

3D Reconstruction Based On Pair Camera and Projector with Sub-Pixel Accuracy

By

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14450

Dissertation submitted in partial fulfillment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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in partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(ELECTRICAL AND ELECTRONIC ENGINEERING)

Approved by,

(Dr. Nicolas Walter)

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD AMINUDDIN BIN ZAINAL

ABSTRACT

In this paper, 3D reconstruction is done by using fringe projection profilometry (FPP). Fringe pattern is analyzed by using inverse function analysis (IFA) that is mathematically prove to improve accuracy compare to traditional methods. However, it known that IFA applied polynomial fittings which suffer from Runge phenomenon due to high degree polynomial used. Thus, this paper will introduce spline fitting in IFA method for 3D reconstruction to avoid Runge phenomenon. Thus, simulation by using MATLAB will be done to prove the ability of this method to produce 3D reconstruction with better accuracy compare to normal IFA.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Recent years, gaining precision and accuracy in 3D reconstruction had become great interest for many researchers.

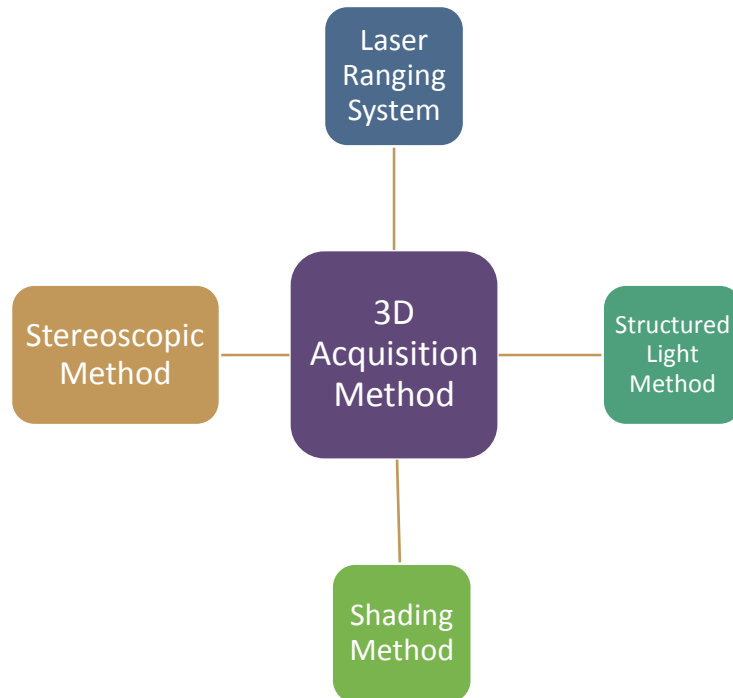


Figure 1.1 – 3D Acquisition Method

There are a few method to acquire 3D information of an object. The first method is Laser Ranging System which applied the principle of reflected laser from the surface of an object and calculate the depth using the different time for the laser to project from transmitter and return to the receiver. The second method is Structured Light Method, where a pattern is projected on the object, by using deformation on the pattern, the depth can be calculated. The third method is Shading Method where shading employ photometric stereo technique is applied to acquire depth measurements. The last method is Stereoscopic Method where

two cameras are used to capture the same point at different angle and the depth is calculated by using triangulation.

In this project, fringe projection profilometry (FPP) is implemented which is categorized under structured light method. A basic fringe projection profilometry usually consists of 5 steps in constructing 3D images as shown in Figure 1.2. The first is setup and projection where all the equipment including camera and projector is set up as shown in Figure 3 and calibrates. Fringe pattern is generated and projects on the reference plane and the objects. The second step is acquisition where the two images are captured. The first image is the reference pattern and the second image is the deformed pattern due to object presence. Next step is fringe analysis, where the phase is deduced by using one of the fringe analysis methods on the fringe images captured. The fourth step is phase unwrapping, where the continuous phase distribution from the wrapped phase map is attained. The last one is conversion, where the unwrapped phase map is converted to absolute height map.



Figure 1.2 – Basic Fringe Projection Profilometry

1.2 PROBLEM STATEMENT

Previous methods in 3D reconstruction were able to be done but with higher errors and affected the accuracy. This is caused by polynomial fitting that causes Runge phenomenon.

1.3 OBJECTIVES

- To develop a sub-pixel 3D reconstruction algorithm
- To apply spline fitting in IFA

1.4 SCOPE OF STUDY

In this paper, the author will explain about the implementation of gamma distortion compensation, empirical mode decomposition, and inverse function analysis in fringe projection profilometry. Simulation in this paper is done by using MATLAB.

CHAPTER 2

LITERATURE REVIEW AND THEORY

In recent years, the research on 3D reconstruction methods were conducted mostly by using fringe projection profilometry [1]. Mostly due to the fact that the technique is able to capture high-resolution 3D images of the objects [1]. However, the presence of non-sinusoidal factors in the fringe projection cause the pattern projected on the object to be deformed and causing phase measurement errors[1, 2]. It has been identified that the causes of the non-sinusoidal waveform appearance are due to the non-linearity gamma distortion from the projector and also non-linearity of the CCD camera response [2, 3].

Based on Zhang et al. [4], gamma distortion is a dominant error source if phases measuring profilometry. Zhang and Huang introduce look-up table (LUT) to compensate the non-linearity in fringe projection [5]. Phase error is calculated and stored in the LUT. The pattern will be almost sinusoidal even though not perfect.

After compensation of the gamma distortion, the fringe is projected on the reference plane and also on the object. Both reference pattern and deformed pattern are captured by camera. They will be noise present in the images and denoising method need to be applied. Noise presence will also introduce phase measurement errors. Boudraa et al introduce denoising technique by using empirical mode decomposition (EMD) [6]. Firstly, the signal is decomposed into intrinsic mode functions (IMF) which an oscillatory components through a process called sifting. One of the two effect of sifting is to remove riding waves and the other one is to smooth uneven amplitude [6]. IMFs must fulfill two requirements [6]:

- I. Extremas' and zero crossings' number must be equal or at least differ by one
- II. Envelope filter's mean value define by local maxima and envelope defined by local minima must be zero at any point

EMD algorithm is introduced based on producing smooth envelopes define by local minima and maxima of a sequence, then a subsequent subtraction of the mean of these envelopes from the initial sequence. Figure 2.1 show the procedure of plotting envelope.

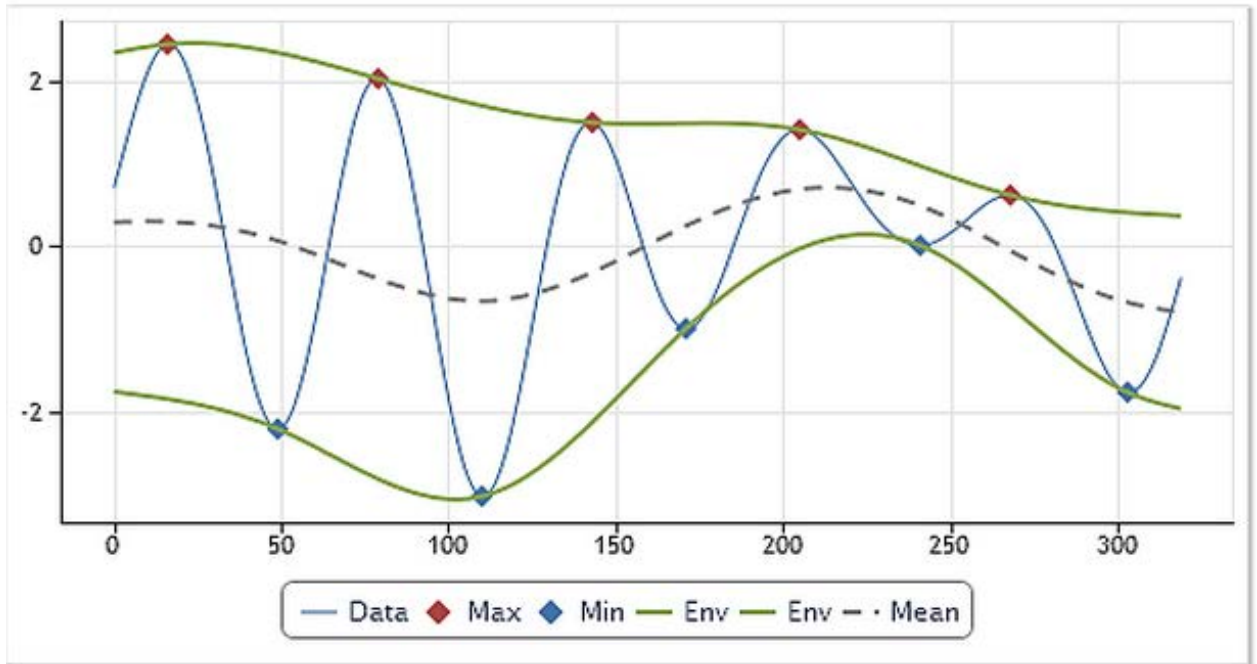


Figure 2.1 – Envelopes plotting and their mean

All the local maxima are connected by using cubic spline lines to produce upper envelope. The same goes with local minima to produce lower envelope. The blue line represent the data and the local maxima and minima is dotted red and blue respectively. The dashed line represent calculated mean of the two envelopes. The calculated mean value then is subtracted from the initial sequence which is the data. The result of the subtraction is the first approximation of the empirical function. The final IMF is obtained by repeating this method replacing the data with the subtraction result as the next sequence. This repeated process is called sifting [6]. This sifting process is stopped after a certain given stoppage criterion is met.

The result of the successful sifting process is the first IMF. The first IMF is subtracted from the original signal and the sifting process is repeated to obtain the next IMF until all IMFs is extracted. It can be known when all the IMFs is extracted when the residue contains no more than two extremas. EMD algorithm will be applied on both reference pattern and deformed pattern to denoise them.

After the first sequence which is projection and acquisition, here comes the fringe analysis which is a very complex part. As mentioned beforehand, there are several methods on fringe analysis done by previous researchers. Takeda and Mutoh [7] introduce Fourier transform profilometry (FTP) which is a computer-based technique that automatically measure 3D shape. FTP obtained the wrapped phase map by applying fast Fourier transform (FFT). The method obtained the spectrum of modulated fringe pattern by applying discrete FFT, then implementing inverse Fourier transform (FT) after the fundamental spectrum is extracted. Finally, the phase measurement of the object is retrieved. However FTP cannot obtain the correct phase measurement due to spectral leakage in the region of discontinuities or the around the large surface slope areas. Therefore, by windowing the fringe pattern before FT is applied can reduce the leakage [8].

Windowed Fourier Transform is introduced to as an upgrade for the FTP [9, 10]. A local window function is introduced into FTP [10]. The general idea of WFT is: dividing the fringe pattern into number of local fringe patterns; each local fringe pattern is then applied with FT; superimposed is applied to all the local fringe pattern to get the whole fringe pattern's spectrum; inverse FT is applied after extracting the fundamental spectrum and the phase measurement is retrieved [8]. The precision is increase by taking larger windows on the signal. However the choice of windows size is crucial and very difficult to determine.

