Superfast phase-shifting method for 3-D shape measurement

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Abstract: Recently introduced DLP Discovery technology allows for tens of kHz binary image switching, which has great potential for superfast 3-D shape measurement. This paper presents a system that realizes 3-D shape measurement by using a DLP Discovery technology to switch binary structured patterns at very high frame rates. The sinusoidal fringe patterns are generated by properly defocusing the projector. Combining this approach with a phase-shifting method, we achieve an unprecedented rate for 3-D shape measurement: 667 Hz. This technology can be applied to numerous applications including medical science, biometrics, and entertainment.

OCIS codes: (110.6880) Three-dimensional image acquisition; (320.7100) Ultrafast measurements; (120.5050) Phase measurement.

References and links

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1. Introduction

With recent advancement of digital video projection technology, 3-D shape measurement techniques based on digital fringe projection and phase-shifting methods have improved drastically. Among these efforts, dynamic real-time 3-D shape measurement has becomes a core subject because of its importance in numerous fields. However, if a digital video projector is used, its

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measurement speed is limited to 120 Hz [1]. This is because the fringe pattern switching rate is usually limited to 120 Hz for a digital-light-processing (DLP) projector.

The most recently developed DLP Discovery technology has enabled 1-bit image switching rate at tens of kHz. This innovation shows great potential for 3-D optical metrology because of its flexibility to control the projected light accurately [2–4]. However, a digital fringe projection and phase-shifting method requires sinusoidal fringe patterns that usually require 8-bit images. Furthermore, 3-D shape measurement using a sinusoidal phase-shifting method has numerous advantages over other techniques because of its speed and accuracy.

This research verifies the feasibility of using the DLP Discovery technology for superfast 3-D shape measurement with a digital fringe projection and sinusoidal phase-shifting method. In particular, we use our recently developed 3-D shape measurement technique that generates sinusoidal phase-shifted fringe patterns by properly defocusing binary structured patterns [5]. Compared to a conventional phase-shifting method in which 255 grayscale values are used, this technique requires only binary (0's, and 255's) grayscale values. It has the following advantages: (1) superfast 3-D shape measurement with this DLP Discovery technology; (2) no precise synchronization between the projector and the camera; (3) no nonlinear projector gamma corrections [6]; and (4) high spatial and temporal resolution. Because the DLP Discovery can switch binary images at tens of kHz rate, if a three-step phase-shifting algorithm is used, the 3-D shape measurement speed can theoretically reach kHz, and even tens of kHz.

In this research, we use a DLP Discovery D4100 with a 0.55″ digital micro-mirror device (DMD) chip. It can switch binary images up to 32,550 frame per second with a resolution of 1,024 $\times$ 768. However, due to the optical module used, the light intensity is too low to perform any measurement at the full speed. With a Phantom V9.1 digital camera, we successfully developed a system that can achieve fringe image acquisition at 2000 Hz rate with decent quality. Because a three-step phase-shifting algorithm is used, the 3-D shape measurement speed is actually 667 Hz.

2. Principle

Phase-shifting methods are widely used in optical metrology because of their numerous advantageous features: (1) *point-by-point measurement*. They can reach pixel-level measurement resolution; (2) *Less sensitive to surface reflectivity variations*, therefore they can be used to measure very complex surfaces; (3) *less sensitive to ambient light*. They have less strict requirements for measurement conditions. A variety of phase-shifting algorithms have been developed, that include three-step, four-step, and least-square algorithms [7].

