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Filter Dependence on the Phase Error of Fourier Transform Profilometry

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Abstract

In phase measuring fringe reflection Fourier transform profilometry, it gets the captured image data from the projected sinusoidal fringe patterns by using the CCD cameras. Added white noise in captured fringe images and its low contrast levels affect the accuracy of three-dimensional surface profile measurements induced the phase errors. In this work, we present phase error reduction method using the low pass spatial image filter and median filter. Experimental results are also demonstrated to evaluate the effectiveness of the low pass filter and median filter. The result shows that white noise in the fringe pattern can be effectively removed and filtered fringe is smoothed. In case of the median filter, it showed negative influence to the phase error, but the low-pass filter evidently reduced the phase error about 30 percent.

Keywords: Fourier Transform Profilometry, Low Pass Filter, Median Filter Phase Error

1. Introduction

Nowadays the development of electronic device technologies including display device, computer, CCD camera, optical image processing software, high spatial pixel resolution and 3D inspection is becoming more important and used more in practical life. This 3D inspection is applicable to area such as biomedical inspection, industrial automation process, robot and computer vision, 3-D printing and reverse engineering[1–3]. Among the several 3-D surface profile measurements the methods based on the structured light fringe pattern reflection are probably studied and used the most. Fourier Transform Profilometry (FTP) encodes simply and flexibly, and requires only one sinusoidal fringe image to measure the surface profile of an object. However, captured patterns include gamma distortions, optical aberrations, low contrast, low signal-to-noise ratio, object surface reflectance variation, which induce deformation of fringe to be non-sinusoidal and the deformation of fringe seriously affect the accuracy of the phase measurements. To overcome this problem, various techniques have been proposed to get the exact sinusoidal fringe patterns[4]. Image sensors and LCD fringe display monitor may produce certain type of noise characterized by random and isolated pixels with out-of-range gray levels, which are either much lower or higher than the gray levels of the neighboring pixels. Such noise can be treated as some impulses corresponding to high spatial frequencies. When the CCD image taken under low illumination, it has low signal-to-noise ratio and is characterized by such random noisy pixels. The previously proposed methods of resolving nonlinear gamma include application of tone correction to the fringe patterns before display, pre-coding of projected fringe to reduce measurement error caused by gamma distortion[3,5]. On the other hand, since the spatial image filtering methods were developed for general display images, they are not most effective for fringe patterns which have more distinct orientation intensity variations compared to the general images[6]. However pre-processing of fringe patterns to eliminate the noise using the low pass filter and median filter is commonly used and its effect on the phase

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error of the FTP method is not described in detail.

In this work, we will propose and demonstrate the simple method to reduce phase error induced by random noise through suppressing removing the random noise on fringe patterns using the low pass spatial filter and median filter.

2. Brief Description of the Fourier Transform Profilometry

A generalized equation for a captured fringe pattern in the spatial fringe analysis may be expressed in the form

$$I(x,y) = a(x,y) + c(x,y)e^{i2\pi f_0 y} + c^*(x,y)e^{-i2\pi f_0 y} \quad \text{......(1)}$$

where * denotes a complex conjugate and

$$c(x,y) = \frac{1}{2}b(x,y)e^{i\phi(x,y)} \quad \text{......(2)}$$

Equation (1) may be transformed into the frequency domain by using the Fast Fourier Transform with respect to the y-axis which results in the following

$$I(x,y) = A(x,y) + C(x, v - f_o) + C^*(x, v + f_o). \quad \text{......(3)}$$

where A, C and C^* refer to the Fourier spectra and v is the spatial frequency in the y-axis. The Fourier spectrum in equation (3) is separated by the carrier frequency f_o. The phase component must be isolated in order to extract 3D shape information using some sorts of filtering. The inverse Fourier transform of the filtered and frequency shifted signal is then computed in order to obtain $C(x,y)$. The phase is calculated using the form[5]

$$\phi(x,y) = \frac{\tan^{-1}(Im[c(x,y)])}{Re[c(x,y)]} \quad \text{......(4)}$$

The resultant phase is called wrapped, as the arctangent function gives a principal value in the range $-\pi$ to π.

