Generating sinusoidal fringe by defocusing: potentials for unprecedentedly high-speed 3-D shape measurement using a DLP projector

Ji Li and Song Zhang*

Department of Mechanical Engineering, Iowa State University, Ames, IA, USA 50011.

ABSTRACT

This paper presents a technique that reaches 3-D shape measurement speed beyond the digital-light-processing (DLP) projector's projection speed. For this technique, a "solid-state" binary structured pattern is generated with each micro-mirror pixel always being at one status (ON or OFF). By this means, any time segment of projection can represent the whole signal, thus the exposure time can be shorter than the projection time. A sinusoidal fringe pattern is generated by properly defocusing a binary one, and the Fourier method can be adopted for 3-D shape measurement. We have successfully reached 2000 Hz 3-D shape measurement speed with good measurement quality. Because the fringe pattern is generated digitally, this proposed technique provides an alternative flexible approach for high-speed applications.

Keywords: High speed; three dimensional; fringe analysis; defocusing; grating.

1. INTRODUCTION

With recent advances in computational technology and shape analysis, high-speed 3-D shape measurement has become unprecedentedly important. Over the years, a number of techniques have been developed. Among these techniques, fringe analysis stands out because of its numerous advantages.[1] A Fourier method reaches the fastest 3-D shape measurement rate because it only requires a single fringe pattern.[2]

Conventionally, the fringe patterns are either generated by a mechanical grating or by a laser interference. These techniques have been widely applied to numerous application in optical metrology. However, it is typically not very flexible for them to adjust the fringe pitch (period) at a desired value.

Digital fringe projection technique, recently emerged as a mainstream, has the advantage of generating and controlling the fringe pitch accurately and easily. However, because of its digital fringe generation nature, the 3-D shape measurement speed is ultimately determined by the fringe projection rate: typically 120 Hz (RGB) for a typical digital-light-processing (DLP) projector. Moreover, because the DLP projector generates the grayscale fringe images by time modulation,[3] the camera exposure time cannot be shorter than the single channel projection time (1/360 sec). This limits its application to measure very fast motion (e.g., vibration) when a very short exposure time is needed.

To capture fast motions, a *solid-state* fringe pattern is usually desirable and a Fourier method[2] is usually necessary. The solid-state fringe pattern can be generated by a mechanical grating, or by laser interference. However, as addressed earlier, it is very difficult for a digital fringe projection technology to produce solid-state fringe pattern, because it typically refreshes at 120 Hz. On the other hand, because of its inherently digital fringe generation nature, the digital fringe generation technique has some advantageous features including flexibility to generate fringe patterns and shift the phase accurately.

This research is to enable digital fringe projection technique to generate "solid-state" by employing our recently developed flexible 3-D shape measurement technology through defocusing.[4] For this technique, instead of using 8-bit grayscale fringe images, the binary graylevel (0s or 255s) is used. This coincides with the fundamental image generation mechanism of the DLP technology that operates the digital micro mirrors in binary status (ON of OFF). Therefore, theoretically, if a micro mirror is set to be a value of 0 or 255, it should stays OFF or ON all the time. By this means, the micro mirror will act as solid-state (does not change), thus the solid-state light should be generated. This binary structured patterns can be converted to seemingly sinusoidal ones if the projector is properly defocused.[4]

*song@iastate.edu; phone 1 515 294 0723; fax 1 515 294 3261; www.vrac.iastate.edu/~song.

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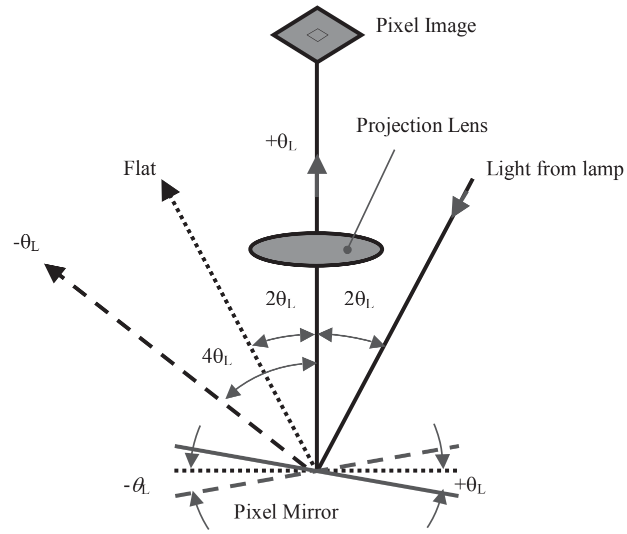


Fig. 1. Optical switching principle of a digital micromirror device (DMD).