To achieve high-speed 3-D shape measurement, a three-step phase-shifting algorithm with a phase shift of $2\pi/3$ is used. Three fringe images can be described as:

$$I_1(x,y) = I'(x,y) + I''(x,y)\cos(\phi - 2\pi/3), \tag{1}$$
$$I_2(x,y) = I'(x,y) + I''(x,y)\cos(\phi), \tag{2}$$
$$I_3(x,y) = I'(x,y) + I''(x,y)\cos(\phi + 2\pi/3). \tag{3}$$

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 Eq. (1)–(3), the phase can be obtained as:

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

This equation provides the wrapped phase with 2π discontinuities. A spatial phase unwrapping algorithm can be applied to obtain continuous phase [8]. The phase unwrapping is essential to detect the 2π discontinuities and remove them by adding or subtracting multiples of 2π point

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by point. Because 3-D information is carried on by the phase, 3-D shape can be retrieved from the phase after phase unwrapping using a phase-to-height conversion algorithm [9].

3. Experiments

Figure 1 shows a photograph of the hardware system developed. It is composed of a DLP Discovery projection system, a high-speed CMOS camera, and a self-developed synchronization circuit. The DLP Discovery projection system includes a DLP Discovery board (D4000) (Texas Instruments, Texas), an ALP High Speed (Digital Light Innovations, Texas) and an optical module (S3X) (Visitech, Norway). In addition, because of the low output light intensity of the optical module, a converging lens (focal length of 175 mm) is placed in front of the projection to reduce the focused image size and increase the image quality. With this projection system, the projected image size is approximately 68 mm $\times$ 50 mm when the projector is properly defocused, so that high-quality sinusoidal fringe images can be generated when the projector is fed with binary structured patterns with 36 pixels per period. The camera used in this system is Phantom V9.1 (Vision Research, NJ), with a frame rate of 1,016 frames per second (fps) for 1,632 $\times$ 1,200 image resolution. In this test, we used only a 576 $\times$ 576 image resolution to reduce the amount of data acquired. The synchronization circuit takes the projection timing signal and sends the trigger signal to the camera for simultaneous image acquisition.

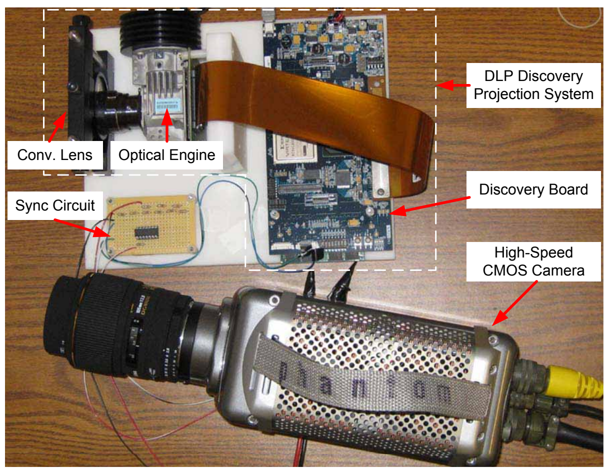

Fig. 1. Photograph of the superfast 3-D shape measurement system.

Figure 2 shows a typical measurement result of a 3-D surface when the fringe image acquisition speed is set to 1,000 fps. The camera exposure time is 500 μs. The projector is properly defocused so that ideal sinusoidal fringe patterns are produced on the surface of the measured objects. Figure 2(a) shows the object to be measured. Figures 2(b)–2(d) shows three phase-shifted fringe images. These fringe images appear to be sinusoidal, a phase shifting algorithm can then be applied to compute the phase map. After applying Eq. (4), the phase is wrapped, as shown in Fig. 2(e). The phase can then be unwrapped to obtain the continuous phase map. Figure 2(f) shows the unwrapped phase map.

