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Binary Code Pattern Unwrapping Technique in Fringe Projection Method

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Abstract— **Due to the growing need to produce three-dimensional data in various fields such as archaeology modeling, reverse engineering, quality control, industrial components, computer vision and virtual reality, and many other applications, the lack of a stable, economic, accurate, and flexible three-dimensional reconstruction system that is based on a factual academic investigation is recommended. As an answer to that demand, Fringe projection has emerged as a promising 3D reconstruction direction that combines low computational cost with both high precision and high resolution. In our previous work, an experimental study and implementation of a simple fringe projection system has been reported which was based on a multi wavelength unwrapping approach. In this paper we implemented a new method of phase unwrapping which is based on time analyses unwrapping approaches. Experimental results have shown that binary code pattern unwrapping method is a stable and reliable method that results in a high level of precision. At the cost of using more pictures the higher level of precision in the reconstructed 3-D model has been achieved. The level of preciseness in the resulting cloud point can be observed directly as a proof of the correctness of whole method.**

Three-dimensional reconstruction of small objects has been one of the most challenging problems over the last decade. Computer graphics researchers and photography professionals have been working on improving 3D reconstruction algorithms to fit the high demands of various real life applications. Medical sciences, animation industry, virtual reality, pattern recognition, tourism industry, and reverse engineering are common fields where 3D reconstruction of objects plays a vital role. Both lack of accuracy and high computational cost are the major challenges facing successful 3D reconstruction. It employs digital projection, structured light systems and phase analysis on fringed pictures. Research studies have shown that the system has acceptable performance, and moreover it is insensitive to ambient light.

Keywords— Digital fringe projection, 3D reconstruction, phase unwrapping, phase shifting.

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I. INTRODUCTION

In recent years there has been an increasing interest in 3D reconstruction of objects. Various methods and algorithms have been developed to fulfill the needs and demands in this particular area. Among these methods, the features and capabilities of digital sinusoidal pattern mapping method(fringe projection), was the subject to several studies. High flexibility, high speed, high accuracy and low cost, can be mentioned as the main characteristics of fringe projection method.

A structured light system such as fringe projection system is similar to a stereo technique as it only uses two devices for 3D shape measurement. However, fringe projection replaces one camera of a stereo system with a projector to project structured patterns, which are encoded through certain codification strategies. Then, the captured structured patterns are decoded. If the code-words (used to encode the structured pattern) are unique, the correspondence between the projector sensor and the camera sensor is uniquely identified, and 3D information can be calculated through triangulation. Generally, structured light systems use binary patterns, where only 0 and 1 s are used for codification. Binary patterns are easier to encode and decode, resulting in a considerable performance gain for the overall system. Three-dimensional measurement techniques are broadly classified into two categories; contact and non-contact approaches, refer to Fig. 1. We will limit our discussion to fringe projection as an effective non-contact approach.

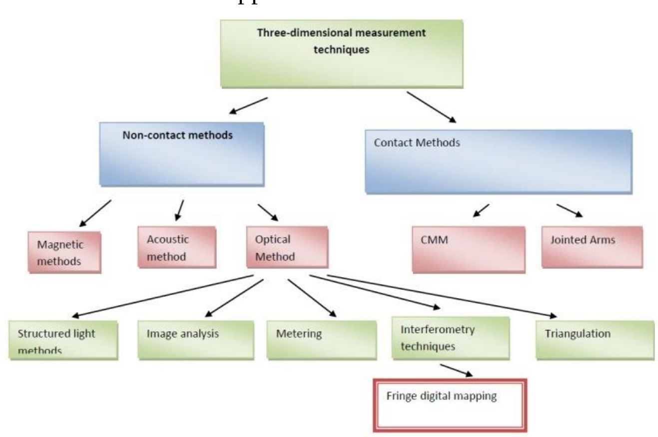


Fig. 1 Three dimensional reconstructed systems.[1]

The major stages of fringe projection method are;

- A sinusoidal pattern is projected over the surface of the object by using a projector, as illustrated in Fig. 2
- A digital camera is used to capture the pattern that has been assorted (phase modulated) by the topography of the object surface.
- The captured pattern is analyzed to extract relevant topographical information of the object (phase).
- A phase unwrapping algorithm is executed in order to unwrap the phase step
- A phase to height conversion method is used to materialized the 3-D dimension in every pixel

Phase modulation analysis uses the *arctan* function, which yields values in the range [-π,+π]. However, true phase values may extend over 2π range, resulting in discontinuities in the recovered phase. Phase unwrapping aims at finding the 2π coefficients, and consequently adding integral multiples of 2π at each pixel to remove such discontinuity.

