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WFF-BM3D: A hybrid denoising scheme for fringe patterns

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ABSTRACT

Fringe patterns are widely used in the optical interferometry. The captured fringe patterns usually have noises, and thus a filtering process for fringe patterns is necessary. The windowed Fourier filtering (WFF) algorithm is proposed specially for fringe pattern denoising. The WFF performs well in continuous areas, but has problems in discontinuous areas. In this paper, we proposed a hybrid denoising scheme which combines the advantages of the local WFF algorithm and non-local block-matching 3D filtering (BM3D) algorithm. This new scheme can recover fringe pattern information from the WFF residuals, and improve the denoising results effectively.

Keywords: Fringe pattern, image denoising, windowed Fourier filtering, block-matching 3D filtering (BM3D)

1. INTRODUCTION

A fringe pattern is a common output of the optical interferometry measurement. Useful Information, such as shape and deformation, can be extracted from fringe patterns. In general, a fringe pattern is modeled as

$$f_0(x, y) = a(x, y) + b(x, y) \cos[\varphi(x, y)], \quad (1)$$

where (x, y) represents the coordinates of pixels; $f_0(x, y)$ is the intensity of the recorded image; $a(x, y)$ is the background intensity; $b(x, y)$ is the fringe amplitude; $\varphi(x, y)$ is the phase distribution¹. Such fringe patterns are called intensity fringe patterns (IFP). The captured fringe pattern often contains noises. Due to this reason, the fringe pattern must be denoised before any further analysis. A fringe pattern with noise can be expressed as

$$f(x, y) = a(x, y) + b(x, y) \cos[\varphi(x, y)] + n(x, y), \quad (2)$$

where $f(x, y)$ is the fringe pattern with noise, and $n(x, y)$ represents the noise. To remove the noises in an IFP, many effective methods have been proposed. These methods can be classified into two types, spatial domain methods and transform domain methods. The mean and median filtering methods¹, the second-order oriented partial-differential equations (OPDEs) method² and the coherence enhancing diffusion (CED) method³ are examples of the spatial domain methods. Meanwhile, Fourier transform⁴, windowed Fourier transform (WFT)⁵, and wavelet transform methods⁶ are widely adopted in the transform domain methods. Windowed Fourier filtering (WFF) method is a WFT based algorithm, and it can provide satisfactory denoising results. The WFF algorithm is a local processing method. It filters noises in a four-dimensional (4D) transform domain. As the noises usually have small windowed Fourier coefficients, they can be identified and removed in the transform domain. However, the WFF algorithm performs better in continuous areas than in discontinuous areas (such as the boundary of two pieces of fringe patterns). This situation indicates that fringe pattern information in discontinuous areas are lost during the denoising process.

We are curious to see whether the lost fringe pattern information can be recovered. The lost information hides in the fringe pattern residuals after the filtering and mix with noises. The block-matching 3D filtering (BM3D) algorithm is the state of the art algorithm for image denoising^{7,8}, and it has been applied to denoise fringe patterns⁹. In this paper, we proposed a hybrid denoising scheme with the WFF and the BM3D on IFPs. From the results, the new scheme effectively removed the noises in the residuals and recovered the lost fringe pattern information.

The rest of paper is organized as follows. The principle of the WFF algorithm is introduced in Sec. 2. In Sec. 3, the principle of the BM3D and the details of the hybrid scheme are provided. In Sec. 4, the experimental results are presented and discussed. The paper is concluded in Sec. 5.

2. WINDOWED FOURIER TRANSFORM AND ITS BOUNDARY PROBLEM

2.1 Windowed Fourier filtering (WFF)

Given a fringe pattern $f(x, y)$, its WFT spectrum⁵ can be represented as

$$Sf(u, v; \xi_x, \xi_y) = f(u, v) \otimes g_{\xi_x, \xi_y}(u, v), \quad (3)$$

where (x, y) and (u, v) are both spatial coordinates; ξ_x and ξ_y are frequency coordinates for x and y directions, respectively; $Sf(u, v; \xi_x, \xi_y)$ is the WFT spectrum; $\otimes$ is the symbol of convolution; and $g_{\xi_x, \xi_y}(x, y)$ is the WFT kernel. The WFT kernel can be further expressed as

$$g_{\xi_x, \xi_y}(x, y) = g(x, y) \exp(j\xi_x x + j\xi_y y), \quad (4)$$

with

$$g(x, y) = (\pi\sigma_x\sigma_y)^{-1/2} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right), \quad (5)$$

where σ_x and σ_y are the standard deviations of Gaussian function in x and y directions, respectively. They determine the window size of the WFT.

