Novel approach to eliminate discontinuities in phase unwrapping applied to Phase-Shifting Profilometry

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Abstract. In order to obtain the 3D information using fringe analysis, phase maps are required and must be recovered from the wrapped phase, so that phase unwrapping is a critical step in the optical measurement by fringe projection. The phase wrapping is the process that determines the values of phase in a range from 0 to 2π and the phase unwrapping is a process in which discontinuity of 2π is removed. Although the phase unwrapping removed of discontinuity of 2π, by several factors in some cases there are errors different to 2π, we propose a new approach to solve this problem by adding a post-processing step, which consist in search the number of sections that contains discontinuities and after these discontinuities are eliminated, the compensation of the values for each section is carried out. The wrapped phase map is extracted from the deformed fringe patterns by the use of Phase-Shifting Profilometry (PSP) technique and particularly using four-step algorithm. Our experimental results show that if the proposed approach is applied after the phase unwrapping step, then obtains better results than the obtained by only using a the phase unwrapping step. Here, the phase unwrapping algorithms; "Itoh Traditional", "Itoh inverse", “Graph Cuts” and “Simple unwrap” are applied to the PSP.

Keywords: Phase wrapping; Phase unwrapping; Phase-Shifting Profilometry; depth image; optical measurement.

1 Introduction

One of the best techniques used in the optical measurement is the fringe projection technique, which utilizes a group of defined fringe pattern (sinusoidal or periodic) projected from a digital projector to the object surface, therefore the object's shape creates distortions in pattern. Then the distortions are captured with a digital camera from another angle, and finally the image is processed to obtain the 3D information of surface [1] [2] [3].

Between fringe projection techniques, Fourier Transform Profilometry (FTP), Wavelet Transform Profilometry (WTP) and Phase-Shifting Profilometry (PSP) are the most used methods, each of them present diverse advantages and disadvantages with respect to other. For instance, when only one image is processed commonly the Fourier

Transform Profilometry is applied, which works as a spatial phase modulation of the pattern carrier with a fundamental frequency f0. Different phase demodulation algorithms can be applied to this carrier pattern. FTP extracts only the term of modulated phase through filtering spectrum, using one or two dimensions FTP and its inverse [1].

When is used more than one image pattern, the PSP algorithms are used due to its numerous advantages, point - by-point measurement (which allows the resolution level pixel-camera), less sensitive to variations in reflectivity surface (facilitating the measurement of complex objects with strong variations in texture) and less sensitivity to ambient light [1] [2][4][5]. In this research we only focus on the PSP technique.

There are numerous methods of phase-shifting in which stands out: "three-step", "four-step" and “double three-step". These methods differ in the number of input images, like the "three-step" approach will use 3 images, "four-step" will use 4 and so on.

To get the height of an object is necessary to obtain the information immersed into the phase; usually these information is wrapped into the phase. The phase modulation is the result of the deformed pattern, projected on the surface and the fringe pattern can be described by phase maps. By analyzing the phase maps, the 3D shape can be recovered [3].If more images are employed the quality of result will improve, but the runtime will increase. We consider that a good relationship runtime-quality is given by the 4-step method, therefore is the method that we select.

Two basic steps to the phase treatment are necessary, which are: the phase wrapping and the phase unwrapping. The phase wrapping is the process that determines the values of phase in a range from 0 to 2π. The phase unwrapping is a process in which discontinuity of 2π is removed to generate a phase map [6] [7] [8].

The phase wrapping can be expressed mathematically as:

$$x_W(n) = W[x(n)] \tag{1}$$

Where $x(n)$ is the original continuous phase, $W[\,]$ is the phase wrapping operation and x_W (n) is the phase wrapping [9].

Knowing that the phase unwrapping is an important part of any optical measurement numerous algorithms have been proposed to create better results in either response time or better resolution in measurements. For example "Itoh traditional”, "Itoh inverse”, “Graph cuts”, “Quality guided”, etc. [10].