Wavelet Transform (WT) applied the demodulation of the deformed fringe pattern capture by the camera and extract the phase and calculate the height of the object [11]. WT perform local filtering operations on a signal by using scaled and shifted version of a mother wavelet. After the mother wavelet is chosen, correct phase measurement can be extracted by adapting the mother wavelet to the fringe pattern. The phase distribution is obtained at ridge point of the wavelet transform [14, 18]. WT method avoid the choosing of windows size which is important in WFT method. Thus, the error is less propagated.

The resultant phase function is wrapped phase map where unwrapping is required before the conversion to real height can be done [12]. Phase unwrapping can be difficult task due to the occurrence of shadows, low fringe demodulation, non-uniforms reflectivity, noise and more in real time [1]. Thus it is very important to properly remove unrelated

phase from the shaped-related phase so that the conversion from phase distribution to real height exhibit less errors, hence achieving higher accuracy.

Hu et al introduced Inverse Function Analysis (IFA) method to be used on FPP [13]. This method is a straightforward method to calculate the shift distribution [13, 14]. Same as previous method, this method require two image of the fringe pattern, which is a reference pattern where the pattern is projected on the reference plane, and a deformed pattern, which is the pattern that is projected on the object [15]. The method reconstruct 3D images by applying computed inverse function on the deformed pattern. Determination of deformed pattern is done by using polynomial fitting. Nonetheless, Runge phenomenon will occur for high degree polynomial fitting [16]. Thus, Hani et al applied spline fitting instead of polynomial fitting to avoid Runge phenomenon [14] and introduce Spline Inverse Function Analysis (SIFA).

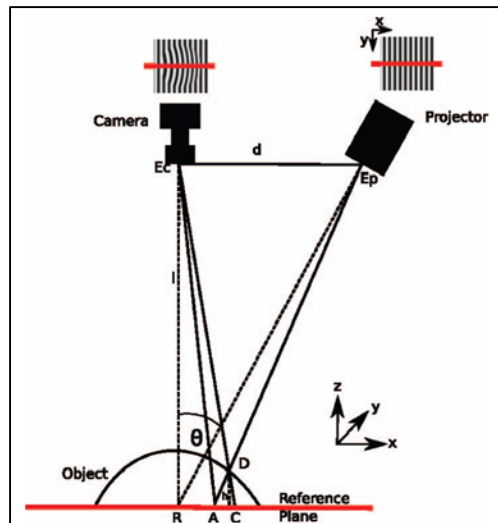


Figure 2.2 – Basic Fringe Projection Profilometry [14]

Figure 2.2 show a basic configuration for fringe projection profilometry. At point R , the axis of both camera and projector crossed at angle θ . Entrance pupil of the camera is represented by E_c and exit pupil of the projector is represented by E_p . l represents the distance of the camera parallel with projector to the reference plane and d_0 represents the

distance between camera and projector. A ray projected from E_p onto point A will be reflected into the camera from the same point, however, if an object present, the ray will be reflect from point C to the camera.

Then, by performing Thales Theorem operation, the height of the object, $D(h)$ can be computed as:

$$h(x) = \frac{l.u(x)}{d_0+u(x)} \quad (1)$$

where $u(x)$ represent the displacement rays due to object presence

The value of $u(x)$ denotes by:

$$u(x) = x - s^{-1}(d(x)) \quad (2)$$

where $s(x)$ represent the original signal

Then, monotonic parts of signal $s(x)$ is extracted. After performing the extraction of each of monotonic parts, spline fitting is applied. The inverse of the fitted function is applied as in equation (2) to the intensity value of the deformed signal to obtain the shift function $u(x)$. The object height can obtain by using equation (1) and value of $u(x)$.

In this paper, a different implementation of spline fitting is proposed. This method is called Global Spline Inverse Function Analysis (GSIFA). GSIFA applied same method as SIFA and IFA only without the monotonic part.

CHAPTER 3 METHODOLOGY / PROJECT WORK

1.1 FLOW CHART

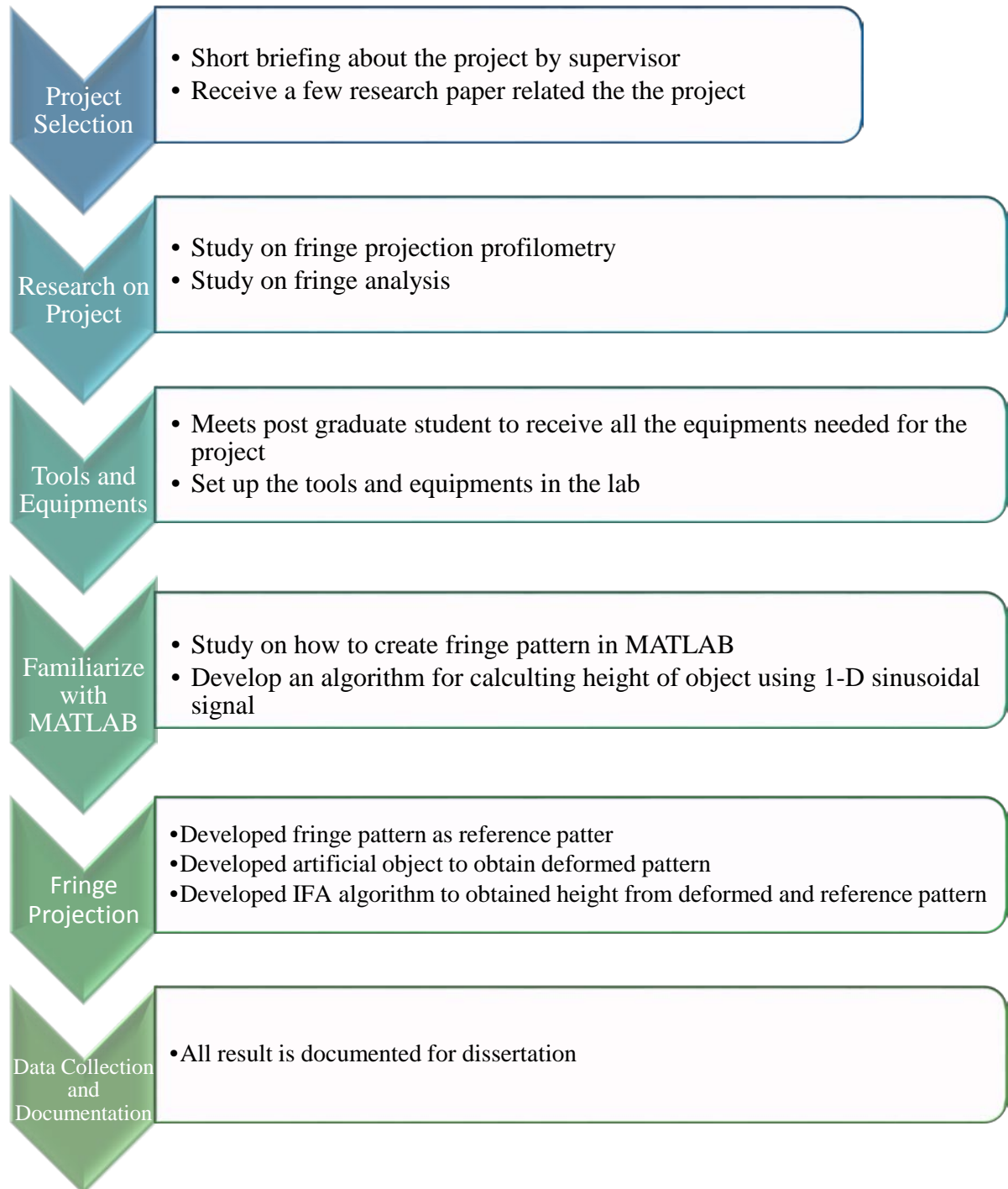


Figure 3.1 – Project Flow Chart

1.2 GANTT CHART

Table 3.1 – Project Gantt chart

Activity/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Project Selection																												
Research on project																												
Tools and Equipment																												
Familiarize with MATLAB																												
Fringe projection																												
Data Collection																												
Documentation																												

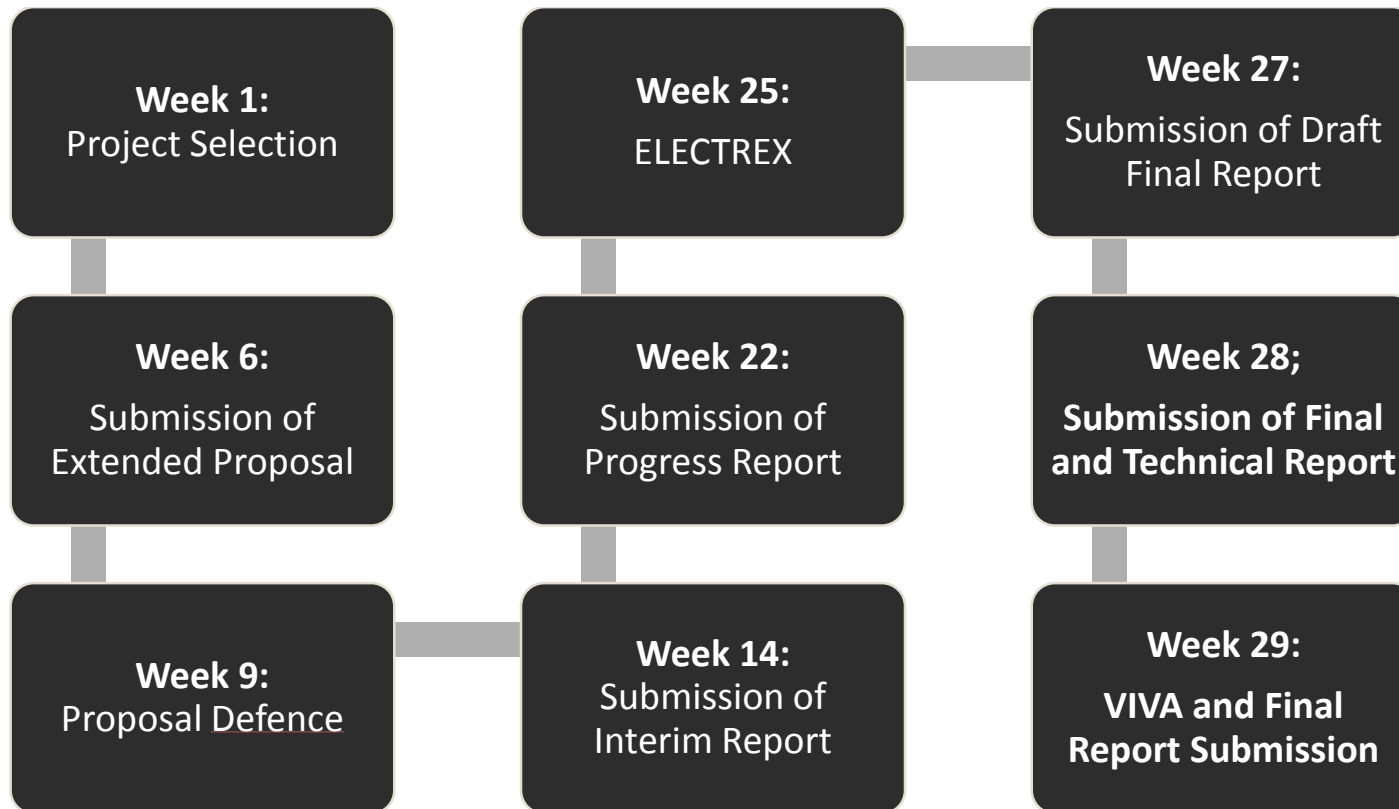


Figure 3.3 – Key Milestone

1.3 EXPERIMENTAL METHODOLOGY

Part 1: Generating of 1-D deformed signal in MATLAB by using artificial object

For familiarization with MATLAB, I did an exercise to generate deformed signal in MATLAB. Steps for computing the deformed signal are as follows:

- i. A sinusoidal signal is created to act as reference signal.
 - a. $t=0:1000;$
 - b. $N=length(t);$
 - c. $f0=10;$
 - d. $x=127.5+127.5*\cos(2*pi*f0*t/N)$
- ii. Artificial object height is created using parabolic equation.
 - a. $parabobj=-10*(t-501).^2;$
 - b. all the negative value of the parabolic equation is change to zero
- iii. The length between camera and projector, length between reference plane and camera-projector is set.
 - a. $d_0 = 300\text{mm}$
 - b. $l = 800\text{ mm}$
- iv. By using equation below, the phase modulation can be measured.
 - a. $Phase=parabobj*2*pi*f0*d0./(parabobj-10)$
- v. Deformed pattern is then computed using calculated phase modulation
 - a. $y = 127.5+127.5*\cos((2*pi*f0*t-Phase)/N);$

Part 2: Generating of 2-D deformed pattern in MATLAB by using artificial object

After completed in generating 1-D deformed signal, I proceed with working in 2-D signal. Steps for computing the 2-D deformed pattern are as follows:

- i. Artificial objects is created first in 3-D coordinates. There are three shape of objects which are:
 - a. Cube
 - b. Parabola
 - c. Cylinder

-
- ii. The length between camera and projector, length between reference plane and camera-projector is set.
 - a. $d_0 = 2000$ mm
 - b. $l_0 = 5000$ mm
 - iii. Phase is calculated by using artificial objects data, Z inside the equation:
 - a. $\text{Phi} = 2 * \pi * f_0 * d_0 * Z ./ (Z - l_0);$
 - iv. The reference pattern is generated as follows:
 - a. $S(i, :) = 128 + \text{pixmidrange} * \cos((2 * \pi * f_0 * y(:)' / \text{yrange}));$
 - v. Deformed pattern is then computed using calculated phase modulation
 - a. $D(i, :) = 128 + \text{pixmidrange} * \cos((2 * \pi * f_0 * y(:)' + \text{Phi}(i, :)) / \text{yrange});$

Part 3: Inverse Function Analysis of 1-D signal

In Part 3, by using the same signal in Part 1, the object is reconstructed by using IFA method.

- i. The local extrema is located on both reference and deformed signal
 - a. $[\text{xmax}, \text{ixmax}, \text{xmin}, \text{ixmin}] = \text{extrema}_x(\text{x_main});$
 - b. $[\text{ymax}, \text{iymax}, \text{ymin}, \text{iymin}] = \text{extrema}_y(\text{y_main});$
- ii. Divide both signal into numbers of monotonic parts based on number of extrema points.
 - a. $x\{i\} = 127.5 + 127.5 * \cos(2 * \pi * f_0 * n_x\{i\} / N);$
 - b. $y\{i\} = 127.5 + 127.5 * \cos((2 * \pi * f_0 * n_y\{i\} - \text{Phase}) / N);$
- iii. Spline interpolation is done on each inverted reference signal's monotonic part and obtain the X values of the signal for each monotonic part.
 - a. $\text{spl_ref}\{i\} = \text{csapi}(x\{i\}, n_x\{i\});$
 - b. $\text{xx_ref}\{i\} = \text{fnval}(\text{spl_ref}\{i\}, x\{i\});$
- iv. Step (iii) is repeated for deformed signal.
 - a. $\text{spl_def}\{i\} = \text{csapi}(y\{i\}, n_y\{i\});$
 - b. $\text{xx_def}\{i\} = \text{fnval}(\text{spl_def}\{i\}, y\{i\});$
- v. Find the difference of X values for reference and deformed signal at each monotonic part.
 - a. $\text{delta}_x\{i\} = \text{xx_ref}\{i\} - \text{xx_def}\{i\};$
 - b. $\text{dx} = \text{cell2mat}(\text{delta}_x);$

Part 4: Inverse Function Analysis of 2-D fringe pattern

In Part 3, by using the same signal in Part 2, the object is reconstructed by using IFA method.

- i. Reference and deformed pattern is loaded into MATLAB.
 - a. `Ref=load('SGamma2.2Parabola.mat','-mat','S');`
 - b. `Ref=load('DGamma2.2Parabola.mat','-mat','D');`
- ii. Performed spline on reference pattern for monotonic parts detection.
 - a. `pp=spline(x,[0 w 0]);`
 - b. `dpp=fnder(pp,1);`
- iii. Performed spline on deformed pattern for monotonic parts detection.
 - a. `pp2=spline(x,[0 wdef 0]);`
 - b. `dpp2=fnder(pp2,1);`
- iv. Find roots to locate the maximum and minimum point of both pattern.
 - a. `zercross=roots(dpp.coefs(k-1,:));`
 - b. `zercross=roots(dpp2.coefs(k-1,:));`
- v. Monotonic parts detection.
 - a. `xf1=w(coordx(k-1):coordx(k));`
 - b. `f1=x(coordx(k-1):coordx(k));`
- vi. Performed polynomials fitting to obtain the curve for each monotonic parts of reference pattern.
 - a. `[f1inv,S,mu]=polyfit(xf1,f1,deg(k-1));`
 - b. `OSf1inv(k-1,1:deg(k-1)+1)=f1inv;`
 - c. `OSSf1inv(k-1)=S;`
 - d. `OSmuf1inv(k-1,:)=mu;`
- vii. Performed reconstruction with partials polynomials for reference pattern
 - a. `approx1=polyval(OSf1inv(k-1,1:deg(k-1)+1),wdef(coordxdef(k-1):coordxdef(k)),OSSf1inv(k-1),OSmuf1inv(k-1,:));`
 - b. `Udefrecl=x-Xdefrecl;`
 - c. `Hdefrecl(k)=(l0*Udefrecl(k)/(Udefrecl(k)+d0));`

Part 5: Spline Inverse Function Analysis of 2-D fringe pattern

In Part 3, by using the same signal in Part 2, the object is reconstructed by using IFA method.

- i. Reference and deformed pattern is loaded into MATLAB.
 - a. `Ref=load('SGamma2.2Parabola.mat','-mat','S');`
 - b. `Ref=load('DGamma2.2Parabola.mat','-mat','D');`
- ii. Performed spline on reference pattern for monotonic parts detection.
 - a. `pp=spline(x,[0 w 0]);`
 - b. `dpp=fnder(pp,1);`
- iii. Performed spline on deformed pattern for monotonic parts detection.
 - a. `pp2=spline(x,[0 wdef 0]);`
 - b. `dpp2=fnder(pp2,1);`
- iv. Find roots to locate the maximum and minimum point of both pattern.
 - a. `zercross=roots(dpp.coefs(k-1,:));`
 - b. `zercross=roots(dpp2.coefs(k-1,:));`
- v. Added extra point to both ends of each monotonic parts for both pattern.
 - a. `dpproots=[0 dpproots]; dpproots=[dpproots x(end)];`
 - b. `dpproots2=[0 dpproots2]; dpproots2=[dpproots2 x(end)];`
- vi. Monotonic parts detection.
 - a. `xf1=w(coordx(k-1):coordx(k));`
 - b. `f1=x(coordx(k-1):coordx(k));`
- vii. Obtain X points from the reference pattern.
 - a. `Ff1inv(k-1)=spline(xf1,[ppval(dpp,coordx(k-1)) f1 ppval(dpp,coordx(k))]);`
- viii. X values is fitted to monotonic part of deformed pattern to obtain the phase shift.
 - a. `approx2=ppval(Ff1inv(k-1),wdef(coordxdef(k-1):coordxdef(k)));`
 - b. `Xdefrec2=[Xdefrec2 approx2(1:end)];`
 - c. `Udefrec2=x-Xdefrec2;`
- ix. Reconstruction is perform by measuring the height of the objects.
 - a. `Hdefrec2(k)=(10*Udefrec2(k)/(Udefrec2(k)+d0));`

Part 6: Global Spline Inverse Function Analysis of 2-D fringe pattern

In Part 3, by using the same signal in Part 2, the object is reconstructed by using IFA method.

- i. Reference and deformed pattern is loaded into MATLAB.
 - a. `Ref=load('SGamma2.2Parabola.mat','-mat','S');`
 - b. `Ref=load('DGamma2.2Parabola.mat','-mat','D');`
- ii. Performed spline on reference pattern for monotonic parts detection.
 - a. `pp=spline(x,[0 w 0]);`
 - b. `dpp=fnder(pp,1);`
- iii. Performed spline on deformed pattern for monotonic parts detection.
 - a. `pp2=spline(x,[0 wdef 0]);`
 - b. `dpp2=fnder(pp2,1);`
- iv. Find roots to locate the maximum and minimum point of both pattern.
 - a. `zercross=roots(dpp.coefs(k-1,:));`
 - b. `zercross=roots(dpp2.coefs(k-1,:));`
- v. The last point is added to both ends of each monotonic parts for both pattern.
 - a. `dpproots=[0 dpproots]; dpproots=[dpproots x(end)];`
 - b. `dpproots2=[0 dpproots2]; dpproots2=[dpproots2 x(end)];`
- vi. Obtain X points from the reference pattern.
 - a. `ppinv(k-1)=spline(ppval(pp,linspace(dpproots(k-1),dpproots(k),newsamp*nbechmonotonicparts+1)),[0 linspace(dpproots(k-1),dpproots(k),newsamp*nbechmonotonicparts+1) 0]);`
- vii. X values is fitted to deformed pattern to obtain the phase shift.
 - a. `Xdefrec3=[Xdefrec3 approx3];`
 - b. `Udefrec3=x-Xdefrec3;`
- viii. Reconstruction is perform by measuring the height of the objects.
 - a. `Hdefrec3(k)=(l0*Udefrec3(k)/(Udefrec3(k)+d0));`

CHAPTER 4

RESULT AND DISCUSSION

In this chapter, I will be discussing on the result for all three parts I have done in the methodology which are:

- i) Generating of 1-D deformed signal in MATLAB by using artificial object
- ii) Generating of 2-D deformed pattern in MATLAB by using artificial object
- iii) Inverse Function Analysis of 1-D signal
- iv) Inverse Function Analysis of 2-D fringe pattern
- v) Spline Inverse Function Analysis of 2-D fringe pattern
- vi) Global Spline Inverse Function Analysis of 2-D fringe pattern

Part 1: Generating of 1-D deformed signal in MATLAB by using artificial object

For the first part, the signal generated is ideal signal where noise is neglected. The reference signal is a perfect sinusoidal with constant frequency at 10 Hz.

