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A comparison study of denoising techniques in fringe pattern analysis

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ABSTRACT

Optical interferometry is a popular technique for high precision measurement. It produces fringe patterns for analysis. The output fringe patterns usually have noises, and thus a filtering process for fringe patterns is necessary. A few filtering algorithms, such as windowed Fourier filtering (WFF), have been proposed specially for fringe pattern denoising. Meanwhile, filtering techniques have been intensively studied for a long time in the general image processing area. It is curious that how the filtering techniques in general image processing area perform on fringe pattern denoising. In this paper, a state-of-the-art filtering algorithm, block-matching 3D filtering (BM3D), is selected and compared with the WFF.

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

1. INTRODUCTION

Optical interferometry is a non-contact, high precision, and full-field measurement technique. It is widely adopted in industry and academia¹. The optical interferometry technique produces fringe patterns as follows:

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

where (x, y) represents the coordinates of pixels; $f(x, y)$ 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 distribution which contains the information to be measured, and $n(x, y)$ is the noise. For convenience, such fringe patterns are called intensity fringe patterns (IFP). When phase-shifts or a carrier frequency is introduced into the fringe patterns, the following exponential phase fringed (EPF) can be obtained²:

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

where j is the imaginary unit.

In the measurement process, the obtained fringe patterns always contain noises, and a denoising process is therefore necessary. To reduce noises in the fringe patterns, a few effective methods have been proposed, such as coherence enhancing diffusion (CED)³, wavelet transform⁴, and the windowed Fourier filtering (WFF)². The WFF method is a local processing method, and it filters the noises in a two-dimensional (2D) transform domain. Because of its randomness, the noise can be reduced by discarding small windowed Fourier coefficients.

Meanwhile, since fringe patterns are images, they can also be processed by general image processing algorithms. In the general image processing area, the denoising problem has been intensively studied for a long time, and a large number of denoising algorithms have been proposed. It is curious to see how the image denoising algorithms perform on denoising fringe patterns. The block-matching 3D filtering (BM3D) is the state of art algorithm for image denoising⁵. It adopts a non-local strategy which stacks similar patches of a noisy image into a three-dimensional (3D) array, and it filters the noises in a 3D transform domain. Due to its good denoising performance, it is selected in this paper to compare with the WFF.

The rest of the paper is organized as follows. The principles of the WFF and the BM3D are introduced in Sec. 2. These two algorithms are compared in Sec. 3. The paper is concluded in Sec. 4.

2. PRINCIPLES OF THE WFF AND THE BM3D

2.1 Windowed Fourier filtering (WFF)

Given a fringe pattern $f(x, y)$, its windowed Fourier transform (WFT) spectrum² 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 spatial extension of Gaussian function, i.e. the window size.

Due to its randomness, the noise usually has small WFT spectrum coefficients. Thus the noise can be filtered by discarding those 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 body of the WFF2 is to compute $\overline{Sf}(u, v; \xi_x, \xi_y)$ for each pair 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. (6).

2.2 Block-matching 3D filtering (BM3D)

The BM3D⁵ is an approach to non-local adaptive nonparametric filtering method through grouping and collaborative filtering. It is divided into two major stages, basic estimate and final estimate. Each stage is further divided into three steps, grouping, filtering and aggregation. In the grouping step, for each reference patch, the algorithm searches all similar patches in the whole image. The found patches are stacked into 3D patch arrays, and one reference patch has one 3D array. A 3D transform is applied to each 3D patch arrays. This 3D transform consists of a 2D transform on each patch in the 3D array and a 1D transform along the third dimension of the 3D array. A shrinkage process is applied to the obtained 3D transform spectrums, followed by an inverse 3D transform. Aggregation is performed for pixels estimated from different reference patches.

The basic estimate and the final estimate have similar steps. The only differences are the input and the shrinkage process. In the basic estimate, the input is the original noisy image, while in the final estimate, the inputs are the original noisy image and the result of the basic estimate. For the shrinkage, hard-thresholding and Wiener filtering are used in the basic and final estimates, respectively⁶.

Fig. 1. The IFPs and EPFs of the Straight, Circular and Peaks examples.