2 Methodology

The PSP four-step used can be described as follows:

$$I_1(x,y) = I'(x,y) + I''(x,y)\,cos[\phi(x,y) + 3\alpha] \tag{2}$$

$$I_2(x,y) = I'(x,y) - I''(x,y)\,sin\,[\phi(x,y) + 2\alpha] \tag{3}$$

$$I_3(x,y) = I'(x,y) - I''(x,y)cos\,[\phi(x,y) + \alpha] \tag{4}$$

$$I_4(x,y) = I'(x,y) + I''(x,y)sin\,[\phi(x,y)] \tag{5}$$

Where $\mathrm{I}'(\mathrm{x},\mathrm{y})$ is the average intensity, $\mathrm{I}''(\mathrm{x},\mathrm{y})$ is the intensity modulation, $\phi(\mathrm{x},\mathrm{y})$ is the phase to resolve. In our case we consider α= pi/2.

$$\phi(x,y) = tan^{-1}\left(\frac{I_4(x,y)-I_2(x,y)}{I_1(x,y)-I_3(x,y)}\right) \tag{6}$$

As shown in Fig.1(a), a set of images with the different fringe pattern projected are acquired, then a pre-processing stage is applied to eliminate the angle distortion of the camera view, an image calibration by using an estimate geometric transform is performed. Later an equalization of histogram for each image is carried out. To obtain the phase map we use the Equation 6. In the next step the phase unwrapping is treated with different algorithms ("Itoh Traditional", "Itoh inverse", "Graph Cuts" and "Simple unwrap"). Finally to the best phase unwrapping algorithm is applied by using the new approach proposed in algorithms 1 and 2, as a post-processing stage.

Before to apply the proposed method to real objects, a simulation of the process by using depth images in grayscale is carried out to verify all equations without errors of calibration.

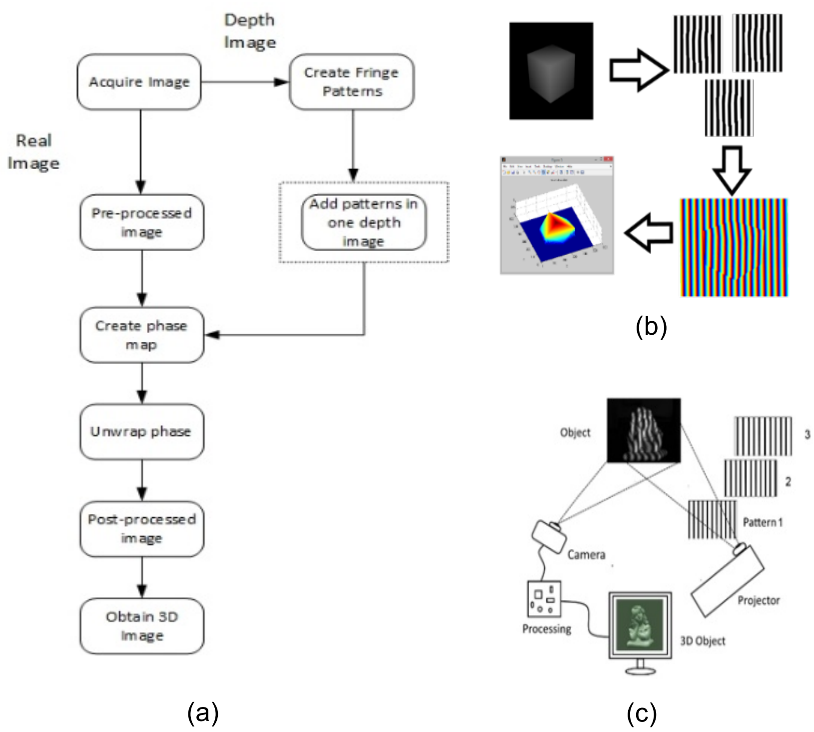

Fig. 1. (a) Methodology. (b) An example using depth images. (c) System architecture.

