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Non-phase-shifting Fourier transform profilometry using single grating pattern and object image

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ABSTRACT

A new white light non-phase-shifting method for eliminating unwanted background in Fourier transform profilometry (FTP) is proposed by using an object image being measured and a single grating image deformed by this object. The background signal of the deformed grating image can be eliminated by using the object image scaled by a contrast ratio of the two images. The proposed method has an advantage over color-encoded FTPs in that the contrast value can be simply calculated from the image itself, regardless of image sensors. Experimental verifications of the proposed method are presented.

1. Introduction

Fourier transform profilometry (FTP) is one of the useful three-dimensional (3-D) shape measurement methods [1–3]. Unlike moiré topography which suffers from fixed 2π sensitivity and requirement of scanning components [4], the FTP is free from these limitations and can perform full field measurement by using simple white-light based setup. When a sinusoidal grating or a Ronchi grating is projected onto an object surface being studied, phase of the projected grating pattern is modulated by spatial profile of the object. This phase modulation is encoded into fundamental frequency spectra of the grating pattern. By recording the deformed grating pattern with an image acquisition sensor, this phase information can be retrieved from the fundamental spectrum by using Fourier transformations. The retrieved phase information is then employed for reconstructing 3-D object surface profile. However besides fundamental components, deformed grating images may also contain lower and higher orders of spectra. When the fundamental component has broad bandwidth, it may be corrupted by the other spectra. This is the inherent drawback of the conventional FTP.

In the past decades, several methods for solving this drawback have been reported [5–12]. In the case of the FTP by using the Ronchi grating projection, elimination of unwanted spectra higher than the fundamental one has been proposed by defocusing the projected pattern [5,6]. Spatial translation of the grating plane or manual adjustment of a focus of projector's lens defocuses the Ronchi grating, yielding quasi-sinusoidal light distribution. However, this method suffers from a phase shift error which may arise from imperfect defocusing process. Consequently, complete spectral elimination is hardly achieved. Improved third-order spectral suppression was reported by area-modulating a square grating into a triangular grating [7]. This method works well, provided a triangular grating to be defocused has short spatial period.

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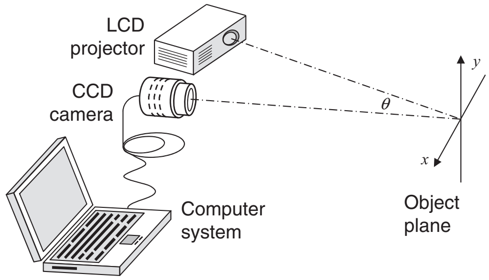

Fig. 1. A schematic diagram of an optical setup for implementing the proposed FTP.

Although high spectral problem may also be solved by utilizing a perfect sinusoidal grating projection, an existence of the zero-order spectrum still limits the FTP performance. An excellent method for removing the zero-order spectrum of the background by using π-phase shifting was reported by Li et al. [8]. This background elimination in the space domain gives better accuracy and three times higher measurement range than the conventional FTP. However, it is not suitable for dynamic object reconstructions. This is because four deformed grating patterns, that are the grating images deformed by the object and the reference plane and their π-phase-shifted images, are required to reconstruct the 3-D object profile.

Alternatively, the zero-order spectrum removal can be accomplished in the frequency domain. Tavares et al. reported a new method for the background elimination by using two orthogonal sinusoidal gratings [9]. The gratings are subsequently projected onto the object under test to generate the deformed grating patterns. The background is eliminated by subtracting two spectra calculated from the two deformed gratings which will result in four fundamental frequencies. To retrieve the desired phase from one of the four fundamental frequency spectra, the unwanted ones are removed by applying a zero threshold. As a result, negative amplitude of the desired fundamental frequencies may be corrupted. Filtering of the zero-order spectrum by using 2-D continuous wavelet transform has also been reported [10]. On the basis of its multi-resolution property, a bank of wavelet filters needs to be generated from a unique function which has a response of band-pass filter by translation, dilations and rotations. A main concern of the frequency domain processing is that precise extraction of the fundamental frequency is hardly achieved when bandwidth of the deformed grating image is broad.

Recently, a projection of two-interlaced color gratings, red and green, with different frequency and one uniform blue color pattern has been proposed for solving this time delay problem [11]. After capturing the deformed pattern by using a color image sensor, three images that are two deformed grating images and one object image are digitally separated. Since a mean intensity value of each pattern is not the same and each color grating has different contrast value, the background information is hardly eliminated without calibrating these values. The calibrations of the mean and the contrast values is done by measuring a transfer function of each encoding color of the image sensor [12]. After the calibrations, the three images are converted into grayscale format. The background elimination can be finally accomplished by subtracting the object image from the grating images. Not only does this method suffer from lengthy processes of measuring the sensor's color transfer function, but, it also suffers from the image calibrations and separations prior to the background elimination. Furthermore, besides it is not cost effective due to the need of color image sensors, this background elimination method cannot be applied to coherent structured illumination systems.

In this paper, white-light non-phase-shifting method for eliminating the unwanted background signal of the FTP by using a single deformed grating pattern and an object image is proposed. In our proposed method, the mean intensity and the contrast values of the deformed grating and the object images are directly calculated from the recorded images. This is the main difference between the proposed method with the color-encoded FTPs described above. After removing digitally the mean intensity from its corresponding image, the resultant object image scaled by its contrast is subtracted from the deformed grating. This eliminates totally the non-uniform background signal. By taking its Fourier transform, a phase information can be retrieved from the fundamental spectrum and is then used to reconstruct the object height in accordance with the conventional FTP. The proposed method has advantages over the previous works in that firstly, uses of a white light illumination and a monochrome image sensor results in low-cost system. Secondly, the calibration process of the mean and the contrast values is simpler and independent upon characteristics of the image sensors. Thirdly, the use of a single grating pattern minimizes simultaneously projection and image acquisition times and phase error caused by abrupt change in amplitude or timing of light projector's synchronization signals known as jitters [13,14]. Finally, the proposed method can also be applied to coherent structured illumination, because it does not require color encoding.

2. Proposed FTP

Fig. 1 shows a schematic diagram of an optical setup for implementing the proposed method which consists of an LCD projector and an image camera aligned in accordance with a crossed-optical-axes geometry [1]. The projector is used to project the white light and the sinusoidal grating pattern to the object being studied, while the monochrome CCD camera captures its corresponding images. The camera and the projector entrance pupils are located at the same distance l_0 from a