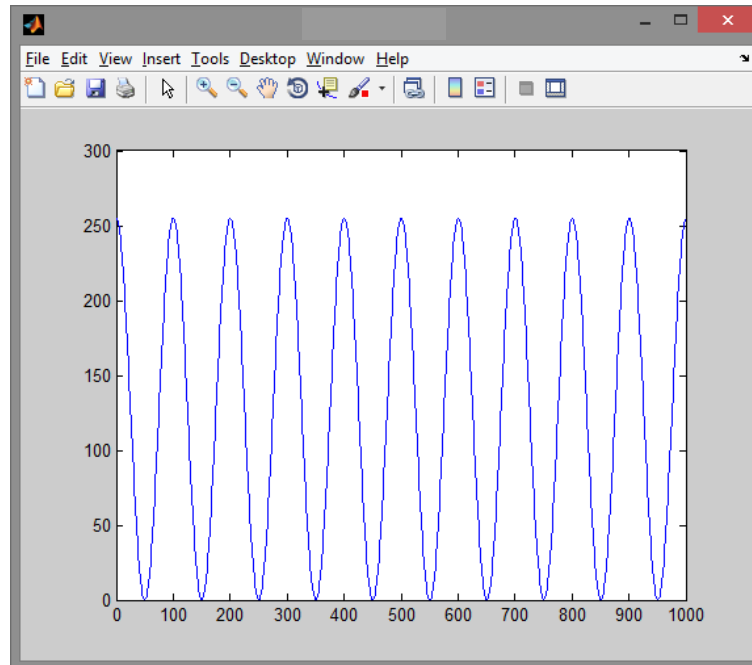


Figure 4.1 – Reference Signal

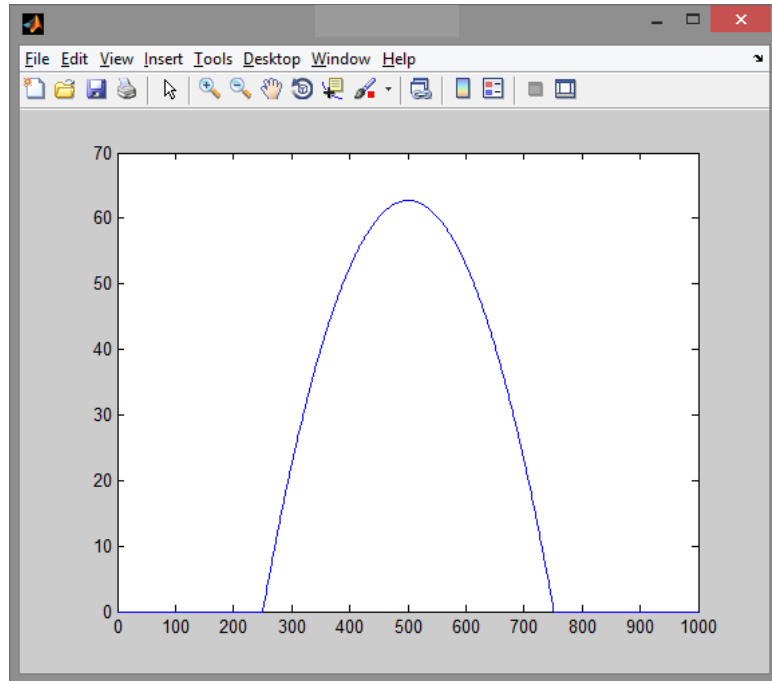


Figure 4.2 – Artificial object height

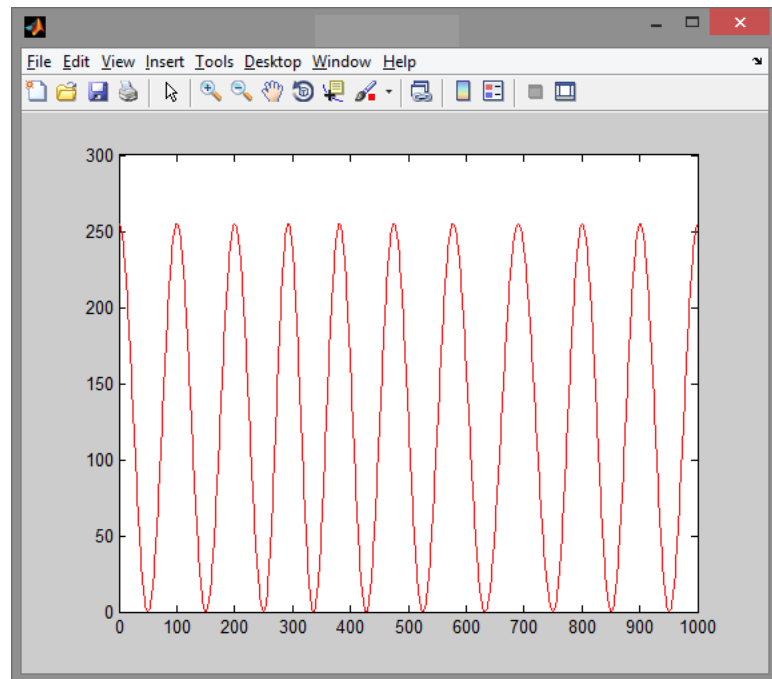


Figure 4.3 – Computed deformed signal

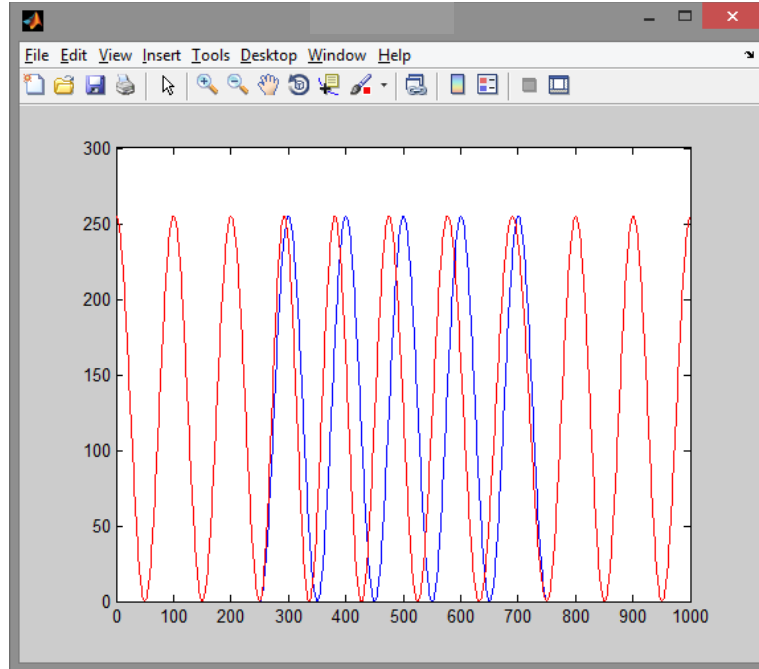


Figure 4.4 – Reference signal and Computed deformed signal comparison

Figure 4.1 show the reference signal with 0 at minima and 255 at maxima. This signal represent 8-bit greyscale. Figure 4.2 show the artificial object height with length ranging from 250mm to 750mm denoting that the object length is 500mm. Phase-shift due to the object presence can be measured by using modified equation (1):

$$u(x) = \frac{d_0 \cdot h(x)}{l - h(x)} \quad (3)$$

Figure 4.3 display the computed deformed signal resulted by adding the phase shift into the reference signal. It can be seen in Figure 4.4 where the signal started to deform at 250s until 750s the same as the object length. The maximum phase shift occur at the middle peaks denoting the maximum height of the object. The frequency of the signal is shifted causing the deformation of the signal.

Part 2: Generating of 2-D deformed pattern in MATLAB by using artificial object

In part 2, almost the same thing is simulated as in part 1 but instead of using 1-D signal, the simulation is done in 2-D signal which include the generation of fringe pattern. The simulation is done for three object shapes which are cube, parabola and cylinder.

