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A novel three-dimensional shape measurement method based on a look-up table

Yanjun Fu*, Zhigang Wang, Guangyu Jiang, Jie Yang

Key Laboratory of Image Processing and Pattern Recognition (Nanchang Hangkong University), Jiangxi Province, 330063, China

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ABSTRACT

Fringe projection profilometry is widely used for three-dimensional shape measurement. In an oblique-angle projection, the fringe cycle is broadened on the reference plane. Phase errors are mainly caused by the nonlinear gamma of the projector and fringe cycle broadening. This study describes a phase error compensation method to eliminate these phase errors. A look-up table that stores phase errors is constructed for phase error compensation. Based on it, a new height equation is proposed. The experimental results show that the proposed method can compensate for the phase errors of the fringe projection profilometry, thereby improving the measurement accuracy significantly.

1. Introduction

Fringe projection profilometry is widely used for 3D shape measurement [1]. Fringe sinusoidal influences the measurement precision in fringe projection profilometry with divergent illumination. When larger objects are measured, the nonsinusoidal waveform is mainly caused by the nonlinear gamma of the projector and the fringe cycle broadening on the reference plane [2], resulting to an additional phase error. The previously proposed methods of resolving nonlinear gamma include the double three-step phase-shifting algorithm [3], 3 + 3 phase-shifting algorithm [4], application of tone correction to the fringe patterns before projection [5], pre-coding of projected grating to reduce measurement error caused by the gamma distortion [6], gamma correction method using a simple one-parameter gamma function technique by statistically analyzing the fringe images [7], a robust and simple scheme by combining a universal phase shift algorithm with a gamma correction method [8], a novel and simple interactive phase compensation algorithm [9], and a look-up table (LUT) [10–13]. LUT is a simple and effective phase error compensation method and can eliminate nonlinear gamma error. Other methods have also been proposed to solve fringe cycle broadening. Wang determined the relationship and the modified height expression between fringe cycles on the virtual reference plane and that on the reference plane [14]. Sansoni proposed an error compensation algorithm to correct the error caused by the cycle broadening of the projection fringe [15]. Rajoub obtained the relationship between the phase and height of a measured object based on a geometric analysis [16]. Salas deduced the relationship among the projection, object, and camera coordinates, and reported that the obtained phase distribution is independent of an equivalent wavelength [17]. Uneven fringe projection is used to obtain evenly spaced fringe in the measured volume [18,19]. The least-squares method is used to correct the phase error [20].

Phase errors caused by the nonlinear gamma of the projector and fringe cycle broadening are shown in Fig. 1. A novel 3D shape measurement method based on LUT is proposed. The proposed method can compensate for two types of phase errors simultaneously. While the previous methods can only compensate for one type of phase error. Thereby the proposed method improves the measurement accuracy significantly. However, in order to achieve higher speed, higher precision measurement, the higher speed and more effective interpolation method and subpixel technology must be carried out in-depth study in future work.

2. Theory

2.1. The measurement system

The measurement system is demonstrated in Fig. 2. The fringe patterns are projected obliquely onto the measured object and the images are captured by a camera. The optical axis of the projector and that of the camera intersect at point O, which is the origin. Points A and C are imaged at the same point in the camera. The projector and the camera are equidistant from the reference plane.

* Corresponding author.
E-mail address: fyjpkh@sina.com.cn (Y. Fu).

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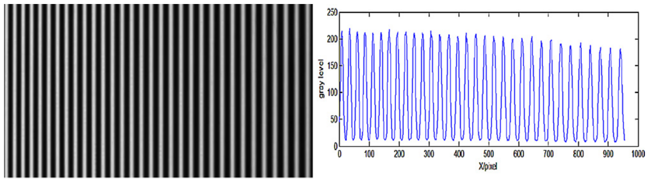

(a). (b)

Fig. 1. (a) A fringe image with cycle broadening and nonlinear gamma. (b) Grayscale of the fringe.

L is the distance between the camera and the reference plane and d is the distance between the camera and the projector. The height of the measured object is represented as [21]:

$$h = \frac{L\Delta\phi}{2\pi f_0 d + \Delta\phi} \tag{1}$$

where f_0 is the frequency of the fringe pattern on the reference plane and $\Delta\phi$ is the phase difference between the corresponding points on the reference and the object surface.

2.2. Phase error caused by fringe cycle broadening

Eq. (1) can be rewritten as:

$$\Delta\phi = \frac{2\pi f_0 dh}{L - h} \tag{2}$$

when measuring a long board with the same height, L, d, and h are fixed values. f_0 gradually decreases along the x-direction because of fringe cycle broadening. Eq. (2) shows that $\Delta\phi$ gradually decreases. The same height should have the same $\Delta\phi$, i.e., $\Delta\phi$ is smaller than the actual value.

During the actual measurement, f_0 is a constant obtained by calibration, Eq. (1) shows that h gradually decreases with $\Delta\phi$. The actual height of the long board is not equal to the measurement height, resulting in an error that is even more evident when larger objects are measured.