3. Image Noise and Filtering

3.1 Image Noise

In the fringe reflection surface profilometry, the sinusoidal grating fringe is projected on the object surfaces through using a LCD monitor or a projector. Also reflection fringe is captured by CCD image sensor. Image sensors and transmission channels may produce certain type of noise characterized by random and isolated pixels with out-of-range gray levels, which are either much lower or higher than the gray levels of the neighboring pixels. Such noise can be treated as some impulses corresponding to high spatial frequencies. Common types of noise found in the digital images, which are uniform (white) noise, Gaussian noise, Negative exponential noise, Salt and pepper noise. In signal processing, it is often desirable to be able to perform some kind of noise reduction on an image or signal[7].

3.2 Low-pass Filters

Low-Pass Filter (LPF) is used for image smoothing and noise. Their effect makes an average of the current pixel with the values of its neighbors, enables to observe a blurring of the output. All elements of the kernels used for low-pass filtering have positive values. Therefore, a common practice used to scale the result in the intensity domain of the output image is to divide the result of the convolution with the sum of the elements of the kernel[8].

$$(x,y) = \frac{1}{c}\sum_{i=k}^{k}.\sum_{j=k}^{k} H(i,j)I_s(X+i, y+j). \quad \text{......(5)}$$

Where $c = \sum_{i=k}^{k}\sum_{j=k}^{k} H(i,j)$

3.3 Median Filters

The Median Filter (MF) is a nonlinear digital filtering technique, often used to remove noise. Such noise reduction is a typical pre-processing step to improve the results of later processing (for example, edge detection on an image). Median filtering is very widely used in digital image processing, because under certain conditions, it preserves edges while removing noise. Neighborhood averaging can suppress isolated out-of-range noise, but the side effect is that it also blurs sudden changes such as line features, sharp edges, and other image details, all corresponding to high spatial frequencies. Specifically, the median filter replaces a pixel by the median, instead of the average, of all pixels in a neighborhood ω [9]

$$y[m,n] = median\{x[i,j], (i,j) \in \omega\} \quad \text{......(6)}$$

where ω represents a neighborhood defined by the user, centered around location $[m,n]$ in the image.

4. Experimental Results

Figure 1 depicts typical fringe reflection optical crossed axes Fourier transform phase measurement profilometry setup. A sinusoidal fringe pattern with a known spatial frequency is displayed on the LCD monitor and the image is captured at CCD camera. In the experiment, we used a resolution of 1280 x 1024, pixel pitch 0.28 mm LCD monitor. CREV is mini cam 8 bit CCD camera has a resolution of 1024 x 768 and a pixel size 4.65μm x 4.65μm and imaging lens focal length is 25mm , F # 1.3.The captured sinusoidal fringe pattern pre-processed by low pass filters and median filters with different rectangle mask size m x n pixels. Figure 2 shows the captured non-LPF original image and LPF image with rectangle mask size 11x11 pixels. In order to show the difference of noise removal effect clearly, we drew an intensity profile of the fringe patterns in Figure 2(a) and Figure 2(b) and the position is marked by red lines. Figure 3 shows the 2D FFT spectrum result of captured fringe patterns; (a) non-LPF, (b) LPF rectangle mask size 5X5 pixels, (c) LPF rectangle mask size 11x11pixels and (d) LPF rectangle mask size 17X17 pixels.

