

Ultra High-speed 3-dimensional Profilometry Using a Laser Grating Projection System

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The grating projection method with phase-shifting technique is very useful in measuring the 3-dimensional (3D) shape with high accuracy and speed. In this work, we have developed an ultra high-speed digital laser grating projection system using a high-power laser diode and a high-sensitivity CMOS camera. With our system, the optical measurement required to find out the profile of a 3D object could be carried out within 2.6 ms, which is a significant (~10 times) improvement compared with those of the previous studies.

Keywords : Ultra high-speed 3D profilometry, 3D shape measurement, Laser grating projection, Phase shifting, Two-wavelength phase unwrapping

OCIS codes : (110.0110) Imaging systems; (110.6880) Three-dimensional image acquisition; (120.0120) Instrumentation, measurement, and metrology; (120.6650) Surface measurements, figure; (100.0100) Image processing

I. INTRODUCTION

The need for rapid and accurate measurements of the 3-dimensional (3D) shape has been steadily increasing. Accordingly, there have been many technologies developed to improve the qualities of 3D shape measurement [1-15]. The fringe pattern projection method based on the phase-shifting technique has been considered very effective for its high speed and accuracy [10, 13-15]. Especially the digital fringe projectors (LCD, DMD, or Polygon-mirror type) have great flexibility in generating fringe patterns since the patterns can be controlled easily by a computer program [12, 15, 16].

Recently we demonstrated a very useful laser grating projection (LGP) system for the measurement of 3D shapes, where a laser diode (LD) and a revolving polygon mirror (PM) were used to generate the grating patterns whose phase could be varied [16]. It was shown that all the optical measurement required to find out the profile of the 3D object could be carried out within 31 ms, which confirmed the validity of our

3D measurement system. The result also implied the more important fact that the speed of 3D measurement could be enhanced remarkably since, in our system, there was no device like LCD or DMD whose response time limits the speed.

The rapid measurement is generally very important since it often makes us observe what used to be unrecognized and understand the phenomenon clearly, as you can see in the ultra-fast photography how much a golf ball is suppressed at the moment a club hits it. In the 3D shape measurement, there has also been an ever increasing need for more rapid measurement for the last several years [17]. For example, research on speaker systems aims to know how the 3D shape of the diaphragm evolves as it makes sounds.

In this work, we have used the high-power LD and high-sensitivity CMOS camera in the LGP system, which resulted in significant reduction of the measurement time. In order to show the flexibility of our LGP system, we have adopted the two-wavelength phase-unwrapping method that is different from the gray code method in the previous work [16]. In addition, we have proposed a schematic that can double the measure-

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ment speed by slightly modifying our measurement system.

II. EXPERIMENT AND RESULTS

Fig. 1 shows the schematic of the LGP system. The laser beam from the LD was converted to the slit beam by a condenser and a rod lens. The polygon mirror (PM) was composed of 14 evenly-divided reflective facets and made 10,000 revolutions per minute. Since the LD was repeatedly turned on and off very rapidly, the laser slit beam reflected from the PM formed a laser grating patterns on the object to be measured. If we capture several different grating images laid on the object, we can find out the 3D shape of the object.

Instead of repeating the same basics of the measurement which has been described in detail in reference [16], we think it will be more appropriate to provide the specifications of the LGP system as shown in Table 1.

Since the frame rate of the CMOS camera (Integrated

Design Tools Inc., M-3) is limited to 500 frames/s at 1280×1024 resolution, we have reduced the region of interest (ROI) to 640×224 to achieve higher frame rate.

Before beginning the 3D profilometry of an object, it is necessary to obtain the images of the laser grating illuminated on the flat surface. Later the data extracted from the laser grating images of the plane are going to be used to correct the 3D shape of the measured object by eliminating the systematic errors caused by lens aberrations, inaccurate system parameters, etc.

Fig. 2 shows such images. Since we adopted the two-wavelength phase unwrapping method [18,19], there are two images present having grating pitches different from each other. Note that the ‘wavelength’ does not mean the optical wavelength, but the pitch of the grating. The pitches at the center of the plane were $\lambda_1 = 2.17$ mm and $\lambda_2 = 2.61$ mm, which indicates that the LD was turned on and off with periods of $1.5 \mu\text{s}$ and $1.8 \mu\text{s}$, respectively. In the gray code method, the dynamic range of the measurement is proportional to 2^n where n is the number of gray code patterns. Hence if the measurement time is not crucial and the roughness of the object is large, the high-bit gray code method is useful. On the other hand, the dynamic range of the two-wavelength phase-unwrapping method can be easily increased since it is inversely proportional to the pitch difference $|\lambda_1 - \lambda_2|$. If the pitch difference is too small, however, the noise in the process of pattern projection and image capturing makes it difficult to achieve the accurate profile of the object. Generally the two-wavelength phase-unwrapping method is advantageous for high-speed 3D profilometry [18, 19].

