INDIAN INSTITUTE OF SPACE SCIENCE AND TECHNOLOGY

Project Report

Fringe Projection Technique for 3D Shape Extraction

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Abstract

3D shape measurement using digital fringe projection technique have been widely studied in academia and applied in industrial fields because of the advantages of non-contact operation, full-field acquisition, high accuracy, automatic and fast data processing. Fringe patterns that contain the 3D shape information is analyzed to extract the wrapped phase, using the method of fourier transform profilometry and then phase unwrapping is done to extract the correct phase and thereby the depth information. A number of unwrapping algorithms are available, out of which the 'Fast Flood Filling' algorithm has been used here.

1. Introduction

Full-field fringe projection techniques have been widely studied in academia and applied in industrial fields because of the advantages of non-contact operation, full-field acquisition, high accuracy, automatic and fast data processing.

Multiple shot methods give highly accurate measurement data for static objects by capturing more than three-fringe pattern images, it could be degraded by disturbance, such as vibration and movement between gap of image shot. Some researchers tried to solve such problem by using high speed CCD cameras and digital micro mirror device (DMD)-based projecting systems to fast acquire three phase-shifted fringe pattern images . Although the wrapped phase map of a moving object can be measured by the three-step phase-shift algorithm, the relative movement between successive captured images causes the shifted phase to an unknown random value, so the method gives inaccurate phase (shape) data. Therefore, in order to measure moving objects and to be against vibration, a good solution is capturing only one gray or color image to calculate phase data map, instead of multiple fringe pattern images.

Single-shot methods are insensitive to vibrational noises since only one image needs to be captured. Until now, various single-shot methods have been actively studied and they can be generally classified into discrete and continuous coding methods. Single-shot discrete coding patterns present a digital profile having the same intensity value for the region represented by the same codeword, so that the size of this region determines the density of the measured object surface. In most cases, the discrete code occupies several pixels, so the resolution is low and the obtained 3D shape data are inaccurate for measuring objects having complex surfaces.

Many algorithms have been studied to calculate phase data, for example, the multiple-step phase-shift algorithm , the Fourier transform algorithm ,the windowed Fourier transform algorithm , the wavelet transform algorithm , the local model fitting algorithm , the spatial phase-shift algorithm, the frequency-guided sequential demodulation algorithm , the regularized phase tracking algorithm etc.

These algorithms calculate the wrapped phase map, modulo 2 pi, which requires being unwrapped for obtaining 3D shape data. In principle, phase unwrapping is a straightforward process by identifying phase difference greater than 2 pi of spatially neighboring pixels for smooth object surface. However, the actual deformed fringe patterns may contain noises, large slopes and/or discontinuities, so the difficulties lead to many developments of phase unwrapping methods.

2. Procedure for 3D shape extraction

Phase calculation-based fringe projection profilometry mainly includes the following several parts: fringe pattern generation and projection, acquisition of deformed fringe pattern on the measured object surface, wrapped and unwrapped phase calculation, 3D calibration, and absolute phase to 3D shape conversion. The procedure of 3D shape measurement from a single-shot image is presented by a flowchart, as shown in figure(1). Demodulating the phase information from the captured image obtains the wrapped phase data, which needs to be unwrapped for shape calculation. The obtained phase data correspond to the shape of the measured objects and their relationship needs to be established by a procedure called as 3D calibration.

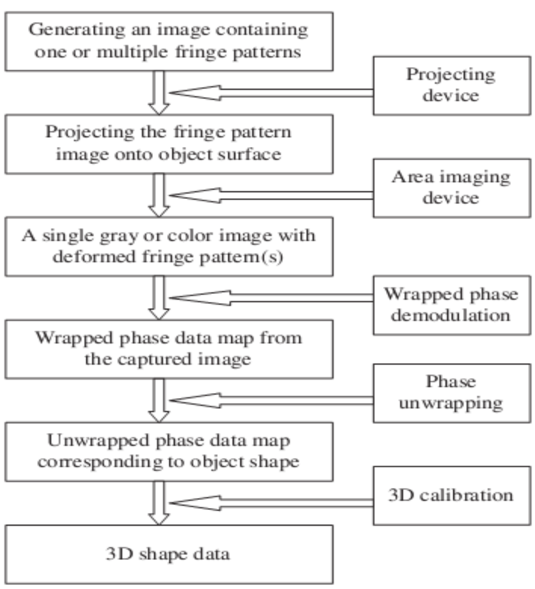


Fig. 1. Flowchart of 3D shape measurement by a single-shot acquisition.

