Improve 4-D shape measurement by using projector defocusing

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ABSTRACT

This paper presents a real-time 3-D, or 4-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 structured patterns. 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 rate of a digital-light-processing (DLP) projector: 120 Hz.

Keywords: Phase shifting; real time; three dimensional; defocusing.

1. INTRODUCTION

With the advancement of computational geometry for shape analysis, high-resolution, real-time 3-D, or 4-D, shape measurement is increasingly important, with broad applications ranging from homeland security to great human health. However, it remains challenging for developing 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 viewing 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, relying 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.

An active system uses an actively devices, such as a laser or a projector, to project pre-defined structured patterns onto the object surface to assist the correspondence identifications. Among 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 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 on by green and blue channels are all lost.

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

Digital fringe projection and phase-shifting methods have the advantage of spatial resolution because more grayscale values are used. Over the years, we have developed 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 real-time.

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 captures when the projector starts projection, and stops 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 1/(max frame rate), to readout the image captured before taking another one. Moreover, a typical DLP projector has different time duration 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

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when external trigger mode is in use. Therefore, it 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 this problem, a typical approach is to employ a high-end camera so that it can captured images when data is readout, and it allows for precise timing changes from frame to frame. However, this type of camera is usually extremely expensive.

We propose to use a new technique that does not require the camera to capture the full channel projection, and it allows the use of a low-cost camera to reach the maximum speed. In particular, 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 projector is defocused to a degree so that the binary patterns become high-quality sinusoidal patterns.10 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 the exposure time is reduced to approximately 36% of the projection time.

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

2. PRINCIPLE

2.1 Synchronization between the projector and the camera

For a DLP projector, the grayscale values of an image are generated digitally by time integration.11 A simple test was performed for a DLP projector, PLUS U5-632H. The output light was sensed by a photodiode, and photocurrent was converted to voltage signal and monitored by an oscilloscope. Figure 1 shows some typical results when it was fed with different color 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 of each channel time is controlled by the electronics of the projector. If 60 Hz input video frequency is used, 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, there are two periods of signal output for each VSync period. It clearly shows that if the supplied signal is reduced to other grayscale values, the output signal becomes irregular. Therefore, if a sinusoidal fringe pattern (varies from 0 to 255) is supplied, the whole projection period must be captured to correctly capture the image projected from the projector. This is not desirable for 4-D imaging, 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 shows 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 1/(tr + te). Here tr = 1/SFR 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 SFR = 30 Hz, and an exposure time of tr = 1/30 second 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. Therefore, the maximum data acquisition speed is one half of the projection speed. A very high-speed CCD camera is usually required if one wants to reach the maximum measurement speed. However, this will significantly increase the cost of the system.

![Typical timing chart for a CCD camera operation under external trigger mode.](image)

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

![Typical timing chart for a single-chip DLP projector.](image)

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

In the meantime, one should notice that if the full grayscale value 255 is used, any time period can be used to represent the signal. It, 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 grayscale values are used, it would be essentially feasible to perform the measurement with shorter exposure time, thus allows for 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.

![Possible timing for an ordinary projector-camera system.](image)

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

### 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 patterns.

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

![Fig. 5. Example of sinusoidal fringe generation by defocusing a binary structured patterns. (a)-(f) shows the fringe images when the projector is defocused to different degrees.](image)

### 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. Although the number of fringe images used are different, they share the common features: (1) at least three fringe images are needed; (2) fringe images are spatially shifted fringe frame to frame; (3) the phase is retrieved point by point from the fringe images; and (4) 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

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

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

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

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

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

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

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. 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 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 digital-light-processing (DLP) projector (PLUS U5-632h), the cameras are digital CCD camera with a image resolution of $640 \times 480$ (Pulinx TM6740-CL), and the frame grabber is Matrox Solios XCL. The calibration technique we used in this research was introduced in Reference.\textsuperscript{14}

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 approximately 2.78 ms. To verify the proposed technique can actually perform measurement, we first measured an uniform white board, as shown in Figure 7. Figures 7(a)-7(c) shows three phase shifted fringe images with the binary structured patterns input. Figure 7(d) shows the phase wrapped phase map. And figure 7(e) shows the 3-D shape measurement result. This 3-D shape measurement result shows it is possible to perform measurement with the defocused binary patterns if the projector is properly defocused, albeit there are some residual measurement errors (vertical stripe noise).

![Fig. 6. Layout of the real-time 3D shape measurement system.](image)

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 Figure 7(e) is depicted in Figure 8(b). It can be seen that the measurement has stripe errors that are caused by the nonsinusoidality 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. This maybe because the defocusing effect cannot get rid of the harmonics of the a square wave. 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 measurement again for both methods. The differences are shown in Fig 8(c) and Fig. 8(d). It 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, 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 the new method can work for complex shape objects. We measured a Zeus sculpture, the measurement results are shown in Fig. 9. This experiment clearly shows that if the camera and the projector are precisely synchronized, 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%), the measurement quality for the binary method does not drop significantly whilst that for the sinusoidal method does.
To demonstrate the real-time capability of the system. We measured a human face with similar facial motion, 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, while does not provides as good result as the sinusoidal method when the camera is properly exposed.

![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.](image)

Fig. 10. 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.

4. CONCLUSIONS

This paper has verified that by utilizing projector defocusing technique to generate phase-shifted sinusoidal fringe images, it seems viable to use an ordinary camera achieve the maximum 3-D shape measurement speed: 120Hz. This technique takes advantage of the working mechanism of a DLP projector to circumvent the precision synchronization problem of the projector and the camera. Our experiments has also showed that with the same exposure time, the binary pattern method generated much 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. Therefore, a phase error compensation method needs to be developed to reduce this residual measurement errors.

REFERENCES


