

# 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 a phase error reduction method using the low pass spatial image filter and median filter. Experimental results have shown to validate the low pass filter and median filter. Although the effect of the filter is to be smoothed the fringe, white noise included in the pattern was able to remove effectively. 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%.

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

## 1. Introduction

Nowadays, 3D inspection (3D surface profilometry) is becoming more useful according to the development of electronic devices such as a display device, computer, high spatial resolution CCD camera, digital image processing software and applied in practical life. These 3D measuring technology is applied to area such as biomedical inspection, industrial automation process, robot and computer vision, 3-D printing and reverse engineering, etc.<sup>1-3</sup>. Fourier transform structured light fringe pattern reflection method is one of the popular profilometry and it is perhaps one of most many studied among the several types of 3D surface profile measurement techniques. In the Fourier Transform Profilometry (FTP) method, fringe patterns is encoded simply and flexibly, and requires only one capture fringe image to evaluation of the surface profile of an object. However, gamma distortions, optical aberrations, low contrast, low signal-to-noise ratio, object

surface reflectance variation is included in the captured patterns, and it is affected seriously to the accuracy of the phase measurements as a induce the deformation of fringe to be non-sinusoidal. To overcome this problem, various techniques have been proposed to get for the exact sinusoidal fringe patterns<sup>4</sup>. The image sensor and the LCD fringe display monitor may make an image containing the noises which are caused by the optical surroundings illumination factors and by electronic noise factors. This image noise can have different sizes and properties for each type, and the intensity value of the image is changed irregularly. Therefore, the intensity values of one pixel in the image sensor is influenced more greater or more smaller than the other adjacent pixels. Such noises affecting to the intensity of image as a random impulse types are can be treated as a high spatial frequency components of the image. If the intensity of illumination is low, the noise in an image sensor become larger and the numbers of pixels with random noisy is increased. The previously

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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<sup>3,5</sup>. 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<sup>6</sup>. 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 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. Basic of the Fourier Transform Profilometry

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

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

where  $*$  is a complex conjugate, so

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

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

$$I(x, y) = A(x, y) + C(x, v - f_0) + C^*(x, v + f_0) \dots \dots \dots (3)$$

where  $A, C$  and  $C^*$  refer to the Fourier spectra, and  $v$  is the spatial frequency in the  $y$ -axis. The Fourier a spectrum in equation (3) is separated by the carrier spatial frequency  $f_0$ . The phase component must be extracted in order to get 3D shape profiles by using the some sorts of filtering. The inverse Fourier transform of the filtered and frequency shifted signal is then computed in order to obtain  $\varnothing(x, y)$ . The phase is calculated using the form<sup>5</sup>

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

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

## 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. The image sensor and the LCD fringe display monitor may make an image containing the noises which are caused by the optical surroundings illumination factors and by electronic noise factors. This image noise can have different sizes and properties for each type, and the intensity value of the image is changed irregularly. Therefore, the intensity values of one pixel in the image sensor is influenced more greater or more smaller than the other adjacent pixels. Such noises affecting to the intensity of image as a random impulse types are can be treated as a high spatial frequency components of the image. Common types of noise found in the digital images, which are uniform (white) noise, Gaussian noise, Negative exponential noise, Salt and pepper noise. In digital image processing, it is often desirable to be reduction of noise on an optical captured CCD sensor image<sup>7</sup>.

### 3.2 Low Spatial Frequency Pass Filters

Low spatial Frequency Pass Filter (LPF) are used for image sharpness reduction and noise. LPF makes an average of the one cell pixels with the values of its adjacent pixels, enables to observe a blurring of the result image. The LPF kernel is used all of the elements have a positive value. Accordingly, it is a general method used to scale the results from the gray level of the output image area is to divide the convolution result of the sum of the elements of the kernel<sup>8</sup>.

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

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

### 3.3 Median Filters

A Median Filter (MF) is a non-linear digital image filtering technique used to reduction the image noise. Under certain conditions for removing noise in during the MF processing, it preserves edges while removing noise. MF processing can suppress the isolated out-of-range noise,

but it also reduce to high spatial frequencies component in an image. Changing the value of all pixels as a the median values, in a peripheral  $\omega$ .

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

where  $\omega$  is centered around location  $[m,n]$  in the image.

### 4. Experimental Results

Figure 1 shows a fringe reflection Fourier transform phase measurement profilometry setup. A low spatial frequency sinusoidal grating fringe pattern is displayed on the LCD monitor and the image is captured at CCD camera. In the experiment, we used a resolution of 1280 x1024, 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 4.65 $\mu$ m x 4.65 $\mu$ m 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 a intensity profile of the fringe patterns in Figure 2(a) and Figure 2(b) and the position is marked by red lines. Figure 3 show the 2D FFT spectrum result of captured fringe patterns; (a) non-LPF, (b) LPF rectangle mask size 5X5 pixels, (c) LPF

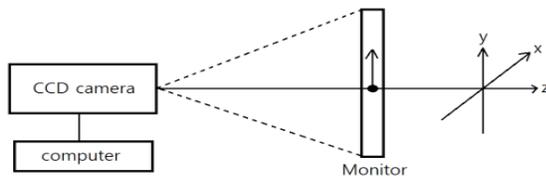


Figure 1. Phase extraction system.

