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Dual-frequency fringe projection for 3D shape measurement based on correction of gamma nonlinearity

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A B S T R A C T

In the fringe projection three-dimensional (3D) shape measurement, the gamma nonlinearity of the digital projector leads to measurement errors, a novel method based on the dual-frequency fringe projection using correction of gamma nonlinearity is proposed. In the proposed method, the pre-coded gamma values of computer generated fringe patterns in digital projector can guarantee the sinusoidal waveforms of the captured fringe pattern, and alleviate the measurement errors caused by the gamma nonlinearity. After the correction of gamma nonlinearity, the shape measurement results by dual-frequency grating projection are analyzed in detail. By combining the advantages of both low frequency and high frequency gratings, the object surface profile is obtained accurately. The simulation and experiment results are presented to validate the proposed method.

1. Introduction

The fringe projection for 3D shape measurement has the advantages of non-contact, high accuracy, fast speed, and automated measurement. The Fourier transform profilometry (FTP) in fringe projection is widely used in online quality inspection of mechanical components, dress making, medical diagnostics, and so on [1–10].

In the 3D shape measurement, it is difficult to measure the object height by using only one grating owing to the difficulty of phase unwrapping. Hence many researchers used the suitable dual-frequency grating to combine the advantages of the low-frequency grating and the high-frequency grating [11–13]. Peng K et al proposed a dual-frequency online phase measurement profilometry method with phase-shifting parallel to moving direction of measured object [11]. Dai M et al proposed a dual-frequency fringe projection system for 3D surface shape measurement. In their method, they use low-frequency fringe patterns to guarantee the accuracy of low-frequency phase for high-frequency phase unwrapping [12].

However, due to the gamma nonlinearity effects of the projector system, the measurement accuracy of the 3D shape will be affected. The correction of gamma nonlinearity is very important in fringe projection 3D shape measurement [13–16]. Ma S et al proposed a fast and accurate gamma correction technique based on a Fourier spectrum analysis. In this method, only two spatial-carrier fringe patterns with different pre-encoded gamma values are needed and the number of fringe patterns required for gamma pre-calibration is significantly reduced without loss of accuracy [15]. Xiao Y et al used an orthogonal sinusoidal grating pre-coded with two different known gamma values to evaluate the gamma value of the pattern. In their method, the captured fringe patterns are well-sinusoidal and the phase errors caused by the gamma nonlinearity are alleviated [16]. To avoid the nonlinear gamma of the projector during the course of the measurement of steep objects, Fu Y et al generated the dual-frequency fringe through software programming based on defocusing, so the fundamental frequency and the third harmonic components can be preserved [13].

There is still a challenge to measure steep or complex object shape by fringe projection technique. We propose a novel dual-frequency grating projection method for steep and complex object shape measurement and discuss the condition of correction of gamma nonlinearity for digital projector. The proposed method is validated by computer simulation and experiments.

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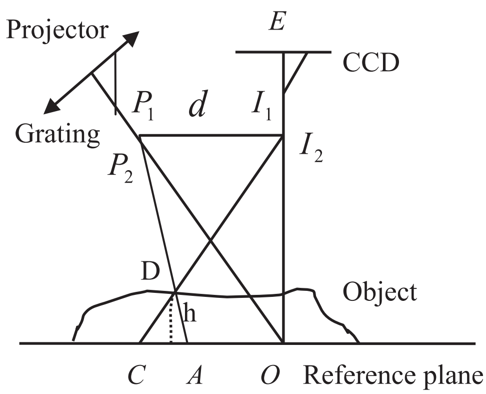

Fig. 1. Optical geometry of measurement system.

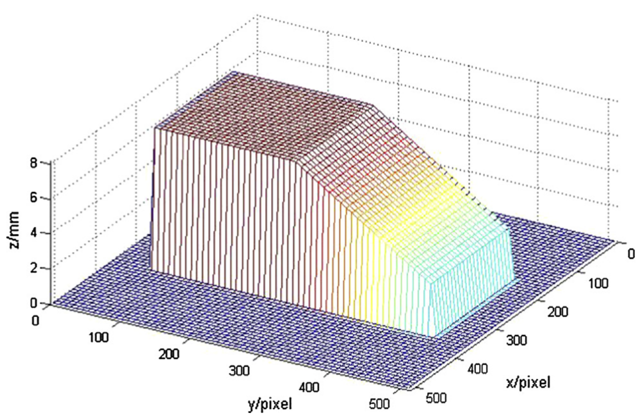

Fig. 2. Simulated steep object.

2. Principle of the method

2.1. Fringe projection system and correction of gamma nonlinearity

FTP method was introduced by Takeda M and Mutoh K [17]. The fringe projection for 3D shape measurement system is shown in Fig. 1. P_1P_2 is the optical axis of projector, L_0 is the distance between CCD (Charge-coupled Device) photocenter I_2 and reference plane, d is the distance between CCD photocenter I_2 and projector photocenter P_2. The curved surface is the object surface to be measured. A and C are two points on the reference plane, D is a point on the object surface, h is the distance between point D and the reference plane.

