SIGNAL PROCESSING ALGORITHMS IN 3-D PROFILE MEASUREMENT WITH FRINGE PROJECTION TECHNIQUE

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ABSTRACT

In this study, 3-D profile determination was investigated with fringe projection technique. Two different setups were built to measure 3-D profile. In first setup LCD projector and digital camera, in second setup Michelson interferometer and CCD camera were used. Fringe patterns obtained from both setups were evaluated with Fourier and Continuous Wavelet phase extraction algorithms. As a result, the 3-D profiles that were found by two setups were compared.

I. INTRODUCTION

The fringe projection technique is mostly used to obtain 3D profile. Takeda and et al. obtained the surface profile with Fourier phase method from fringe patterns [1]. The studies were made to develop this analysis method [2]. In Fourier phase method, the Fourier transform of the signal is found. After the filtration is made in spatial frequency domain, the inverse Fourier transform of the filtered signal is obtained. The wrap phases of the inverse Fourier transform of the signal are determined. These wrap phases are unwrapped with a proper algorithm. The unwrapped phases are much sensitive to noise. Most algorithms have been developed to pass this problem [3]. Another method depends on the calculation of the phase of continuous wavelet transform of the signal and the unwrapped of the obtained phases [4,5].

In this article, two different setups are built for projection technique. In first setup Michelson interferometer was used to produce fringe patterns. For second setup a projector was used. As a result, obtained signals from both setups were evaluated with Fourier and continuous wavelet algorithms. The profiles obtained with these algorithms were compared.

II. METHODS

-Continuous Wavelet Phase Method (CWT Phase)

$$I(z) = I_0[1 + V(z)\cos(kz + \phi(z))] \quad (1)$$

Where I_0 mean DC Intensity, $V(z)$ visibility of the fringe, $\phi(z)$ height modulated phase, k spatial carrier frequency. The condition in equation 2 should be provided to obtain the profile of a surface.

$$k \gg \left|\frac{d\phi}{dz}\right|_{\max} \quad (2)$$

One dimensional CWT of the signal is given as follows,

$$W(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} h\left(\frac{z-b}{a}\right).I(z).dz \quad (3)$$

where h is mother morlet wavelet. a is scale factor, b shifting parameter. Wrap phase distributions are obtained from the phase of the CWT. The phase is given by

$$\phi = \tan^{-1}\left(\frac{\mathrm{Im}(W(a,b))}{\mathrm{Re}(W(a,b))}\right) \quad (4)$$

where Im(W(a,b)), Re(W(a,b)) are imaginer and real part of the CWT, respectively. The wrap phases are unwrapped. The difference between the unwrapped phase distributions of the fringe patterns obtained from both reference and object is calculated by

$$\phi_s(x,y) = \phi_0(x,y) - \phi_R(x,y) \quad (5)$$

where $\phi_0(x,y)$, $\phi_R(x,y)$ are the unwrapped phases of the object and reference respectively. The height values of the object surface are calculated by using this phase difference as follows,

$$z(x,y) = \frac{L.p_0(\frac{\phi_s(x,y)}{2\pi})}{p_0.(\frac{\phi_s(x,y)}{2\pi}) - d} \quad (6)$$

where L is distance from pupil of the camera to the reference plane, d is distance between pupils of the camera and the projection, p_0 is period of fringe on the reference plane, z is surface height.

The simulation studies were made to test this method. The CWT of the simulated fringe pattern (660x524 pixels) for one row in Figure 1 is shown in Figure 2.

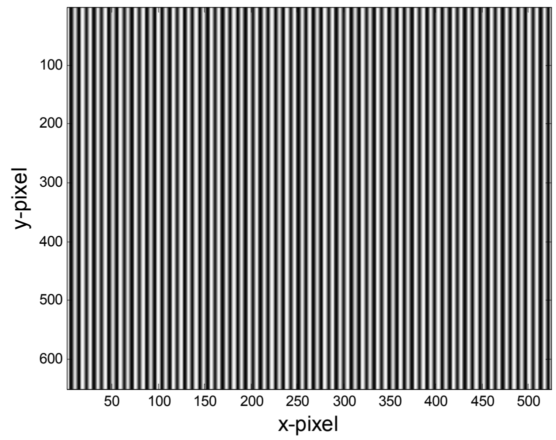

Figure 1. The simulated fringe pattern.