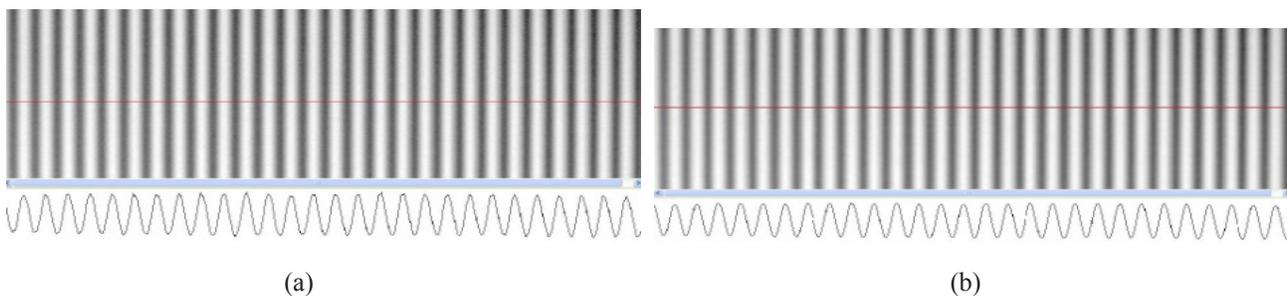


Figure 2. Captured sinusoidal fringe patterns image and intensity profile. (a) Non-LPF fringe pattern image. (b) LPF pre-processed image with rectangle mask size 11x11 pixels.

rectangle mask size 11x11pixels, (d) LPF rectangle mask size 17X17 pixels.

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. Butwhen 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 differences of noise removal effect clearly, we drew an intensity profile of Figure 6(a) and Figure 6(b) and the position are

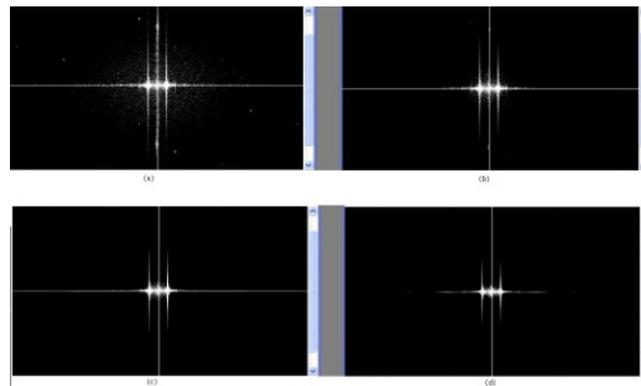


Figure 3. Two-dimensional FFT spectrum with different LPF pre-processing. (a) non-LPF, (b) LPF mask size 5x5, (c) LPF mask size 11x11, (d) LPF mask size 17x17.

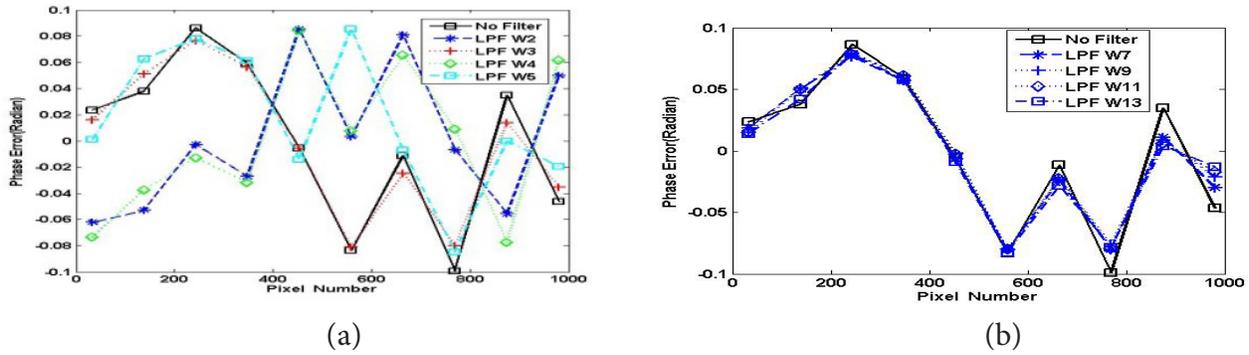


Figure 4. Image pixel point phase error change by the LPF filtering with different rectangle mask size  $m \times n$  pixels.

