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A strategy for 3d object digitalization using pre-filtering and post-filtering stages

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Abstract

In this paper a strategy for 3D object Digitalization, using a pre-filtering and post-filtering stages where the pre-filtering is carried out by the Windowed Fourier Filtering and the post-filtering it is done by a least square algorithm is proposed. The objective of the pre-filtering and post-filtering is to obtain a phase unwrapping with less non-smooth 3D object zones, which is a critical part in the Modified Fourier Transform Profilometry. Phase unwrapping is a fundamental step due to the fact that the object's height (depth information) is present in the wrapped phase. In most of the previous work, where the phase unwrapping results are analyzed, it is possible to detect many zones of non-smooth 3D object.

Keywords: 3D digitalization; pre-filtering; profilometry; Fourier; FTP; MFTP; MFTPsof

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1. Introduction

The 3D digitalization is the process, where the characteristics of an object are stored in the memory of a computer, like its form, volume and dimensions [1]. There are many methods for 3D object digitalization, like the Fourier Transform Profilometry (FTP) proposed by Takeda and Mutoh[2] at 80's, the Modified Fourier Transform Profilometry (MFTP) proposed by Pedraza et al [3] at 2007, and the Fringe Pattern Analysis using Wavelet Transforms by Abdulbasit [4] at 2008. In these works the basic idea is to project a fringe pattern, over an object, and the scene where the distortion pattern is captured by a camera. This distortion in the scene is caused by de object's shape, and this scene contains the 3D information about the object. When the Fourier Transform or Wavelet Transform is applied (and its inverse respectively), the wrapped phase of the object is obtained, were the phase unwrapping step is applied as described by Gens [5], Hussein et al. [6], Pedraza et al.[7] and Sotomayor et al.[8], so the height of the 3D object is calculated. In most of the previous work, the phase unwrapping was analyzed presenting a non-smooth 3D shape of the object, because the high frequency provoked many areas with non-smooth 3D shape at the reconstruction, as can be show in Fig 1. In some papers are shows the pre-filtering for the 3D Object digitalization as example Kemao [9] proposed the Windowed Fourier Filtering and he show a Graphical User Interface for the filtering.

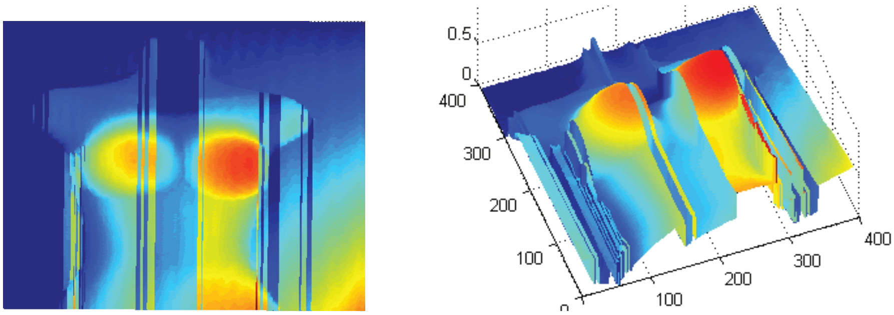

Fig 1.(a) and (b) None smooth mannequin 3D shape.

The mannequin shape presents as non-smooth 3D reconstruction as shown on Fig 1. In order to achieve a smooth 3D reconstruction, we propose the use of a pre-filtering step, then applying the Modified Fourier Transform Profilometry (MFTP), and later a post-filtering step, done after the phase unwrapping. These steps constitute a methodology which is the main contribution of this work.

2. MFTP

The MFTP proposed by Pedraza et al. [3] uses the experimental setup described by Sotomayor et al. [8] as shown in Fig 2, and it is used for the 3D Digitalization. The setup includes a computer, a fringe projector, a photographic camera, and the object to digitalize.

