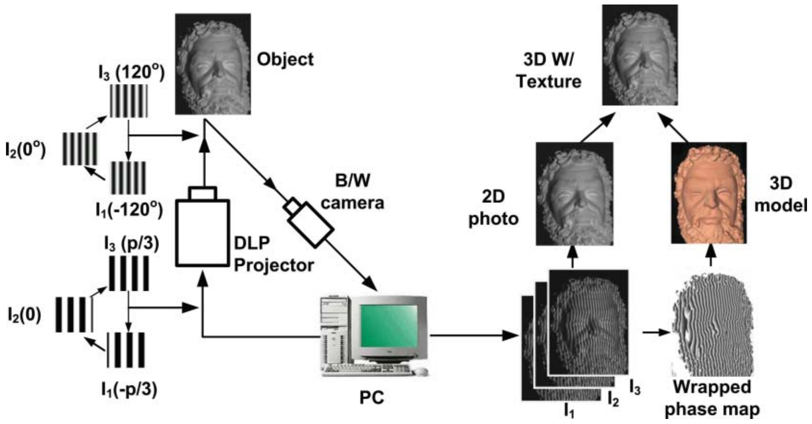

Fig. 6 Layout of the real-time 3-D shape measurement system.

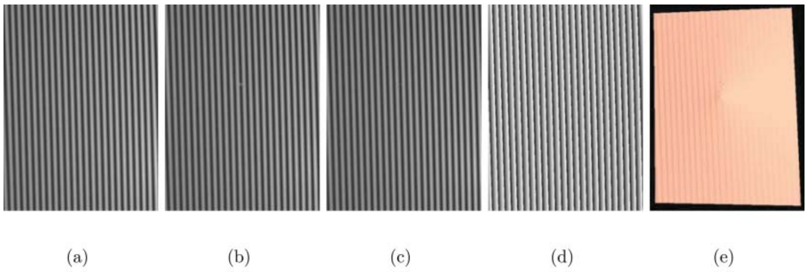

Fig. 7 Measurement result of a uniform white board: (a) $I_1(x, y)$, (b) $I_2(x, y)$, (c) $I_3(x, y)$, (d) Phase map, and (e) 3-D shape.

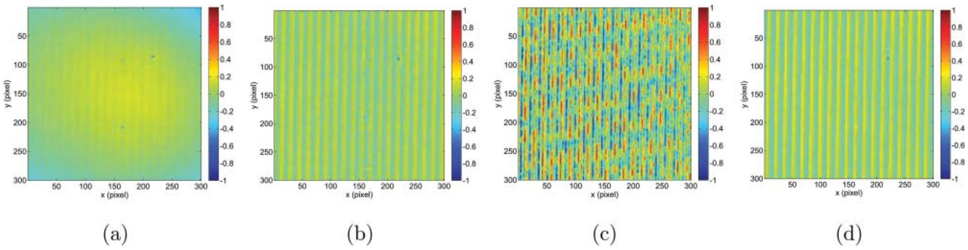

Fig. 8 Comparison between the binary method and the sinusoidal method with different exposure time: (a) 3-D results with the sinusoidal fringe patterns and proper exposure time (2.78 ms), (b) difference between 3-D results with the binary method and result shown in (a) when exposure time is set to be 2.78 ms (rms error: 0.08 mm), (c) the difference between 3-D results with the sinusoidal method and result shown in (a) when exposure time is set to be 1.00 ms (rms error: 0.33 mm), and (d) difference between 3-D results with the binary method and result shown in (a) when exposure time is set to be 1.00 ms (rms error: 0.12 mm).