Next we carried out the 3D profilometry. The object used in the experiment is shown in Fig. 3. The dimension of the object was 190 (width) \times 160 (height) \times 80 (depth) mm^3 .

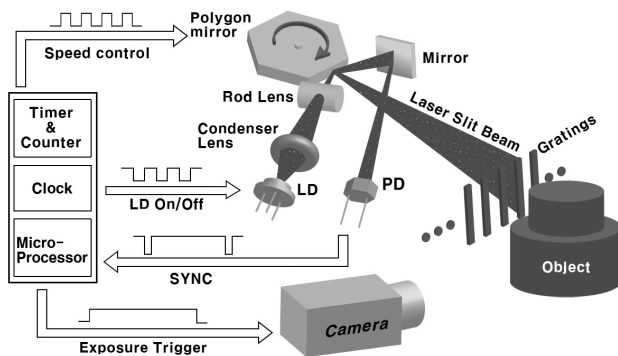


FIG. 1. Schematic diagram of laser gratings projector.

TABLE 1. Specifications of the LGP system

Items	Specification
Polygon Mirror	14 facets
Rotating Speed of Polygon Mirror	10,000 rpm
Laser Diode	120 mW, Optical wavelength = 660 nm
Focal Length of Condenser Lens	4.6 mm
Diameter of Rod Lens	7 mm
CMOS Image Sensor Pixel Size	12 μm
CMOS Resolution	1280 X 1024
Frame Rate of Camera	500 frames/sec @1280 X 1024
Imaging Lens	f = 25 mm, F# = 0.95
Main Clock of LD Modulation	40 MHz
Programmable Logic Device	ALTERA MAX
Microprocessor	ATMEGA128

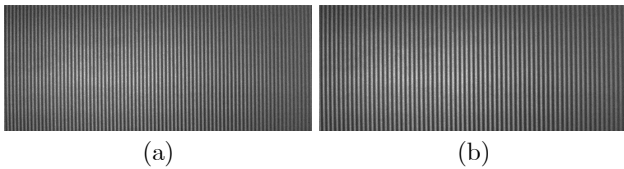


FIG. 2. Images of the laser gratings laid on the reference plane with pitch of (a) 2.17 mm and (b) 2.61 mm.

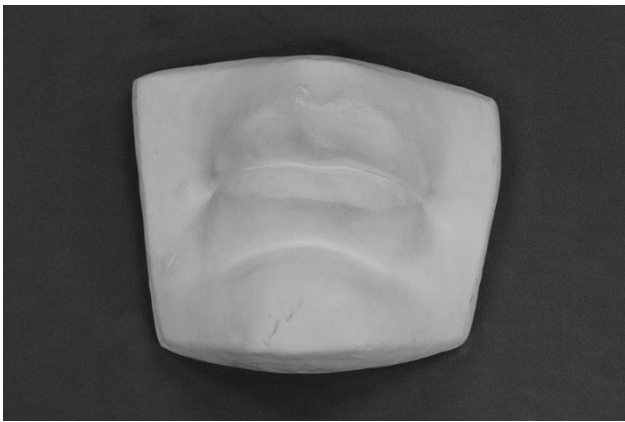


FIG. 3. Photograph of the sample object (W:190 mm, H: 160 mm, D: 80 mm).

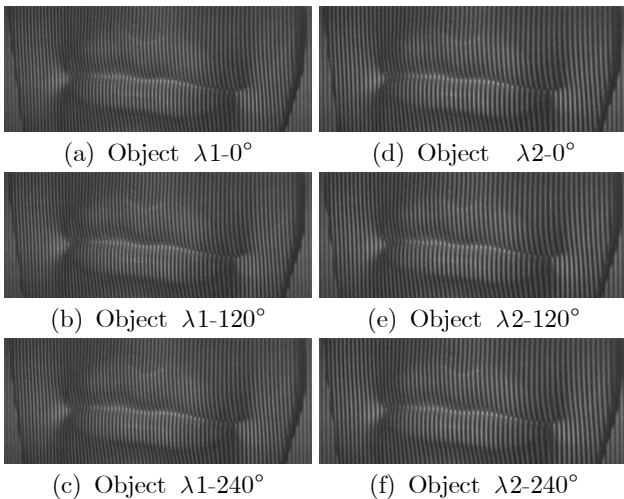


FIG. 4. The images of the laser gratings illuminated on the object.