Fig 1.

2.1 Fringe Projection Technique

Sinusoidal fringe patterns of desired phase and frequency can be generated using softwares like MATLAB. This pattern is then made to project onto the desired object. The frequency should be so adjusted that the line spacings of the pattern falling onto the object are sufficient. A photograph of the object in this condition is taken and is given as input to the processing algorithm. The procedure is as shown in the figure(2).

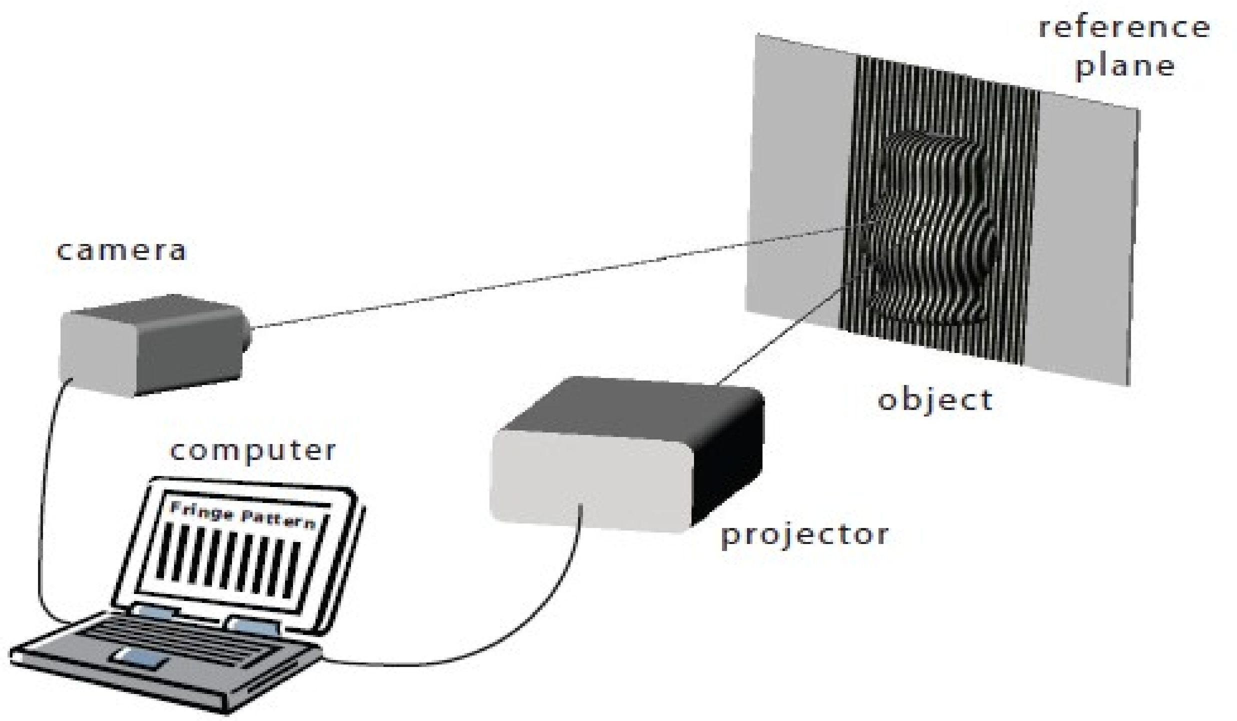
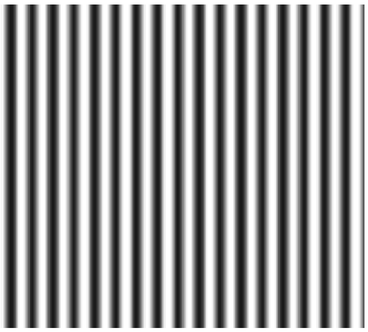


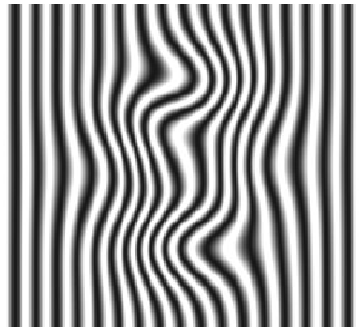
Fig 2.