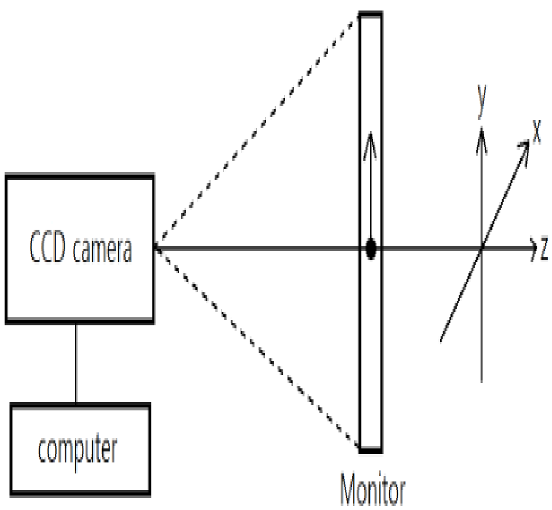
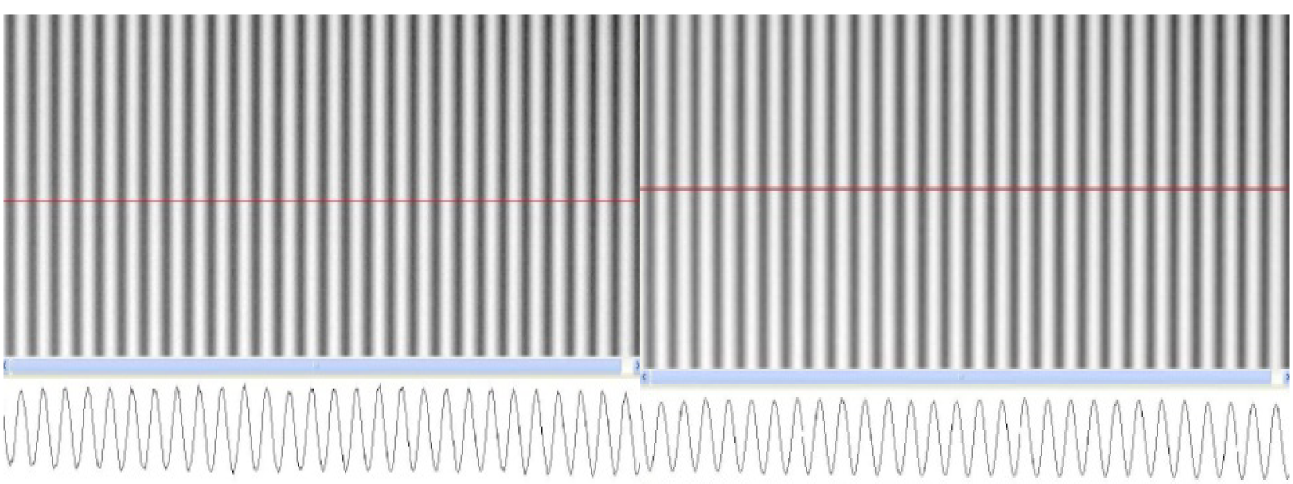


Figure 1. Phase extraction system. The sinusoidal fringe pattern is displayed on the LCD monitor.

Phase component is extracted through inverse Fourier transform of the isolated first order Fourier spectra. If use same capture images, every image pixel point should get some fixed phase values. But when we applied low-pass filter with different rectangle mask size to the same image, its phase error value was changed. Figure 4 shows phase error values according to the different LPF rectangle mask size at one image pixel line.

Figure 5 shows the experimental results for the low-pass filter with different rectangle mask size, which was used to suppress the noise in acquired fringe pattern. Through using the low pass filter, we can remove several sources of errors that can mitigate phase error by pre-processing to the fringe patterns.

Figure 6 shows the captured pre-processed MF filtering image with rectangle mask size 2x2 pixels and rectangle mask size 11x11 pixels. In order to show the



(a) (b)

Figure 2. Captured sinusoidal fringe patterns image and intensity profile. (a) Non-LPF fringe pattern image. (b) LPF pr-processed image with rectangle mask size 11x11 pixels.

