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High resolution image restoration algorithm of wavefront coding system based on wiener filter and wavelet de-noising

Qiang Li[a], Feng Xu*[a], Xiaonan Zhao[a], Yujia Yao[a] and Yunxiang Li[a]
[a]Key Lab of Advanced Optical Manufacturing Technologies of Jiangsu Province & Key Lab of Modern Optical Technologies of Education Ministry of China, Soochow University, Suzhou, Jiangsu, 215006, PR China.

ABSTRACT

As the light travels through the wavefront coding (WFC) system, the modulation transfer function(MTF) of the WFC system was very low, consequently the intermediate blurred image has been received by the detector. However, there is no zero point in the passband of the MTF of the WFC imaging system, and the target information cannot be saved very well. An appropriate filter can be used to restore the sampled intermediate image. The noise of the system is enlarged in the restoration process where the signal be amplified by the filter, and the signal to noise ratio(SNR) of the image is reduced. In order to solve the above issues, an improved algorithm has been proposed in this paper. The noise is controlled by the wavelet in the reconstruction process, and the intermediate blurred image is restored by the wiener filter algorithm with a prior knowledge of the degradation function. Thus, the wavelet de-noising and wiener filter algorithm are combined to restore the middle blurred image of the WFC system. Finally, the restoration image with the diffraction limit level is acquired in image detail restoration and noise control.

Keywords: Wavefront coding, image restoration, wavelet de-noising, wiener filter algorithm

1. INTRODUCTION

Wavefront coding imaging technology was widely used to extend the depth of field of the optical systems. An intermediate blurred image is acquired using this technology, thus, an appropriate filter is needed for restoring the intermediate blurred image. The traditional restoration algorithm is the wiener filter and there are many image restoration algorithms of the WFC system were proposed[1-4]. However, the PSF of the WFC system is affected easily by the tilt and decenter of the phase mask and the noise of CCD, which cannot achieve a high resolution image after the restoration. So the accurate acquisition of the PSF of the WFC system is particularly important for the restoration. Thus the research of the high resolution image restoration algorithm is particularly important for the WFC system.

In this paper, a new method of image restoration based on wiener filter and wavelet de-noising has been proposed. The noise can be controlled by the wavelet in the restoration, and the intermediate blurred image is restored by the wiener filtering algorithm[5].

2. WFC TECHNOLOGY AND TRADITION ALGORITHM

2.1 Wavefront coding technology

WFC imaging technology was first proposed to extend the depth of field of optical systems by Dowski and Cathey in 1995[6].The technique is based on the modulation of the wavefront by means of a suitable phase mask which placed at the pupil of optical system, it can make the imaging performance of the optical system insensitive to the defocus over a range of distances around the image plane. Although the image captured at the image plane is blurred. It can be restored by a simple digital filtering process, which using the representative PSF as a deconvolution filter.The detailed procedure of wavefront coding technology is depicted in Figure 1.

*xf750617@suda.edu.cn

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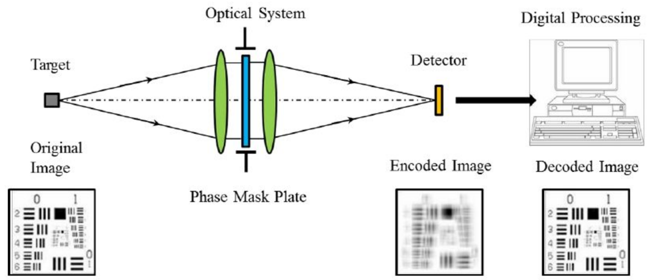

Figure 1. Principle of WFC optical imaging system

At present, the typical rotational asymmetric mask of the WFC system is a cubic phase mask. The cubic phase mask profile of the WFC system is given by

$$z = \alpha(x^3 + y^3) \tag{1}$$

where α is the phase constant. The modulation transfer function(MTF) of the system is shown in Figure 2. The figure shows that the change of MTF is very small in different focus and field of view, which indicate that after the cubic phase mask inserting the WFC system, the sensitivity to defocus is greatly reduced. This makes it possible to apply the same digital processing restores the image for all values of misfocus.

