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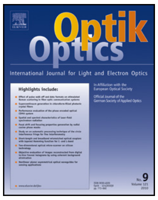

Optimized design of composite grating in real-time three-dimensional shape measurement

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ABSTRACT

A new method for improving the measuring precision in real-time three-dimensional (3D) shape measurement by optimizing structural parameters of composite grating is proposed. By analyzing the formation mechanism of composite grating, in which three phase-shifting sinusoidal gratings with equal phase-shifts $2\pi/3$ are modulated by three carrier gratings with different carrier frequencies along the orthogonal direction respectively, it is found that the measuring precision can be improved by optimizing the period of phase-shifting sinusoidal gratings inside the composite grating when the frequencies of carrier gratings are selected properly. Three typical surfaces (cone, peaks-function, saddle) are selected according to the complexity of the measured object to design optimized composite gratings. Experimental results show that the proposed method can improve the measuring precision in real-time 3D shape measurement.

1. Introduction

Phase Measuring Profilometry (PMP) [1–7] is an optical three-dimensional (3D) sensing technology using fringe pattern projecting and phase-shifting, in which N ($N \geq 3$) frames of phase-shifting sinusoidal gratings are projected onto the measured object surface by a digital light projector (DLP) and then N frames of corresponding deformed phase-shifting patterns are captured by a CCD camera for whole-field height reconstruction. PMP has its advantages in diverse practical application fields such as 3D imaging, biological medicine, industrial inspection, product quality control and reverse engineering due to its characteristics of non-contact, higher precision and easier implementation [8,9]. But in traditional PMP (TPMP), multiple frames of deformed phase-shifting patterns must be captured, so it is not conducive to real-time 3D shape measurement such as fast measurement and on-line inspection. In order to realize real-time 3D shape measurement, a composite structured light pattern was proposed by Guan et al. [10], in which multiple frames of phase-shifting sinusoidal gratings used in TPMP are modulated respectively along the orthogonal direction with different carrier frequencies and then summed together to form a composite grating (CG). In this method, only one frame of CG is projected onto the measured object surface and only one frame of corresponding deformed pattern is captured to retrieve multiple frames of deformed phase-shifting patterns used in TPMP, and then the height of the measured object can be reconstructed using TPMP. Compared with TPMP, the method proposed by Guan et al. has a great prospect for dynamic 3D shape measurement of a continuous object.

In the present paper, by analyzing the structural characteristics of CG proposed by Guan et al., it is found that the measuring precision is associated with the period of phase-shifting sinusoidal gratings inside the CG and the frequencies of carrier gratings inside the CG. So a new method for improving the measuring precision in real-time 3D shape measurement by optimizing structural parameters of CG is proposed.

2. PMP based on composite grating (CG)

PMP is not only insensitive to surface reflectivity variations of objects and ambient light, but also is highly precise [11,12]. However, since multiple frames of deformed phase-shifting patterns must be captured, the image processing speed is slow for real-time 3D shape measurement. In 2003, Guan et al. proposed a composite structured light pattern for real-time 3D shape measurement, in which multiple frames of phase-shifting sinusoidal gratings used in TPMP are modulated respectively with cosine waves with dif-

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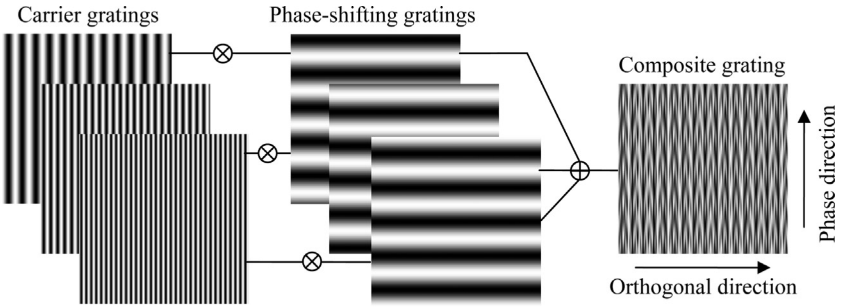

Fig. 1. Forming procedure of a composite grating (CG).

ferent carrier frequencies along the orthogonal direction and then summed together, as shown in Fig. 1.