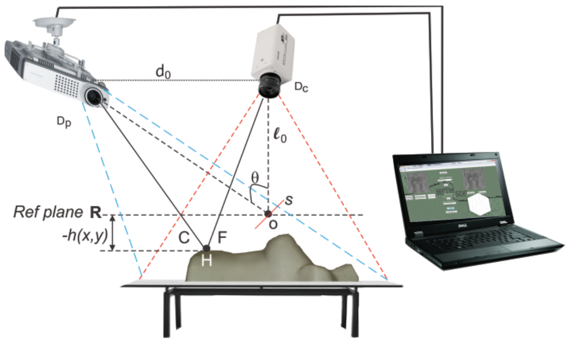

Fig 2. Experimental setup at the MFTP.

On Fig 2, the imaginary plane R as a reference for the measure of the height $h(x,y)$ about the particular object is considered. In this paper, a strategy for the smoothing 3D shape after phase unwrapping is presented, which is a fundamentally step at the Modified Fourier Transform Profilometry. In most of the previous work, when the phase unwrapping results are analyzed, it is possible to detect many areas without non uniform smoothing. In this work we propose the use of a least square algorithm which will be presented on section 4, at the post processing step for a best smoothing 3D shape. The object with projected fringes can be represented by the following equation:

$$g(x,y) = a(x,y) + b(x,y) * \cos[2 * \pi f_0 x + \varphi(x,y)] \qquad (1)$$

Where $g(x,y)$ is the intensity of the image at point (x,y), $a(x,y)$ represents the background illumination, $b(x,y)$ is the contrast between the light and dark fringes, f_0 is the spatial-carrier frequency and $\varphi(x,y)$ is the corresponding phase of the distorted fringe pattern, observed from the camera. The x axis is line to the plane R as shown in Fig 2, and the y axis is perpendicular to R, for a generic object with many variations in height $h(x,y)$, the fringe pattern observed from the camera is a distorted fringe pattern, as shown in Fig 3, meanwhile Fig 3 (a) shows a mud pig, the fringe pattern is in Fig 3 (b), and the Fig 3 (c), the fringe pattern is distorted by the shape of the object.

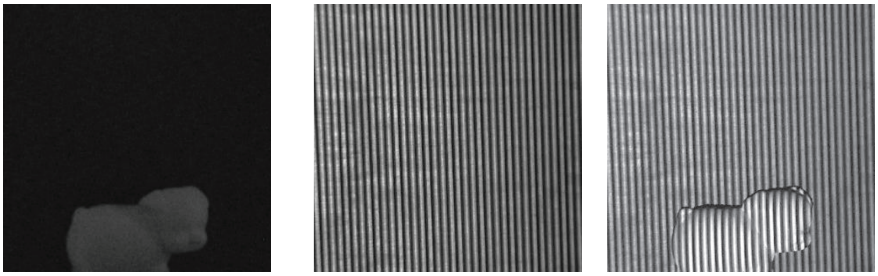

Fig. 3 (a) Mud pig; (b) Fringe pattern; (c) Fringe pattern over a mud pig.

The image about Fig 3 (c) is represented by equation 1, and can be rewritten as:

$$g(x,y) = a(x,y) + c(x,y)\exp(2\pi i f_0 x) + c * (x,y)\exp(-2\pi i f_0 x) \qquad (2)$$

where

$$c(x,y) = \frac{1}{2}\, b(x,y)\exp[i\varphi(x,y)] \qquad (3)$$

and * is the convolution.