To verify the performance of the proposed technology, an inexpensive off-the-shelf DLP projector (less than $400) is used to generate the sinusoidal fringe patterns, and a high-speed CMOS camera is used to capture the fringe images reflected by the object. Our prototype system has successfully reached 2000 Hz rate with good quality. In contrast, if a conventional fringe generation technique is used, once the capturing rate goes beyond 360 Hz, the waveform of the capture fringe pattern becomes nonsinusoidal in shape, and measurement error will be significantly increased. Because the fringe pattern is generated digitally, this proposed technique provides an alternative flexible approach for high-speed 3-D shape measurement that is traditionally utilizes a mechanical grating, or a laser interference.

Section 2 introduces the principle of the proposed technique. Section 3 shows some experimental results. Section 4 discusses the advantages and limitations of the proposed technology, and Sec. 5 summarizes this paper.

2. PRINCIPLE

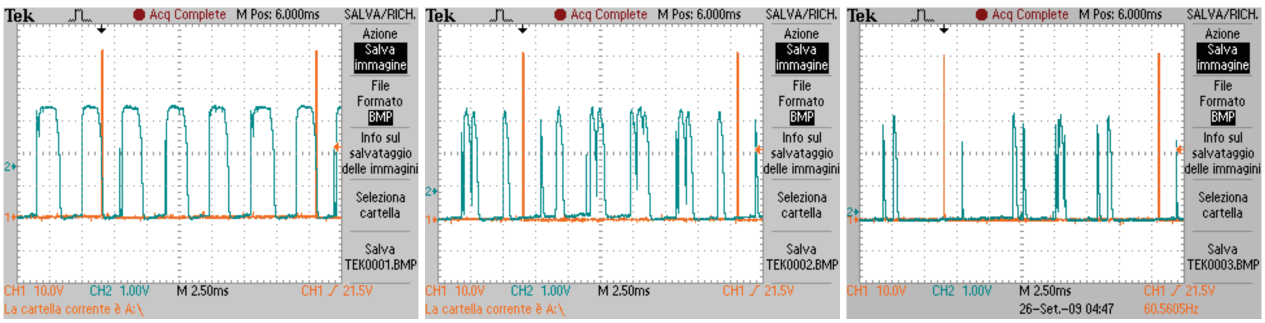
2.1 Revisit of digital-light-processing (DLP) technology

Digital light processing DLP^{TM} concept originated from Texas Instruments in the later 1980's. In 1996, Texas Instruments began its commercialized DLP^{TM} technology. At the core of every DLP^{TM} projection system there is an optical semiconductor called the digital micro-mirror device, or DMD, which functions as an extremely precise light switch. The DMD chip contains an array of hinged, microscopic mirrors, each of which corresponds to one pixel of light in a projected image.

Figure 1 shows the working principle of the micro mirror. Data in the cell controls electrostatic forces that can move the mirror $+\theta_L$ (ON) or $-\theta_L$ (OFF), thereby modulating light that is incident on the mirror. The rate of a mirror switching ON and OFF determines the brightness of the projected image pixel. An image is created by light reflected from the ON mirrors passing through a projection lens onto a screen. Grayscale values are created by controlling the proportion of ON and OFF times of the mirror during one frame period - black being 0% ON time and white being 100% ON time.

DLP^{TM} projectors embraced the new DMD technology to generate the color images. All DLP^{TM} projectors include light source, a color filter system, at least one digital micro-mirror device (DMD), digital light processing electronics, and an optical projection lens. For a single-chip DLP projector, the color image is produced by placing a color wheel into the system. The color wheel, that contains red, green, and blue filters, spins at a very fast speed, thus red, green, and blue channel images will be projected sequentially onto the screen. However, because the refreshing rate is so high, human eyes can only perceive like a color image instead of three sequential ones.