The projected CG can be expressed as

$$I^{\mathrm{p}}\left(x^{\mathrm{p}},y^{\mathrm{p}}\right)=C^{\mathrm{p}}+D^{\mathrm{p}}\sum_{n=1}^{N}I_n^{\mathrm{p}}\left(x^{\mathrm{p}},y^{\mathrm{p}}\right)\mathit{cos}\left(2\pi f_n^{\mathrm{p}}x^{\mathrm{p}}\right)\qquad(1)$$

where, $(x^{\mathrm{p}}, y^{\mathrm{p}})$ are the projector coordinates, the y^{p} dimension is in the direction of the depth distortion and is called the phase dimension, the x^{p} dimension is perpendicular to the phase dimension and is called the orthogonal dimension. C^{p} and D^{p} are the average intensity and the intensity modulation of modulated CG. $f_n{}^{\mathrm{p}}$ are the carrier frequencies along the orthogonal direction. N is the total number of phase-shifting steps. $I_n{}^{\mathrm{p}}$ is the intensity distribution of nth frame of phase-shifting sinusoidal grating of N-step phase-shifting algorithm with equal phase-shifts $2\pi/N$, which can be described as

$$I_n^{\mathrm{p}}(x^{\mathrm{p}},y^{\mathrm{p}})=A^{\mathrm{p}}+B^{\mathrm{p}}\cos\left(2\pi f_{\Phi}y^{\mathrm{p}}-2\pi n/N\right)\qquad(2)$$

where, A^{p} is the average intensity relating to the pattern brightness and background illumination, B^{p} is the intensity modulation relating to the pattern contrast and surface reflectivity. $n = 1, 2, \ldots, N$. f_{φ} is the spatial frequency of phase-shifting sinusoidal gratings inside the CG, which not only affects spectrum overlap between adjacent carrier channels, but also determines the sampling frequency for the measured object. According to the formation mechanism of phase-shifting sinusoidal gratings, f_{φ} can be expressed as

$$f_{\Phi}=\frac{n_{\mathrm{p}}}{Y_{\mathrm{p}}}\qquad(3)$$

where, Y_{p} is the total length of phase-shifting sinusoidal gratings inside the CG along the phase direction, n_{p} is the number of periods of phase-shifting sinusoidal gratings inside the CG.

The reflected deformed pattern from the measured object surface captured by the CCD camera can be described as

$$I(x,y)=C+D\sum_{n=1}^{N}\left[A^{\mathrm{p}}+B^{\mathrm{p}}\cos\left(2\pi f_{\Phi}y^{\mathrm{p}}+\varphi(x,y)-2\pi n/N\right)\right]\mathit{cos}\left(2\pi f_n x\right)\qquad(4)$$

where, (x, y) are the image coordinates, $\varphi(x, y)$ is the phase distortion related to height of the measured object, f_n are the actual carrier frequencies in the camera view which may be different from the $f_n{}^{\mathrm{p}}$ due to perspective distortion between the projector and the camera. Each individual deformed phase-shifting pattern used in TPMP can be retrieved by calculating fast Fourier transformation (FFT) of Eq. (4), filtering in spatial frequency domain by band-pass filters to separate out each channel and then calculating inverse fast Fourier transformation (IFFT) of the filtered images. The practical deformed phase-shifting patterns after band-pass filtering can be expressed as

$$I_n(x,y)=A+B\cos\left(2\pi f_{\Phi}y^{\mathrm{p}}+\varphi(x,y)-2\pi n/N\right)\qquad(5)$$

The value of the phase distortion $\varphi(x, y)$ is determined from the N frames of deformed phase-shifting patterns after filtering by [2]

$$\varphi(x,y)=\arctan\left[\frac{\sum_{n=1}^{N}I_n(x,y)\sin\left(2\pi n/N\right)}{\sum_{n=1}^{N}I_n(x,y)\cos\left(2\pi n/N\right)}\right]\qquad(6)$$

Since the value of phase distortion $\varphi(x, y)$ calculated from Eq. (6) is wrapped in the range of $[-\pi,\pi]$, the phase distribution is discontinuous. It is necessary to obtain continuous phase distribution to avoid ambiguities between neighboring pixels. By using a phase unwrapping algorithm [13–18], the continuous phase related to height of the measured object, $\psi(x, y)$, can be calculated. Height distribution of the measured object can be calculated based on the mapping relationship [19,20] between phase and height, which can be expressed as

$$\frac{1}{h(x,y)}=a(x,y)+b(x,y)\frac{1}{\psi(x,y)}+c(x,y)\frac{1}{\psi^2(x,y)}\qquad(7)$$

where, the phase-to-height mapping coefficients $a(x, y)$, $b(x, y)$ and $c(x, y)$ depend on the parameters of system setup and require to be calibrated. They can be calculated by measuring at least four standard parallel planes with different known height, including the reference plane.

3. Optimized design of composite grating (CG)

In the 3D shape measurement system based on CG projection, spectrum overlap in spatial spectrum distribution of the captured deformed pattern always occurs to some extent, and the spectrum overlap is related to the divergence characteristic of the light

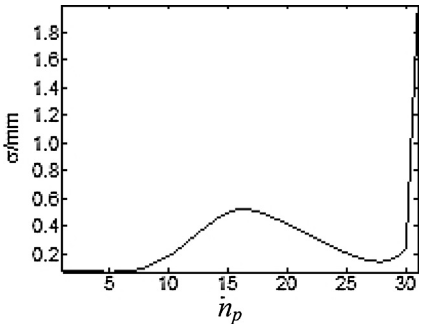

Fig. 2. The RMS trend map.