FFT (Fast Fourier Transform) is applied to the signal in the *x* direction only. Equation 2 can be re-written as:

$$G(f,y) = A(f,y) + C(f - f_0, y) + C * (f + f_0, y) \qquad (4)$$

The capital letters denote the Fourier spectra and f is the spatial frequency to the *x* axis. Since the spatial variations of $a(x,y)$, $b(x,y)$, and $\varphi(x,y)$ are slow compared with the spatial frequency f_0, we applied a low pass filter to center f_0 at the origin in order to obtain $C(f,y)$. The inverse Fourier Transform of $C(f,y)$ with respect to f is applied and the obtained $c(x,y)$ defined at equation 3 when the complex logarithm is calculated we have:

$$\log[c(x,y] = \log[\left(\frac{1}{2}\right) b(x,y)] + i\varphi(x,y) \qquad (5)$$

Now the phase $\varphi(x,y)$ in the imaginary part is obtained and can be written as:

$$\varphi(x,y) = \varphi_0(x,y) + \varphi_z(x,y) \qquad (6)$$

Where the phase $\varphi_0(x,y)$ is obtained by the projection angle corresponding to the reference plane, and $\varphi_z(x,y)$ is proportional the height of the object to analyze. Once the phase $\varphi_z(x,y)$ is calculated we can see that the result lies between the

–π and π values, and this known like the phase wrapped. Gens [5], Hussein et al. [6], Pedraza et al.[7] and Sotomayor et al.[8] Described different algorithms for the phase unwrapping. The phase unwrapping can be defined as the process to solve the ambiguity problem, and visually is presented as discontinuities as shown in Fig 1, where it is observed the result of a wrapped phase and the recovery of the discontinuities. The phase unwrapping is a very important and complex step in 3D object digitalization.

The triangles Δ**AHB** and Δ**CHD** (in Fig. 2) are similar and can be written as:

$$\frac{CD}{-h} = \frac{d}{L} \tag{7}$$

therefore:

$$\varphi_z(x,y) = \frac{h(x,y)\,2\pi f_0 d}{h(x,y) - L} \tag{8}$$

The equation 8 can be re-written in function of the distribution phase as:

$$h(x,y) = \frac{L\varphi_z(x,y)}{\varphi_z(x,y) - 2\pi f_0 d} \tag{9}$$

3. Windowed Fourier Filtering

The principle of Windowed Fourier Filtering (WFF) can be derived by combining the Windowed Fourier Transform (WFT) and its Inverse:

$$Sf(u,\varepsilon) = \int_{-\infty}^{\infty} f(x)g(x-u)\exp(-j\varepsilon x)\,dx \tag{10}$$

$$f(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Sf(u,\varepsilon)g(x-u) \times exp(j\varepsilon x)d\varepsilon du \tag{11}$$

Where $g(x)$ is a window, which can be chosen as a Gaussian function:

$$g(x) = \exp(-x^2/2\sigma^2) \tag{12}$$

The equation of the WFF is written as:

$$f(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \{[f(x) * h(x,\varepsilon)] * h(x,\varepsilon)\}d\varepsilon \tag{13}$$

Here, $h(x,\varepsilon) = g(x)\exp(j\varepsilon x)$ and * is the convolution with respect to the *x* variable. For the WFF implementation the equation 12 can be written as:

$$\bar{f}(x) = \frac{1}{2\pi}\int_{a}^{b} \{\overline{[f(x) * h(x,\varepsilon)]} * h(x,\varepsilon)\}d\varepsilon \tag{14}$$

Where the term $f(x) * h(x,\varepsilon)$ establishes a threshold value, if the absolute value is less than a fixed threshold, then the value is considering as noise, when $\bar{f}(x)$ is obtained, the image is filtered, as can be show in Fig 4 (b).

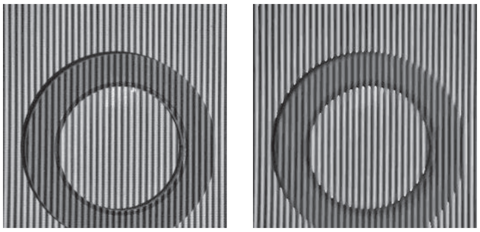

Fig. 4. (a) Scene captured; (b) Scene Pre-filtered.

After this step, we applied the MFTP to obtain the phase unwrapping, and the post-filtering is applied using a linear regression which will be presented in the next section.