The unwrapped phase map can be further converted to 3-D geometry by applying the calibration method introduced in reference [9]. Figure 4 shows the measurement results plotted in 3-D. It can be seen here that the 3-D surface profile is well captured, the reconstructed 3-D shape has very high quality. This experiment demonstrated that superfast 3-D shape measurement is feasible by using a DLP Discovery technology with its high speed binary structured

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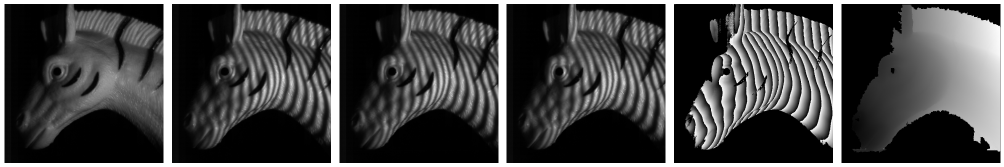
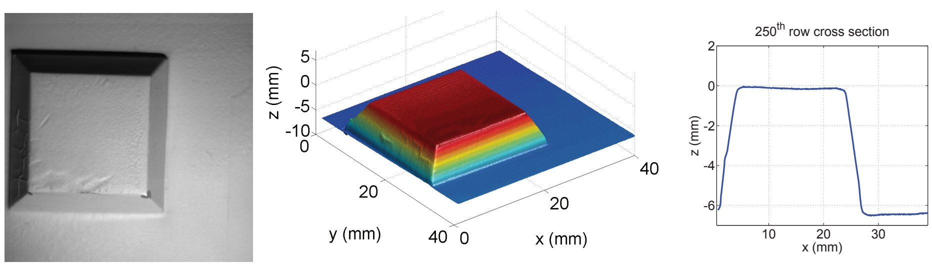


(a) (b) (c) (d) (e) (f)

Fig. 2. Example of measuring a 3-D surface. (a) Photograph of the object; (b) $I_1(2\pi/3)$; (c) $I_2(0)$; (d) $I_3(2\pi/3)$; (e) Wrapped phase map; (f) Unwrapped phase map.

image switching mode. It should be noted that the 3-D shape is smoothed by a 5 $\times$ 5 Gaussian filter to reduce the most significant random noise.

To verify the accuracy of the measurement system, we measured a trapezoidal shape object with a height of 6.35 mm. Figure 3 shows the measurement result. The measured height, depth from the top surface to the bottom surface, is 6.54 mm. The error is approximately 0.19 mm (or 3.0%). It should be noted that the calibration technique [9] used in this research is a linear approximation. This technique is essentially to measure a flat reference plane, find the phase difference point by point between the measured object phase the and the reference phase, and approximate the depth (z) by scaling the phase. The scaling factor is determined by measuring a known step height object. Because this is an approximation, the accuracy is not very high [10]. We cannot implement a high-accuracy structured light system calibration technique such as the one introduced in Reference [10]. This is because the existing techniques require the projector be in focus, which is not the case for our system. We are exploring a new method to accurately calibrate a defocused projector, and if successful, it will significantly improve the measurement accuracy.



(a) (b) (c)

Fig. 3. Measurement results of a known height object. (a) Photograph of the object; (b) 3-D plot of the measured result; (c) Plot of one cross section.

To investigate the maximum speed the system can reach, we tried a fringe acquisition speed of 2,000 fps. Because a three-step phase-shifting algorithm is used, the 3-D shape measurement speed is actually 667 fps. In this measurement, the camera exposure time is set to 497 μs. Because the 3-D shape measurement speed is so fast, it can actually be used to measure the vibration of a cantilever beam. Figure 5 (Media 1) shows some frames of a sequence of 3-D data. Due to the camera memory limitation, the image resolution is reduced to 480 $\times$ 480 to capture a longer sequence of data. To visualize the motion process of vibration, a multimedia video is submitted. The video is played at 30 fps, which is more than 20 times slower than the actually motion. It clearly shows the geometry shape variations over time when the beam is vibrating.