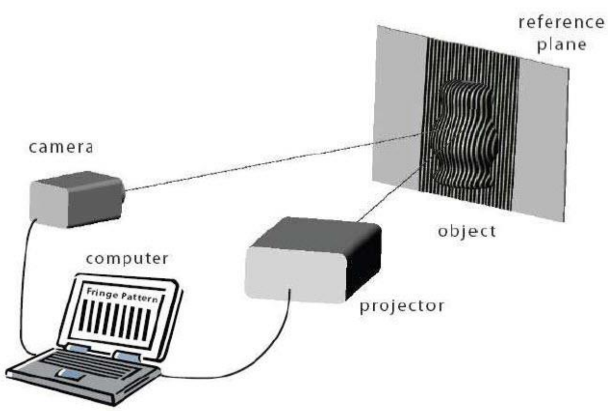


Fig. 2 Fringe projection arrangement[3]

The paper is organized as follows. Section II highlights previous research studies for fringe analysis. Then, Section III and Section IV present the fringe projection system set up and results, respectively. Finally, Section V offers concluding remarks and suggestions for future work.

II. Prior and Related Work

Fringe digital mapping was first proposed by Rowe *et al*.[1][2] in 1967. Phase detection has been one of the most active research areas over the last decade. It can be broadly classified into two main categories:

- Time-based analysis
- Frequency-based analysis

Common phase detection approaches found in literature were based on either Fourier transform [4] [5] [6] [7] [8] [9] [10], interpolated Fourier transform [11], continuous wavelet transform [12] [13] [14], two dimensional continues wavelet transform, discrete consign transform, neural network, phase locked loop, spatial phase detection, or phase transition [15].

Quan *et al.* [16] proposed the phase transition approach for small object measurement. In 2001, Berryman *et al.* [17] compared three different approaches (Fourier transform, phase transition, and spatial phase detection) on the reconstruction of a sphere using simulated data. Their experiments showed that in low noise conditions, phase transition produces the best results. With more than 10 % noise, using Fourier transform would be a good choice. However, on high noise levels spatial phase detection showed superior results.

Suutton *et al.* [18] proposed a phase detection scheme based on the use of Hilbert transform with Laplacian pyramid. The proposed scheme produces high precision level.

Gdeisat *et al.* [19] used two-dimensional continuous wavelet transform to eliminate the low component's frequency of the fringe. Then, Fourier transform was employed for phase detection. This method offers acceptable results; taking into consideration that it uses only one fringe.

III. FRINGE PATTERN ANALYSIS USING PHASE SHIFTING

The image of a projected pattern(sinusoidal patterns) can be written as the following commonly used standard formula :

$$g(x,y) = a(x,y) + b(x,y)\cos(2\pi f_0 x + \varphi(x,y)) \quad (1)$$

where, $a(x,y)$ is the background intensity, $b(x,y)$ is the amplitude modulation of fringes, f_0 is the spatial carrier frequency, $\varphi(x,y)$ is the phase modulation of fringes (the required phase distribution). Equation (5) contains three unknowns; $a(x,y)$, $b(x,y)$, and $\varphi(x,y)$. As a result, three independent equations are needed to eliminate $a(x,y)$ and $b(x,y)$. This goal can be achieved by using three identical fringe patters shifted by known amounts (2π/3 radians). This leads to the following three equations:

$$g_1(x,y) = a(x,y) + b(x,y)\cos(2\pi f_0 x + \varphi(x,y) - \tfrac{2}{3}\pi) \quad (2)$$

$$g_2(x,y) = a(x,y) + b(x,y)\cos(2\pi f_0 x + \varphi(x,y)) \quad (3)$$

$$g_3(x,y) = a(x,y) + b(x,y)\cos(2\pi f_0 x + \varphi(x,y) + \tfrac{2}{3}\pi) \quad (4)$$