Figures 3 and 4 show fringe pattern before and after projection respectively.



g0(x,y) = b(x,y) cos(2pi*f0*x + phi0(x,y))

Fig 3.



g(x,y) = a(x,y) + b(x,y) cos(2pi*f0*x + phi(x,y))

Fig 4.

This deformed fringe pattern is processed using some fringe pattern analysis algorithm to obtain the wrapped phase.

2.2 Fourier Transform Profilometry

The deformed fringe pattern can be represented by the equation

g(x,y) = a(x,y) + b(x,y) cos(2*pi*fo*x + phi(x,y)). **(1)**

Here **a(x,y)** represents intensity variations of background, related to object's texture, **b(x,y)** is the fringe amplitude modulation term, due to non uniform reflectivity of object's surface, **fo** represents the spatial carrier and **phi(x,y)** contains the information regarding the object's shape. The aim of Fourier Transform Profilometry is to extract **phi(x,y)** from **g(x,y).**

(1) can be written as:

g(x,y) = a(x,y) + (1/2)*b(x,y) exp j(2*pi*fo*x + phi(x,y)) + (1/2)*b(x,y) exp -j(2*pi*fo*x + phi(x,y)).

g(x,y) = a(x,y) + c(x,y) exp(j*2*pi*fo*x) + c*(x,y) exp(-j*2*pi*fo*x), where

c(x,y) = (1/2)*b(x,y) exp (j*phi(x,y)).

Fourier Transform of this equation will be of the form

G(f,y) = A(x,y) + C(f-fo,y) + C*(f-fo,y).

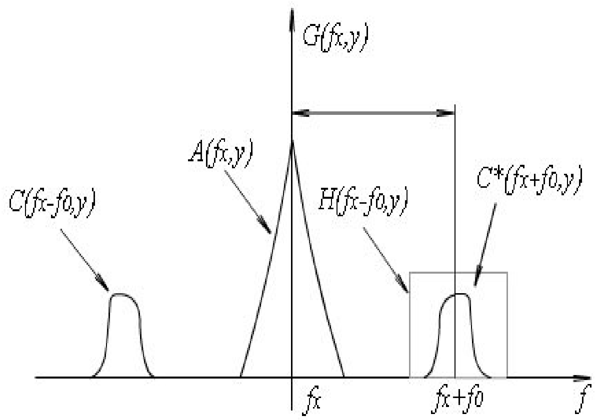


Fig 5

Filtering the spectrum centered around **fo** and translating to the origin results in

G(f,y) = C(f,y).

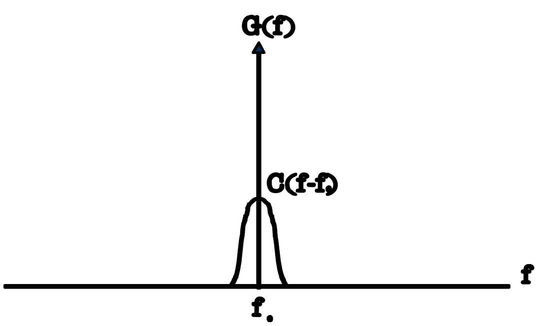


Fig 6

Inverse transformation to the image shown in figure (6) and calculating the phase