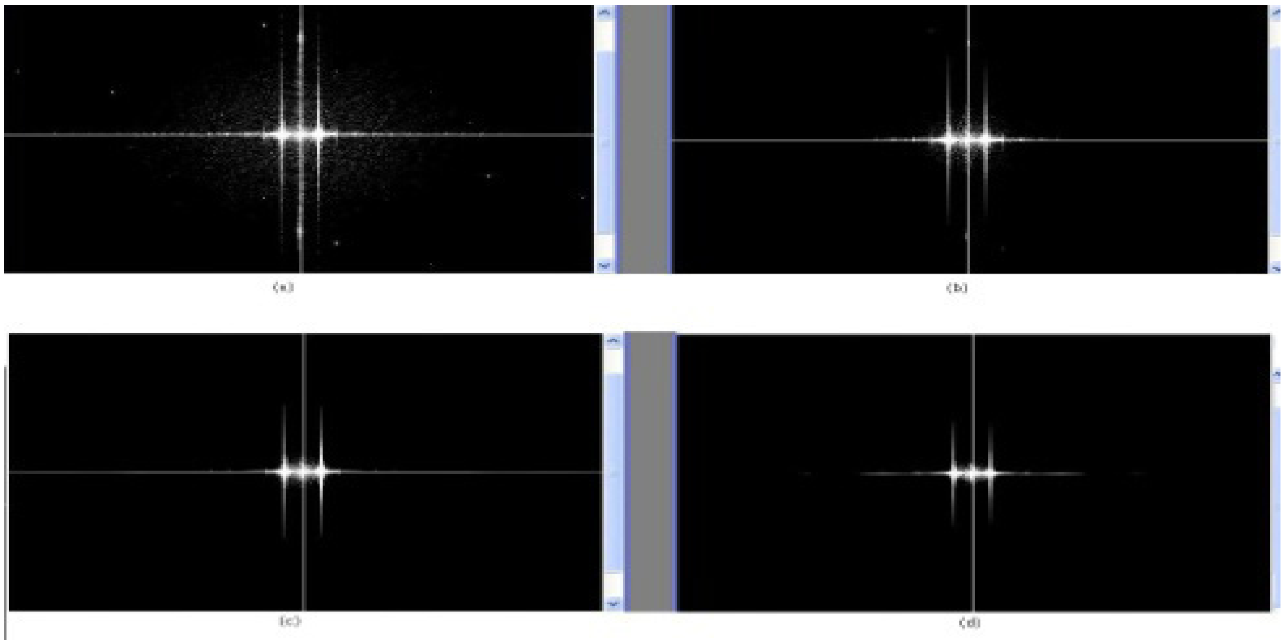
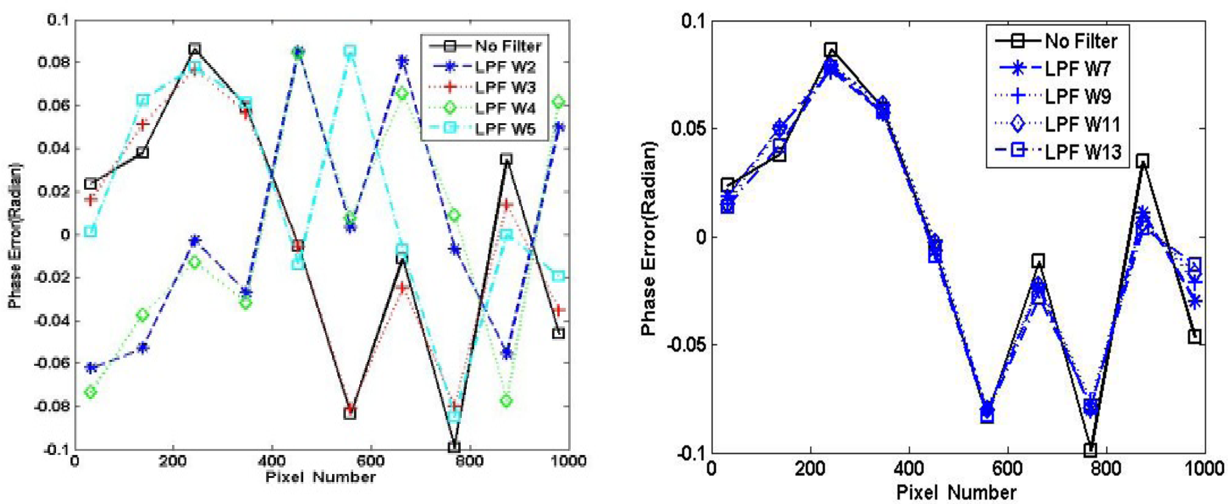