Solving the above three equations, the phase $\varphi(x,y)$ can be obtained as:

$$\varpi(x,y) = \tan^{-1}\left[\!\left[\frac{\sqrt{3}(I_1 - I_3)}{2I_2 - I_1 - I_3}\right]\!\right] \quad (5)$$

IV. PHASE UNWRAPPING

There are many applications of digital image processing in industrial, medical and military that part of the procedure is dependent upon the phase extraction of input images. Magnetic Resonance Imaging (MRI), Synthetic Aperture Radar (SAR), fringe digital mapping, tomography, are spectroscopy, are just a few examples of the mentioned examples. These systems use longstanding or novel algorithm in phase extraction process. Even so, considering as a result of using the arc tan functions, the extracted phase contains 2p jumps. The extracted phase is totally useless, unless the phase be unwrapped. The procedure of determining these discontinuities on the wrapped phase, resolving them and achieving the unwrapped phase is called phase unwrapping. Phase unwrapping is one of the most active areas of research in image processing, and so many different algorithms and methods are provided as a solution to the phase unwrapping problem. Mathematical explanation of the phase unwrapping problem can be provided as follows:

$$\Phi = \varphi + 2K\pi$$

Where Φ is the unwrapped phase, φ is the ambiguity phase, and K is an integer number, which counts the number of coefficients of 2π.

Figure 2.17 illustrates a wrapped and unwrapped phase and their profiles accordingly.

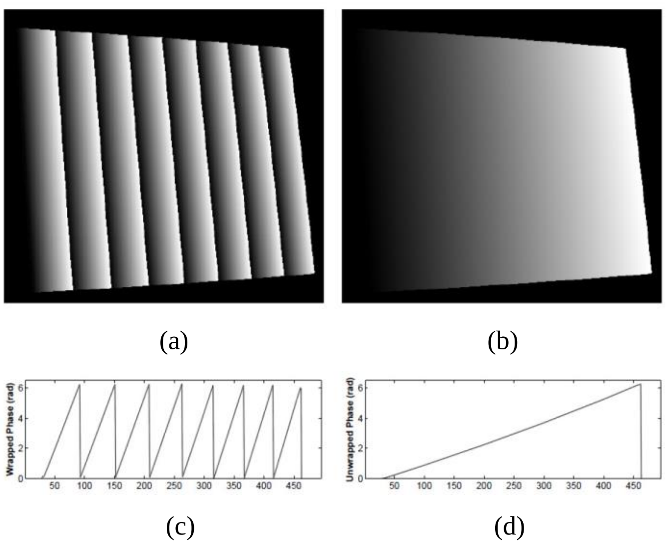


Figure 3 (a):wrapped phase (b) unwrapped phase (c)a profile of the wrapped phase (d) profile of the unwrapped phase

There are three major solutions for solving the phase ambiguity or phase unwrapping :

- **spatial analyses :**

The main advantage in this method is that there is no need for additional helping patterns. In this method, all the pixels of wrapped phase will be processed and every two neighbor pixels that have sudden jump in their phase value, will be identified and $2\pi i$ coefficients will be added to the target pixels accordingly. This method is dramatically time consuming, and significantly inadequate facing complex objects and shadows.

- **Multi wavelength analyses:**

In this method, at least three additional fringe patterns with wavelength equal to the width of the projector should be obtained. In the next step $2\pi i$, coefficients will be calculated using these big wavelengths, and will be applied to the phase of the smaller wavelengths affording more precision. The main foible of this method is the considerable calculating error in the large wavelength phase. Consequently, The phase unwrapping results will not be precise. Considering the mentioned possible calculating errors these errors, They may be caused in using white shiny objects or high levels of contrast in projector light. The main advantage of this method is that it leads to greater precision at the expense of requiring only three additional patterns.

- **Time analyses :**

In this method binary code, patterns will be created according to each wavelength area and will be projected on the object such that the phase ambiguity can be calculated by using these code patterns. The only disadvantage in this method is that it needs more patterns, For instance, in our practical attempts, we used eight patterns to solve the phase ambiguity.

