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Shape from Pattern Light Projection: Object having a diffusive and specular surface

Sosuke Tsukamoto *
Graduate School of Sciences and Engineering
Yamaguchi University

Hidetoshi Miike †
Faculty of Engineering
Yamaguchi University

Abstract

We propose a depth evaluation method which utilizes a liquid crystal projector. The method is based on the phase shift technique. A sinusoidal grating pattern is used. The phase wrap problem is solved by the introduction of hierarchical pattern projection starting from one-cycle sinusoidal grating. We assume that the object have a diffusive and specular surface. Then the specular surface generates an area of highlights. The highlights may cause erroneous results on phase estimation. This paper describes the influence of highlights on the phase estimation. And confirmed that the influence is almost negligible except for the center of highlights.

1 Introduction

The range finder [1, 2] is a realistic tool to obtain the three-dimensional (3D) shape information in terms of accuracy and measurement time. A lot of methods and improvements have been proposed (e.g. [3, 4]), however, special equipment like a laser light source is required. On the other hand, the moiré topology (e.g. [5]) is useful to estimate the shape of the object with higher accuracy, but there is no definitive soluition to solve the phase wrap (unwrap) problem.

Meanwhile, under the development of liquid crystal devices, liquid crystal projectors have come into wide use recently. The projector can project any patterns onto the object and the resolution is improving day by day, so it is the trend to use the projector instead of the special equipment. But the resolution of the projector is limited (compared to the scaning laser light method). Required accuracy of 3D shape is not achieved in the use of the projector with the conventional method.

*Address: 16–1 Tokiwadai 2–chome, Ube-shi, 755–8611 Japan. E-mail: tsuka@sip.eee.yamaguchi-u.ac.jp
†Address: 16–1 Tokiwadai 2–chome, Ube-shi, 755–8611 Japan. E-mail: miike@kde.yamaguchi-u.ac.jp

In this study, we try to develop a reliable method to recover 3D shape using pattern light projector. The method is based on the phase shift technique [6]. The projector projects a sinusoidal grating pattern onto the object. The phase wrap problem can be solved by the introduction of hierarchical pattern projection starting from one-cycle sinusoidal grating. To obtain absolute depth information of the object, the camera acquires diffusively reflected patterns on the object, and the triangulation is used [7].

On the other hand, as described in ref. [8], the specularly reflected pattern is sensitive to the surface tilt of the object. By assuming that the object have a diffusive and specular surface, we can estimate the subtle shape of the object surface through the specularly refrected pattern. Problem is that the specular surface generates areas of highlights. The highlights may cause erroneous results on phase estimation. It is possible to suppress the highlights by polarizing the light after reflection on the object, however, the polarizer cannot eliminate perfectly the influence of the highlights.

To overcome this problem, we introduce the second camera that locates on another place. Even if the image acquired by the second camera has highlights, the position on the object is different. Thus, we can mark the areas of highlights on each image and apply the other camera's depth information to the area.

2 Depth Estimation

2.1 Triangulation

To obtain the depth information of the object, the triangulation is used. Figure 1 shows the measurement system for the proposed method. Fundamentally, projected pattern has one-cycle sinusoidal grating. The pattern is shifted with constant velocity (see Fig. 2).

$$P(x', y', t) = A_p \sin\left(2\pi\left(t/T + x'/L\right)\right) + B_p, \quad (1)$$

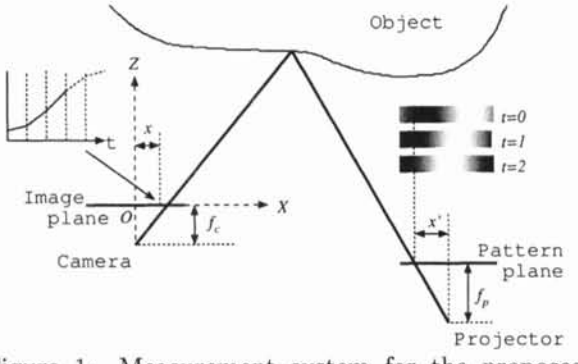

Figure 1: Measurement system for the proposed method.