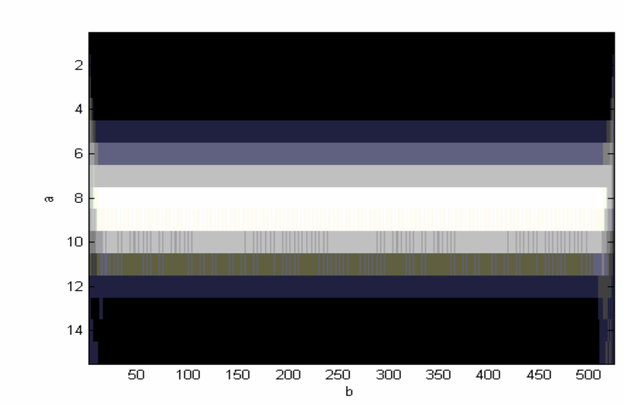

Figure 2. For one row the CWT of the simulated fringe pattern.

The wrap and unwrapped phase distributions are given in Figure 3,4 respectively. This process is made for both reference and object fringe patterns. The profile is obtained by substituting the difference (ϕ_s) between the reference and object unwrapped phase distributions into the equation (6).

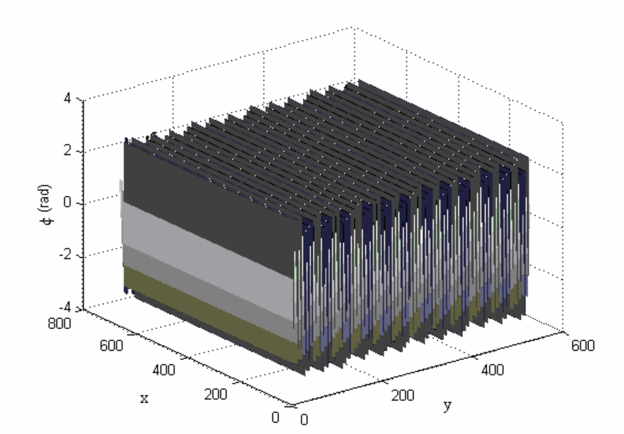

Figure 3. The wrap phase distributions of the CWT of the simulated fringe pattern.

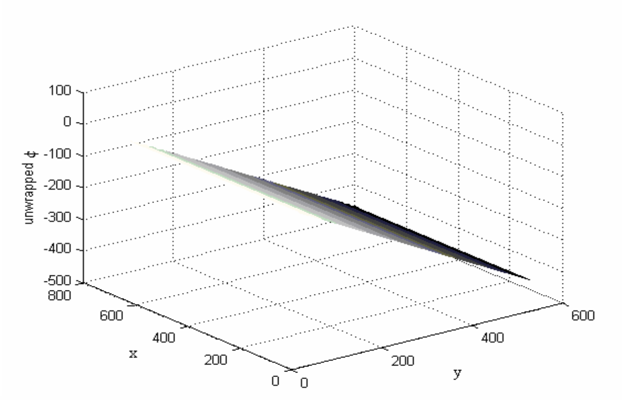

Figure 4. Unwrapped phase distribution of the CWT of the simulated fringe pattern.