The Third method of these methods(Binary code patterns analyses)has been used in this paper. If the projector has 100 width pixels, then in each row, the fringe patterns will be repeated every 20 pixels. As a result, phase ambiguity of each pixel will be increased with the amount of 2π after each 20 pixels. In view of the above remark, if the phase ambiguity of each pixel is equal to $2k\pi i$ then, k values will be distributed in k = 0-1-2-3-4. where i is the $2k\pi$ coefficients.

V. PHASE TO HEIGHT CONVERSION

After phase unwrapping, height information of the measured object can be extracted. There are two common approaches to calculate depth information from the unwrapped phase map: relative coordinate calculation and absolute coordinate calculation. Absolute coordinate calculation is based on triangulation to estimate the absolute coordinate of every pixel in the world coordinate system. This approach requires precise knowledge about intrinsic and extrinsic parameters of both camera and projector. Thus, a system calibration step is essential. On the other hand, in the relative coordinate calculation approach, the depth of each pixel is calculated using a reference plane. A calibration process is not required. Moreover, the relative depth calculation approach is computationally less expensive compared to the absolute approach. Fig 4 shows a schematic diagram that illustrates the relative depth calculation approach. Points P and I are the perspective centers of the DLP projector and the CCD camera, respectively. The optical axes of the projector and the camera coincide at point O. After the system has been set up, a flat reference plane is measured first whose phase map is used as a reference for subsequent measurements. Then, the height of the object surface is measured relative to this reference plane.

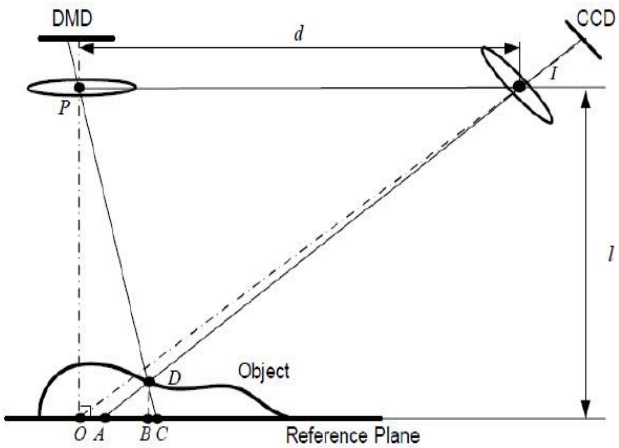


Fig. 4 Schematic diagram of phase-to-height conversion using the relative depth calculation approach.

From the projector point of view, point *D* on the object surface has identical phase value as point *C* on the reference plane, i.e. $\varphi_D = \varphi_C$. On the other hand, from the CCD camera point of view, point *D* on the object surface and point *A* on the reference plane are imaged on the same pixel. By subtracting the reference phase map from the object phase map, we obtain the phase difference at this specific pixel:

$$\varphi_{AD} = \varphi_{AC} = \varphi_A - \varphi_C \tag{6}$$

Assume that points *P* and *I* are planned to be on the same axes with a distance *l* to the reference plane and a distance *d* between them, and that the reference plane is parallel to the device. Hence, the triangles *PID* and *CAD* in Fig. 4 are similar. Therefore:

$$\frac{d}{AC} = \frac{l-\overline{DB}}{\overline{DB}} = \frac{l}{\overline{DB}} - 1 \tag{7}$$

where, *d* is the distance between the camera and the projector. Since *d* is much larger than *AC* for real measurement, this equation can be simplified as:

$$h(x,y) = \overline{DB} \cong \frac{1}{d}\overline{AC} = \frac{1}{d}\frac{\varphi_{AC}}{2\pi f} = K.\varphi_{AC} \tag{8}$$

where, *f* is the frequency of the projected fringes in the reference plane, *K* is a constant coefficient, and φ_{AC} is the phase containing the height information.