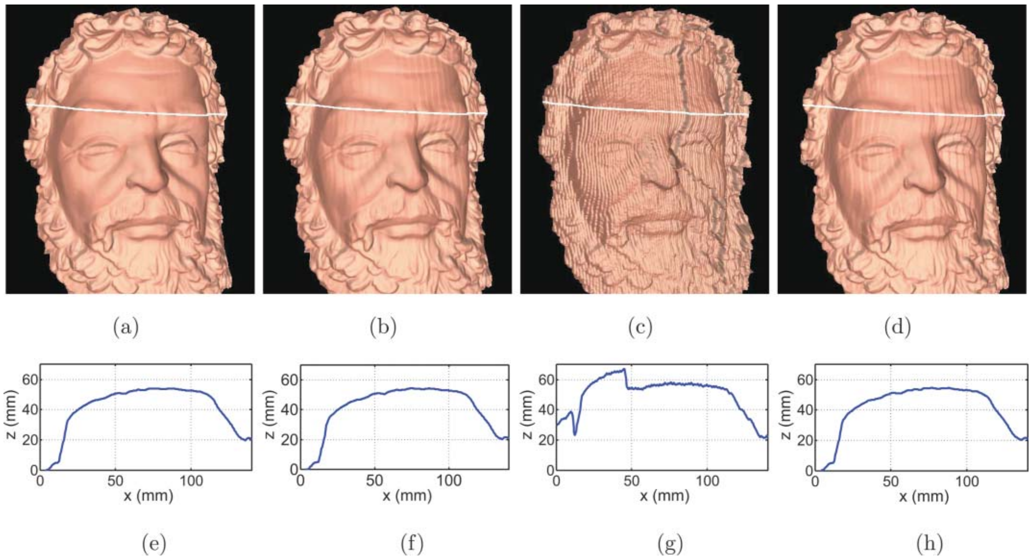

Fig. 9 Experimental results of a complex sculpture when for both methods with different exposure time: (a) Sinusoidal method with 2.78-ms exposure time, (b) binary method with 2.78-ms exposure time, (c) sinusoidal method with 1.00-ms exposure time, (d) binary method with 1.00-ms exposure time; (e–h) cross sections of (a–d), indicated as white lines.

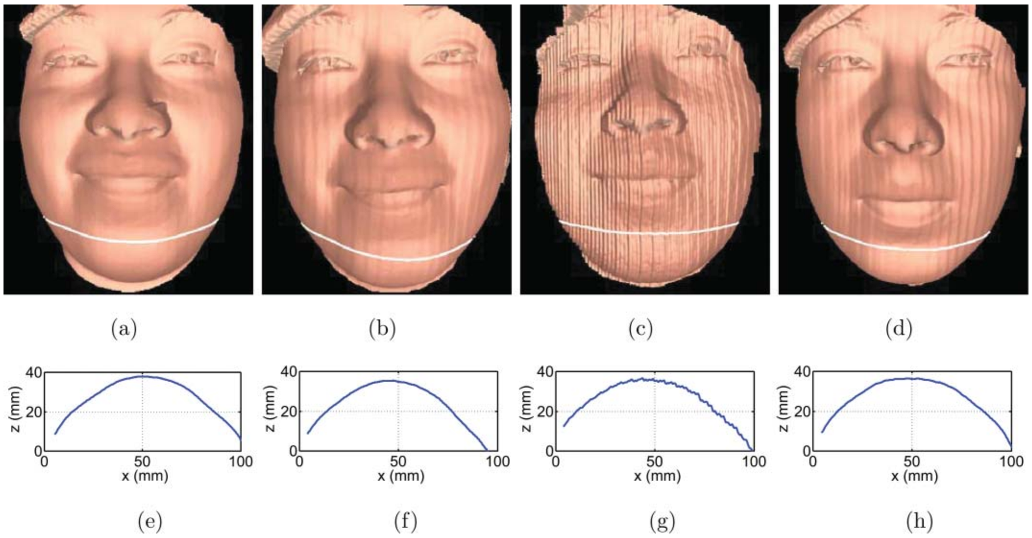

Fig. 10 Experimental results of a complex sculpture for both methods with different exposure times: (a) sinusoidal method with 2.78-ms exposure time, (b) binary method with 2.78-ms exposure time, (c) sinusoidal method with 1.00-ms exposure time, (d) binary method with 1.00-ms exposure time; (e–h) cross sections of (a–d), indicated as white lines.

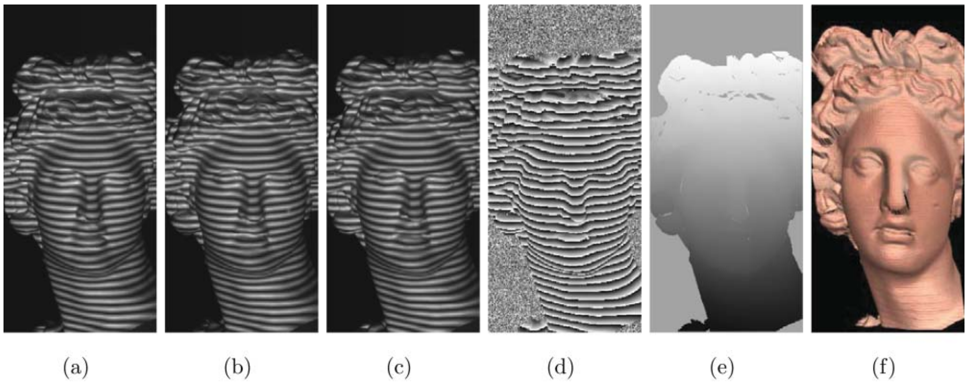

Fig. 11 Experimental results when the camera captures the projected fringe images at 360 Hz with an exposure time of 0.78 ms: (a) Fringe pattern $I_1(-2\pi/3)$, (b) fringe pattern $I_2(0)$, (c) fringe pattern $I_3(+2\pi/3)$, (d) wrapped phase map, (e) unwrapped phase map, and (f) 3-D shape.

when the external triggering mode is used. All experimental results presented here are to verify the potential of the proposed technique. The calibration technique we used in this research was introduced in Ref. 15.