-Fourier Phase Method

In this method the Fourier transform of the fringe pattern is obtained. The Fourier transform of *I(z)* in equation (7) is given by

$$I(f) = I_0.\delta(f) + I_0.V(f) * [\frac{1}{2}\delta(f - \bar{f}_0) + \frac{1}{2}\delta(\bar{f}_0 + f)].\exp(-2\pi z_0 f) \quad (7)$$

The filtration process is used to obtain rightly the phase.

$$S(f) = I(f).H(f) \quad (8)$$

where $H(f)$ is the transfer function of the Gaussian filter. After filtration process, the inverse Fourier transform is found. The wrap phase obtained from inverse Fourier transform is as follows

$$\phi = \tan^{-1}\left(\frac{\mathrm{Im}\left\{F^{-1}\left\{S(f)\right\}\right\}}{\mathrm{Re}\left\{F^{-1}\left\{S(f)\right\}\right\}}\right) \quad (9)$$

This wrap phase is unwrapped by using a proper algorithm. This process is repeated for both reference and object fringe patterns. The phase difference is calculated with equation (5). Substituting this difference into the equation (6), the object profile is achieved.

The simulation was made to test Fourier transform method. For one row, the fast Fourier transform of the simulated fringe pattern (660x524 pixels) that is given in Figure 1 is shown in Figure 5. The wrap phase distribution obtained by the inverse Fourier transform of the filtered signal is given in Figure 6. The unwrapped phase is calculated as in Figure 7. This process is made for both the reference and object fringe patterns. Substituting the difference between two phase distributions into equation (6), the 3-D profile is obtained.

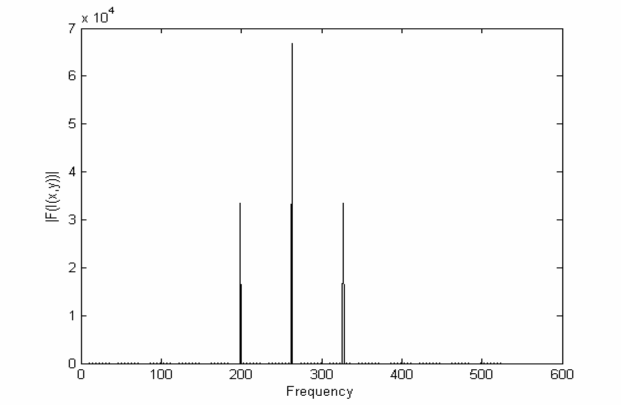

Figure 5. For one row the Fourier transform of the simulated fringe pattern.

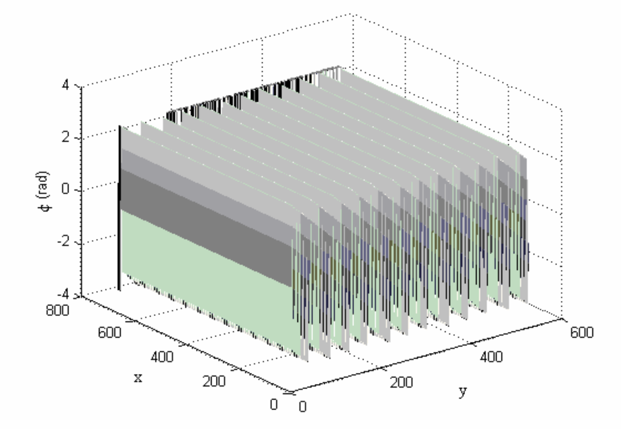

Figure 6. The wrap phase distributions of the inverse Fourier transform of the filtered simulated fringe pattern.

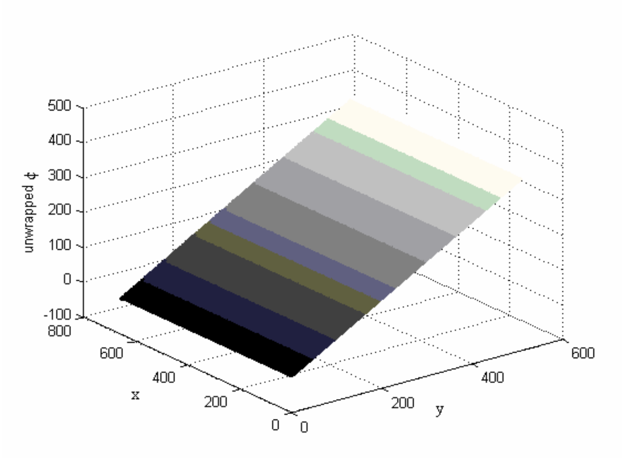

Figure 7. Unwrapped phase distribution of the inverse Fourier transform of the filtered simulated fringe pattern.

