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Efficient approach for three-dimensional shape measurement using fringe projection by complex coefficient FIR band-pass filter

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ABSTRACT

An efficient approach for three-dimensional (3D) shape measurement is proposed. Phase distribution is obtained directly by filtering deformed fringe pattern with complex coefficient finite impulse response (FIR) band-pass filter. Firstly, a FIR low-pass filter is designed; its bandwidth is half of that of the deformed fringe pattern. Secondly, the complex coefficient FIR band-pass filter is gained by moving the frequency spectrum of low-pass filter to the position where the frequency spectrum of deformed fringe pattern located. Finally, the phase distribution is obtained by filtering the deformed fringe pattern with designed filter and calculating the argument of the filtered pattern. The experimental results reveal that a high resolution 3D image with texture can be obtained. Compared with conventional Fourier transform profilometry (FTP), the standard deviation of phase difference between these two methods reaches only 0.75%. As a result, this approach provides a new way to obtain phase distribution of deformed fringe pattern in spatial domain instead spatial frequency domain.

1. Introduction

Optical 3D measurement are extensively used in many applications [1–8], such as 3D model reconstruction, surface profile measurement, virtual reality, television stunt, medical and cosmetic plastic surgery, industrial product designs, sculpture and art heritage conservation, etc. The major advantages of optical methods compared to traditional methods lie in their non-contact, non-destructive nature, flexibility and high precision. There are primarily two approaches for 3D shape measurement. One approach is to use a single pattern. The phase of the deformed fringe pattern is obtained with a Fourier, wavelet or other analysis method. The other approach is to use multiple patterns. This is more accurate and robust than the first approach because more information is obtained with this approach.

3D measurement based on fringe projection is one of the important methods. The phase distribution of deformed fringe pattern must be obtained firstly. Then the 3D shape of measured objects may be acquired by phase-height mapping algorithm and imaging model of camera. Generally, there are two kinds of basic methods to obtain the phase distribution of deformed fringe pattern. Thefirst one is to use at least three fringe patterns, then, the phase distribution is gained with phase shifting method (phase measurement profilometry PMP) [8,9]. The second one is to use one or two fringe patterns. It is suitable for dynamic object measurement [10]. The phase distribution is gained with several transform methods, such as spatial phase detection (SPD) [11], Fourier transform profilometry (FTP) [12,13], wavelet transform profilometry (WTP) [14–16]. In the FTP method, the phase distribution of deformed fringe pattern is obtained with Fourier transform, filtering in spatial frequency domain and inverse Fourier transform. SPD is similar to FTP in the form of the pattern and the method of data acquisition, however, the calculations for deriving the phase distribution is greatly simplified. In addition, there is an intrinsic symmetric error in SPD, but it can be ignored when the slope of the object to be measured is not very large. WTP is proposed to improve the measurement accuracy in one fringe projection method. The obtained phase is more accurate than FTP or SPD. But this method is time consuming because the phase distribution is gained by temporal-frequency analyzing.

In this paper, we propose a 3D measurement method using fringe projection by complex coefficient FIR band-pass filter. With this method, the accuracy of retrieved phase agrees with that of FTP, however, but the operation of data processing is simplified compared to FTP. Furthermore, high-resolution 3D image with texture can be obtained. It can be applied to 3D model reconstruction, virtual reality and entertainment, etc. The experimental results are presented.

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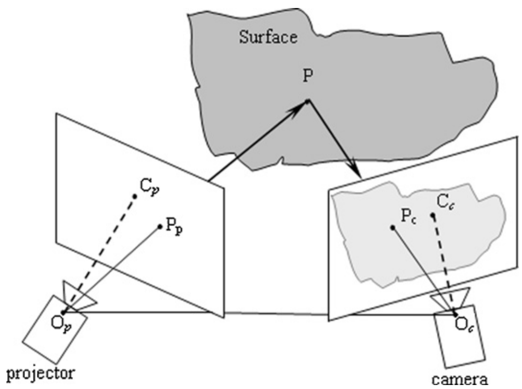

Fig. 1. Sketch of 3D measurement system.

2. Theory

2.1. Principle of 3D measurement

The sketch of 3D measurement system based on fringe projection is shown in Fig. 1. It consists of a projector and a camera. The fringe pattern is projected onto the object surface and modulated by the height of object. The deformed fringe pattern is captured by the camera. Its intensity can be expressed as following:

$$g(x, y) = a(x, y) + b(x, y)\cos[2\pi f_0 x + \varphi(x, y)] \tag{1}$$

where $a(x, y)$ is the background intensity; $b(x, y)$ denotes amplitude of the fringe; $f_0 = 1/p$ represents the spatial frequency and p is the period of fringe in captured image of reference plane; $\varphi(x, y)$ denotes the phase modulated by the height of object. After the phase distribution of deformed fringes is obtained, the 3D shape of object is expressed as [17].

$$\begin{cases} Z(x, y) = \sum_{n=0}^{N} c_n(x, y)\varphi^n(x, y) \\ X(x, y) = a_1(x, y) + b_1(x, y)Z(x, y) \\ Y(x, y) = a_2(x, y) + b_2(x, y)Z(x, y) \end{cases} \tag{2}$$

where x, y are coordinates of sample point in coordinate system of camera image plane; a_1, a_2, b_1, b_2 and c_n are parameters which can be obtained by calibrating the measurement system; N is the order of polynomial.