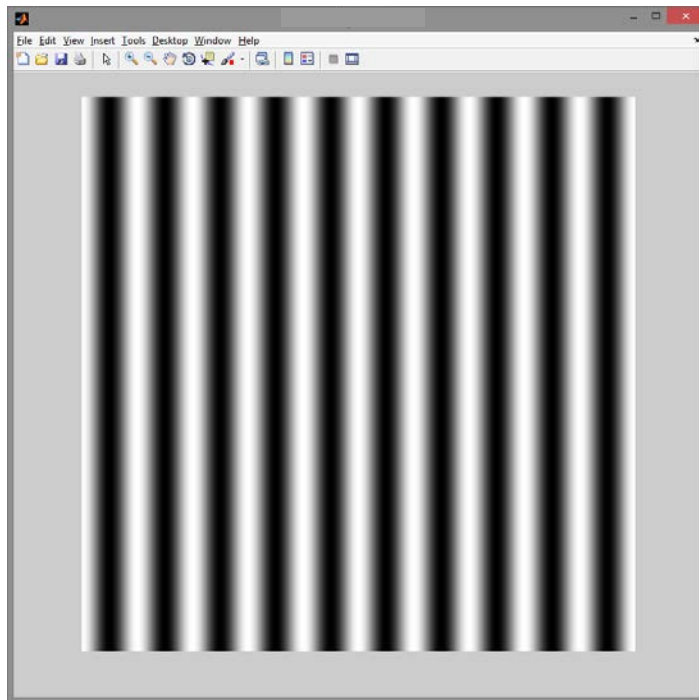


Figure 4.5 – Reference Pattern

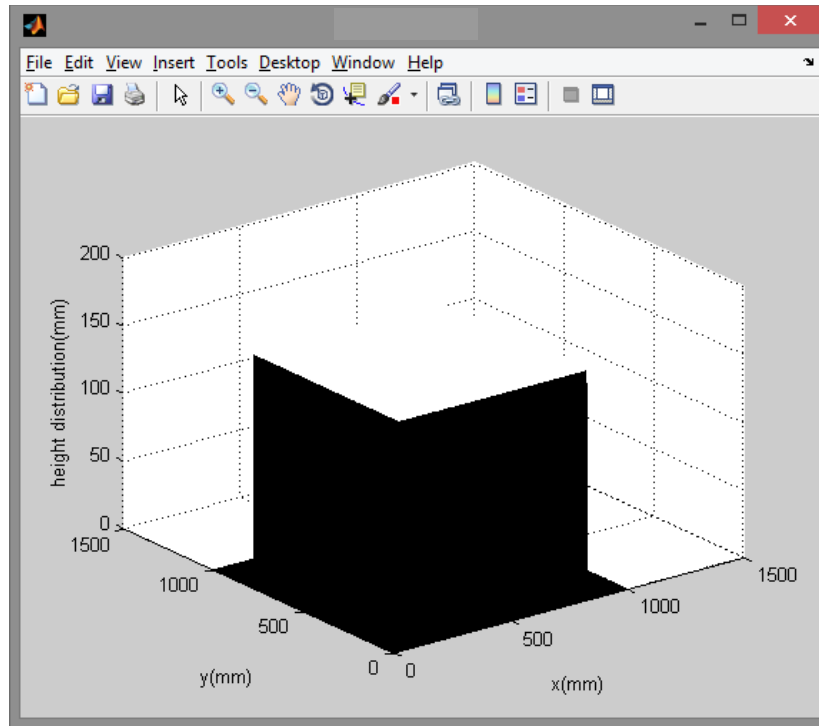


Figure 4.6 – Cube shape generated using MATLAB

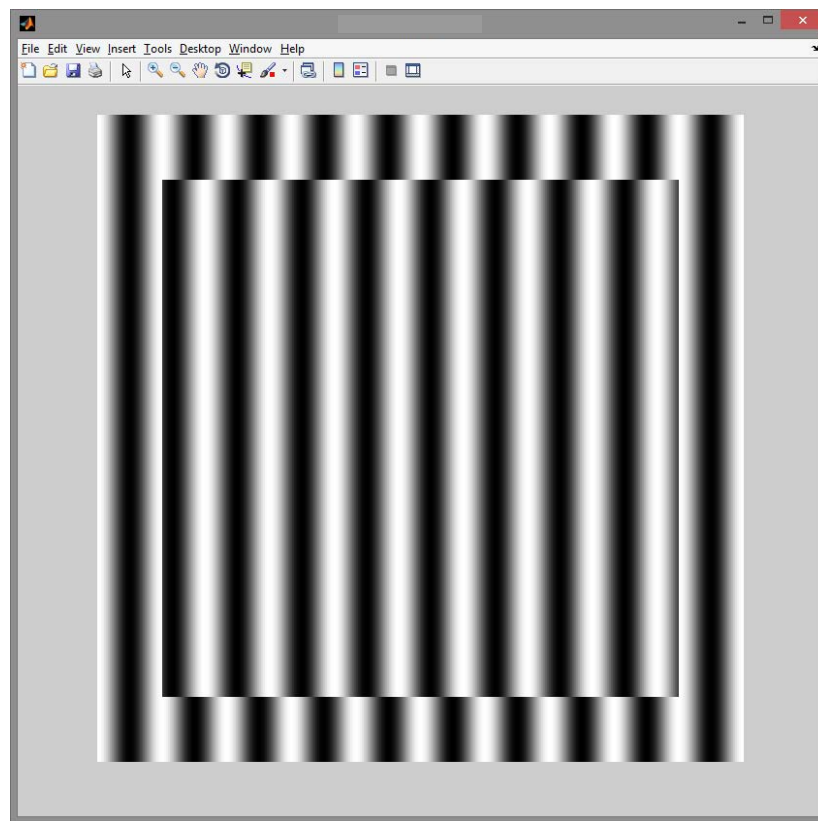


Figure 4.7 – Deformed pattern of a cube shape

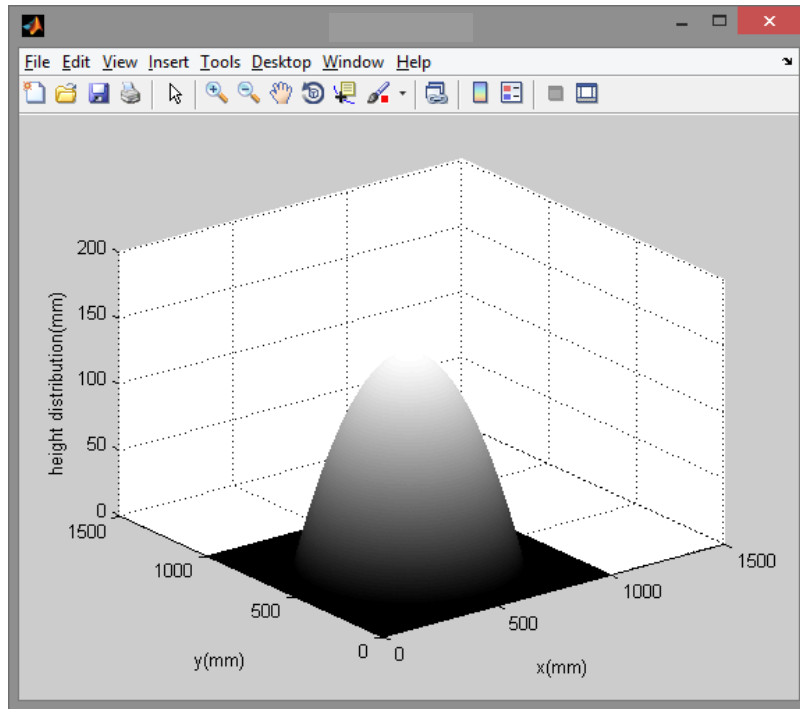


Figure 4.8 – Parabola shape generated using MATLAB

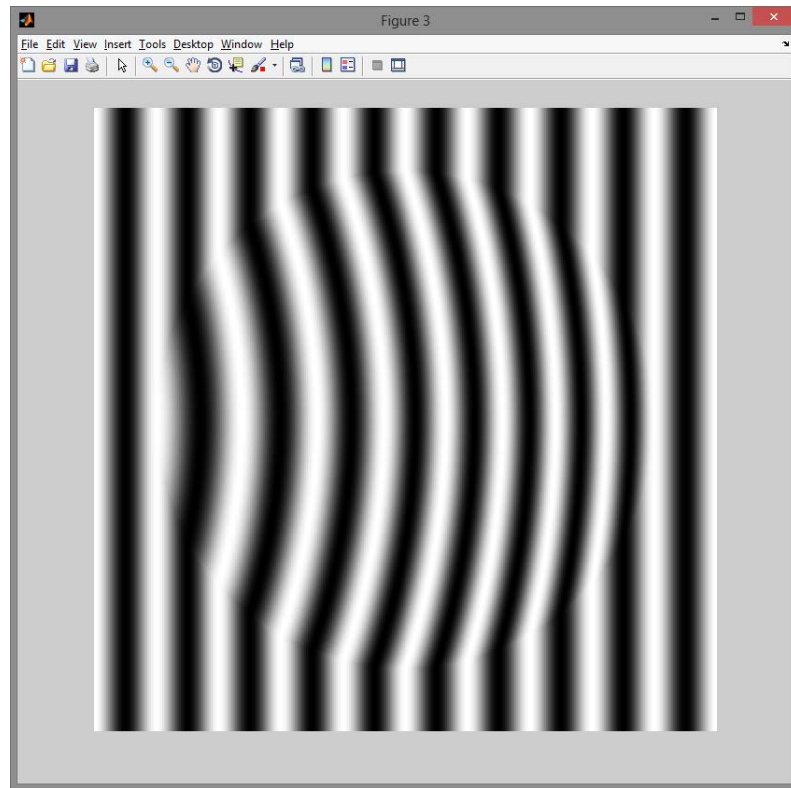


Figure 4.9 – Deformed pattern of a parabola

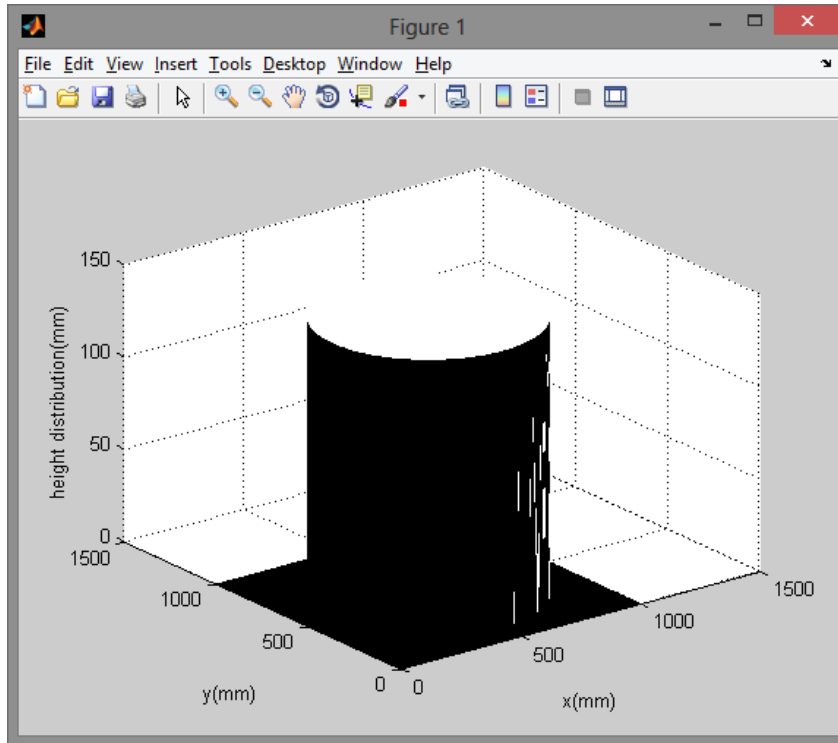


Figure 4.10 – Cylinder shape generated using MATLAB

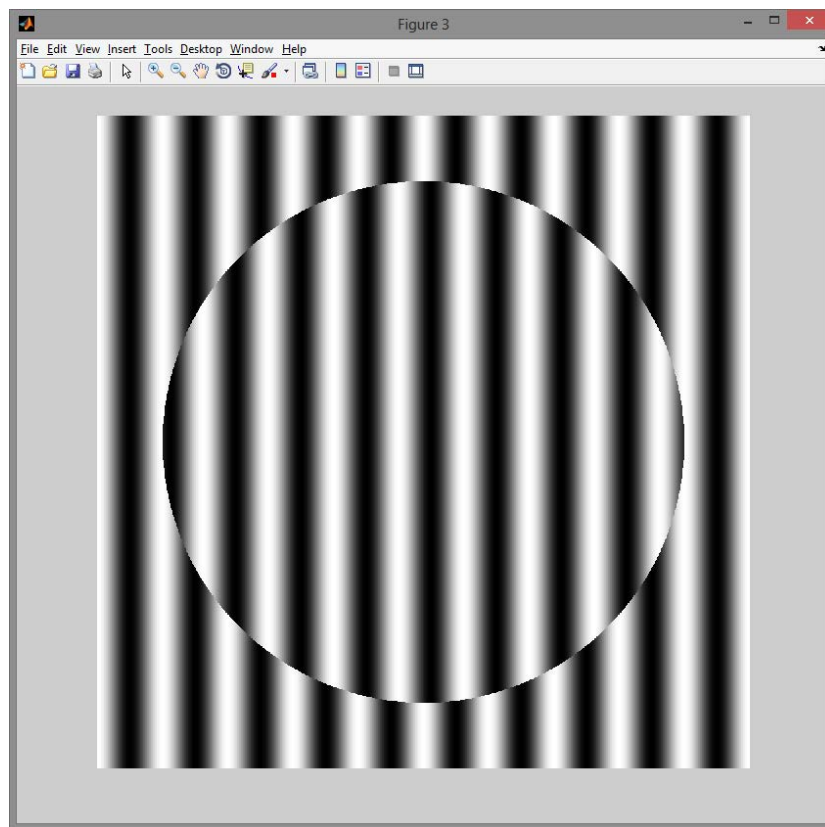


Figure 4.11 – Deformed pattern of a cylinder

In part 2, Figure 4.5 shows the reference pattern. When cube as in Figure 4.6 is used, the deformed pattern generated is as Figure 4.7. Figure 4.8 and Figure 4.9 show artificial parabola is used as object. Figure 4.10 and Figure 4.11 show an artificial is used as an object. The deformation of the pattern is different for different object shape. Thus, by measuring the phase shift of the deformed pattern compared to the reference pattern, the height of the shape can be determined.

Part 3: Inverse Function Analysis of 1-D signal

As described in methodology, Part 3 used the same reference signal and deformed signal generated at Part 1.