4. Linear Regression

The simplest approach to fit a set of points is carried out by a least square algorithm. This method consists on fitting a straight line to a set of observations defined by the points: (x_1, y_1), (x_2, y_2)… (x_n, y_n) as described by chapra and canale [10]. A linear regression, is a tendency of the analyzed points, as is observed in Fig 6, where is shown a set of analyzed points, the line that happens among them is the tendency of the points (linear regression by least square).

This method uses the equation of the straight line expressed by equation 15.

$$y = a_0 + a_1 x + e \tag{15}$$

Where the coefficients that represents the intersection with the axis and the slope, are a_0 and a_1, respectively. The produced error by the estimation and the true value is represented by *e*. Suppose *e*=0, the coefficients of equation 15 are calculated using the equations 16 and 17.

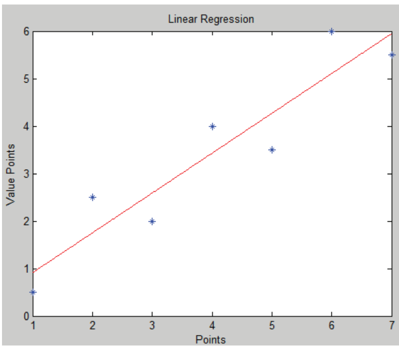

Fig. 6. Linear regression by square minimums.

$$a_1 = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - \left(\sum x_i\right)^2} \tag{16}$$

$$a_0 = \bar{y} - a_1 \bar{x} \tag{17}$$

In this way, it is possible to use the linear regression considering the tendency of the missing values in the areas where the smoothing is non-uniform, obtained at the phase unwrapping.

5. Proposed Methodology

The proposed methodology can be shown in Fig. 7.

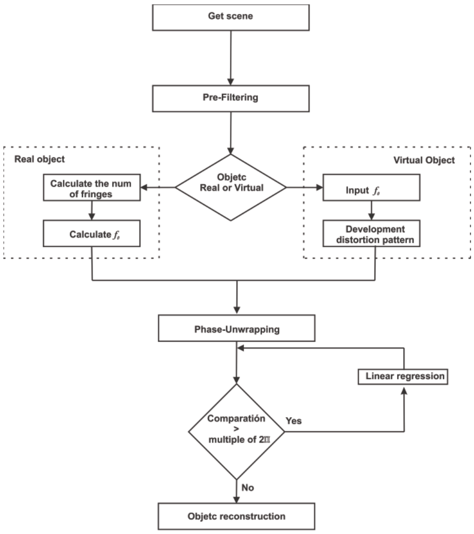

Fig 7. Proposed Methodology.

The proposed methodology contemplates the following steps: the first consists in the acquisition of the scene to reconstruct, which could be done by a capture device or a stored scene in the computer memory. In the second step a pre-filtering is carried out, which in this case, uses the Fourier Transformed Windowed as filter. Later on, is it identified if the scene corresponds to one real object or a virtual object. In case of one real object, the number of fringes projected on it is calculated, as well as the space frequency f_0. If it is one virtual object, the space frequency f_0 is introduced and the distortion fringes pattern is created. Then, the phase unwrapping is done, and it is evaluated if the phase wrapping presents an area with non-uniform smooth, by comparing with neighboring pixels. If the comparison result is greater to some multiple of 2π, the value is corrected trough an analysis by means of linear regression by square minimums. Finally, we proceed to the object reconstruction.

Fig 8 shows the analysis of fringes about the object, which has distorted pattern of fringes (origin fringes), has the wrapped phase, which one is unwrapping, observing two areas with a non-uniform smooth 3D shape, when we applied the linear regression we can obtained a best uniform smoothing at 3D object.