III. EXPERIMENTAL

In this paper, two setups are used to obtain 3-D profile. In first setup, the Michelson interferometer is built to produce the fringe pattern. This setup is given in Figure 8. The image of the object with fringe pattern is recorded by CCD camera that has 576x768 pixels. The light source (He-Ne laser) which is used in the Michelson setup has 632.8nm of wavelength and power with 2 mW.

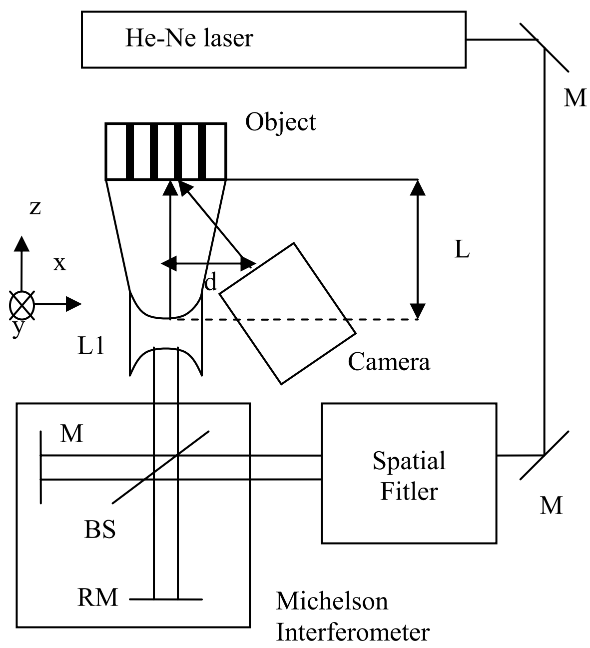

Figure 8. Fringe projection setup with michelson interferometer and CCD camera. M:Mirrors, RM:Reference mirror, BS:Beam splitter, L1: Lenses

The fringe pattern on the object surface that is used in measurements is shown in Figure 9.

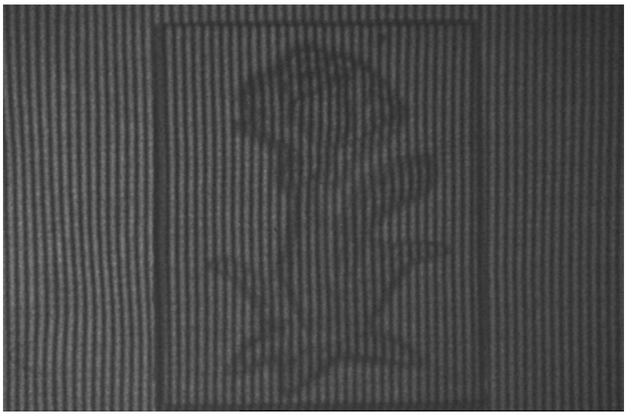

Figure 9. The object with fringe pattern that is produced by Michelson interferometer

The reference and object images that are obtained by first setup are evaluated by Fourier phase algorithm. The profile of the object surface is given in Figure 10. The small details on the surface can not be captured with this algorithm. The accuracy of Fourier algorithm is highly low. The Gaussian filter which is used in this algorithm can not completely filter the signal in spatial frequency domain.