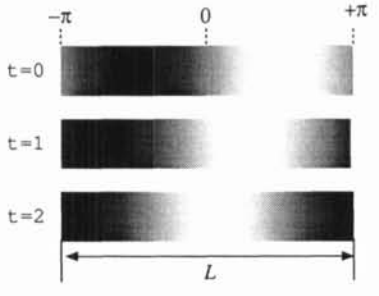

Figure 2: Sinusoidal grating pattern ($\omega = \pi/4$)

where x' and y' are the position of the pattern plane (the origin of the coordinate is located at the center of the plane), P is a brightness of the pattern, A_p and B_p are the bias, t [frame] is a time, T [frame] is a time span to move the patterns one cycle, and L [pixel] is a widths of the pattern plane.

On the assumption that intensity of the pattern is proportional to the image brightness, the temporal changes of the brightness on any point in the image show a sinusoidal wave.

$$I(x, y, t) = A_i \sin(2\pi t/T + \phi(x, y)) + B_i, \qquad (2)$$

where x and y are the position of the image plane (the origin of the coordinate is located at the center of the plane), I is an image brightness, and A_i and B_i are the bias of the intensity.

The phase of the sinusoidal signal corresponds to the position where the pattern is projected at the beginning ($t=0$). By compairing eq.(1) and eq.(2), we can obtain the following relationships.

$$\phi(x, y) = 2\pi x'/L, \qquad (3)$$

$$x'(x, y) = \frac{\phi(x, y)L}{2\pi}. \qquad (4)$$

The projected pattern has the same phase on the vertical direction. Therefore, the depth of the point can be estimated as the intersection of the line (starting from the camera's focal point, toward the point on the image plane) and the plane (consisting of the projector's focal point and the same phase line on the pattern). The phase estimated is as follows.

$$\phi(x, y) = \tan^{-1} \frac{\sum_{t=0}^{T-1} I(x, y, t) \cos\left(\frac{2\pi t}{T}\right)}{\sum_{t=0}^{T-1} I(x, y, t) \sin\left(\frac{2\pi t}{T}\right)}. \qquad (5)$$

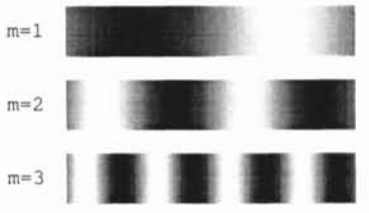

Figure 3: Example of higher frequency patterns.

2.2 To achieve higher accuracy

Since the projected pattern described above has only one-cycle sinusoidal wave in space, the phase resolution is not enough. We have introduced a hierarchical pattern projection method [7]. At the first step, we project the one-cycle ($m = 1$) grating pattern and obtain rough information of the phase distribution all over the image. The second step, we increase the wave cycle in space to two-cycles ($m = 2$). However temporal pattern shift required is only one-cycle (see Fig. 3). If we acquire the image sequence in the same frames, the pattern shift velocity should slow down. Thus, we can revise the phase information as follows.

$$\phi_m(x, y) = \phi_{m-1}(x, y) + \frac{1}{2^{m-1}} \cdot \tan^{-1} \frac{\sum_{t=0}^{T-1} I_m(x, y, t) \cos\left(\frac{2\pi t}{T} + 2^{m-1}\phi_{m-1}(x, y)\right)}{\sum_{t=0}^{T-1} I_m(x, y, t) \sin\left(\frac{2\pi t}{T} + 2^{m-1}\phi_{m-1}(x, y)\right)}, \qquad (6)$$

where m is the number of cycles on the pattern plane.

By the repetition of these processes from two- to many-cycles, we obtain reliable information for the phase. The number of the cycle m can be increased up to the limits of the projector's resolution (M_{max}).

3 Experiment and Result

3.1 Influence of highlights

As it was mentioned above, the highlights may cause erroneous results on phase estimation. To

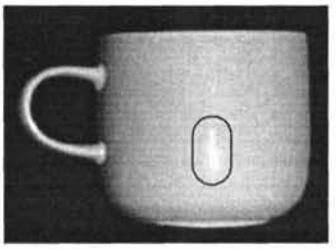

Figure 4: A mug image acquired without polarizer.