A DLP projector produces a grayscale value by time integration.[3] A simple test was performed for a very inexpensive DLP projector, Dell M109S. The output light was sensed by a photodiode, and photocurrent is converted to voltage signal and monitored by an oscilloscope. Figure 2 shows some typical results when it was fed with uniform images with different grayscale values. The projector synchronizes with the computer's video signal through VSync. If the pure green, RGB = (0, 255, 0), is supplied, there are five periods of signal output for each VSync period and the signal has the duty cycle of almost 100% in during each channel duration. When the grayscale value is reduced to 128, approximately half of the channel is filled. If the input grayscale value is reduced to 64, a smaller portion of the channel is filled. These experiments show that if the supplied grayscale value is somewhere between 0 and 255, the output signal becomes irregular. Therefore, if a sinusoidal fringe pattern varying from 0 to 255 is supplied, the whole projection period must be captured to correctly capture the image projected from the projector. This is certainly not desirable for high-speed 3-D shape measurement where the exposure time must be very short.



(a) (b) (c)

Fig. 2. Example of the projected timing signal if the projector is fed with different grayscale value of the green image. (a) 255; (b) 128; (c) 64.

2.2 Principle of generating fringe pattern by defocusing

In the previous section, we have discussed that if the micro mirror of the DLP projector is fed with 0 or 255, it will remain the state of OFF or ON 100% of time. Therefore, if only 0 or 255 is used for each pixel, the projected light will be *solid-state*. This provides the insight that it might be feasible to generate solid-state fringe patterns by the DLP technology. However, it also indicates that only 0s or 255s can be used in order to do so. This means that it is impossible to generate 255 gray level sinusoidal fringe patterns in a conventional fashion.

Defocussing has been used to get rid of pixel effects for a long time, but using it to make smooth irradiance profiles is new. Our recent study showed that by properly defocusing a binary structured pattern, an approximately sinusoidal one can be generated.[4] Figure 3 shows some typical results when the projector is defocused to different degrees while the camera is in focus. It shows that if the projector has a different defocusing level, the binary structured pattern is distorted to different degree. Fig. 3(a) shows the result when the projector is in focus: clear binary structures on the image. With the degree of defocusing increasing, the binary structures become less and less clear, and the sinusoidal ones become more and more obvious. However, if the projector is defocused too much, sinusoidal structures start diminishing, as indicated in Fig. 3(f). Fig. 3(g)-Fig. 3(l) illustrate one cross sections of the associated fringe patterns. This experiment indicates that a seemingly sinusoidal fringe pattern can indeed be generated by properly defocusing a binary structured pattern.

2.3 Fourier method for 3-D shape measurement

Fourier method for 3-D shape measurement was proposed by Takeda and Mutoh in 1983,[2] and has been widely applied to many applications.[5] This technique has the advantage of 3-D shape measurement speed because only one single fringe image is required. Essentially, it takes one single fringe images to perform Fourier transform, a band-pass filter is applied to keep the carrier frequency component, and finally the phase is obtained by applying an inverse Fourier transform for phase calculations. Typically, a fringe pattern can be mathematically represented as

$$I = a(x,y) + b(x,y)\cos(\phi(x,y)), \tag{1}$$

where $a(x,y)$ is the DC component or average intensity, $b(x,y)$ the intensity modulation or the amplitude of the carrier fringes, and $\phi(x,y)$ the phase to be solved for.

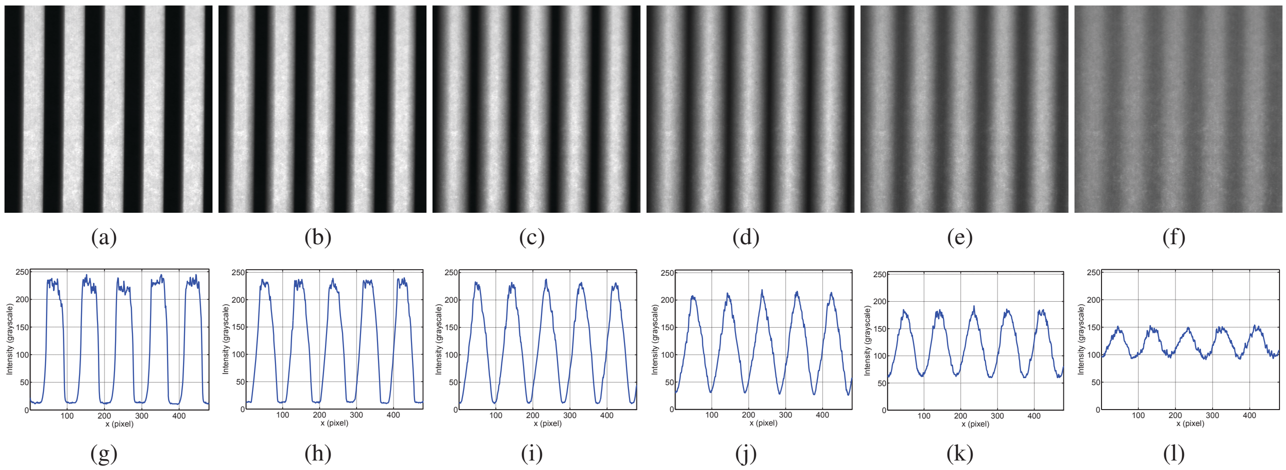


Fig. 3. Example of sinusoidal fringe generation by defocusing a binary structured patterns. (a) shows the result when the projector is in focus; (b)–(f) show the result when the projector is increasingly defocused. (g)–(l) illustrate the 240 row cross section of the corresponding above image.