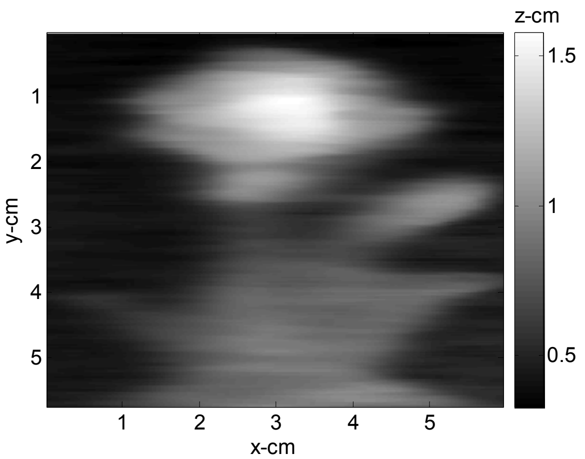

Figure 10. The profile of the object that is calculated by Fourier phase transform for first setup.

The profile of the surface which is obtained by using CWT phase algorithm is presented in Figure 11. This algorithm can capture better than the Fourier phase algorithm. The result has more details as it can be seen from color bar in Figure 11.

The Morlet wavelet that is used to filter the signal in CWT phase algorithm makes better filtration than Gaussian filter in Fourier phase method. Therefore the noise can be eliminated better than Fourier's.

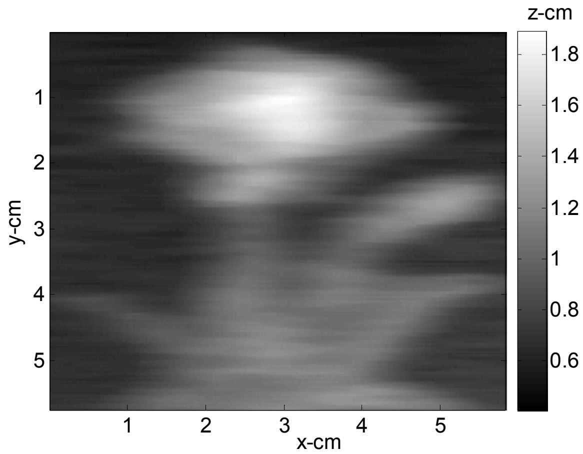

Figure 11. The profile of the object that is calculated by CWT phase algorithm for first setup.

In second setup the LCD projector is used to reflect the simulated fringe pattern on the object surface. This setup is shown in Figure 12. The pattern on the object surface (look at Figure 13) is recorded by digital camera which has 1704x2272 pixels.

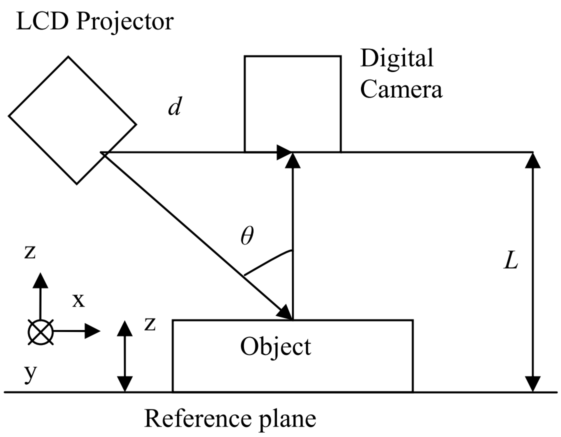

Figure 12. Fringe projection setup with LCD projector and digital camera. L is distance from pupil of the camera to the reference plane, d is distance between pupils of the camera and the projection.

The fringe patterns of the object and reference are evaluated by Fourier and CWT phase algorithms. The profiles that are calculated with these algorithms are shown in Figure 14, 15.

The evaluation results show that the CWT phase algorithm can calculate better and more accurate than Fourier algorithm.