phi(x,y) = atan{Im[c(x,y)]/Re[c(x,y)]} **(2)**

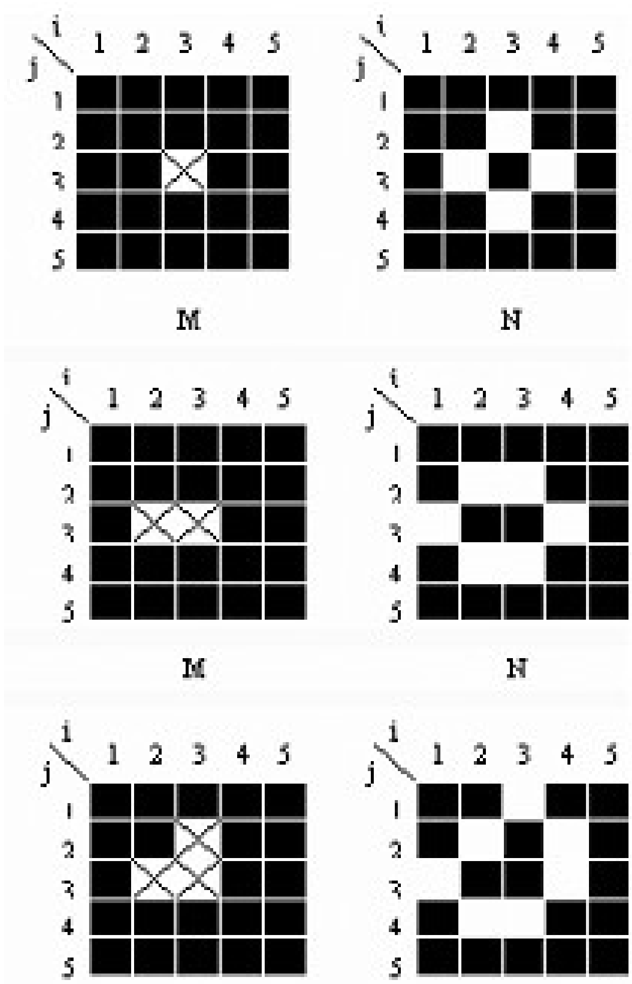
This gives the wrapped phase.

2.3 Phase Unwrapping using quality guided Flood Filling algorithm

Non-guided path-following approaches carry out phase unwrapping on row-by-row or column-by-column path basis on the phase map. In case there is a phase jump or noise in the wrapped phase map, the methods fail to recover the true phase and these errors will propagate to the following processed pixels. In order to solve the problem, quality-guided flood-fill algorithm is proposed. The details of quality-guided flood-fill algorithm are shown below. In order to clearly describe the process, let us assume that we have a cursor with its position indicating the pixel on which phase unwrapping is currently carried out.

Step 1. Firstly, find out the pixel with the highest quality parameter on the quality map $Q(x,y)$. We assume that phase value of this point on the wrapped phase map is the same as the true phase (or we are able to unwrap this point to yield the true phase value). Put the cursor to this point and mark the point as “unwrapped”, and then start the unwrapping process as follows.

Step 2. Check the quality parameters of the four pixels surrounding the cursor, that is, the pixels to the left and the right, the ones above and below. Find out the pixel with the highest quality parameter and move the cursor to the pixel and then unwrap the phase value.



Step 3. Let $\varphi_r(n)$ indicates the wrapped phase of current cursor point, $\varphi_r(n-1)$ and $\varphi(n-1)$ indicate the wrapped phase and unwrapped phase of previous point respectively. The unwrapped phase of current cursor point $\varphi(n)$ can be determined as following:

$$\phi(n) = \begin{cases} \phi(n-1) + \Delta\phi_r(n) + 2\pi & if \quad \Delta\phi_r(n) \leq -\pi \\ \phi(n-1) + \Delta\phi_r(n) & if \quad -\pi < \Delta\phi_r(n) < \pi \\ \phi(n-1) + \Delta\phi_r(n) - 2\pi & if \quad \Delta\phi_r(n) \geq \pi \end{cases}$$

where $\Delta\phi_r(n) = \phi_r(n) - \phi_r(n-1)$ Upon completion of the above, th e pixel is marked as "unwrapped".

Step 4. Check the surrounding pixels around unwrapped pixels and select the pixel with the highest quality parameter and move the cursor to the pixel, then repeat Step 3 until all pixels have been unwrapped.

So, the algorithm operates as follows: A starting pixel with a high quality value is selected and its four neighbors are examined. These neighbors are unwrapped and stored in a list called the "adjoin list". The algorithm then proceeds iteratively as follows: The list pixel with the highest quality value is removed from the list, and its 4 neighbors are unwrapped and placed in the list. The pixels are sorted and stored in the list in the order of their quality values. If a neighbor has already been unwrapped, it is not placed in the list. This iterative process of removing the highest quality pixel from the list, unwrapping its four neighbors and inserting them in the list continues until all the pixels have been unwrapped.

The algorithm requires arrays for the phase, the bit flags, and the solution. It also requires an array to store the quality map. This algorithm must employ a "list trimming" procedure, to keep the size of the list small. Without this procedure, the execution time would be an order of a magnitude longer.