Figure 3. Two-dimensional FFT spectrum with different LPF pre-processing. (a) non-LPF, (b) LPF mask size 5x5, (c) LPF mask size 11x11, (d) LPF mask size 17x17.



(a) (b)

Figure 4. (a), (b) Image pixel point phase error change by the LPF filtering with different rectangle mask size mxn pixels.

differences of noise removal effect clearly, we drew an intensity profile of Figure 6(a) and Figure 6(b) and the position are marked by red lines. The captured sinusoidal fringe patterns images pre-processed by median filter with different rectangle mask size. Figure 7 shows phase error values according to the different MF rectangle mask size at one image pixel line. Figure 8 shows the experimental results for the median filter with different rectangle mask size,which was used to suppress the noise in acquired fringe patterns.

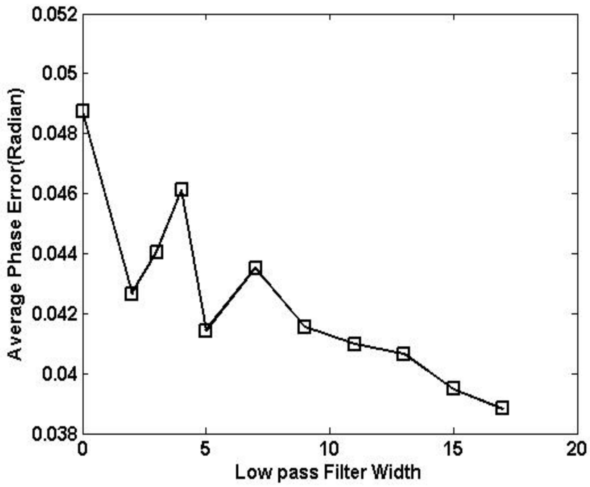
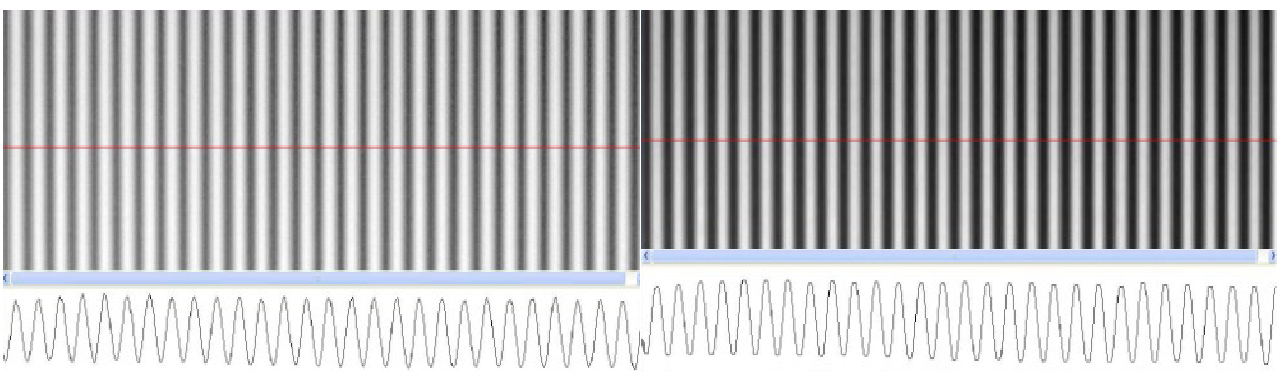


Figure 5. Experimental results show the average phase errors that can mitigate by LPF pre-processing to the fringe patterns.