2.2. Frequency spectrum character of deformed fringe

Eq. (1) can be written as following; according to Euler's formula.

$$g(x, y) = a(x, y) + q(x, y) + q^*(x, y) \tag{3}$$

where $q(x, y) = (1/2)b(x, y)\exp\{j[2\pi f_0 x + \varphi(x, y)]\}$. Performing Fourier transform to Eq. (3), we get

$$G(f, y) = A(f, y) + Q'(f - f_0, y) + Q'^*(f + f_0, y) \tag{4}$$

where $A(f, y)$ represents the component of the spectrum that corresponds to the background variation, $Q'(f - f_0, y)$ and $Q'^*(f + f_0, y)$ are the Fourier transform of $q(x, y)$ and $q^*(x, y)$, respectively, and f denotes the spatial frequency in the x direction. The main components of the Fourier spectrum are separated by f_0, as shown in Fig. 2. Q' and Q'^* are a complex–conjugate pair, so only one phase between them is needed to extract. In FTP, $Q'(f - f_0, y)$ is obtained by filtering spectrum of $g(x, y)$ in spatial frequency domain and $q(x, y)$ is obtained by calculating the inverse Fourier transform of $Q'(f - f_0, y)$. According to filter theory, we can also extract $q(x, y)$ from $g(x, y)$ by filtering $g(x, y)$ with complex coefficient FIR band-pass filter in spatial domain directly.

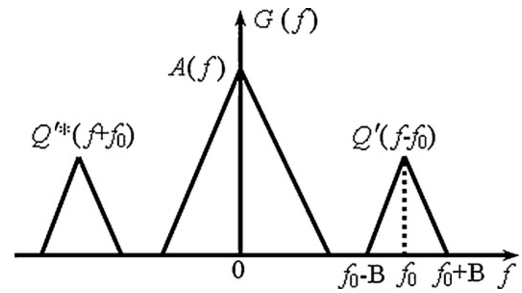

Fig. 2. Spectrum of deformed fringe.

2.3. Design of complex coefficient FIR band-pass filter

We can find from Fig. 2 that $q(x, y)$ could be extracted if $A(f, y)$ and $Q'^*(f + f_0)$ were filtered out. Only complex coefficient band-pass filter can reach this requirement. The accurate phase information is the key point to obtain height information of objects. As a result, a complex coefficient FIR digital filter, whose phase-frequency response is strict linear, is suitable to filter deformed fringe pattern. According to the spectrum characteristics of deformed pattern, the amplitude-frequency character of complex coefficient FIR band-pass digital filter is shown in Fig. 3(a), and it can be expressed as following:

$$|H(e^{j2\pi\eta})| = \begin{cases} 2, & f_0 - B \le \eta \le f_0 + B \\ 0, & \text{other} \end{cases} \tag{5}$$

where $H(e^{j2\pi\eta})$ is the transfer function of filter, $2B$ denotes the bandwidth of $q(x, y)$. The filter can be obtained by shifting the spectrum of a real coefficient low-pass filter to corresponding position. The amplitude-frequency character of low-pass filter is shown in Fig. 3(b). It can be expressed as following:

$$|H(e^{j2\pi\eta})| = \begin{cases} 2, & -B \le \eta \le B \\ 0, & \text{other} \end{cases} \tag{6}$$

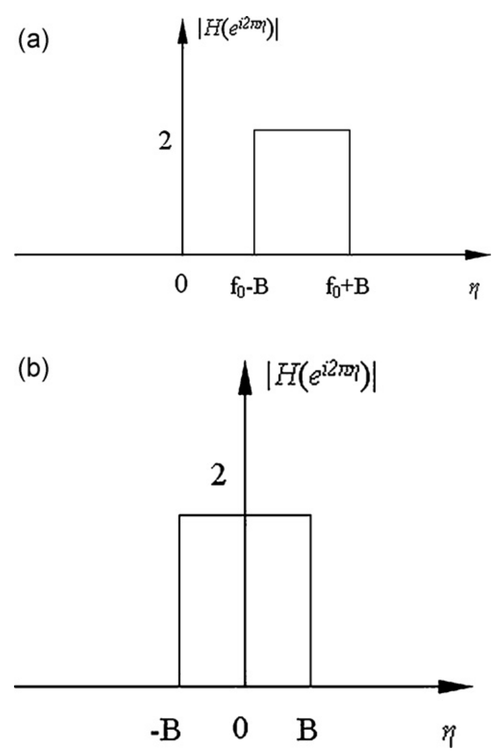

Fig. 3. Amplitude-frequency character. (a) Band-pass filter and (b) low-pass filter.