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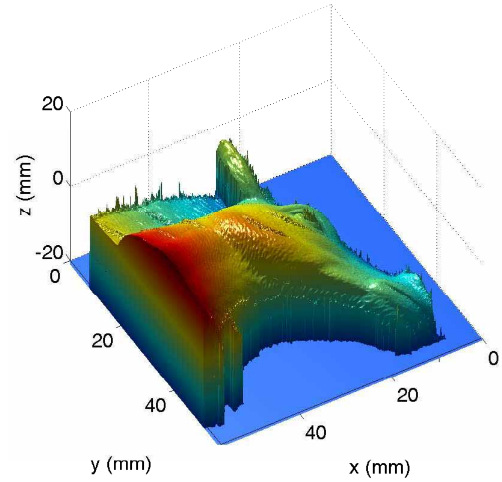

Fig. 4. 3-D plot of the measurement.

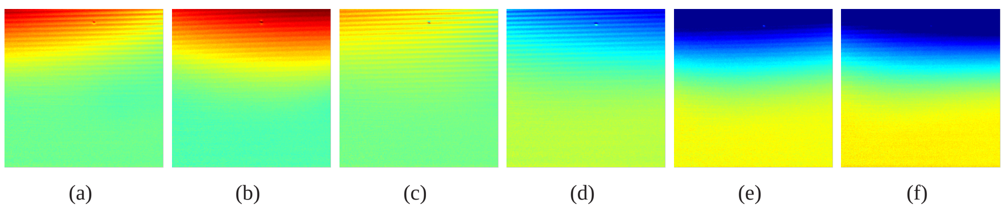

Fig. 5. Measurement results of a vibrating cantilever beam. The color of the image indicates depth, *z*, information (Media 1).

The same set of data is then visualized in 3-D plot. Figure 6 shows the 3-D plot of the data shown in Fig. 5(a). Another multimedia file, Fig. 6 (Media 2), submitted along with this paper shows the 3-D plot video of the vibrating beam. This experiment clearly demonstrated that at 667 fps, it is possible to measure cantilever beam vibration by using a phase-shifting method. However, the results also indicate some stripes caused by the motion, which is primarily due to the fact that the vibration speed is faster than the camera can capture. But overall, the 3-D shape is well captured.

4. Summary

This paper has presented a superfast 3-D shape measurement technique by integrating our recently proposed flexible 3-D shape measurement technique into the DLP Discovery technology. We have successfully reached an unprecedented 667 Hz 3-D shape measurement speed, albeit we have not achieved the maximum frame rate, which should be over 10,000 Hz because of the light intensity of the projection system. Because intrinsically, a DLP technology can switch binary images at MHz, it is potentially feasible to achieve MHz 3-D shape measurement rate by adapting this proposed 3-D shape measurement technology.

Even though the speed of this proposed system could reach an unprecedentedly high level, it also presents new challenges that need to be addressed to overcome the associated limitations. Comparing a conventional fringe generation approach where a focused projector is used, the

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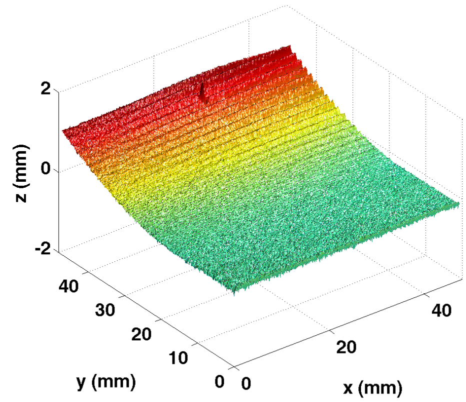

Fig. 6. Measurement results of a vibrating cantilever beam and plotted in 3-D (Media 2).

proposed technique has the following two main limitations: (1) accuracy is lower. This is because there is no existing technique to calibrate a defocused projector. The linear approximation cannot reach high accuracy if the measurement range is large; and (2) the measurement range is smaller. Unlike a conventional approach where the fringe patterns are always sinusoidal, the fringe patterns in this proposed system are not sinusoidal when the projector is close to be focused. The nonsinsuiodal fringe pattern will introduce additional measurement error. To over these limitations, we are developing new calibration technique for defocused projectors, and are exploring certain means to circumvent the problems induced by nonsinusoidal waveform when the projector is close to be focused.

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