With respect to one pitch (or wavelength) of the laser grating, we made three different grating patterns by changing the phase of the grating. The phase difference between successive grating patterns was 120° . After capturing these three grating images, we changed the grating pitch and repeated the same procedure for the other grating pitch. Hence we have obtained six images in total which are shown in Fig. 4.

With the high-power LD and high-sensitivity CMOS camera, we could capture the images in facet by facet, which means the whole process of acquiring the six

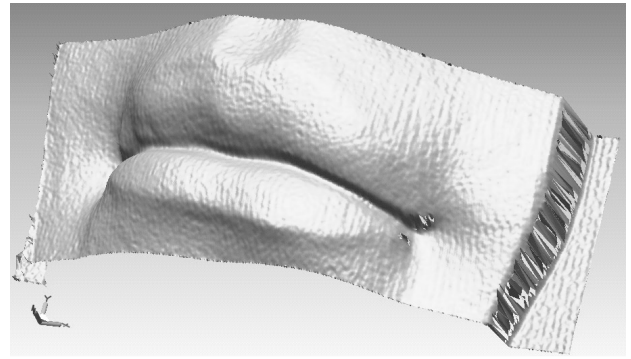


FIG. 5. Reconstructed 3D image of the object.

images was carried out while the laser beam was encountering the six facets of the PM. Since the PM was revolving 10,000 times per minute, the measurement time is found to be as small as 2.572 ms, which is ~ 10 times shorter than those of the previous research [11, 12, 20, 21].

Using the signal processing algorithm with the data obtained in Fig. 2 and Fig. 4, we reconstructed the accurate 3D image of the object (Fig. 5), which confirms the validity of our 3D profilometry.

III. CONCLUSIONS

In this work, we have demonstrated the ultra high-speed 3D profilometry using a laser grating projection system composed of a high-power LD, a polygon mirror, and a high-sensitivity CMOS camera. The measurement time of 2.572 ms has been achieved, which is ~ 10 times enhancement compared with the earlier researches.

Such a short measurement time is difficult to obtain with the conventional liquid crystal display (LCD) or digital micromirror device (DMD) projection system where, apart from the slow response time of the LCD or DMD, the change of grating patterns needs the transmission of a large amount of 2-dimensional image data.

With our LGP system, it is possible to capture as many as 389 3D profiles per second, which will satisfy the most demanding requirements of today's researches [17]. It is also expected that we can double the measurement speed by adding a green and a blue laser diode to our LGP system and adopting the color camera (Fig. 6).

In the 3D profilometry using the system shown in Fig. 6, we can project the two gratings having different pitches simultaneously by allocating the narrower pitch (λ_1) to the red LD and the wider pitch (λ_2) to the blue LD. The green LD does not create any grating pattern but provides a constant background color. The intensity of the green LD is around half of that of the bright line in the laser gratings. By analyzing the color

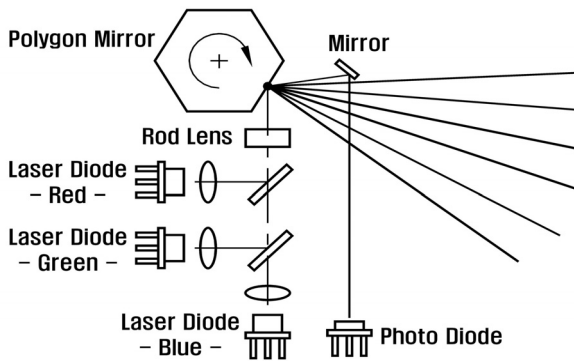


FIG. 6. Schematic of the color 3D profilometry system.

images of the projected patterns, we can obtain the color texture of the object as well as the 3D shape of the object [8, 12, 20, 21]. In this way, the LGP system using the polygon mirror can provide all the functions that the LCD or DMD projection system is having.

Since we can cast two gratings at the same time, the time to gather the optical information can be reduced by half compared with the system using only one laser diode. Therefore the color 3D profilometry system can acquire 778 3D frames/s where each frame includes the information on both profile and colors of the object. Furthermore, it will not be impossible to achieve the frame rate of 1000 if we increase the angular velocity of the polygon mirror by 30%.

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