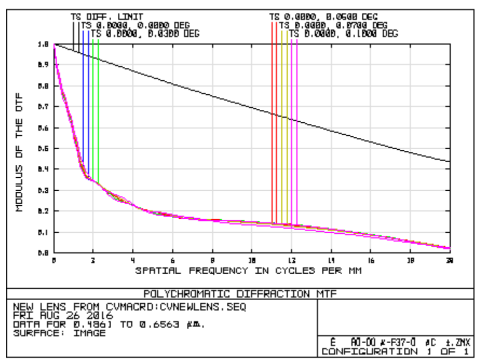

Figure 2.MTF of the WFC system

2.2 Traditional restoration algorithm

Wiener filter is one of the earliest and best known approaches to linear image restoration. It seeks an estimate that minimizes the statistical error function $e^2 = E\{(f - \hat{f})^2\}$. The solution to this expression in the frequency domain is

$$\hat{F}(u,v) = [\frac{1}{H(u,v)} \frac{|H(u,v)|^2}{|H(u,v)|^2 + S_\eta(u,v)/S_f(u,v)}]G(u,v) \tag{2}$$

Where

$H(u,v)$ = the degradation function

$|H(u,v)|^2 = H^*(u,v)H(u,v)$

$H^*(u,v)$ = the complex conjugate of $H(u,v)$

and the ratio $S_\eta(u,v)/S_f(u,v)$ is named the noise-to-signal power ratio.

When there is no noise, $S_\eta(u,v) = 0$,Wiener filter is the inverse filter; when $S_\eta(u,v) \neq 0$,the noise-to-signal power ratio is used to correct the restoration process and eliminate the ill posed problem when H is small or equal to zero.

3. IMAGE RESTORATION ALGORITHM

Wiener filter algorithm is widely used to the restoration of the blurred image of WFC system, but the restoration in the high frequency part is not ideal. In this paper, the wavelet de-noising and Wiener filtering algorithm are combined to improve the resolution of the high frequency part.

3.1 A model of the image degradation/restoration process

A degradation function H together with an additive noise term is operated on an object plane $f(x, y)$ to produce a degraded image $g(x, y)$

$$g(x, y) = H[f(x, y)] + \eta(x, y) \tag{3}$$

If H is a linear, spatially invariant process, the degenerate model is simplified as follow

$$g(x, y) = f(x, y) * h(x, y) + \eta(x, y) \quad . \tag{4}$$

The objective of restoration is to obtain an estimate $\hat{f}(x, y)$ of the original image based on the given $g(x, y)$, some knowledge about the degradation function H and the additive noise term $\eta(x, y)$. The process of degradation and restoration is shown in Fig.3.

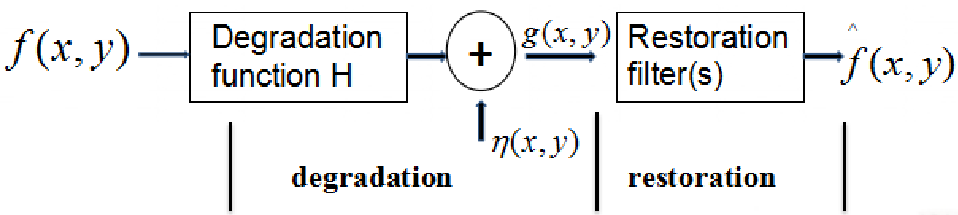

Figure 3. A model of the image degradation/restoration process

3.2 Wavelet transform

Wavelet transform is developed in the past 20 years of the new signal processing technology, which is a time-frequency localization analysis method with a switchable time-frequency window. A higher frequency resolution and lower time resolution can be acquired in the low-frequency part while a lower frequency resolution and higher time resolution can be acquired in the high-frequency part.

The function of wavelet transform in time domain is given as follows

$$WT_x(a, \tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \psi^*(\frac{t-\tau}{a}) dt \qquad a > 0 \tag{5}$$

The function in frequency domain is expressed as follows

$$WT_x(a, \tau) = \frac{\sqrt{a}}{2\pi} \int_{-\infty}^{+\infty} X(\omega) \psi^*(a\omega) e^{j\omega\tau} d\tau \tag{6}$$

Where $X(\omega)$, $\psi(a\omega)$ respectively is the Fourier transform of $x(t)$, $\psi(t)$.