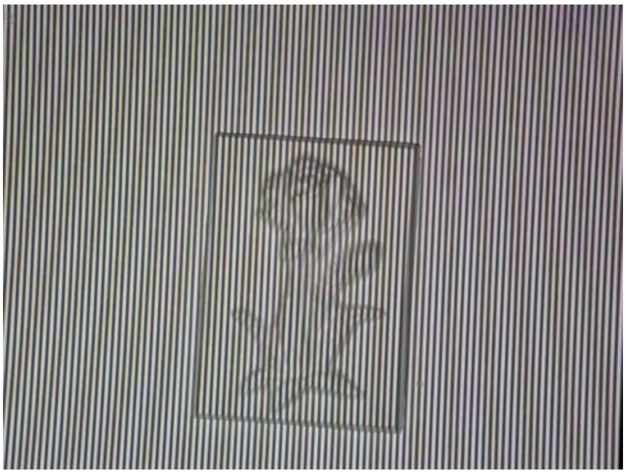

Figure 13. The object with fringe pattern that is reflected by LCD projector.

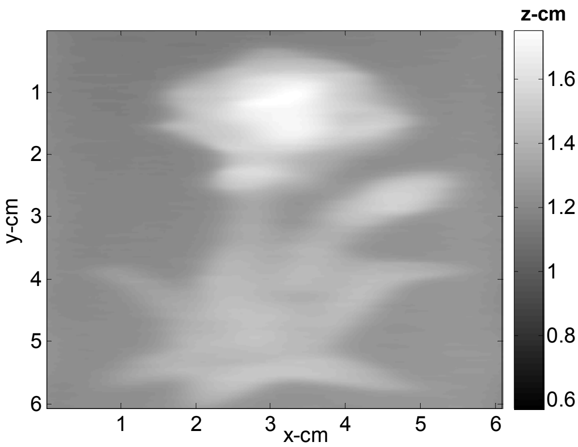

Figure 14. The profile of the object that is calculated by Fourier phase transform for second setup.

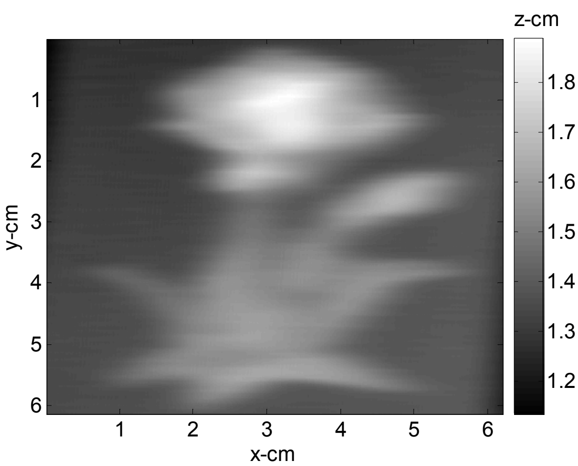

Figure 15. The profile of the object that is calculated by CWT phase algorithm for second setup.

IV. RESULTS AND DISCUSSION

In this work the fringe projection technique is used to determine 3-D surface profile. This technique is realised by two different setups. In first setup the fringe pattern is produced by the Michelson interferometer and this pattern on the object surface is recorded by the CCD camera. In second setup the simulated fringe pattern is reflected on surface of the object by LCD projector and the pattern distribution on the surface is obtained by digital camera.

These digital images are analyzed by Fourier and CWT phase algorithms. 3-D profiles that are obtained with these algorithms have been given. The best profiles are achieved with second setup that is used LCD projector and digital camera. Because first setup with Michelson interferometer is more sensitive to noise than second setup. The fringe pattern that is produced by Michelson interferometer is distorted by random vibration effect and intensity noise. These effects create an important difference between the reference and object images.

If this noise can be eliminated and a camera with high resolution is used, the setup with Michelson interferometer has more advantage than another one. Because it is easier to produce fringe pattern with high frequency by Michelson interferometer to determine 3-D surface profile of the object whose heights change very quickly. However, the fringe pattern with high frequency can not be projected on the object by LCD projector that has limited resolution.

Moreover in this work the best result profile are achieved by CWT phase algorithm. The results are obtained more accurate by this algorithm. Because the Morlet wavelet makes filtration with an adapted filter that retains the main features of the signal but reduces the noise.

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