If Eq. (1) can be rewritten in complex form as

$$I = a(x,y) + \frac{b(x,y)}{2}\left[e^{j\phi(x,y)} + e^{-j\phi(x,y)}\right]. \tag{2}$$

If a bandpass filter is applied in the Fourier domain so that only one of the complex frequency component is preserved, we will have

$$I_f(x,y) = \frac{b(x,y)}{2}e^{j\phi(x,y)}. \tag{3}$$

Then the phase can be calculated by

$$\phi(x,y) = \arctan\left\{\frac{Im[I_f(x,y)]}{Re[I_f(x,y)]}\right\}, \tag{4}$$

here $Im(X)$ is to take the imaginary part of the complex number X, and $Re(X)$ to get the real part of the complex value X. This equation provides phase values ranging from $-\pi$ to $+\pi$. The continuous phase map can be obtained by applying a phase unwrapping algorithm.[6] 3-D coordinates can be calculated once the system is calibrated.[7]

3. EXPERIMENTS

To verify the performance of the proposed algorithm, we developed a 3-D shape measurement system as shown in Fig. 4. We used an inexpensive LED projector Dell M109S whose cost is less than $400 and is very compact. The projector has an image resolution of 858×600, and 10,000 hours of life time. The brightness of the projector is 50 ANSI Lumens. The projection lens is a F/2.0, f = 16.67 mm fixed focal length one. The projection distance is 559.4-2000.3 mm. The DMD used in this projector is 0.45-inch Type-Y chip. The camera used in this system is a high-speed CMOS camera, Phantom V9.1 (Vision Research, NJ), it can capture 2-D images at 2000 Hz rate with a image resolution of 480×480. The exposure time used for all experiments is 250 μs. Because the brightness of the projector is not enough if the camera has a very short exposure time, a converging lens is placed in front of the projector is focus the projected image onto an area of approximately 67 mm $\times$ 50 mm.

We first measured a static object using the system described above. Figure 5 shows the measurement result. Figure 5(a) shows the photograph of the sculpture to be measured. Figure 5(b) shows the captured fringe image that shows seemingly sinusoidal patterns. A 2-D Fourier transform is then applied the fringe image that will result in the map in frequency domain as shown in Fig. 5(c). Once a proper band-pass filter is applied, the wrapped phase can be obtained by applying Equation (4). Figure 5(d) shows the wrapped phase map. A phase unwrapping algorithm[8] is then applied to unwrapped

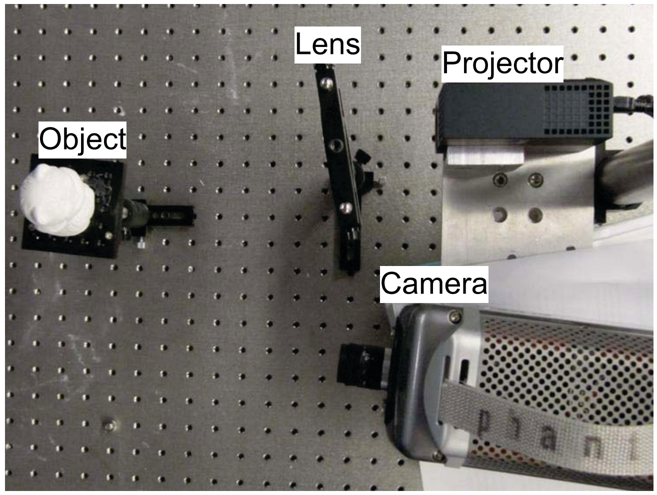
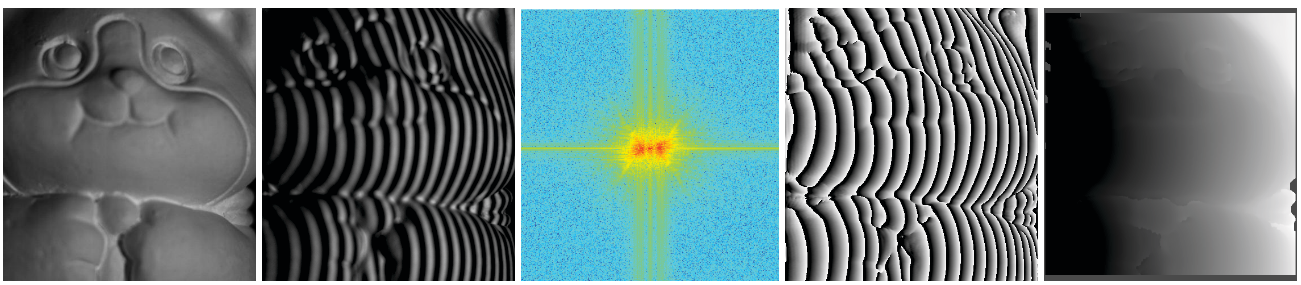