The complete process of PSP is simulated as if it were real objects (using depth image).In Fig.1(c) the real system architecture can be observed. Here, the sinusoidal defined patterns are projected to an object, then the image is captured, after angle pattern will be shifting (usually 120 ° in case of three step and 90 ° in four step algorithm), then re-capture the image and so until get 3 or more images, the images being processed by using Equation 6 to obtain the phase map (contains the information of the height of the object), finally tridimensional object is obtained by the phase unwrapping. Fig.1(b) show one example using depth images where projected patterns are created artificially and is given the same treatment that used in images of real objects (except the calibration of the distortion angle).

To calculate error, we used the difference between the reconstructed image (pixel by pixel) and the three-dimensional representation of the depth image. In the depth image each pixel has a value of 0 (black) to 255 (white) which may be represented by a value from 0 to 1 (depth) to obtain the reconstructed image as in Fig. 2.

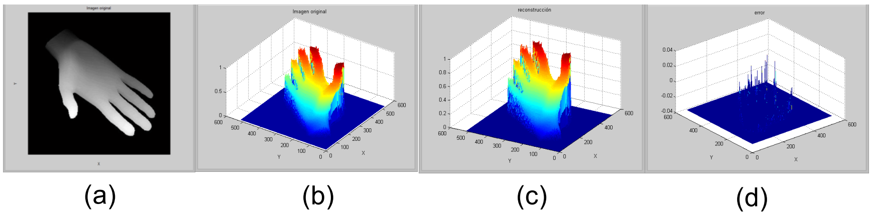

Fig. 2. (a) Example of depth image, (b) Three-dimensional representation of the depth image, (c) Reconstructed image using PSP, (d) Three-dimensional representation of the error.

2.1 Algorithms of phase unwrapping

Since there are many algorithms of phase unwrapping and the main authors differ which is more suitable, the most used were analyzed:

- **Simple unwrap.** This algorithm simply corrects the phase angles in a vector adding multiples of $\pm 2\pi$ when absolute jumps between consecutive elements [11].
- **Itoh traditional.** The algorithm of Itoh involves unwrapping the rows one by one to verify discontinuity between the values of the row, followed by an unwrapping in columns (same as one by one) [10].
- **Itoh inverse.** The algorithm of Itoh Inverse involves unwrapping the rows one by one to verify discontinuity between the values of the columns, followed by an unwrapping in row (same as one by one) [10].
- **Graph cuts.** The algorithm implemented for Phase Unwrapping via Graph Cuts use max-flow/min-cut calculations described by José M. Bioucas-Dia and Gonçalo Valadão in 2007 [12].

Fig. 3 shows the results evaluating the most common algorithms of phase unwrapping with three different test objects (a fish, a box with a half disposable cup and one mask), Fig. 3(a) shows the result of applying a simple unwrap algorithm, Fig. 3(b) shows the result of applying the Itoh traditional algorithm, Fig. 3(c) shows the result of applying the Itoh inverse algorithm and Fig. 3(d) shows the result of applying the Graph cuts algorithm. At the end of the test the best results are given by the Graph cuts algorithm. Although the phase unwrapping removes the discontinuity of 2π, in some cases there are errors different to 2π creating sections with jumps in the image, therefore we propose a post-processing stage to solve this problem. At first instance by finding the sections where jumps occurred through a reference line and are evaluated pixel by pixel to check the discontinuity, if one discontinuity is founded, its value is store in a matrix (with the pixel position and value where occurred the discontinuity) then all values of discontinuity are eliminated for each section compensating the value with one sum. The methodology is completely described in the algorithms 1 and 2.