The list trimming procedure works as follows: When the size of the list exceeds a predetermined bound, half of the pixels with the lowest quality values are removed from the list and marked with a special flag. We will refer to these pixels as "postponed" pixels because they will be placed back on the list later. Their unwrapped values are not changed. The minimum quality threshold is then set to the lowest quality of the pixels that remain on the list. No pixel whose quality below this threshold will be inserted in the list. Such a pixel when encountered will instead be unwrapped and then marked “postponed”. The algorithm proceed until the adjoin list becomes empty. At this point, all the remaining pixels that adjoin the unwrapped pixels have quality values that are too low. The minimum quality threshold must then be reduced, at which point the postponed pixels whose quality values exceeds this new threshold are placed on the list, and the processing continues.

The advantage of quality-guided flood-fill is that phase unwrapping is always carried out following the paths of high quality pixels, that is, with relatively small variance from pixel to the next. As phase unwrapping errors are more likely to occur at pixels with lower quality, such a quality-guided approach will be able to improve the robustness of phase unwrapping.

The details of quality-guided flood-fill algorithm are shown below. It is divided into three sections: Quality guided path follower, updating the adjoin list, and insertion of pixels into adjoin list.

Quality Guided path follower

```
Let MinQualityThresh be a small value
Let MaxListSize be a suitable value
Select a starting pixel
Store its phase value in the solution array
Mark the pixel unwrapped
Update the adjoin list
While (adjoin list is not empty)
     Fetch the highest quality pixel from the adjoin list
     Update the adjoin list
     If (adjoin list is empty)
          For (every postponed pixel)
               Insert the pixel in the adjoin list
          End
     End
End
```

Update the Adjoin list

```
For (each of the four adjoining pixels)
     If (the pixel is not unwrapped and not postponed)
          If (the pixel is not a border pixel)
               Unwrap the pixel and store the value in the
               solution array
               If (the pixel’s quality exceeds MinQualityThresh)
                    Insert the pixel in the adjoin list
                    Mark the pixel unwrapped
               End
          End
     End
End
```

Insert pixel in Adjoin list

```
Place the pixel on the adjoin list, preserving the quality order
If (the number of pixels in the adjoin list exceeds MaxListSize)
     For (each of the MaxListSize/2 lowest quality pixels on the
     list)
          Mark the pixel postponed
          Remove the pixel from the list
     End
     Let MinQualityThresh = lowest quality value of remaining
     pixels
End
```

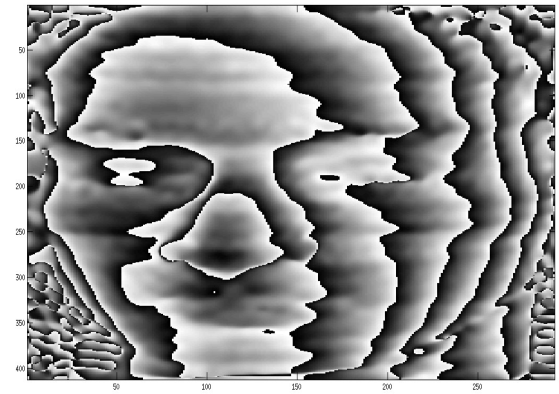
3. Conclusion

Demodulation of fringe patterns is necessary for many optical metrological systems. Two dimensional Fourier transform profilometry method is chosen for the determination of phase. The unwrapping algorithm used which is “Quality guided phase unwrapping” is found to be very effective and reasonably good in the presence of noise, fringe discontinuities and shadows. This is because phase unwrapping is done based on the quality of wrapped phase values and so the error is not accumulated and propagated as the procedure proceeds.