3. COMPARISON BETWEEN THE WFF AND THE BM3D

3.1 Configurations

In this paper, two types of fringe patterns, IFP and EPF, are used. For each type of fringe patterns, three fringe patterns with the size of 512×512 , including Straight, Circular and Peaks, are simulated by MATLAB. For each IFP, the fringe amplitude is simulated to be $b(x, y) = 127.5$, while the additive Gaussian noises are set as $\sigma = 20, 40, 60, 80, 100, 120$ and 140 . Thus approximately, σ/b ranges from 0 to 1. As for each EPF, its real and imaginary parts are simulated as two IFPs. In Fig. 1, the wrapped phase maps of the IFPs and the corresponding EPFs, are represented. The WFF2 code is the same as in Ref. 7, while the BM3D code is downloaded from Ref. 8. When the WFF2 and the BM3D are executed, their default parameters are used. The default parameters for the WFF2 provide a convenient yet effective way to use the WFF2, although manually set parameters could yield better results². The default parameters for the BM3D are nearly optimal⁶.

The WFF2 accepts both IFPs and EPFs as the input. In the BM3D, when the input is an IFP, it is processed directly; when the input is an EPF, the real and imaginary parts of EPFs are processed separately, and the final denoised EPF consists of both denoised real and imaginary parts.

3.2 Results

Fig. 2. Selected denoised IFPs and EPFs of the Circular example.

In Fig. 2, filtering results of Circular fringe patterns are provided. The Straight and Peaks examples have similar results. As a quantitative measure, the mean absolute errors (MAEs) are evaluated. The MAEs between the filtered and ideal

intensities of IFPs and the MAEs between the filtered and ideal phases of EPFs are shown in Fig. 3 and Fig. 4, respectively. Both the WFF2 and the BM3D is able to denoise the fringe patterns effectively. The WFF2 outperforms the BM3D. In the IFP examples, the MAEs of the BM3D are 30% higher than the WFF2. In the EPF examples, the MAEs of the BM3D are more than 3 times higher than the WFF2. However, since the BM3D has been continuously improved since its publication, better performance is possible. For example, in our simulation, the real and imaginary parts of an EPF are processed by the BM3D separately. When writing this paper, an idea of directly applying the BM3D to EPFs was proposed⁹. It is interesting to note that, if we further increase the noise level, the BM3D may perform better, but the WFF2 outperforms it again by simply increasing the threshold. Experimental fringe patterns have also been tested with similar filtering results.

Fig. 3. The comparison of the mean absolute errors of the WFF2 and the BM3D in the IFPs.

Fig. 4. The comparison of the mean absolute errors of the WFF2 and the BM3D in the EPFs.

3.3 Discussions

The WFF2 highlights the idea of local processing. From measurement point of view, local processing seems reasonable, because the fringe patterns are usually obtained from optical measurement and nearby data are more or less correlated. The phase of fringe pattern in a local block is usually simple and can be modeled as a polynomial. Furthermore, there is prior knowledge that the fringe patterns are in the form of cosine or exponential functions, as shown in Eqs. (1) and (2), respectively. Consequently, a local (windowed) Fourier transform provides a sparse representation for the fringe data and enables effective filtering. On the contrary, the BM3D is non-local. From signal processing point of view, it builds up numerical correlation by block matching in the data processing stage. The sparsity is then achieved by grouping similar but non-local patches. The BM3D is thus able to utilize more data for collaborative filtering than the WFF2. Furthermore, the BM3D does not assume the data type and thus is able to filter any images. However, the characteristics of fringe patterns utilized by the WFF2 are ignored by the BM3D. Apparently the WFF2 and the BM3D are two denoising approaches developed from different viewpoints. Since both of them achieve high correlation and sparsity, they are expected to be effective in denoising. Finally, we mention that, local processing is solely used for demodulation of a single closed fringe pattern².

4. CONCLUSIONS

The WFF2 and the BM3D are two different denoising techniques. The WFF2 is a local processing method and it is specially designed for fringe pattern denoising. The BM3D uses a non-local strategy to denoise image. In this paper, we compare their denoising performances for fringe patterns. The results show that both of them work satisfactorily, while the WFF2 outperforms the BM3D in the examples presented in this paper.

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