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A correlation-based phase unwrapping method for Fourier-transform profilometry

Chunsheng Yu, Qingjin Peng*

Department of Mechanical & Manufacturing Engineering, University of Manitoba, Winnipeg, Man., Canada R3T 5V6

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Abstract

A new phase unwrapping algorithm based on correlation map for Fourier-transform profilometry (FTP) method is presented in this paper. It is a quality-guided phase-unwrapping method. The modulation is used as an effective parameter to indicate the reliability of the fringe image for the quality-guided phase-unwrapping method. A filtering window is introduced to calculate the modulation easily. A correlation-map function is proposed to calculate the reliability of the fringe image and to avoid choosing the width of the window in calculating the modulation. As the value of the correlation-map function is lower in areas of the local shadow and abrupt discontinuity than that in other areas, the correlation-map function is used as a guide to find the optimized phase-unwrapping path. The experimental results show that the method is feasible.

Keywords: FTP; Correlation; Phase unwrapping

1. Introduction

Fourier-transform profilometry (FTP) method [1,2] is an effective tool for non-contact three-dimensional (3D) data acquiring applications. It requires only one or two images for a full field analysis [3]. Since the phase calculated by the FTP method gives principal values ranging from $-\pi$ to π, the phase distribution is wrapped into this range and has discontinuities with 2π jumps, when the phase variation is larger than 2π. These discontinuities can be corrected by adding or subtracting 2π according to the phase jump ranging from $-\pi$ to π or vice versa. The procedure of constructing the continuous natural phase is called phase unwrapping. Phase unwrapping is an important process in the FTP method for the height calculation of an object from phase data. For a perfect-wrapped phase distribution, the continuous natural phase can be obtained by comparing the wrapped phase in neighboring pixels, and adding or subtracting multiples of 2π to obtain the real phase between the two pixels [4]. The unwrapped phase is a cumulative function of the original wrapped phase; phase unwrapping should be path-independent. The natural phase should be single valued. But in practice, irregular changes of object's surface may result in the shadow or excessive density or sparsity of the fringe distribution on the deformed fringe image. These factors may result in phase discontinuities, low modulation or regional undersampling of the fringe [5]. It is impossible to obtain a correct natural phase in such areas [4]. Therefore, phase unwrapping is path-dependent. As phase unwrapping is a cumulative process, an error at a given point can propagate along the unwrapping path. Choosing an optimized unwrapping path to avoid error accumulation has been addressed by some researchers.

The reviews of phase-unwrapping algorithms were presented from the early 1990s [6–9]. These algorithms can be classified into three categories [10,11]: global algorithms, region algorithms [12], and path-following algorithms. The path-following algorithms can be further classified into three groups: path-dependent methods [13], residue-compensation methods and quality-guided methods. The global algorithms are robust for noisy fringe images but time consuming [10]. The region algorithms

*Corresponding author. Tel.: +1 204 474 6843; fax: +1 204 275 7507.
E-mail address: pengq@cc.umanitoba.ca (Q. Peng).

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are not as robust as the global algorithms but they are faster [10]. The path-dependent methods are fast but fail with noisy fringe images [11]. The residue-compensation algorithms are efficient at the execution time, but not robust [10]. In quality-guided methods, a reliability map is used to identify the pixel's reliability of the wrapped phase. The reliability is used to guide the direction of phase unwrapping. The path of phase unwrapping is always along the optimized direction from the pixel with high reliability value to the pixel with low reliability value. Therefore, the error is limited to local minimum areas even in the worst case. The quality-guided method has therefore, attracted many researchers' attention in phase-unwrapping methods [10].

Su and Chen [14] presented a review of quality-guided methods. The review shows that the modulation function is a very important parameter of reliability in phase unwrapping, as the value of the modulation in the areas of local shadow and abrupt discontinuities is lower than that in other parts. The low modulation means low phase reliability [15]. The modulation has been successfully used in research to produce an optimized reliability map for phase unwrapping, such as cross-amplitudes [16], edge detection with the modulation [17], and the fitting error with the modulation [18]. However, the modulation calculating needs careful consideration for the FTP method.

