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Oriented boundary padding for iterative and oriented fringe pattern denoising techniques

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ABSTRACT

Optical interferometric techniques offer non-contact, high accuracy and full filed measurement, which are very attractive in various research and application fields. Fringe patterns are the recorded results of these techniques and often require denoising at the pre-processing step to increase the accuracy and robustness of information retrieval. Among various fringe pattern denoising techniques, iterative and oriented denoising techniques based on partial differential equations in the spatial domain are effective and widely used. However, these techniques introduce errors near boundary areas if traditional image padding methods such as zero padding and symmetric padding are used. Due to a large number of iterations needed in these techniques, the error will flood from the boundary into the inner part of the fringe pattern. Since fringe patterns have a flow-like structure represented by fringe orientation, padding along the fringe orientation helps to reduce the error. An oriented padding method is thus proposed for iterative and oriented fringe pattern denoising techniques that require partial derivative estimations. Simulated fringe patterns are tested and quantitative results are given to demonstrate the performance of the proposed method. Experimental results are also given for verification.

1. Introduction

Accurate and efficient measurement is widely required in the modern industry. Optical interferometric techniques [1] have been proven to be attractive in both research and engineering fields for non-contact, highly sensitive and full-field measurements. Various optical interferometric techniques have been designed for different application fields such as mechanical engineering and material engineering. Common results of these optical interferometric techniques are fringe patterns with the following discrete numerical presentation,

$$f(x,y) = a(x,y) + b(x,y)\cos\,[\varphi(x,y)] + n(x,y), \tag{1}$$

where $a(x,y)$, $b(x,y)$, $\varphi(x,y)$and $n(x,y)$ are the background intensity, fringe amplitude, phase distribution and additive noise, respectively. Usually the phase $\varphi(x,y)$ is directly related to the measurement information and needs to be retrieved. The phase retrieval from a single closed fringe pattern is of interest but difficult, especially with the presence of noise, either additive noise or speckle noise.

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Fringe pattern denoising is therefore often required as pre-processing. The cosine function in (1) with a continuously varying phase gives a flow-like structure to fringe patterns, which can be well measured by the fringe orientation. With the aid of the fringe orientation, an important group of fringe pattern denoising techniques based on the partial differential equations have been proposed [2–6]. These techniques are carried out through an iterative operation as follows,

$$f(x,y;t+1)=f(x,y;t)+\beta\times f_t(x,y;t),$$
$$f(x,y;0)=f_0(x,y), \tag{2}$$

where $f(x,y;t)$ denotes the image intensity at pixel (x,y) and iteration t; $f_t(x,y;t)$ is the first order derivative of $f(x,y;t)$ with respect to time t; $f_0(x,y)$ is the original noisy fringe pattern; β is a positive constant; the symbol $\times$ denotes multiplication. A large iteration number ranging from 100 to 200 is quite common.

In (2), the term $f_t(x,y;t)$ controls the evolvement of the fringe pattern and plays an essential role during the denoising. This term can be generally represented as [6],

$$\begin{aligned} f_t=&\lambda_1(f_{xx}\sin^2\theta+f_{yy}\cos^2\theta-2f_{xy}\sin\theta\cos\theta)\\ &+\lambda_2(f_{xx}\cos^2\theta+f_{yy}\sin^2\theta+2f_{xy}\sin\theta\cos\theta)\\ &+r(f_x,f_y,\theta,\theta_x,\theta_y),\end{aligned} \tag{3}$$

where f_{xx}, f_{xy} and f_{yy} are second order derivatives of f; θ is the fringe orientation; λ_1 and λ_2 control the diffusion strength in the direction perpendicular and parallel to the fringe orientation, respectively; $r(f_x,f_y,\theta,\theta_x,\theta_y)$ is a complementary term to make the diffusion accurately follow the designed orientation, which involves first order derivatives f_x, f_y, θ_x, and θ_y [6].