VI. System Setup

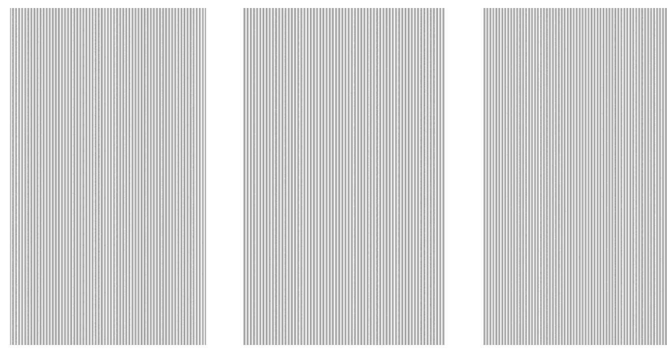
To conduct experiments to test viability of binary code patterns method presented in section [IV], we built a projection system with the configuration shown in Fig. 2. Our system is composed of a Casio XJ-A256 digital light processing unit (DLP), a PC with Intel Core i3 processor, and a Nikon D5100 DSLR camera. The DLP has the following technical specifications: 3000 ANSI lumens, 1800:1 contrast ratio, 16:10 aspect ratio, and a 1280x800 resolution. The DLP chip is 0.65-inch, and computer resolution is up to SXGA + (1600x1200). The camera has a resolution of 16.2 mega pixels and a kit sensor lens of 23.6x15.6 mm CMOS(DX format). A tripod was used to fix the camera during the experiments. A remote controller was used to capture the images without touching the camera on the tripod.

An object has been used which is a chalky white sculpture of a woman. We used the phase shifting approach (as explained in Section [III]) during the fringe pattern analysis phase. The results are presented in the next section.

VII. Experimental Results

A. Creating the fringe patterns

We used Matlab to create the fringe patterns and to process the images Fig. 5 present samples of the fringe patterns used in our experimentations.



(a) (b) (c)

Fig. 5 Fringe patterns with minimum gray value of 50 and maximum gray value of 200, maximum projector resolution 1280 -800, a wavelength of 20, and fringe transitions of: (a) -2π/3, (b) 2π/3, (c) zero.

B. Code patterns generating

It is possible to use binary codes to generate the code patterns. In view of the width of the projector equal to 1280 pixels (n=1280), and also considering the fact that each area is equal to 20 pixels, as a result; there are 64 areas to be coded(64=1280:20). 64 is equal to 2 to the power of 6. Consequently, we need six binary pictures (code patterns) to code 64 areas.

The code value will be a number between 0 to 63 which actually is the 2π coefficients in phase ambiguity and can be used to unwrap the phase. It is mandatory to create one black and one White binary patterns, in order to binarize the grey level pictures. Hence, a threshold value should be defined based on the grey values norms, and for each code if value is greater than the threshold, then it is going to change to one, otherwise it is going to change to zero. Therefore, the number of binary code patterns will be raised up to eight. Fig. 6 illustrates eight binary code patterns profiles, and Fig 7 illustrates the eight binary fringe patterns.