In FTP method, a filter window is required to calculate the modulation [14]. A small window can simplify phase unwrapping for the FTP method, but it may decrease the precision of the 3D data by eliminating useful parts of the spectrum [4]. A big window can bring information of higher orders and zero frequency into the fundamental frequency; the wrong phase unwrapping is inevitable. Therefore, the width of the window should be chosen carefully, based on the shape and surface of the measured object. It will take some time to obtain a proper width of the window.

A correlation-based phase-unwrapping method is proposed in this paper to avoid choosing the width of the filter window for phase unwrapping in FTP method. The reliability of the phase data is calculated by a correlation-map function.It simplifies the procedure of phase unwrapping for the FTP method. In the method, phase-shifted sinusoidal fringe images are generated by the computer with phase shift $0, \pi/2, \pi, 3\pi/2$. A deformed fringe image is obtained in the FTP method. The correlations between the computer-generated fringe images and the deformed fringe image are calculated by the correlation-map function. The value of the correlation-map function is higher in areas of smooth surface than that in areas of height discontinuity, shadow and speckle-like noise. Therefore, the correlation-map function is related to fringe quality. Starting from a pixel with the maximum value of the correlation-map function, the unwrapping procedure is guided by the value of the correlation-map function from the pixel with high fringe quality to the pixel with low fringe quality. The error of the phase unwrapping is limited to local minimum areas.

This paper is organized as follows: Section 2 introduces the FTP method. In Section 3, the correlation-based phase unwrapping method is analyzed. The proposed algorithm is described in Section 4. The experimental result of the proposed method is shown and discussed in Section 5.

2. The FTP method

The FTP method was introduced by Takeda et al. in 1983 [2]. In this method, a Ronchi fringe or a sinusoidal fringe is projected onto the object surface through a projection system. When the fringe is put on the object's surface, the deformed fringe image can be expressed by

$$g(x, y) = r(x, y) \sum_{n=-\infty}^{n=\infty} A_n \exp(\mathrm{i}(2\pi n f_{r0} x + n\phi(x, y))). \quad (1)$$

When the fringe is put on the reference plane, the fringe image is written as

$$g_0(x, y) = r_0(x, y) \sum_{n=-\infty}^{n=\infty} A_n \exp(\mathrm{i}(2\pi n f_{r0} x + n\phi_0(x, y))), \quad (2)$$

where $r(x, y)$ and $r_0(x, y)$ are non-uniform distributions of reflectivity on the surface of the object and on the reference plane, respectively. A_n is the weighting factors of Fourier series, f_{r0} is the fundamental frequency of the observed fringe image, $\phi(x, y)$ is the phase resulting from the object height distribution, and $\phi_0(x, y)$ is the original phase on reference plane.

The one-dimensional (1D) Fourier transform of the observed image (in Eq. (2)) is computed and the Fourier spectrum of the image can be obtained. A filter function is used to obtain the fundamental component of the Fourier spectra. The inverse Fourier transform is applied to the fundamental component, an image that only carries the deformed fringe information is obtained as

$$\widehat{g}(x, y) = A_1 r(x, y) \exp(\mathrm{i}2\pi f_{r0} x + \phi(x, y)). \quad (3)$$

The same operation is applied to Eq. (3), then

$$\widehat{g}_0(x, y) = A_1 r_0(x, y) \exp(\mathrm{i}2\pi f_{r0} x + \phi_0(x, y)). \quad (4)$$

The phase $\Delta\phi(x, y)$ is

$$\Delta\phi(x, y) = \mathrm{Im}\{\log[\widehat{g}(x, y)\widehat{g}_0^*(x, y)]\}. \quad (5)$$

The phase obtained in Eq. (5) is wrapped. In order to obtain the correct phase distribution, the wrapped phase distribution has to be converted to a continuous phase distribution by a phase-unwrapping method.

3. Analysis of the correlation-based phase-unwrapping method

In image processing, correlation is a standard method of estimating the degree to which two series are correlated. If two images are captured, one is the source image $g_0(x, y)$; the other is the template image $g(x, y)$. These two images