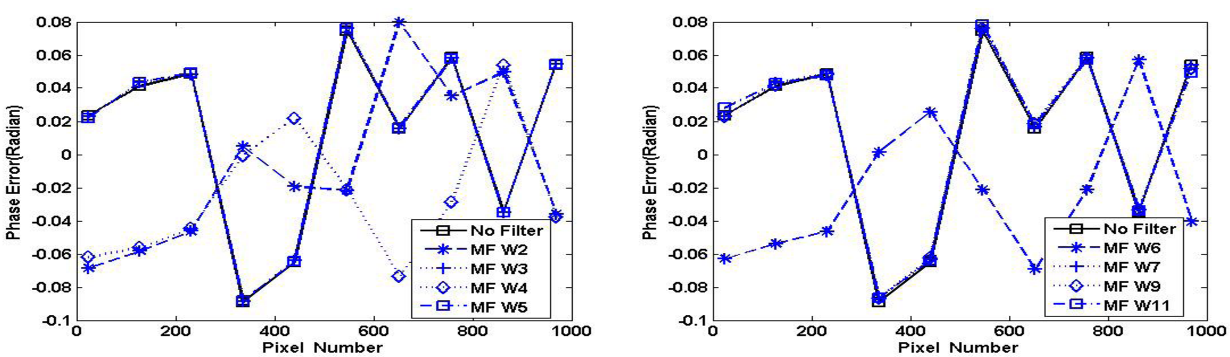
5. Conclusion

We have discussed a phase error reduction effectiveness depend on the spatial filters for image noise which is introduced by the image capture CCD device and LCD display monitors in fringe reflection Fourier transform profilometry. General spatial filtering methods such as low-pass filtering and median filtering are used to remove added white noise in images. However, if images are sinusoidal grating fringe patterns, spatial filtering mask is used as a rectangle of m x n pixels, and the structures and intensity profiles of the fringe pattern is processed, fringe pattern may be deformed according to mask size. While noise is reduced in the experiment, we obtained the phase information by Fourier transform and analyzed the phase error using various mask size with different filter. Experimental results show that the low-pass filtering is more effective in mitigating those average phase error



(a) (b)

Figure 6. Captured MF filtering sinusoidal fringe patterns image and intensity profile. (a) MF image with rectangle mask size 2x2 pixels. (b) MF image with rectangle mask size 11x11 pixels.



(a) (b)

Figure 7. (a),(b) Image pixel point phase error change by the MF filtering with different rectangle mask size m x n pixels.

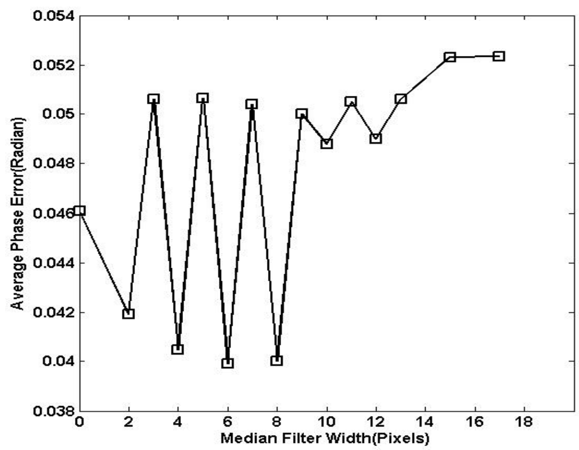


Figure 8. Experimental results showed the average phase error changes with different MF filtering mask size.

and it can produce an accurate phase extraction in the white noise circumstance.

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