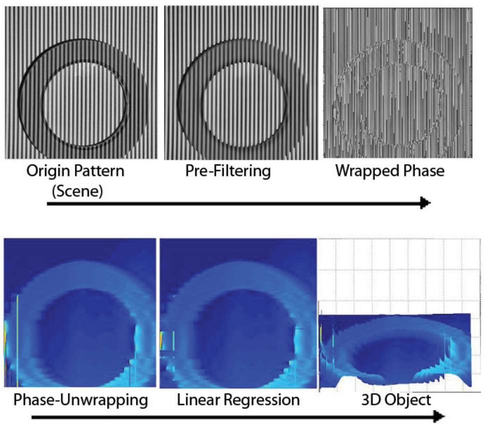

Fig. 8. Object fringes analysis.

6. Tests and Results

Different scenes were captured with photography camera and pre-filtering of the scene was carried out, then the Modified Fourier Transform Profilometry Software (MFTPsof) [1] processed it, in order to obtain the unwrapping phases, which are analyzed, to detect and to smooth the 3D object. For digitalization, different objects were used such as: a mud sun, a mug pig, a masking tape, among others. In the mud sun case only some sections was analyzed, in the Fig 9(a), the unwrapping phase shown, the complete object form is not observed, which also is the turn out to realize the process without the pre-leaked one, also a strip is observed (non uniform smooth 3D shape) that is desired to correct. Fig 9 (b) the pre-filtrate is applied and then is process by MFTPsof software. In Fig 9 (c) show the results applying the propose methodology. Fig 10 (a) show the profile about the line 148 where the non-smooth 3D shape is showed. Fig 10 (b) the same line after applying the methodology is viewed.

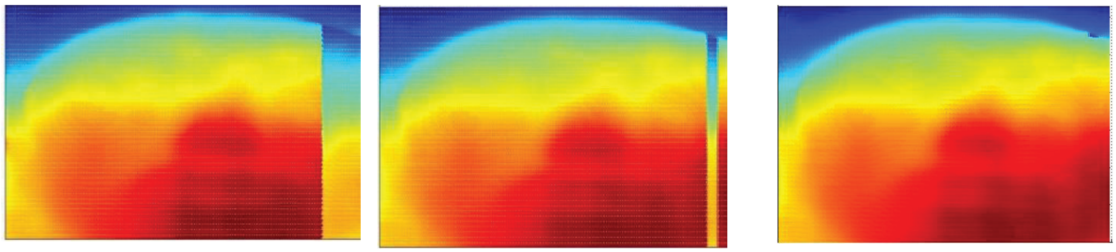

Fig 9 Reconstruction of Mud Sun. (a) Object using the MFTP methodology; (b) Object using a pre-filtering ; (c) 3D object using the proposed methodology.

Fig 10. (a) Profile of line 148 using, the MFTP methodology; (b) Profile of line 148 using the proposed methodology.

Fig. 11 (a) shows the phase unwrapping of a mannequin phantom without the pre-filtering step. Fig (b) a pre-filtering phase is used and Fig. (c) The proposed methodology is applied.

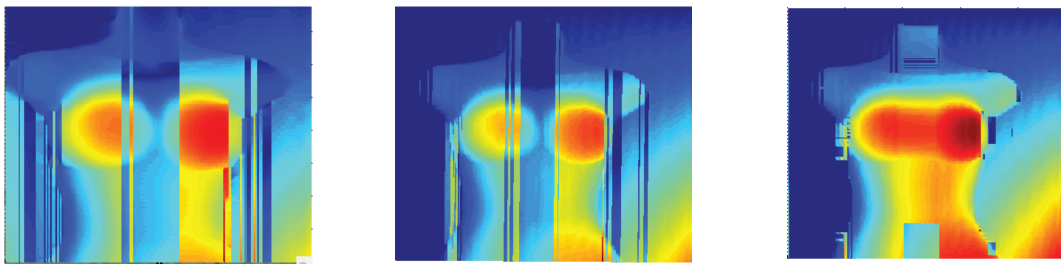

Fig. 11. (a) Object using the MFTP methodology; (b) Object using a pre-filtering; (c) 3D object using the proposed methodology.