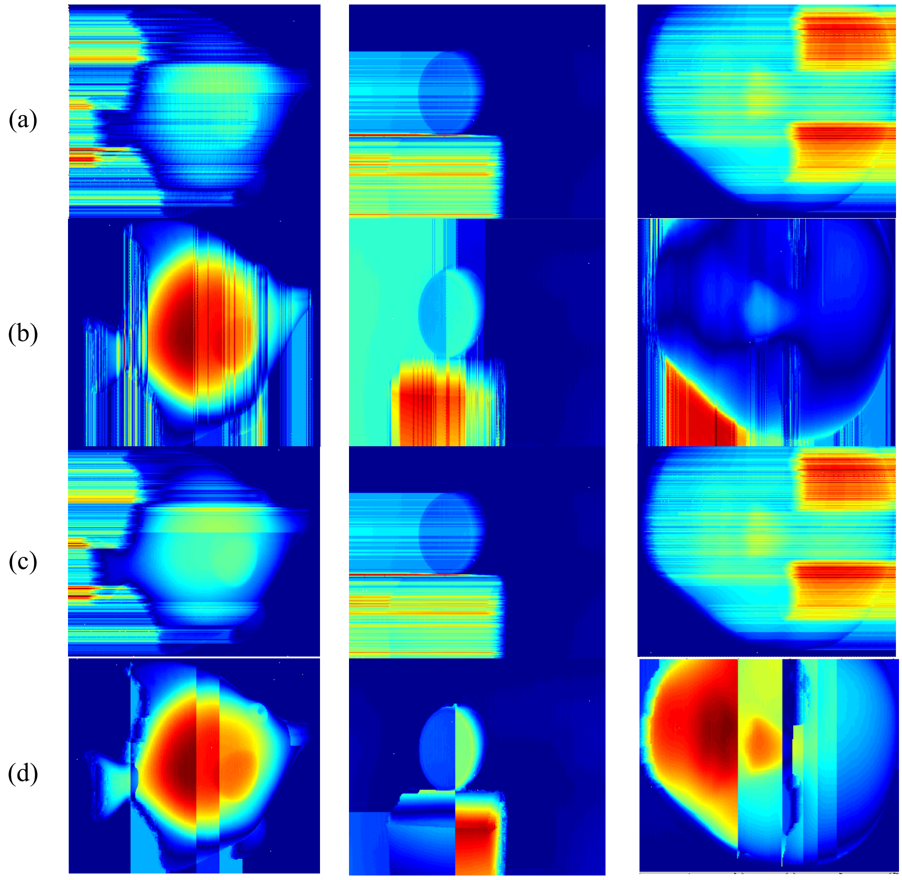

Fig. 3. The results evaluating the most common algorithms of phase unwrapping with three different test objects (a fish, a box with a half disposable cup and one mask), (a) Simple unwrap, (b) Itoh traditional, (c) Itoh inverse, (d) Graph cuts.

Algorithm 1: Find sections

```
input wi =unwrapping image (M x N)
// Define  reference line
line = wi (number of row cross section , :)
number of sections = 0
for i = 2→N
        current pixel = line (i)
        previous pixel = line(i-1)
        discontinuity = current pixel – previous pixel
        if discontinuity > threshold
                number of sections ++
// border values are stored
                Section Value(number of sections, 1) = i
                Section Value(number of sections, 2) = i - 1
                Section Value(number of sections, 3) = discontinuity
        end if
end for
Section Value(number of sections +1,2)= N;
```

Algorithm 2: Delete discontinuity

```
input wi =wrapping image (M x N), line = wi ( M/2 , :), Section Value(:,1) =
previous pixel to discontinuity, Section Value(:,2) = next pixel to discontinuity,
Section Value(:,3) = value of discontinuity
e = discontinuity to fix = 0
if number of sections > 0
        for j = 1 → number of sections
                v1 = Section Value(j,1)
                v2 = Section Value(j,2)
                e = Section Value(j,3)
                for l =1 →M
// linC = line to correct
                        linC = wi (l , :)
                        for k = v1→v2
                                linC(k)=linC(k) -e
                                wi (1 , :)= linC
                        end for
                end for
        end for
end if
```

Finally the image with discontinuity is corrected but to correct the background it is necessary to apply a mask created from raw data.