The noise is usually random, and it has very small WFT spectrum coefficients. Thus the noise can be removed by discarding these small coefficients. In the 2D WFF (WFF2) algorithm, the filtered fringe pattern $\bar{f}(x, y)$ is obtained through an inverse WFT (IWFT), which is described as follows

$$\bar{f}(x, y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \overline{Sf}(x, y; \xi_x, \xi_y) \otimes g_{\xi_x, \xi_y}(x, y) d\xi_x d\xi_y, \quad (6)$$

with

$$\overline{Sf}(u, v; \xi_x, \xi_y) = \begin{cases} Sf(u, v; \xi_x, \xi_y) & \text{if } |Sf(u, v; \xi_x, \xi_y)| \geq \text{threshold}, \\ 0 & \text{if } |Sf(u, v; \xi_x, \xi_y)| < \text{threshold}, \end{cases} \quad (7)$$

where $\overline{Sf}(u, v; \xi_x, \xi_y)$ is the filtered spectrum. The main task of the WFF2 is to compute $\overline{Sf}(u, v; \xi_x, \xi_y)$ for all combinations of ξ_x and ξ_y taken from $[\xi_{xl}, \xi_{xh}] \times [\xi_{yl}, \xi_{yh}]$, threshold it, and use it for the reconstruction in Eq. (7).

2.2 The WFF2's discontinuity problem

The WFF2 algorithm assumes that the phase is linearly distributed in a small window. This assumption works well for most cases, but it has some problems in the discontinuous areas, such as the boundary of two pieces of fringe patterns or the boundary of the captured image. Usually, these discontinuous areas contain explicit phase changes, and thus the linear model used by the WFF2 cannot perfectly fit it.

In this paper, as we focus on the IFPs, Eq. (2) can be rewritten as follows in a simplified way

$$f = a + \frac{b}{2} \exp(j\varphi) + \frac{b}{2} \exp(-j\varphi) + n, \quad (8)$$

and the filtered fringe pattern can be further rewritten as⁵

$$\bar{f} = \bar{a} + \frac{\bar{b}}{2} \exp(j\varphi) + \frac{\bar{b}}{2} \exp(-j\varphi) + \bar{n}, \quad (9)$$

where $\bar{b} = \left[1 - \exp\left(\frac{-R^2}{4\pi}\right)\right] b$, $R = \sqrt{8\pi \ln \left[\frac{b}{\text{threshold}} \left(\frac{4\pi\sigma_x^2}{1+\sigma_x^4 c_{xx}^2} \frac{4\pi\sigma_y^2}{1+\sigma_y^4 c_{yy}^2} \right)^{\frac{1}{4}} \right]}$, $c_{xx} = \frac{\partial^2 \varphi}{\partial x^2}$, and $c_{yy} = \frac{\partial^2 \varphi}{\partial y^2}$. The detailed derivation can be found in Ref. 5. According to Eq. (9), the phase is kept, and the amplitude of the filtered fringe pattern is reduced by $\left[1 - \exp\left(\frac{-R^2}{4\pi}\right)\right]$. This proves that some fringe pattern information is hiding in the WFF2 residuals. Moreover,

the amplitude of the regions with high local curvature, such as the discontinuous areas, is reduced more than the regions with lower local curvature. The WFF2 residual signal can be expressed as follows,

$$f_R = (f_0 - \bar{f}_0) + (n - \bar{n}). \quad (10)$$

Obviously, there are two potential solutions to improve the filtered fringe pattern. One solution is to improve the WFF2 algorithm to reduce the hidden fringe pattern in the WFF2 residuals, i.e. reduce the value of $f - \bar{f}$ in Eq. (10), so that $\bar{f} \approx f$ and no useful information is lost. Modeling the phase as a higher order polynomial is a possible method but it explicitly increase the complexity of the WFF2 algorithm. The other solution is to recover the lost information from the residual signal f_R by removing $n - \bar{n}$. The recovered information is denoted as $\bar{f}_R$. Consequently, the improved filtered fringe pattern f_H is obtained by adding the WFF2 result and the recovered information as follows

$$f_H = \bar{f} + \bar{f}_R. \quad (11)$$

The residual f_R is an edge-like image with noises. This inspires us to remove the noise term by image denoising techniques. The BM3D is considered as the state of the art image denoising method, and it can collaborate with the WFF2 to enhance denoised fringe patterns. In the next section, the details of this hybrid method are introduced.

3. RECOVERING FRINGE PATTERN FROM RESIDUALS

3.1 Principle of the BM3D

The BM3D⁷ is a non-local filtering method by using grouping and collaborative filtering. The algorithm has two major stages, basic estimate and final estimate. Each stage consists of three steps, grouping, filtering and aggregation. In the grouping step, the algorithm looks for all similar patches in the whole image for each reference patch. The found patches form a 3D patch array for each reference patch. Then, a 3D transform is applied to each 3D patch array. This 3D transform is composed of a 2D transform and a 1D transform. The 2D transform is applied on each patch in the 3D array and the 1D transform is applied along the third dimension of the 3D array. After that, a shrinkage process is applied to the spectrums of the 3D transform, followed by an inverse 3D transform. Pixels are finally estimated by aggregating different reference patches.

The basic estimate and the final estimate have similar steps. Only the input and the shrinkage process are different. The basic estimate uses the original noisy image as its input, and the final estimate uses the original noisy image and the result of the basic estimate as the input. For the shrinkage, hard-thresholding and Wiener filtering are used in the basic and final estimates, respectively⁸.