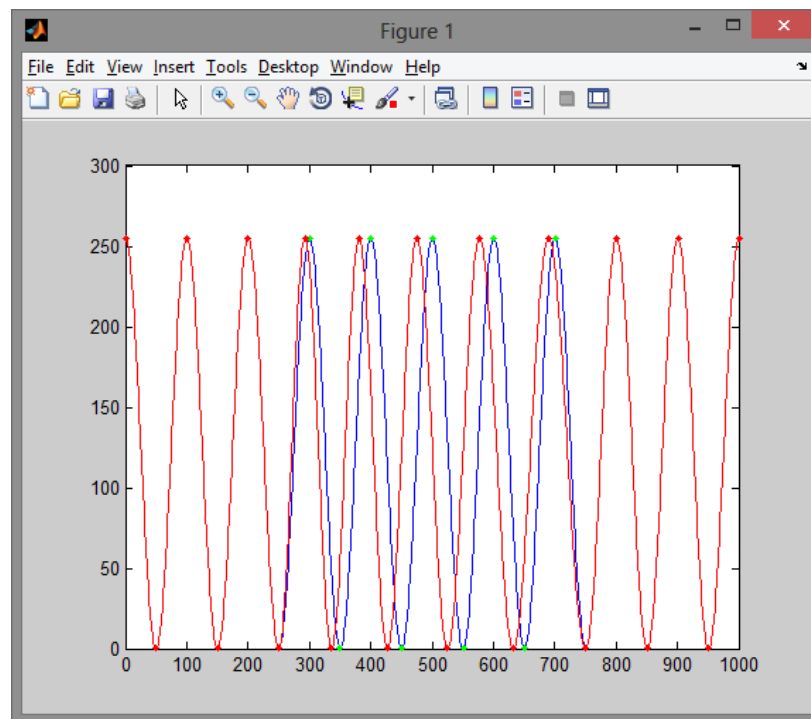


Figure 4.12 – Reference and Deformed Pattern with Detected Local Extrema

Figure 4.12 shown the comparison of reference and deformed pattern. The local extrema is detected and mark. The green dot represent the maximum and minimum point of the reference signal while the red dot represent the maximum and minimum point of deformed signal.

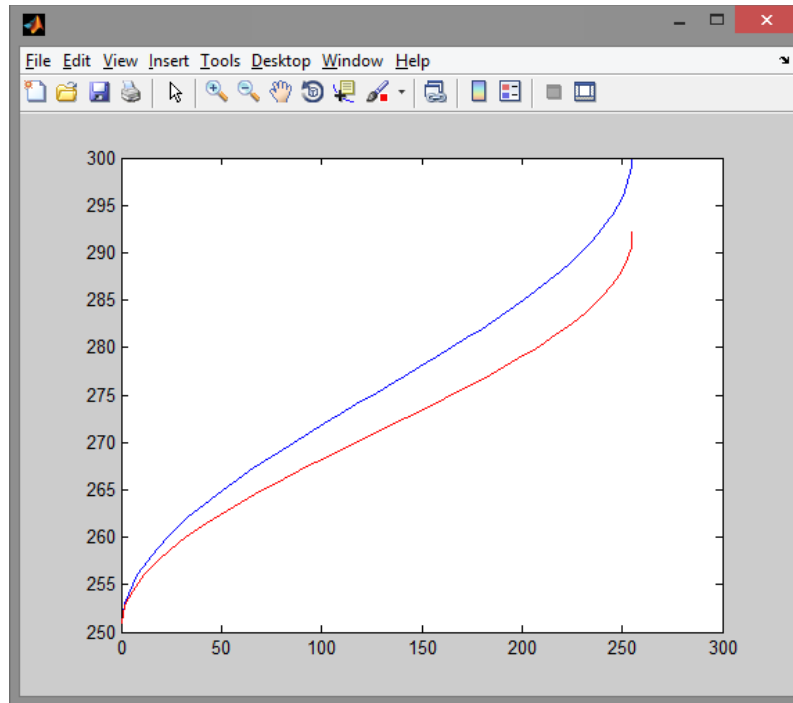


Figure 4.13 – A Monotonic Part of the Reference and Deformed Pattern

Figure 4.13 shows an inverted monotonic part of the reference and deformed pattern. Blue colored signal represent the reference signal and red colored signal represent the deformed signal. The phase difference between each monotonic is calculated and each part is superimpose to obtain the overall phase difference.

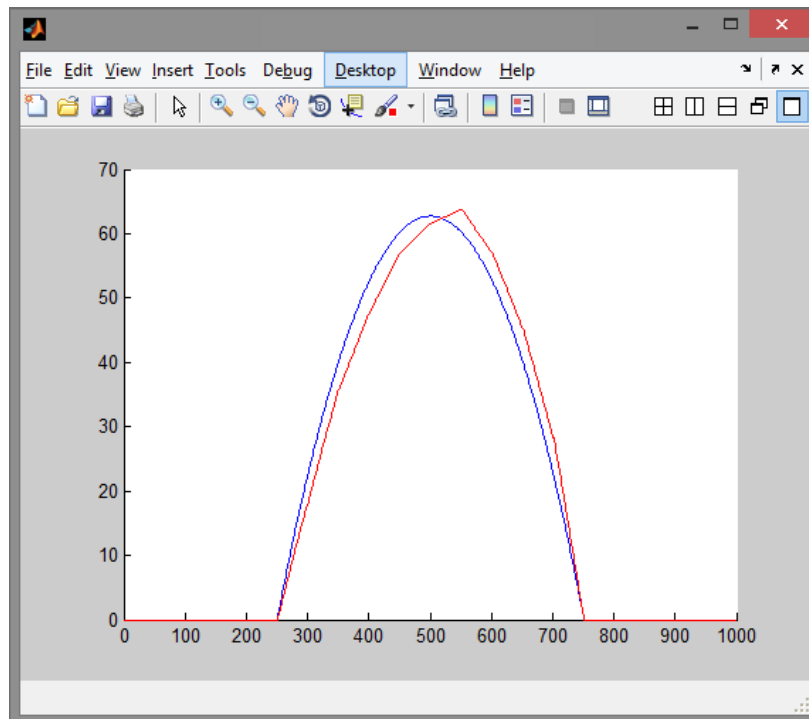


Figure 4.14– Comparison of Calculated and Reference Object Height

Figure 4.13 show the calculated object height compared to the reference object height. Calculated height show slight distortions due to inaccuracy of MATLAB calculations. The written MATLAB code is not 100% perfect and causing the distortions.

Part 4: Inverse Function Analysis of 2-D Fringe Pattern

For part 4, the reconstruction is done first on parabola object as in part 2.