3 Experimental results

A set of four images which contain a real object were considered [13] and are shown on Fig. 4 where four different shifting angles of the fringe pattern are projected to a fish. Another set of images were taken and are shown on Fig. 5. These images are ideal to observe a discontinuity error different to 2π such as shadow effect inherent in projection, on-uniform reflectance but a good calibration of projection. In the phase map is evident this aspects as Fig. 6 that show the difference between a good and bad calibration as well as the shadow effect.

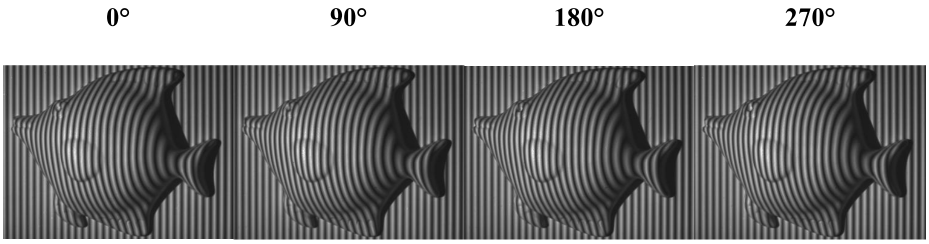

Fig. 4. Patterns projected to a fish taken of data raw of Chen Lujie [13].

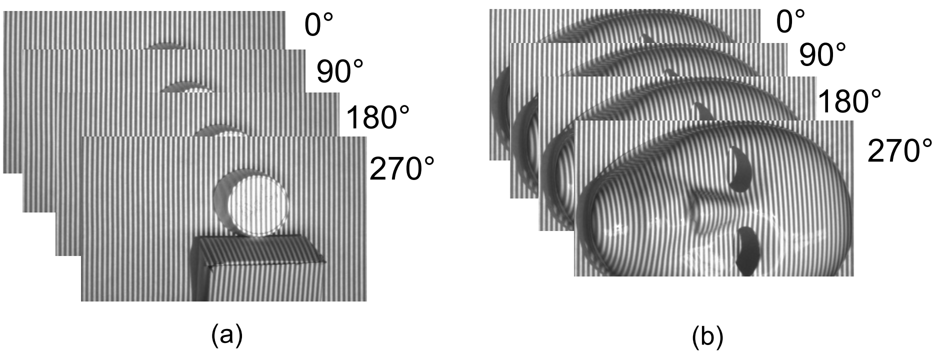

Fig. 5. Images taken for us, (a) Patterns projected to a box with a half disposable cup, (b) Patterns projected to a mask.

The Computer used to carry out the experiments is a Lenovo Y510p with 8GB of RAM, Intel® Core™ i7-4700MQ 2.4GHz and Windows 8.1 64 bits. The algorithms were implemented in Matlab R2013b. In the experiment system, the sinusoidal fringe patterns was generated by Acer K11+ with native resolution of 858 X 600 (SVGA) and 200 lumens and capture by DAVID-CAM-3-M with 1280x960 of resolution.

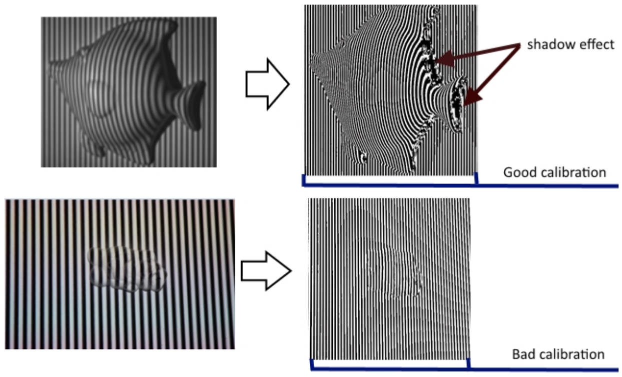

Fig. 6. Examples of shadow effect, good and bad calibration of projection.