Fig. 4. Photograph of the test system.



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

Fig. 5. Example of sinusoidal fringe generation by defocusing a binary structured patterns. (a) Photograph of the object; (b) Fringe image; (c) Frequency map after Fourier transform; (d) Wrapped phase; (e) Unwrapped phase.

the phase obtained continuous phase map as shown in Figure 5(e). The unwrapped phase map can be converted to 3-D coordinates using a phase-to-height conversion algorithm introduced in Ref.[9] Figure 6 shows the 3-D plot of the measurement. The result looks good, however, some residual stripe errors remains. This might be because the defocusing technique cannot generate ideal sinusoidal fringe patterns, and a phase error compensation algorithm needs to be developed to reduce this type of errors.

Because the fringe capturing speed is very fast (2000 Hz), this technique can be used to measure a faster motion, e.g., vibration. To verify this capability, a vibrating cantilever beam is measured. Figure 7 shows some typical measurement frames. This experiment clearly shows that the motion is well captured for such a simple system setup.

As a comparison, we used the same system set up and a conventional sinusoidal fringe generation method to capture the fringe images at 2000 Hz rate. Figure 8 shows some typical recorded fringe images that do not appear be sinusoidal in shape. Therefore, high-quality 3-D shape measurement cannot be performed from them.

4. DISCUSSIONS

By properly defocusing binary structured patterns to be sinusoidal, the DLP projector can essentially be converted into a digital *solid-state* fringe generation system. Because of its digital fringe generation nature, there are some advantageous features associated with it

- *Flexible:* Because the fringe patterns are generated digitally, it is easier than a mechanical grating to change the fringe patterns, e.g., fringe pitch.
- *Adaptable:* This system can be easily converted to a phase-shifting based 3-D shape measurement system because the phase shift can be easily generated by spatially moving the binary structured patterns. In fact, we have developed

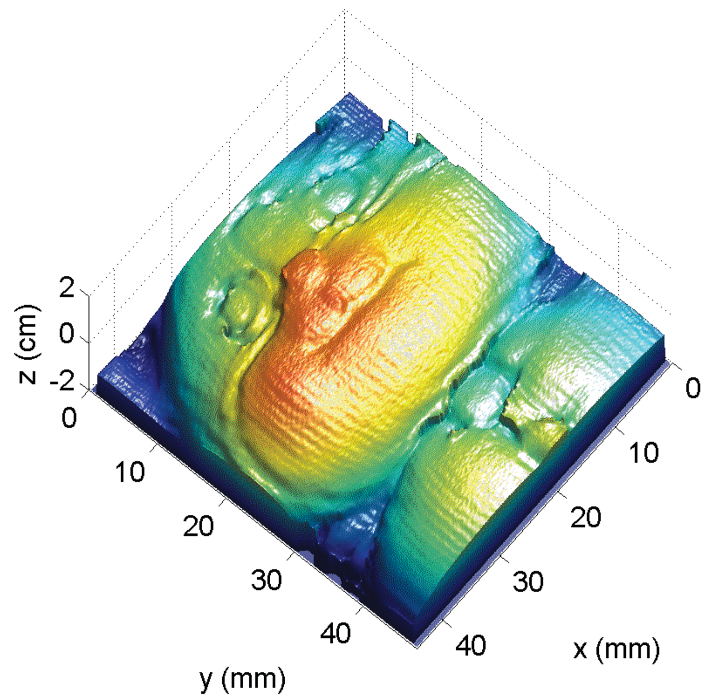


Fig. 6. 3-D plot of the measurement result shown in Fig. 5.