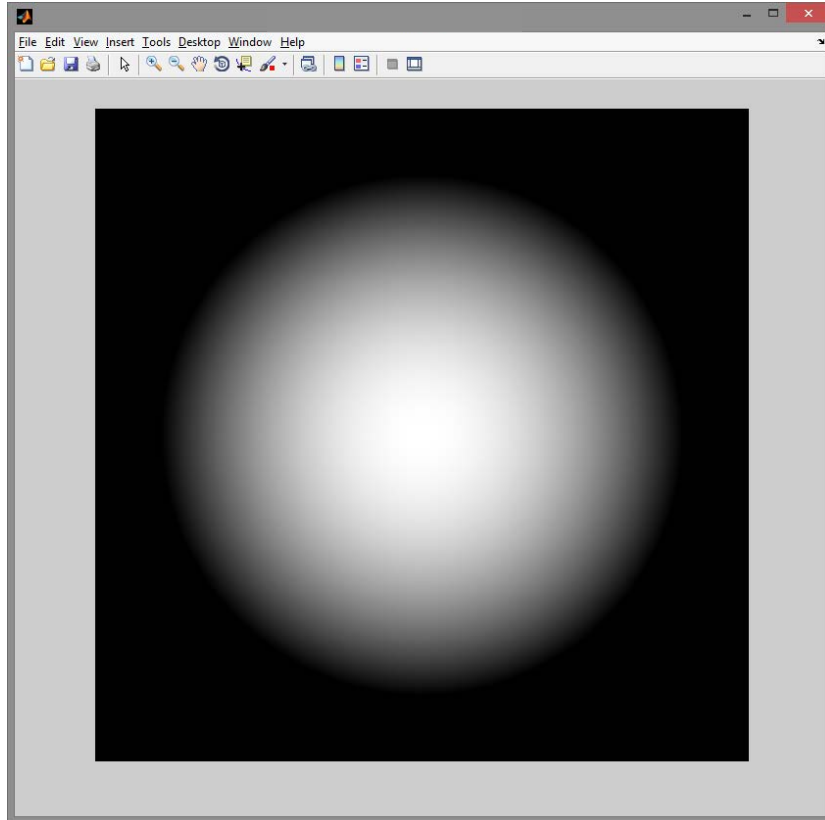


Figure 4.15– Artificial parabola object

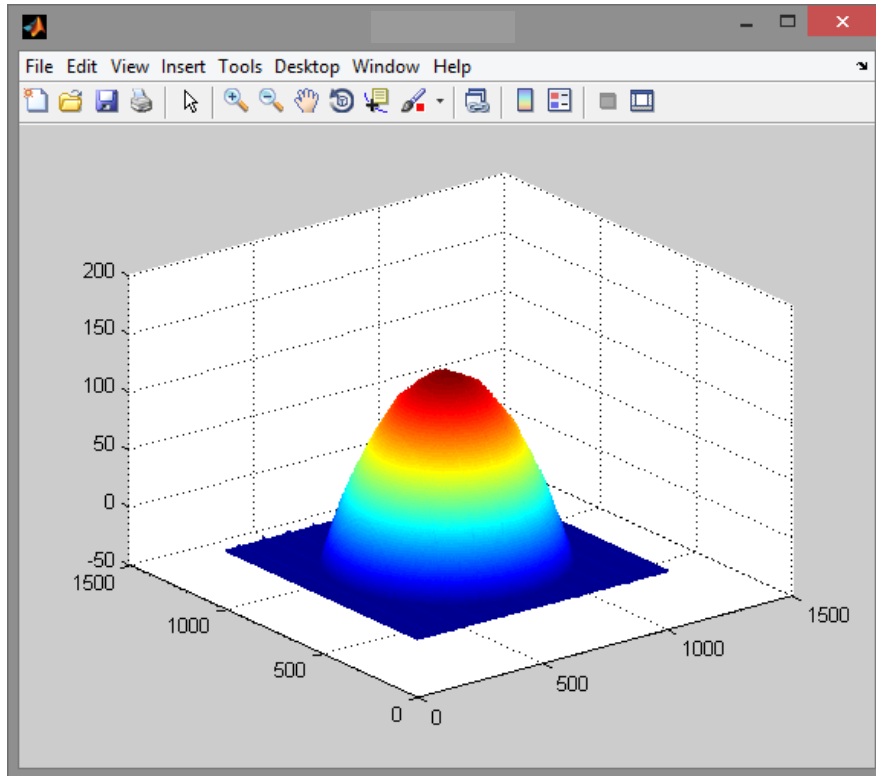


Figure 4.16– Reconstructed Parabola using IFA

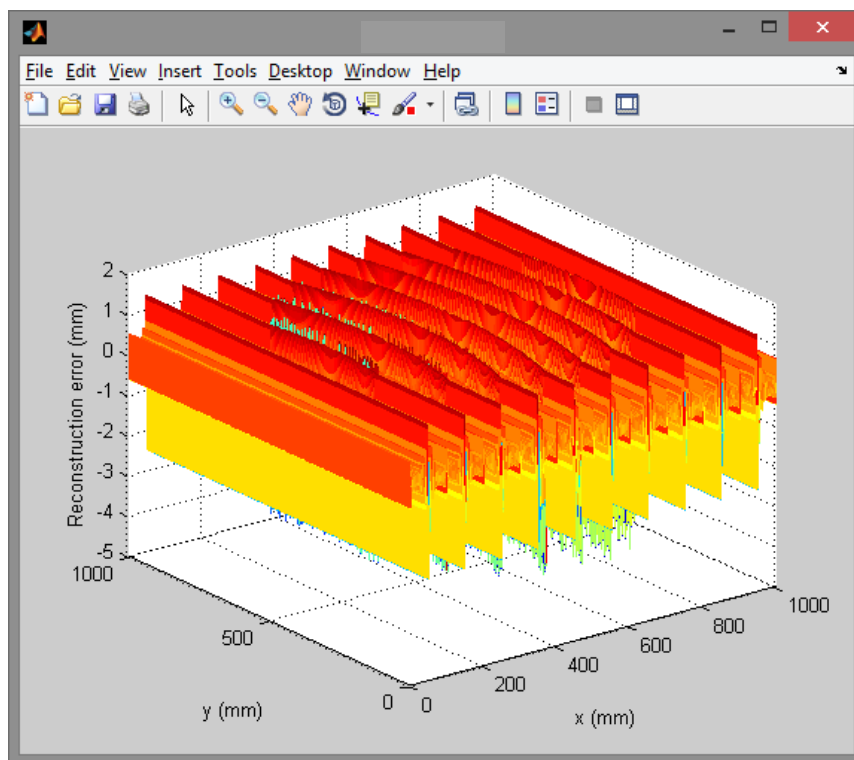


Figure 4.17– Reconstruction Error for Parabola using IFA

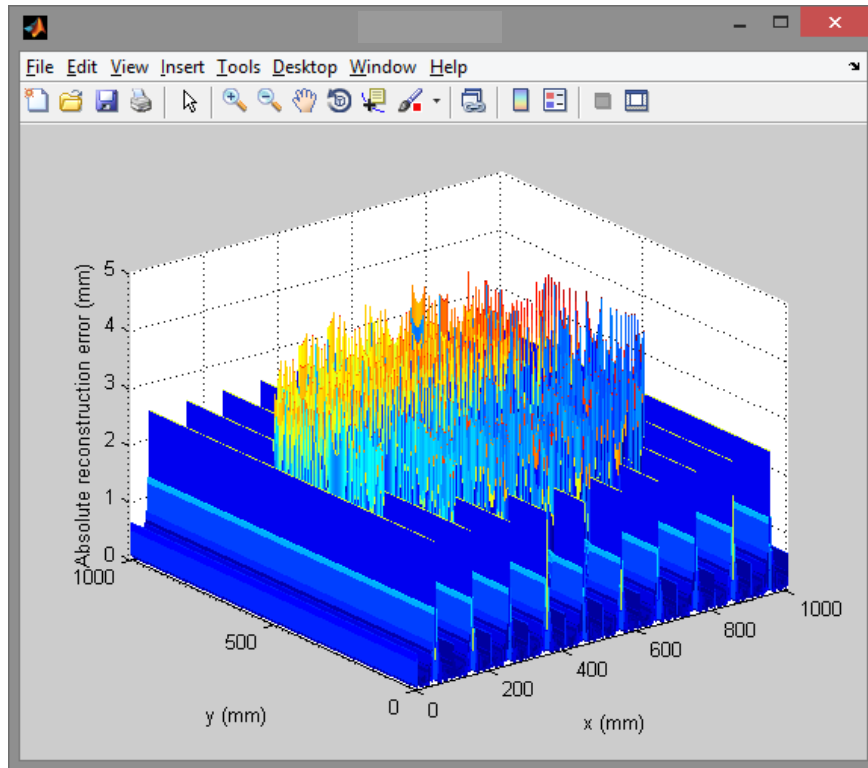


Figure 4.18– Absolute Reconstruction Error for Parabola using IFA

Figure 4.16 shows the reconstructed parabola using IFA method. Figure 4.17 shows the reconstruction error for parabola while Figure 4.18 shows the absolute reconstruction error of parabola using IFA.

The mean error of IFA method is 0.3149mm. The standard deviation error for IFA method is 0.3655mm.

Part 4: Spline Inverse Function Analysis of 2-D Fringe Pattern

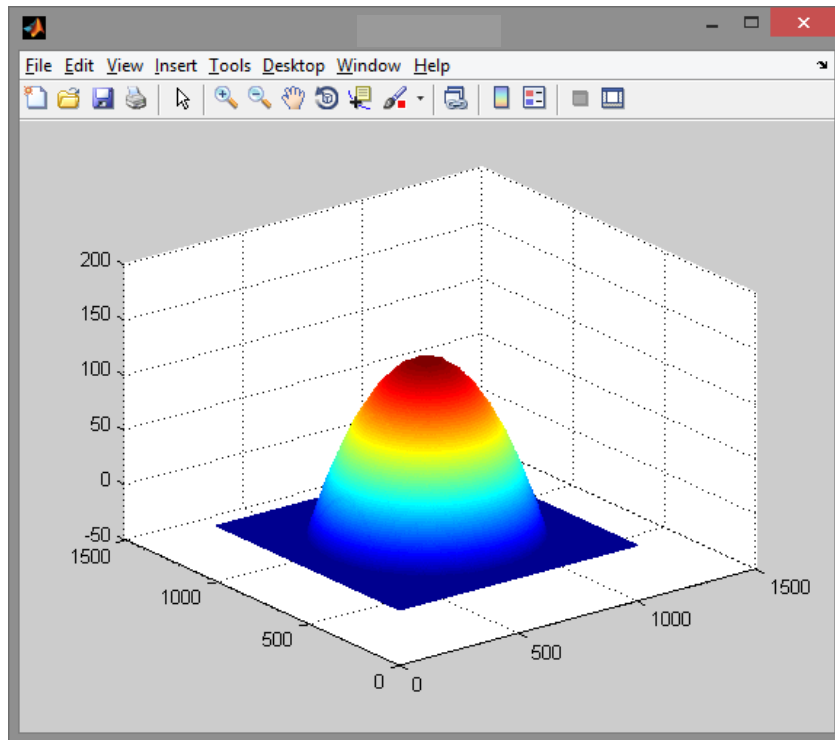


Figure 4.19– Reconstructed Parabola using SIFA

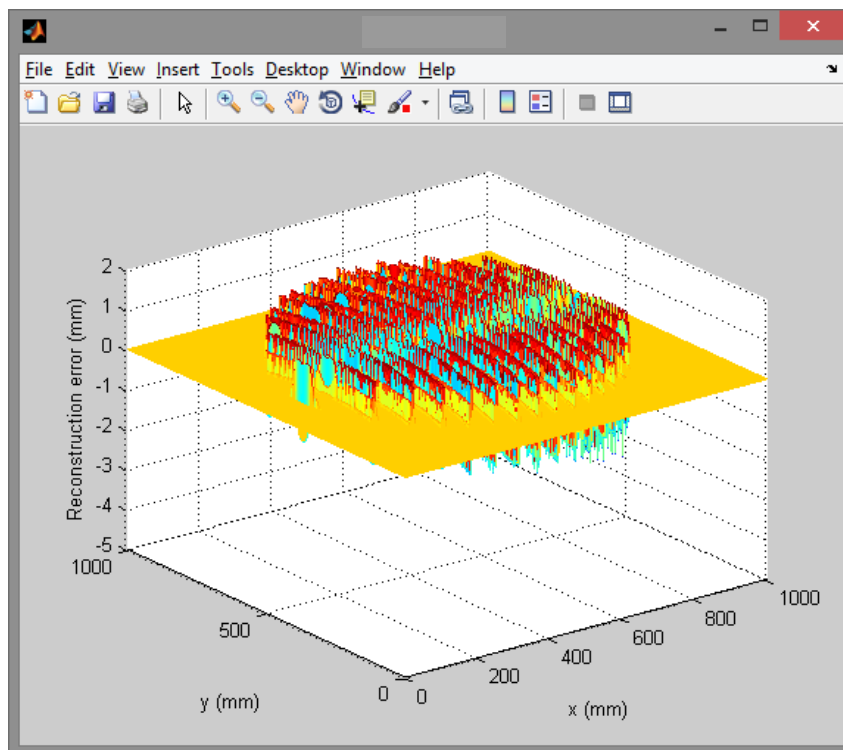


Figure 4.20– Reconstruction Error for Parabola using SIFA

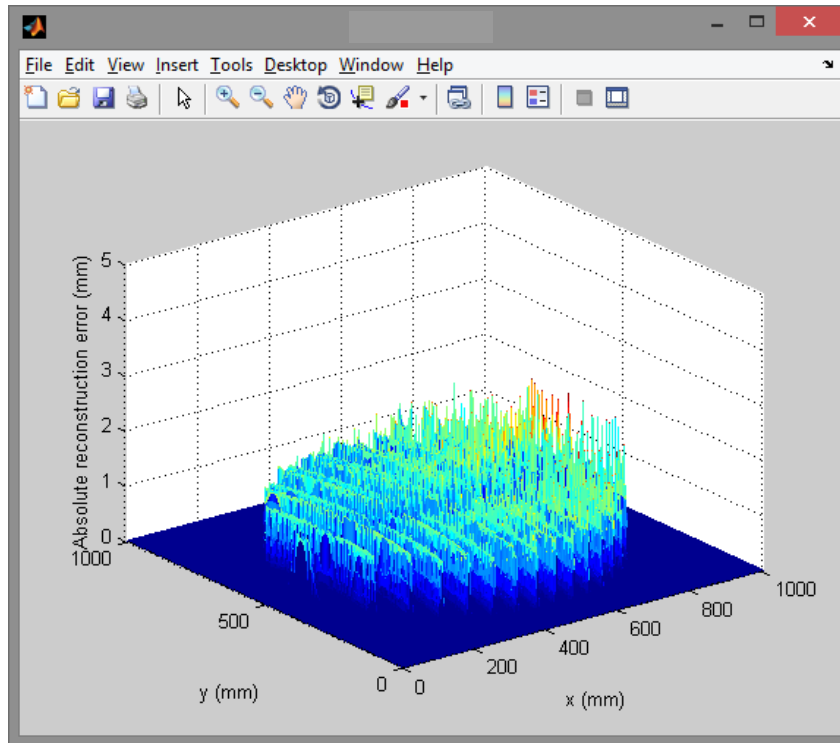


Figure 4.21– Absolute Reconstruction Error for Parabola using SIFA

Figure 4.19 shows the reconstructed parabola using SIFA method. Figure 4.20 shows the reconstruction error for parabola while Figure 4.21 shows the absolute reconstruction error of parabola using SIFA.

The mean error of IFA method is 0.039mm. The standard deviation error for IFA method is 0.1577mm.