4. Results

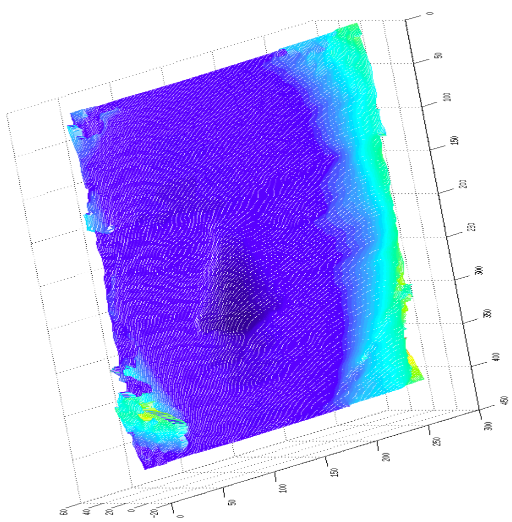
Fringe projected image

Fig 7



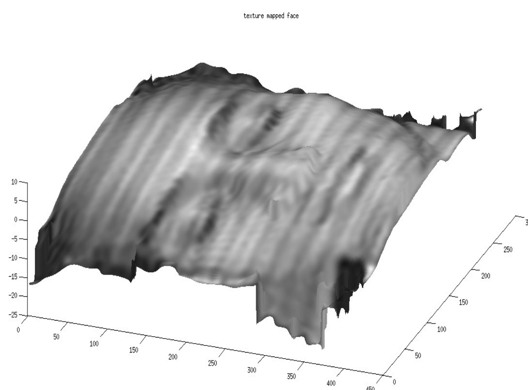
Wrapped Phase image

Fig 8



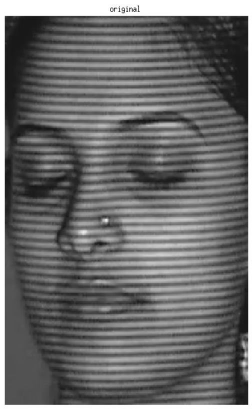
Un wrapped phase

Fig 9



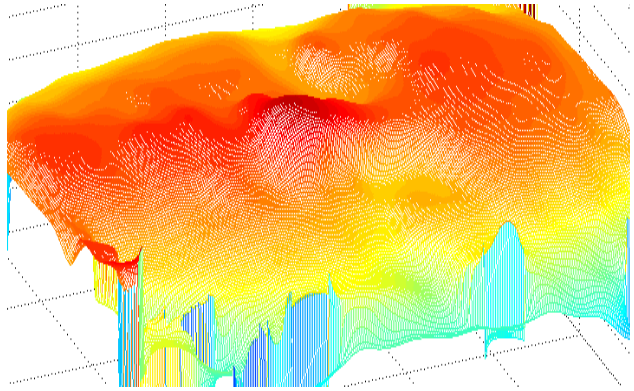
Texture mapped un wrapped phase

Fig 10



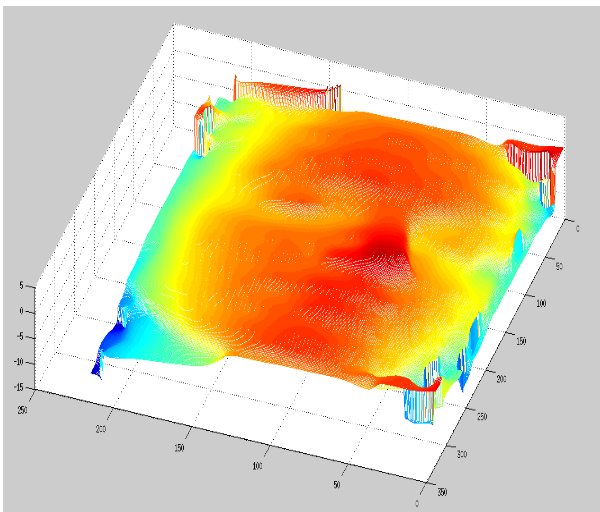
Fringe projected image

Fig 11



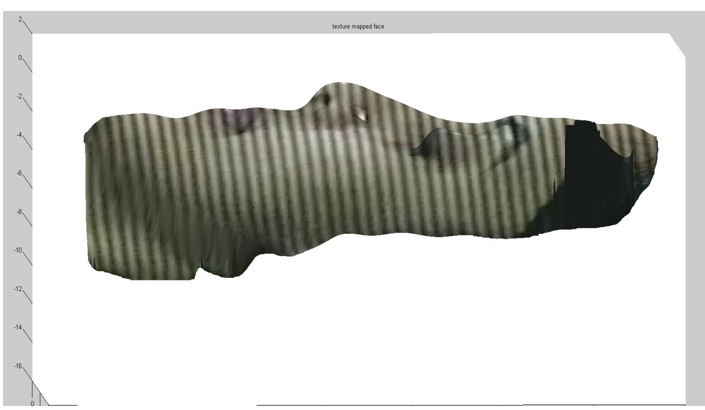
Un wrapped phase image

Fig 12



Un wrapped phase image from another angle

Fig 13



Un wrapped phase with texture mapping

Fig 14

Note: During experimentation, it is better to take a fringe projected face image as well as a non fringe projected face image, which can be used during texture mapping for better visually appealing 3 D face models.

5. References

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