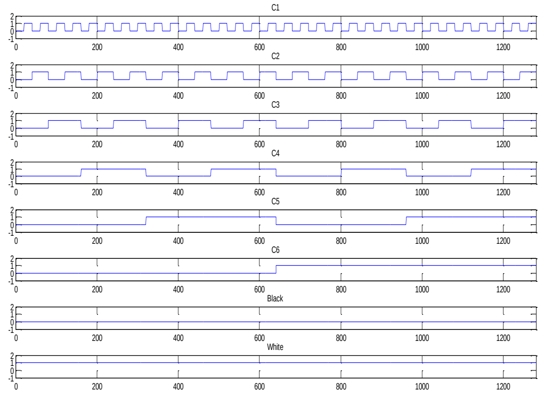


Figure 6 Binary codes patterns profiles

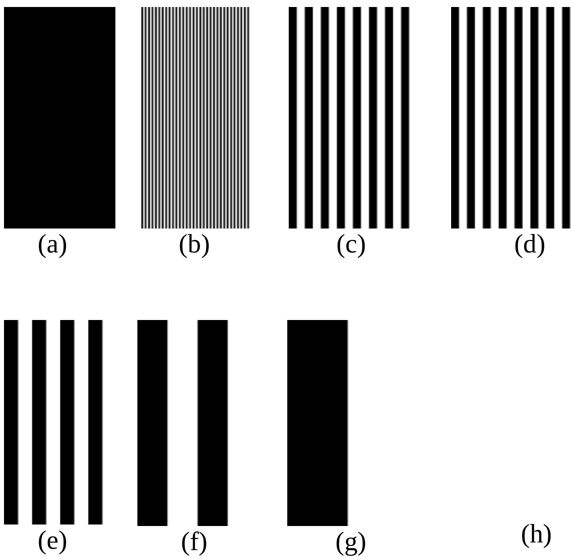


Figure 7 (a) black pattern (b)-(g) binary code patterns (h) white pattern

C. Three dimensional reconstruction

Three fringe patterns and eight code patterns were created and projected on the object and reference plane separately. Each one of the mentioned groups of eleven pictures was analyzed, and the phase map of each was calculated accordingly. Fig 8 and Fig. 9 present the projected patterns and binary code patterns on the object and reference plane respectively.

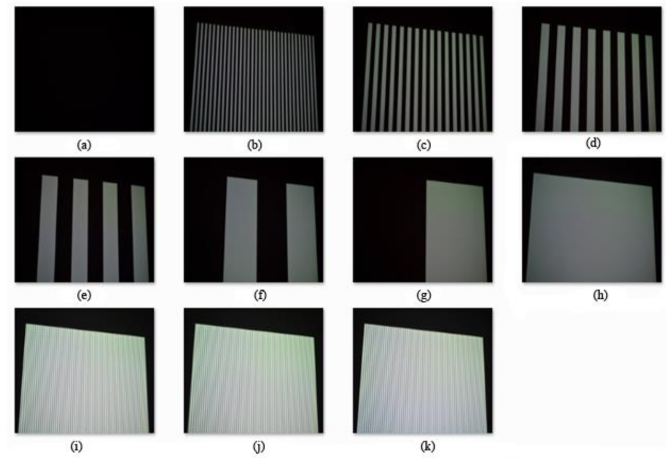


Figure 8 (a)-(h) binary patterns projected on the reference plane (i)-(h) fringe patterns projected on reference plane

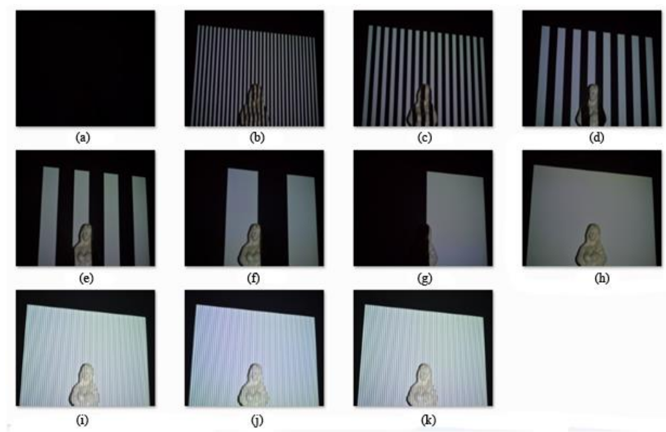


Figure 9 binary patterns projected on the object (i)-(h) fringe patterns projected on the object

Accordingly the object phase and reference plane phase can be achieved. Fig. 10 and Fig.11 present the reference plane phase and object phase.