Part 5: Global Spline Inverse Function Analysis of 2-D Fringe Pattern

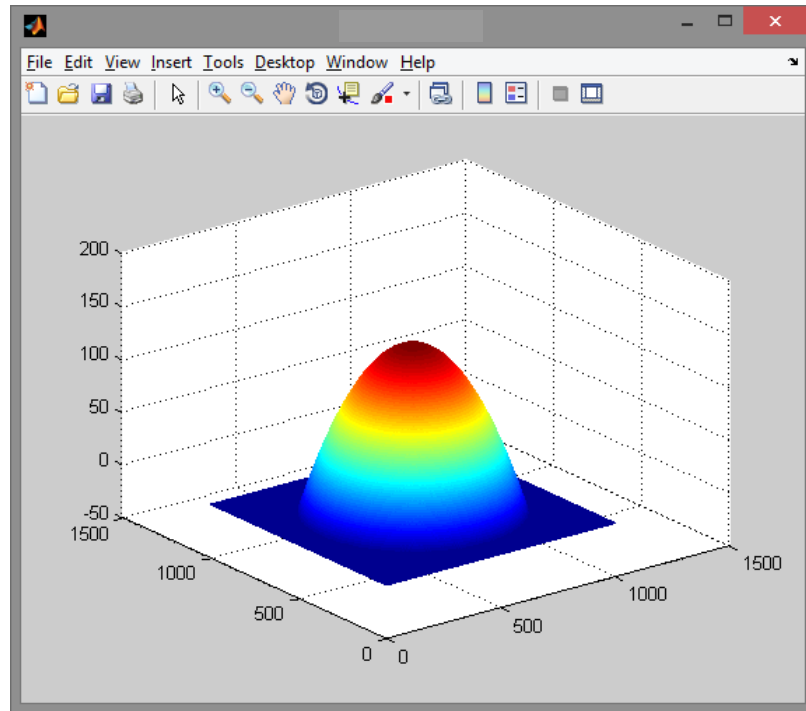


Figure 4.22– Reconstructed Parabola using GSIFA

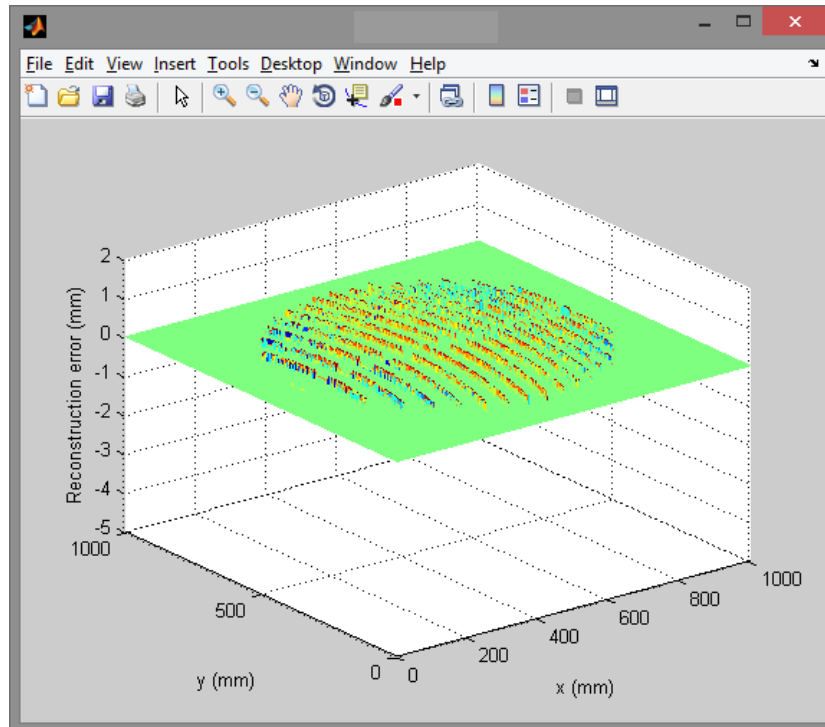


Figure 4.23– Reconstruction Error for Parabola using GSIFA

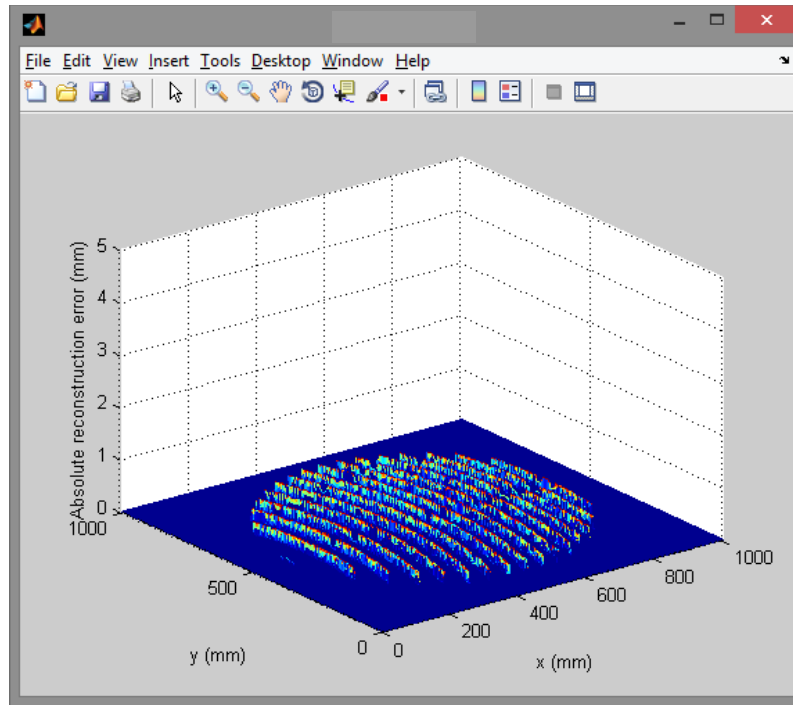


Figure 4.24– Absolute Reconstruction Error for Parabola using GSIFA

Figure 4.22 shows the reconstructed parabola using GSIFA method. Figure 4.23 shows the reconstruction error for parabola while Figure 4.24 shows the absolute reconstruction error of parabola using GSIFA.

The mean error of IFA method is 0.0023mm. The standard deviation error for IFA method is 0.0188mm.

Table 4.1 – Reconstruction errors on all three methods

Reconstruction Method	Mean Reconstruction Error (mm)	Standard Deviation Error (mm)
IFA	0.3149	0.3655
SIFA	0.0390	0.1577
GSIFA	0.0023	0.0188

Table 4.1 shows all the reconstruction errors for all methods. It can be seen that GSIFA has the lowest errors for both mean and standard deviation errors.

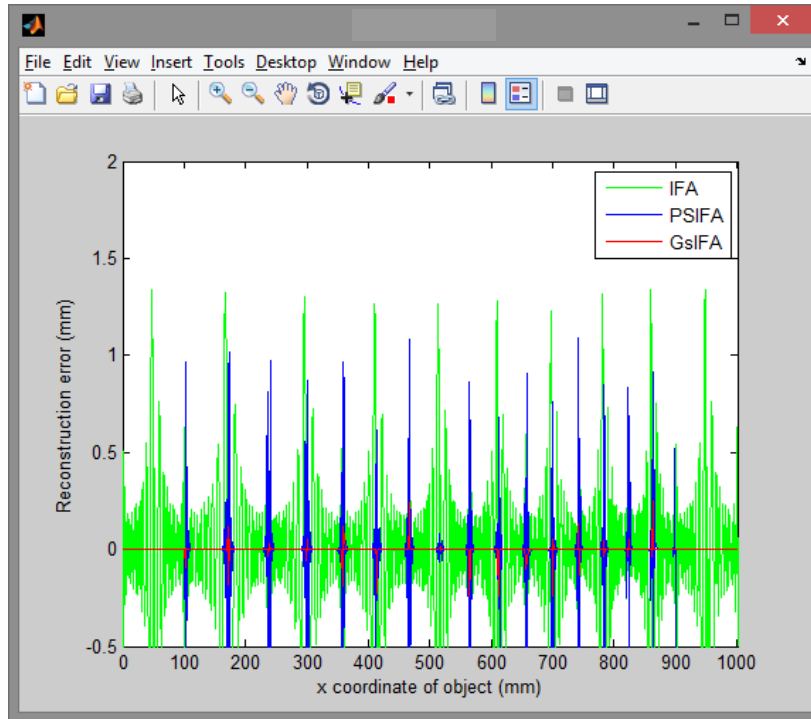


Figure 4.24–Reconstruction Error for all three methods

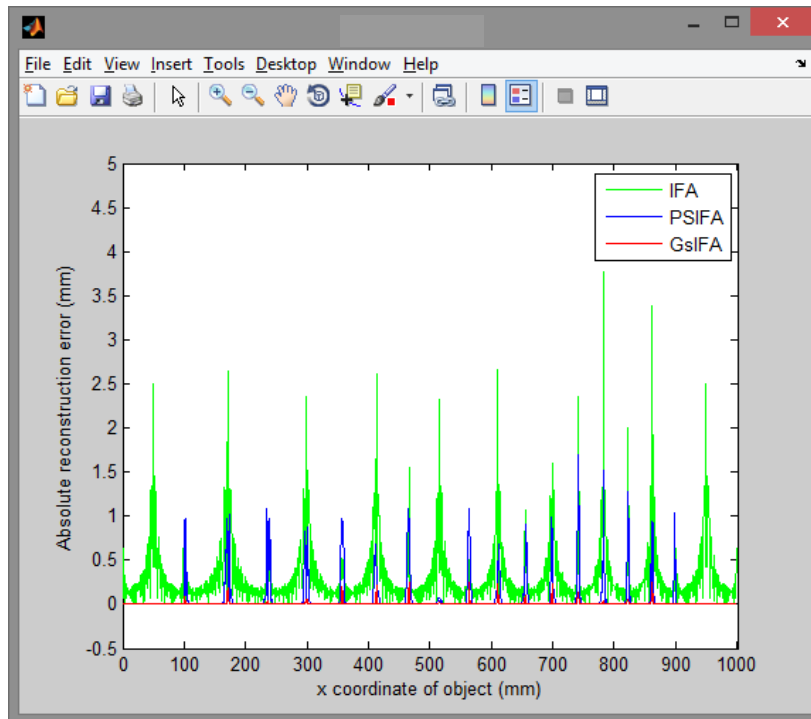


Figure 4.25– Absolute Reconstruction Error for all three methods

Figure 4.24 and 4.25 shows that the reconstruction error is the lowest for GSIFA. IFA method uses polynomial fitting with high degrees that causes periodic oscillation or Runge Phenomenon at the interval of monotonic parts. However, SIFA and GSIFA use cubic spline fitting which is very low in degree and will not causes periodic oscillation.

By using mean reconstruction error, it can deduce that GSIFA is 16 times better than SIFA and 137 times better than IFA.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Spline Inverse Function Analysis (SIFA) method applied in this paper has shown improvement over normal IFA by 8 times. Moreover, Global Spline Inverse Function Analysis (GSIFA) is 16 times better than SIFA and 137 times better than IFA. GSIFA method introduced in this paper provide more reliable method for 3D reconstruction compared to previous method. Oscillation occur in the reconstruction is very small thus the errors is reduced significantly.

The simulation is done on based on ideal case where noise and non-sinusoidal factor are neglected. In real case, there will be noise and non-sinusoidal factor such as gamma distortion present during the projection of fringe. Thus, 3D reconstruction using real objects should be done in the future to further study the accuracy of this method.

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