The projector was modified so that three color channels will have equal time duration; thus, the camera can use the same exposure time all the time. Because the projector refreshes at 120 Hz, each channel actually lasts for ∼ 2.78 ms. To verify that the proposed technique can actually perform a measurement, we first measured a uniform white board, as shown in Fig. 7. Figures 7(a)–7(c) show three phase-shifted fringe images with the binary-structured pattern input. Figure 7(d) shows the wrapped phase map, and Fig. 7(e) shows the 3-D shape measurement result. This 3-D shape measurement result shows it is possible to perform measurements with the defocused binary patterns if the projector is properly defocused, albeit there are some residual measurement errors (vertical stripe noises).

As a comparison, we measure the same board with the conventional sinusoidal fringe generation method; the result is shown in Fig. 8(a). In this experiment, we treat the result of the sinusoidal method with the proper exposure time as the ground truth and use the difference between any other measurement with this one to evaluate the quality of performance. The difference between the conventional method with proper exposure time (2.78 ms) and the result obtained previously as shown in Fig. 7(e) is depicted in Fig. 8(b). It can be seen that the measurement has stripe errors that are caused by the non-sinusoidality of the defocused fringe pattern. Although the binary patterns can turn into seemingly sinusoidal ones if the projector is properly defocused, this experiment shows that the pattern is actually not ideally sinusoidal.[16] This maybe because the defocusing effect cannot eliminate the harmonics of the square wave, if rather suppressing this effect. The difference error is very small, approximately root-mean-square (rms) error of 0.08 mm.

We then reduce the exposure time to be 1.00 ms and perform the measurement again for both methods. The differences are shown in Figs. 8(c) and 8(d). This clearly shows that the binary method generates much better result when the exposure time is shorter than the projection time. This experiment also shows that if the exposure time is much shorter than the projection time, then the sinusoidal method cannot perform the measurement correctly, while the measurement quality of the binary method does not significantly drop. It should be noted that during all experiments, the relative physical position between the object (flat board) and the system was fixed. The proper defocusing was realized by adjusting the projector's focal distance. The coordinate calculations for the defocused system is approximate because the calibrated parameters of projector changes if its focal distance is changed.

To further demonstrate that the new method can work for complex shape objects, we measure a Zeus sculpture and the measurement results are shown in Fig. 9. This experiment shows that if the camera and projector are precisely synchronized, then the sinusoidal method works better than the binary one. However, if the camera's exposure time is much shorter than the projection channel time (36%), then the measurement quality for the binary method does not drop significantly while that for the sinusoidal method does.

To demonstrate the real-time capability of the system, we measured a human face with similar facial motion, and the measurement results are shown in Fig. 10. This experiment again confirmed that the binary method outperforms the sinusoidal one when the exposure time is shorter than the projection channel time, whereas it does not provide as good a result as the sinusoidal method when the camera is properly exposed.

Because the camera we use has a maximum frame rate of 200 Hz with full resolution (640×480), all previous experimental data were captured at 180 Hz. However, the camera allows for faster capture speed for partial imaging. In this example, we use a resolution of 224×480 to reach the 500 sampling rate. For a typical asynchronized camera, the data readout takes 2 ms. Because each color channel lasts 2.78 ms for our camera, it leaves 0.78 ms for image exposure. Thus, we set the exposure time of the camera to be 0.78 ms for data capture. Figure 11 shows one measurement example; it clearly shows that the fringe patterns as well as the 3-D shape are well captured. This experiment demonstrated that indeed a 120-Hz 3-D shape measurement rate can be reached if a camera can sample the data as fast as 500 Hz.

4 Conclusions

This paper has verified that by utilizing the projector defocusing technique to generate phase-shifted sinusoidal fringe images, it seems viable to use an ordinary camera to achieve the maximum 3-D shape measurement speed of 120 Hz. This technique takes advantage of the working mechanism of a DLP projector to circumvent the precise synchronization problem of the projector and the camera. Our experiments have also shown that, with the same exposure time, the binary pattern method generated much a brighter image than the traditional sinusoidal pattern method. This is another advantage of using the new method for high-speed 3-D shape measurement, where the illumination intensity would be an important factor to consider. The drawback of this technique, as shown in the experimental results, was that it seems to be impossible to generate ideal sinusoidal fringe patterns by defocusing. Another drawback is that the fringe contrast is reduced to generate ideal sinusoidal fringe patterns by this defocusing.[17] We are currently investigating means to alleviate these problems by hardware means or software approaches. Moreover, comparing to the traditional sinusoidal fringe projection techniques, this technique has another shortcoming: shorter depth range of measurement. This is because, for a traditional method, the fringe patterns are sinusoidal for all depth ranges, while for this method, only when the projector is defocused to a certain degree do the structured patterns become sinusoidal. We are currently exploring methods to increase the measurement depth range. Even with these shortcomings, this technique still shows great improvement on high-speed 3-D shape measurement.

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