The line 148 is analyzed to get the profile. Fig 12(a) shows the profile without the pre-filtering and post-filtering, and the corresponding profile about line 148 with the methodology applied is shown in Fig 12(b).

Fig. 12. (a) Profile of line number 148 using the MFTP methodology; (b) Profile of line number 148 using the proposed methodology.

A 3D reconstruction comparison between MFTP and the propose methodology are shown in Fig 13(a) and 13(b) respectively.

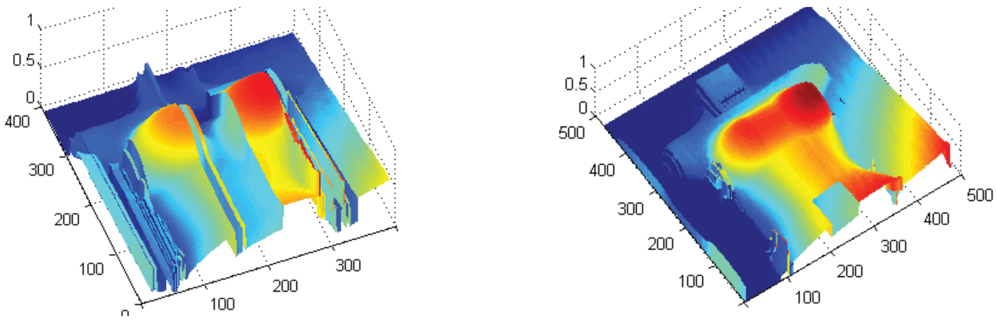

Fig. 1.3 (a) 3D Object using the MFTP; (b) 3D Object using the proposed methodology.

When the methodology was applied to the masking tape, the following result was obtained: Fig 14(a) shows the phase unwrapping without the pre-filtering step, Fig 14(b) uses pre-filtering, and Fig 14(c) depicts the result of the proposed methodology.

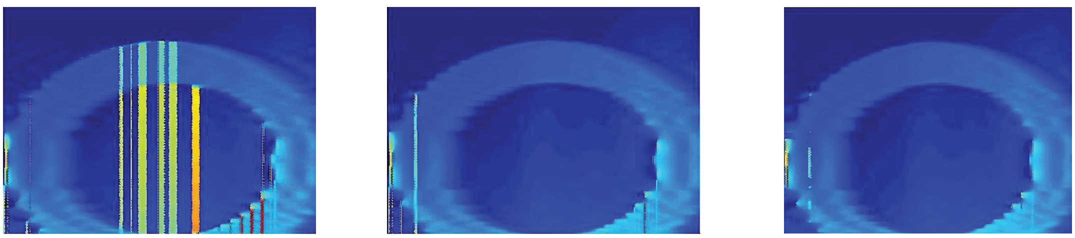

Fig. 14. (a) Object using the MFTP; (b) Object using a pre-filtering; (c) 3D object using the proposed methodology.

Fig 15(a) show the profile about line 148 where the pre-filtering is applied and Fig. 15(b) show the corresponding profile with the methodology is applied.

Fig. 15.(a) Profile of line number 148 without proposed methodology; (b) Profile of line number 148 using the proposed methodology.

7. Conclusion and future work

When the pre-filtering to fringe pattern is applied, a 3D object with notable smoothing is obtained, but some objects have a non-uniform smoothing, when the linear regression is applied, as a tendency of the neighboring pixels in non-uniform areas. We can have a 3D object with a best smoothing in these areas. The use the linear regression by least square is an easy form but efficient to this proposal. But when many areas with non-uniform smooth are presented at the 3D shape, these areas are not completely smoothed. As future work we will apply different kinds of filtering in the pre-filtering step, and we will develop a module for pre-filtering and post-filtering in the MFTPsof software.

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