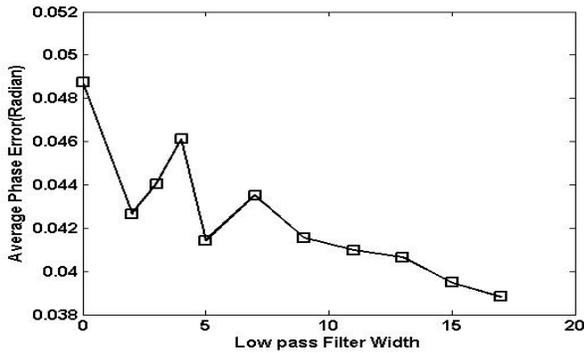


Figure 5. Experimental results show the average phase errors that can mitigate by LPF pre-processing to the fringe patterns.

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.

### 5. Conclusions

We have discussed a phase error reduction effectiveness depends on the spatial filters for image noise which is

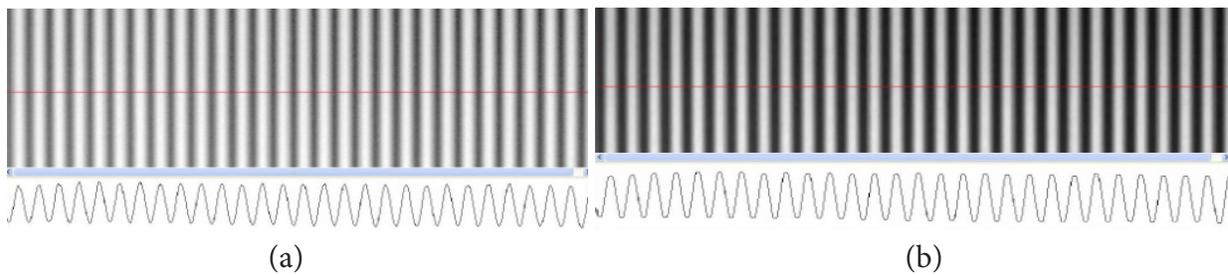


Figure 6. Captured MF filtering sinusoidal fringe patterns image and intensity profile. (a)MF image with rectangle mask size  $2 \times 2$  pixels. (b) MF image with rectangle mask size  $11 \times 11$  pixels.

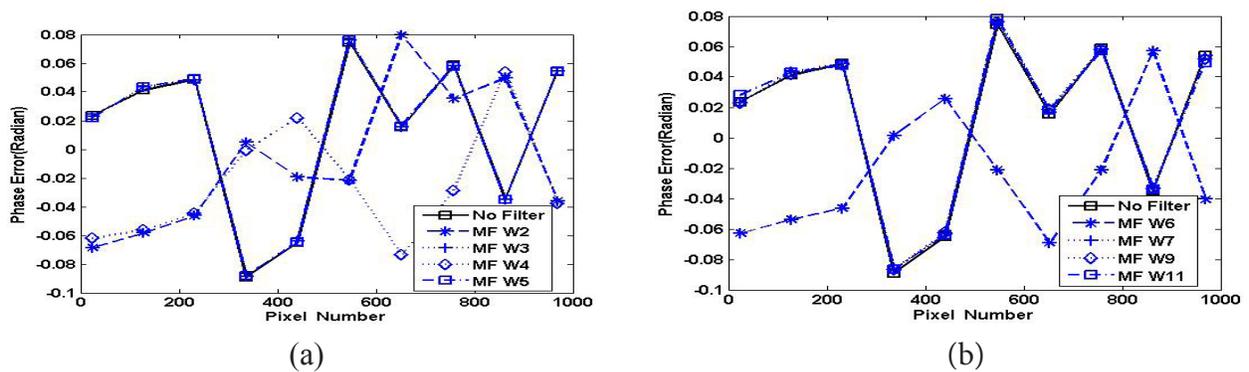
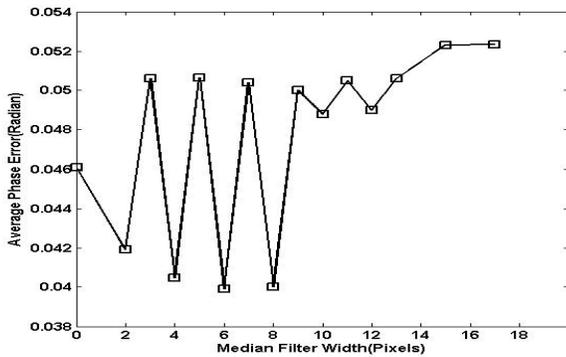


Figure 7. Image pixel point phase error change by the MF filtering with different rectangle mask size  $m \times n$  pixels.



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

introduced by the image capture CCD device and LCD display monitors in fringe reflection Fourier transform profilometry. By using the spatial frequency filtering techniques such as a low-pass filter and median filter, we could do remove added white noise in images. However, if images are sinusoidal grating fringe patterns, spatial filtering mask is used as a rectangle of  $m \times n$  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 and it can produce an accurate phase extraction in the white noise circumstance.

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