2.3. Phase error compensation method

In this study, a phase error compensation method based on a LUT is proposed, in which the unwrapped phase is considered as the abscissa and the phase error as the ordinate. For a smooth-surfaced object, the wrapped phase is calculated by a four-step phase shift method, and the unwrapped phase is obtained by a simple phase unwrapping algorithm. For a complex-surfaced object, the unwrapped phase can be determined by temporal phase unwrapping algorithm [22]. The steps to establish a phase error LUT are as follows:

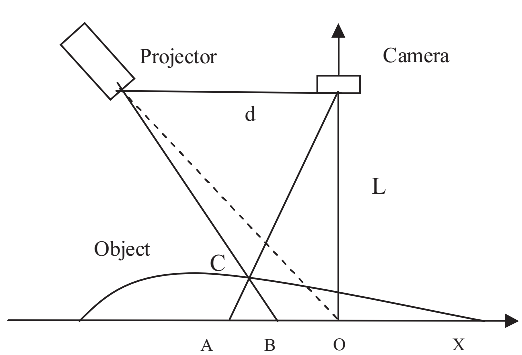

Fig. 2. The experiment system.

1. The sinusoidal fringe is projected onto the reference plane, and a four-step phase shift method is used to obtain the wrapped phase. The unwrapping phase is then obtained.
2. The image of the reference plane is analyzed to determine the grayscale of the row cross sections. The largest integer number of the fringe cycle is analyzed to obtain N, which is the average number of the sampling points in a fringe cycle. The ideal phase is $2\pi x/N$, where x is the pixel number. At a later instance, the value of N need not be very strict.
3. The phase error at each point is calculated as:

$$\Delta[\phi(x, y)] = \phi(x, y) - \frac{2\pi x}{N} \tag{3}$$

where $\Delta[\phi(x, y)]$ is the function of the unwrapped phase $\phi(x, y)$ and the x and y coordinates.

4. A phase error LUT is established, in which the unwrapped phase is considered as the abscissa and the phase error as ordinate. $\{\phi(x, y), \Delta[\phi(x, y)]\}$ is the required phase error LUT.

Multi-vice images of the reference plane are collected to eliminate the influence of random noise. The average unwrapped phase value is then calculated, considered as the unwrapped phase value.

After establishing the phase error LUT, the phase error can be compensated using the LUT when an object is measured as follows:

1. Assuming that the unwrapped phase of a point on the reference plane is $\phi_{ref}(x, y)$, the corresponding phase error $\Delta[\phi(x, y)]$ is obtained from the LUT. The actual unwrapped phase value is $\phi_{ref}(x, y) - \Delta[\phi(x, y)]$.
2. Assuming that the unwrapped phase of a point on the object surface is $\phi_{obj}(x, y)$, then $\phi_{obj}(x, y)$ has a relation with f_0, based on Fig. 2. Hence, the needed compensated unwrapped phase is $\phi_{obj}(x, y)$. The corresponding phase error $\Delta[\phi(x, y)]$ is obtained from the LUT. The actual unwrapped phase value is $\phi_{obj}(x, y) - \Delta[\phi(x, y)]$.
3. The actual unwrapped phase difference is obtained, and h is obtained using Eq. (1).

2.4. New height equation

A new height equation can be deduced. Point C is any point on the object surface and point B is the corresponding point on the reference plane, $\phi_c = \phi_B$ (Fig. 2). The specific relationship between the coordinates and the unwrapped phases is shown in Fig. 5(b). The actual unwrapped phase value is derived as

$$\phi_c - \Delta[\phi(x, y)] = \phi_B - \Delta[\phi(x, y)] = \phi_B - \left[\frac{\phi_B - 2\pi x_B}{N}\right] = \frac{2\pi x_B}{N}$$

$$\phi_A - \Delta[\phi(x, y)] = \phi_A - \left[\frac{\phi_A - 2\pi x_A}{N}\right] = \frac{2\pi x_A}{N},$$

then $\Delta\phi = 2\pi(x_B - x_A)/N$.

Assuming that the length of a single pixel on the image is k_1 and the magnification of the camera imaging system is k_2, then the fringe cycle on the reference plane is Nk_1k_2. Thus, $f_0 = 1/Nk_1k_2$. Substituting this expression into Eq. (1), we have:

$$h = \frac{L\Delta\phi}{2\pi f_0 d + \Delta\phi} = \frac{Lk_1k_2(x_B - x_A)}{d + k_1k_2(x_B - x_A)} \tag{4}$$

If $d \gg k_1k_2(x_B - x_A)$, then

$$h = \frac{Lk_1k_2(x_B - x_A)}{d} = k(x_B - x_A) \tag{5}$$

where $k = Lk_1k_2/d$, which is obtained through calibration. The results are consistent with that in the literature [23]. Thus, the proposed theory is correct.