The implementation of f_t involves the calculation of the fringe derivatives. When the derivatives of boundary pixels are calculated, pixels beyond the boundary are needed. Zero padding or symmetric padding [7,8] is commonly used, which either adds zeros or mirror-reflects the image data to an image boundary. Both boundary padding methods ignore the fringe structure and consequently cause distortion around an image boundary. The distortion will go further inside the fringe pattern due to a large number of iterations. The distortion caused by denoising in the boundary region introduces errors in the later phase retrieval process that requires denoising as preprocessing [9,10]. Some methods have been proposed to perform image padding [11–15]. Image inpainting and texture synthesis can predict and fill the lost parts of images [11–13], which can be possibly used for fringe patterns. However, image inpainting is not effective to reproduce the texture [12,13] to which high-density fringe pattern is similar, while texture synthesis borrows information from similar patches [11,13], which should be avoided in the processing of measurement data such as fringe patterns. For fringe patterns, an iterative Fourier transform method has been proposed to extrapolate them [14,15]. However, it requires that the spectrum band of the fringe pattern is narrow, which is not always true. The flow-like structure of the fringe patterns gives the possibility to predict the boundary pixels along the fringe orientation. Orientation-based padding, or called oriented padding, is proposed to reduce the distortion. In this paper, the oriented padding method is used in boundary regions. With small modifications, this method can be used for discontinuous fringe patterns to prevent the distortion in discontinuous regions, for which segmentation methods [16,17] need to be applied to identify discontinuous regions first. Note that the gradient-based method [18,19] is a widely used approach for the fringe orientation estimation in the oriented filters and also involves the derivatives calculation. In this method, the derivatives are averaged over neighboring pixels so that the noise influence is suppressed. Further, for boundary pixels, only the neighboring pixels within the image are considered. Our experiments show that the padding performances of using the estimated orientation and ideal orientation are almost identical. Thus, we consider that the estimated orientation can be directly used for oriented padding.

2. Oriented padding method

The purpose of boundary padding is to increase the image size by appending pixels to the image boundary, so that the derivatives of boundary pixels can be calculated. In each iteration of an iterative and oriented denoising technique mentioned above, the width of only one pixel along four image boundaries are padded. In other words, we do the following in each iteration: (a) a fringe pattern of size $m\times n$ with a coordinate interval of $[1,m]\times[1,n]$ is padded and enlarged. The enlarged fringe pattern has a size of $(m+2)\times(n+2)$ with a coordinate interval of $[0,m+1]\times[0,n+1]$ and the padded pixels are assigned coordinates $(0,y)$, $(x,0)$, $(m+1,y)$ and $(x,n+1)$; (b) the derivatives of pixels in the coordinate interval of $[1,m]\times[1,n]$ are calculated based on the enlarged fringe pattern; (c) the fringe pattern is smoothed using these derivatives. This coordinate system is used throughout the paper. To facilitate the oriented padding, the relationship of the boundary pixels and pixels beyond boundary is needed and can be established through the fringe contour.

2.1. Fringe contour

A fringe pattern has contours where pixels are connected and have the same fringe intensity. Because usually the background intensity $a(x,y)$, fringe amplitude $b(x,y)$ and phase $\varphi(x,y)$ are varying continuously, the contours in a fringe pattern represented by (1) are more obvious than general images and become a unique feature that can be used for fringe denoising. For the simple fringe pattern shown in Fig. 1(a), the contours are parallel straight lines. Three contours are highlighted as examples.

To examine the local property of a contour, we assume that in a local area, $a(x,y)$ and $b(x,y)$ are constant, and $\varphi(x,y)$ is linear. The fringe model in a local region near (x,y) can be established as

$$f(x+\gamma,y+\eta)=a(x,y)+b(x,y)\cos\left[\varphi(x,y)+\omega_x(x,y)\gamma+\omega_y(x,y)\eta\right], \tag{4}$$

where $\omega_x(x,y)$ and $\omega_y(x,y)$ are the phase derivatives along x and y axes, respectively. It can be seen that the local contour passing through (x,y) satisfies

$$\omega_x(x,y)\gamma+\omega_y(x,y)\eta=0, \tag{5}$$