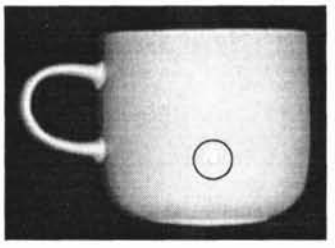

Figure 5: A mug image acquired with polarizer.

confirm the highlights influence, we carried out the experiment under two conditions that the polarizer is used or not. Figure 4 and Fig. 5 show the acquired images for this experiment. These images were acquired in the following conditions: $T=10$ [frame], $L=1024$ [pixel] and $M_{max}=9$. Circles on the figures indicate the areas of highlights.

To remove the background of the object in depth estimation, we put a black curtain in the rear, and a simple thresholding is used. Since the object has a specular surface, the highlights appear on a part of the object. The results of the absolute depth information obtained by the proposed method is shown in Fig. 6 and Fig. 7. The gray levels represent the depth information with the nearer point to be brighter.

3.2 Removing the influence of highlights center

The highlights center can be rejected by a simple thresholding, too. If the second camera is introduced and located in another place, the position of the center of highlights shifts to a different place on the object. Therefore, we can replace the depth information at the center of highlights by the depth information obtained from the second camera.

Figure 8 shows the estimated depth of the first camera adopting the above depth replacement technique.

3.3 Discussion

As shown in Fig. 6 and Fig. 7, regardless of the introduction of the polarizer, the estimated depth at the center of highlights has an error.. However, excepting for the center of highlights, the proposed method evaluate the depth information successfully.

The cause of the error ib the depth estimation at the center of highlights can be considered as follows. In spite of the temporal pattern shift on the object, the brightness at the center of highlights remains almost constant. This is caused by a brightness saturation at the center of highlights. For the proposed method, the S/N (signal-to-noise ratio) of the temporal brightness change is very important in the phase estimation. To obtain a high S/N at the center of highlights, we have to drop the intensity of the pattern light, or reduce the aperture of lens. However, this may reduce the S/N at the dark place on the image.

We also carried out the experiment in a reduced aperture condition. To compare the result with the depth replacement by the second camera (see Fig. 8), a sectional depth distribution across the center of highlights (sliced horizontally) is shown in Fig. 9. The solid line shows the depth distribution obtained by the depth replacement, and the dotted line shows the depth distribution obtained from the image acquired under the reduced aperture condition. The horizontal axis shows x-coordinate of the image, and the vertical axis shows the depth at the point. In this situation, the temporal change of the brightness at the center of the highlights increases compared with the case in Fig. 7. Thus, the depth around the center of highlights is successfully estimated. The depths around the area, however, still remain significant

Figure 6: Estimated depth of the mug image that acquired without polarizer.

Figure 7: Estimated depth of the mug image that acquired with polarizer.

Figure 8: Integrated depth using two cameras.

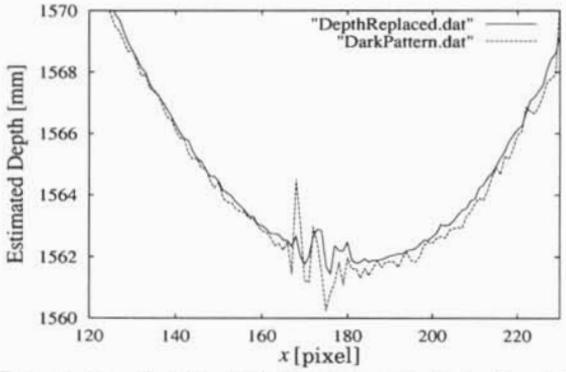

Figure 9: Depth distribution sliced horizontally across the center of highlights.

errors.

4 Summary

We have proposed a method that utilizes the liquid crystal projector to measure the 3D shape of the object having diffusive and specular surface. Our aim is to measure the shape with high accuracy by use of the speculary reflected pattern information. Through the comparison of results under two conditions, the polarizer is introduced or not, we confirmed that the highlights effect is almost negligible. However, the depth information at the center of highlights is not reliable. To overcome this problem, we introduced the second camera, and adopted the depth information obtained by the second camera to the center of highlights. But the depth information around the center of highlights is still fluctuated.

If the surface of the object is almost flat, we may estimate the subtle shape of the surface by introduction of specuraly reflected patterns. Including to make use of the speculary reflected patterns, the treatment of the brightness of the pattern is left for our future work.

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