The different test objects are a fish, a box with a half disposable cup and one mask. Fig.7 shows the comparison between the phase unwrapping before and after the algorithms proposed were applied, also shows the reference line (96th row cross section) where the jumps are more noticeable, moreover it is shows the 3D reconstruction as a mesh and a surface. It can be observed that the most of the discontinuity errors were eliminated with the algorithms proposed. Only persist the error in the background of each image but not in surface in the test object.

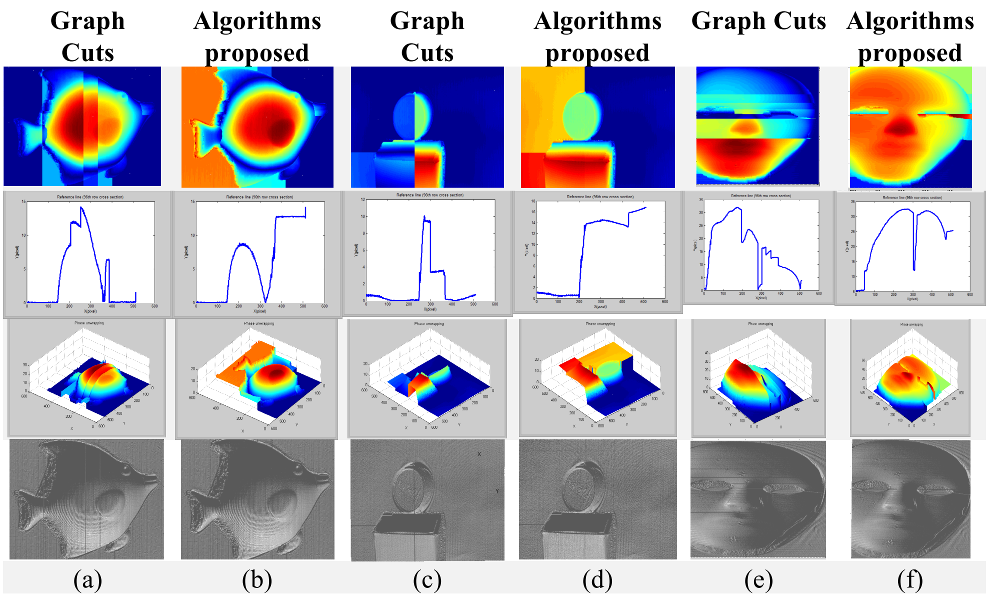

Fig. 7. Comparison between the images before of the algorithms proposed ((a), (c), (e)) and after the algorithms proposed ((b), (d), (f)).

4 Conclusions and Future Work

This research described as use the Phase-Shifting Profilometry to obtain tridimensional information (particularly four-step method) through each stage; pre-processing (where the image will be adequate for the future processing), phase wrapping (stage where extracted the phase information using PSP), phase unwrapping (process in which discontinuity of 2π is removed to generate a phase map) and post-processing (stage where we propose two algorithms to eliminate the discontinuity after of phase unwrapping).

Moreover, a novel approach can be described as the elimination of the discontinuity different to 2π (applied to PSP) caused by bad calibration, noise in the image and shadow effect. This discontinuity is achieved by finding and correcting each section of discontinuity. The new approach are divided in two algorithms after of the phase unwrapping, the first algorithm finds all the sections where there are jumps inside the image and the second algorithm compensates the discontinuity with only one sum. The proposed algorithms are simple to implement and show more accurate results in the surface of the objects than previous works presented, in which only a simple unwrapping algorithm is used. Finally in the new approach only persist the errors in the background but eliminates the errors in the surface.

As future work it is proposed to implement the algorithms in an embedded system based on the ARM processor and improve post-processing adding a mask to remove background noise. Also correct the error in the background through a mask from raw images or using a quality-guided method.

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