Assume $\phi(x, y)$ indicates the phase that contains the height information $h(x, y)$ of the measured object. In the case of $L_0 >> h(x, y)$, the relationship between $h(x, y)$ and $\phi(x, y)$ can be simplified as follows [17]

$$h(x,y) = -\frac{L_0}{2\pi f_0 d}\phi(x,y) \quad (1)$$

where f_0 is the fundamental frequency of the grating.

If $\phi(x, y)$ is determined, $h(x, y)$ can be calculated by Eq. (1). Hence, the 3D surface shape of the object measured can be achieved.

During the course of the surface shape measurement, there is a gamma nonlinearity in the digital fringe projector and gamma nonlinearity will produce the gamma nonlinearity distortion. The input and output light intensity has the following relationship in correction of gamma nonlinearity transform [18]

$$g(x,y) = [g_0(x,y)]^{\gamma} = \sum_{l=0}^{\infty} A_l cos\{l[2\pi f_0 x + \phi(x,y)]\} \quad (2)$$

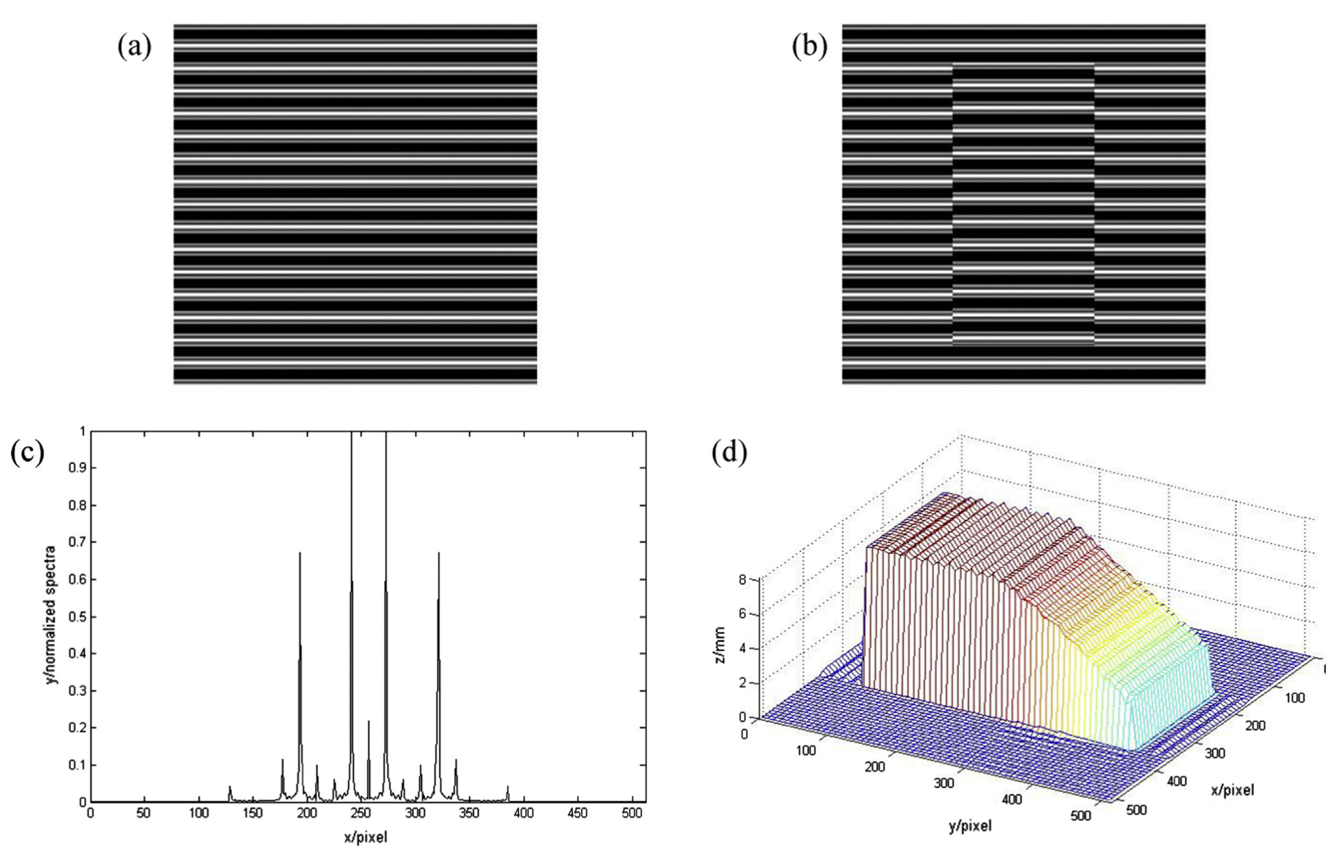

Fig. 3. Simulation results before correction of gamma nonlinearity, (a) and (b) dual-frequency fringe modulated by the reference plane and the simulated object, respectively, (c) dual-frequency spectra along x axis after correction of gamma nonlinearity in Fig. 3(a), (d) the reconstructed 3D object shape.