Several following features of wavelet transform are list for the de-noising aspect: lower entropy, multi-resolution properties, decorrelation and the flexibility of the selection of wavelet basis. Depending on the different processing methods of wavelet coefficients, a common de-noising method can be divided into three categories:(1) the maximum of wavelet transform modulus;(2) correlation of an adjacent scale wavelet coefficients;(3) wavelet transform domain threshold.

Wavelet threshold method is used to de-noise in the article. The basic idea is that the modulus of the layer wavelet decomposition coefficients which are greater or smaller than a certain threshold value is processed separately, and then the processed wavelet coefficients are used in the de-noised image.

4. ALGORITHM IMPLEMENTATION AND SIMULATION RESULTS

The process of the algorithm simulation is list as follows: firstly, the wavelet de-noising algorithm is used to restrain the noise of point spread function (PSF) of wavefront coding system; and then the intermediate blurred image is restored by the wiener filter with the processing PSF, using different proportions to enhance the characteristic of the high frequency part, so as to achieve the purpose of the improving image qualities, the algorithm is shown in Figure 4.

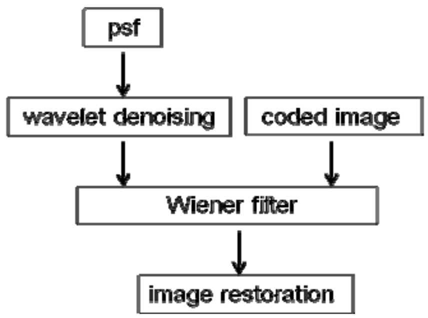

Figure 4. Flow chart of algorithm

The simulation is based on Matlab2014a, the PSF of the wavefront coding system is used as the deconvolution filter, respectively take the depth of focus at 0mm, +1.5mm, -1.5mm, +3.2mm, -3.2mm. Figure 5 is the initial image, figure 6 are the PSF of the wavefront coding imaging system of the different depth of focus.

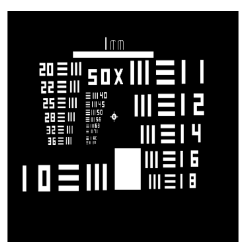

Figure 5. Initial image

Figure 8 and 9 are the results of two different recovery algorithms for the intermediate blurred image restoration. Figure 8 are the restoration images by the wiener filter restoration algorithm and Figure 9 are the restoration images by the wiener filter restoration algorithm with the wavelet de-noising for the PSF, the two restoration methods indicate that the second restoration algorithm is higher and clearer in resolution especially in the high- frequency part.