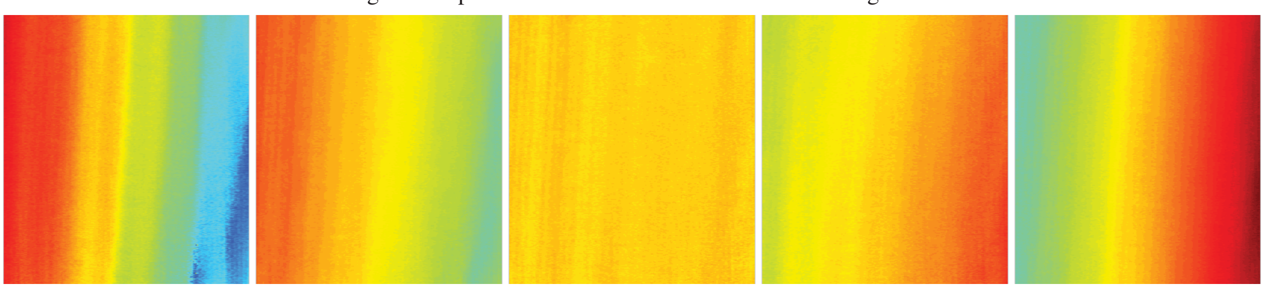


Fig. 7. Experimental results of a vibrating cantilever beam.

a superfast 3-D shape measurement system based a similar fringe generation approach employing a faster binary structured pattern switching system (DLP Discover).[10] We have successfully realized 3-D shape measurement speed of 667 fps using a three-step phase-shifting algorithm.

- *Compact:* The whole system including the illuminator are packaged into the DLP projector. The DLP projector, especially the LED-based projector becomes smaller and smaller, thus the 3-D shape measurement system can be miniaturized by taking advantage of the new hardware technology.
- *Inexpensive:* The DLP projector becomes cheaper and cheaper, there are some with a price below $200 (e.g., Optoma PK100 Pico Projector).

However, because the projector is defocused, the depth range is relatively smaller comparing with a traditional sinusoidal fringe generation technique. Another possible shortcoming is that it is theoretically not possible to generate ideal sinusoidal fringe pattern from this manner, therefore, some phase error compensation methods need to be developed to reduce the associated measurement errors.

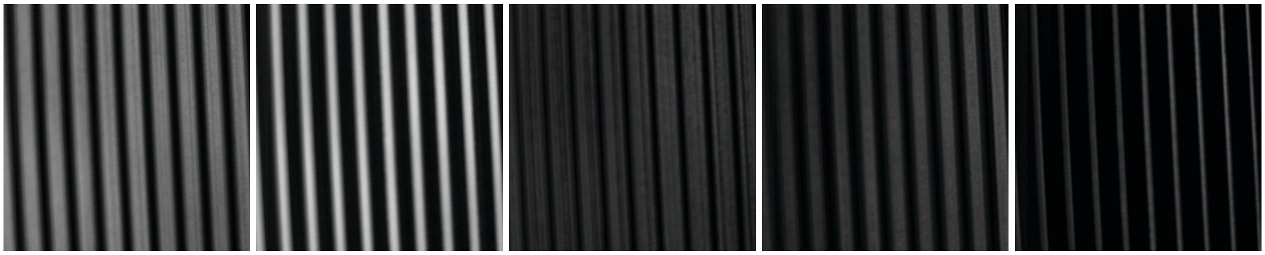


Fig. 8. Captured fringe image when a conventional sinusoidal fringe generation technique is used.

5. CONCLUSIONS

This paper has presented a technique that achieves unprecedented 3-D shape measurement speed with a DLP projector. It eliminates the speed bottleneck of a conventional sinusoidal fringe generation technique by adopting the 3-D shape measurement based based on a defocusing technique. Because only binary structure patterns, with each micromirror always being one stage (ON or OFF), are used, the exposure time can be shorter than projection time. By this means, the system can measure faster motion with high quality. Experiments have been presented to demonstrate we could achieve 3-D shape measurement speed at 2000 Hz rate if a Fourier fringe analysis technique is used. This proposed methodology has the potential to replace a conventional mechanical grating method for 3-D shape measurement while maintains the merits of a digital fringe generation technique. In the future, we will work on developing methodologies to compensate for the residual phase error that are caused by the nonsinusoidality of the fringe patterns.

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