3.2 The WFF-BM3D: a hybrid denoising scheme

The BM3D is a very effective algorithm on image denoising, and its performance on fringe pattern denoising has been examined⁹. Although the BM3D performs worse than the WFF2 for continuous fringe patterns⁹, it works better on discontinuities because of its non-local strategy. A hybrid scheme is thus proposed, which uses the WFF2 (a local method) to denoise a fringe pattern, and uses the BM3D (a nonlocal method) to recover the information around discontinuities. This hybrid scheme is named WFF-BM3D. Meanwhile, one straightforward solution is also applicable, which combines the continuous areas of the WFF2 result and the discontinuous areas of the BM3D directly. This method is named Mosaic method in this paper, and it is compared with the proposed WFF-BM3D method in the later experiments.

4. EXPERIMENTAL VERIFICATION

4.1 Experiments

To verify the performance of the proposed WFF-BM3D scheme, a clean image simulated by MATLAB, as shown in Fig. 1 (a), is used. This image (512×512) is made up of two pieces of fringe patterns with different frequencies and directions. Then, a noisy image, as shown in Fig. 1 (b), is generated by adding additive Gaussian noise to the clean image. The standard deviation of the noise is 50. During the experiment, the default parameters of the WFF2 and the BM3D are used. The reason of using the default parameters is the default parameters provides nearly optimal results and an easy way to use the algorithms^{3,8}.

Fig. 1. (a) Simulated clean fringe pattern; (b) corresponding noisy fringe pattern.

The results of the WFF2, the BM3D and the Mosaic method are shown in Fig. 2 (a) - (c), respectively, while their respective error maps comparing with the ground truth are shown in Fig. 2 (d) - (f). In order to understand the performances of these algorithms quantitatively, we first manually segment the image into continuous and discontinuous areas. The pixels whose distances to the boundary are within 30 pixels belong to the discontinuous areas, while the remaining pixels belong to continuous areas. The mean absolute error (MAE) is defined as the mean of the absolute value of an error map. The MAEs of different algorithms in different areas are shown in Table 1 and show that the Mosaic method is the best among these three algorithms.

Fig. 2. The results of (a) the WFF2, (b) the BM3D, and (c) the Mosaic; the error maps of (d) the WFF2, (e) the BM3D, and (f) the Mosaic.

To perform the WFF-BM3D, the residual map of the WFF2 is first calculated and shown in Fig. 3 (a), which shows the information discarded by the WFF2. Obviously the information in the discontinuous areas should be recovered, if possible. Applying the BM3D to this residual map gives a filtered residual map (shown in Fig. 3 (b)), which looks appealing as the desired information is clearly presented without noise. We thus want to add the filtered residual map (Fig. 3 (b)) back to the fringe pattern denoised by the WFF2 (Fig. 2 (a)), which can be achieved by three possible ways. The first way, named full update, is to add back the filtered residual map directly. Because the WFF2 has achieved a good fit in the continuous areas, it is not necessary to update pixels in these areas. Thus the second way, named discontinuous area update, is to add back the pixels in the discontinuous areas only. The third, named selective update, only adds back the pixels with high local standard deviation. The result and the error map of the third way are shown in Fig. 4 (a) - (b), while the first two methods have visually similar results. We can find the quality of the pixels in the boundary areas are improved, and nearly all distortions are corrected. The MAEs of these three ways of the WFF-BM3D are shown in Table 1, which shows that the WFF-BM3D (selective update) gives the best result.

Fig. 3. (a) The residual map of the WFF2; (b) the residual map after filtered by the BM3D.

Fig. 4. (a) The result of the WFF-BM3D (selective update); the error map of the WFF-BM3D (selective update).

Table 1. The MAEs of different algorithms in both discontinuous and continuous areas.

	WFF2	BM3D	Mosaic	WFF-BM3D (full update)	WFF-BM3D (discontinuous area update)	WFF-BM3D (selective update)
Continuous Areas	0.0131	0.0218	0.0131	0.0139	0.0131	0.0131
Discontinuous Areas	0.0413	0.0228	0.0228	0.0223	0.0223	0.0217

4.2 Discussions

From the theoretical analysis and experimental results, the following points can be observed.

- As expected, the WFF2 works well in the continuous area, while the BM3D works well in discontinuous area. The proposed hybrid scheme is originated from this fact;
- The WFF2 is a local processing algorithm, while the BM3D is a nonlocal one. The BM3D works well for discontinuous areas because of its nonlocal feature. The collaboration of local and nonlocal algorithms performs better than either single algorithm;
- Among different collaboration ways, the WFF-BM3D (selective update) is most intelligent and performs best, while all others are worth trying.
- It can be seen from Eq. (9) that amplitude is reduced from b to $\bar{b}$. The influence of this fact on the proposed scheme needs further exploration.

5. CONCLUSIONS

The WFF2 and the BM3D are two types of denoising techniques. The WFF2 is specially designed to remove noises in fringe patterns, but it has problems if the fringe pattern is discontinuous. The BM3D is a general image denoising method which, in contrast, works well in the discontinuous areas. In this paper, we proposed a hybrid method combining the advantages of the WFF2 and BM3D. The results show that this hybrid method can effectively improve the denoising performance.

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