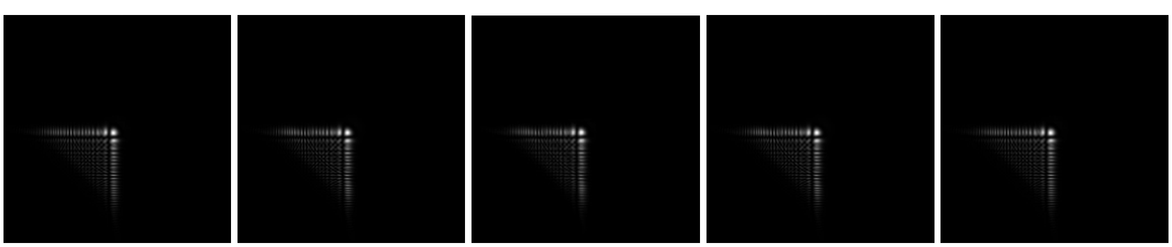

Figure 6. PSF of the different depth of focus

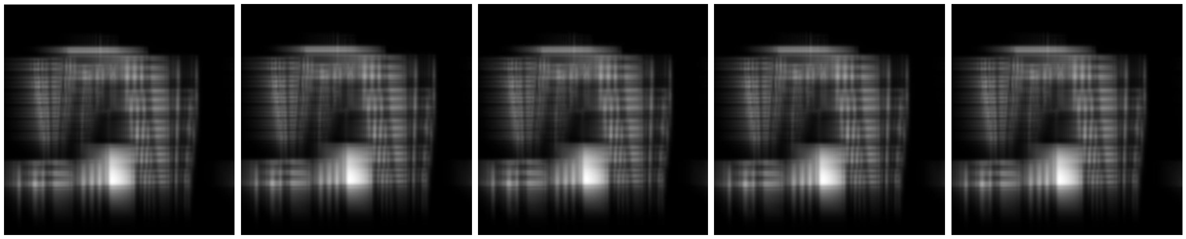

Figure 7. Intermediate blurred image

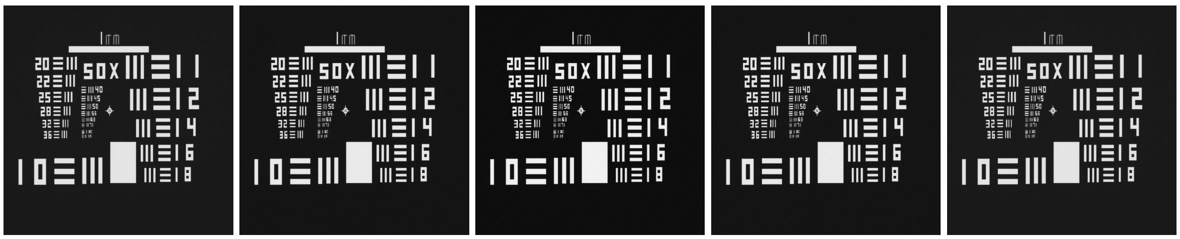

Figure 8. Blurred images of fig.7 restored by wiener filter algorithm

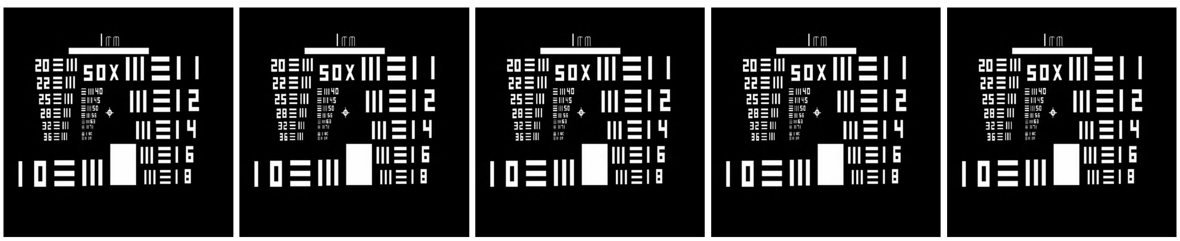

Figure 8. Blurred images of fig.7 enhanced by wiener filter with wavelet de-noising algorithm

Peak Signal to Noise Ratio (PSNR) is usually used to evaluate the quality between the restoration image and original image. the higher PSNR means the better recovery, and the distortion will be smaller. Two concepts are defined here, one is the mean square error (MSE), and the other is the peak signal to noise ratio (PSNR), they all can be used to evaluate the quality of the restoration image. The formulas are list as follows

$$MSE = \frac{1}{mn}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}\left\| f(x,y) - f^{\wedge}(x,y)\right\|^2 \tag{7}$$

$$PSNR = 10 \cdot \log_{10}\left(\frac{MAX_f^2}{MSE}\right) \tag{8}$$

Where MAX (255) is the maximum gray level. The lager PSNR value, the smaller the difference between the restoration image and the original image, the more information of the original image, the better quality of the image.

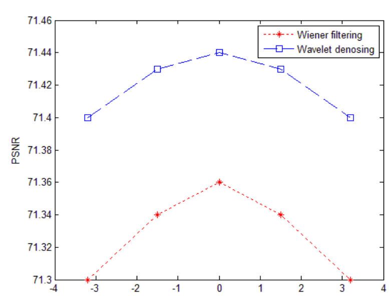

Figure 10. PSNR of the restored images in different depth of focus

As can be seen from figure 10, in the process of image restoration of the WFC system, with the increase of the depth of focus, the corresponding PSNR value decreases and the image restoration resolution gradually decrease. The restoration image by wiener filter is not so ideal, and the use of wavelet de-noising method for the WFC system can effectively improve the resolution of the restoration image.

5. CONCLUSION

The wiener filter and wavelet de-noising algorithm has been used to restore the intermediate blurred images of WFC system. The simulation results show that wiener filter algorithm works well in low frequency restoration parts, but in high frequency parts. Wiener filter combined with wavelet de-noising algorithm on the intermediate blurred image restoration, can effectively correct the defects of single wiener filter algorithm, which can greatly improve the results of high frequency portion of the restored image. High resolution of the restored images can be acquired by this way.

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