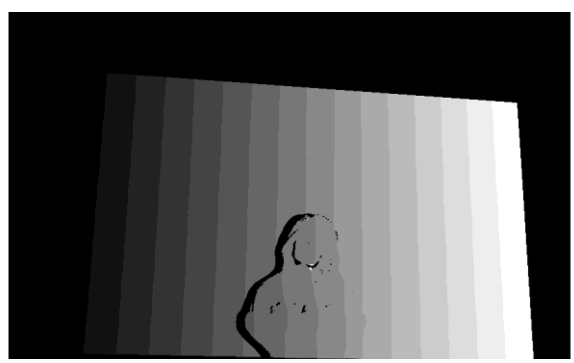


Figure 10 object phase

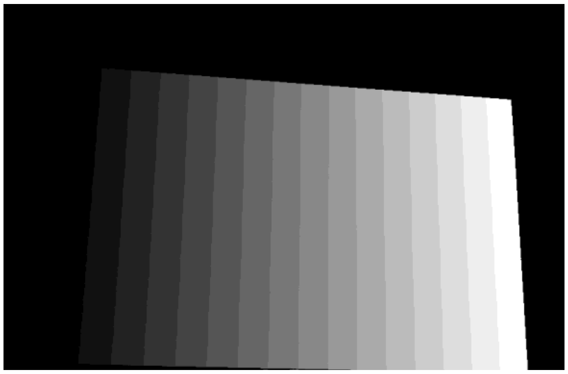


Figure 11 reference plane phase

By subtracting the object phase from the reference phase the finalized phase map can be achieved. Fig 12 present the finalize phase map.

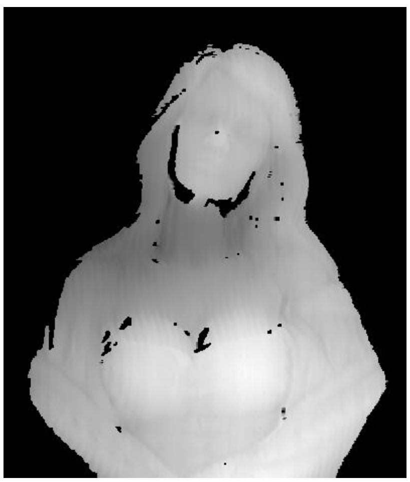


Figure 12 object phase map

We used phase to height conversion as explained in section [V]. Following are the final results. The reader should observe that Fig 15 illustrates the cloud point of original object showing in Fig. 13

Figure 13 Object

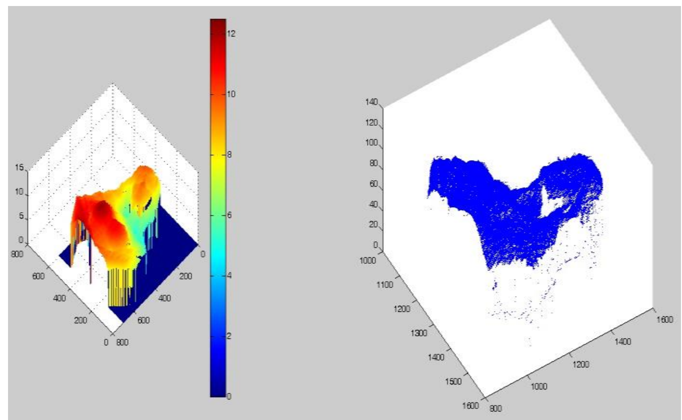


Figure 14 phase map in color(left) and its corresponding cloud point(right)

Fig 14 (left) illustrates the colored phase map that helps us to compare the topography of the real object with the height distribution of the resulting phase map.

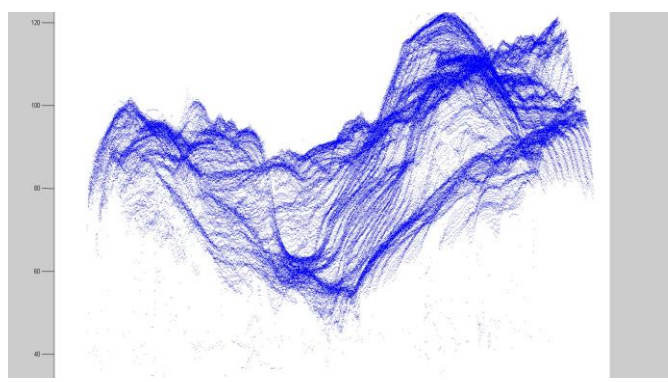


Figure 15 object cloud point

III. Conclusion

Fringe projection is a powerful approach for 3D reconstruction of objects. In this paper, we developed a standalone implementation using one of the most advanced unwrapping algorithms in fringe projection method. Due to the fact that it uses greater number of pictures it has more level of accuracy compared with our previous method[1] that used spatial analysis for phase unwrapping. Experimental results demonstrated that using the new unwrapping algorithm captures more object details at the expense of using more pictures. In future, we plan to extend our experiments to consider other unwrapping methods in fringe projection analysis approaches. We aim at using sets of objects with various features like sudden changes in topography and more complexity in surface details to study the response of each approach to specific object features.

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