SUPER RESOLUTION 3D SCANNING USING SPATIAL LIGHT MODULATOR AND BAND CORRECTION

Akshay Pethe
University of Kentucky, akshaypethe@gmail.com
ABSTRACT OF THESIS

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Multi Frequency Phase Measuring Profilometry is the most popular lateral contact 3-D Scanning technique. The Phase Measuring Profilometry is limited in resolution by the projector and cameras used. Conventional signal projectors have a maximum of 2000 to 4000 scan lines limiting the projector resolution. To obtain greater detail with higher resolution the PMP technique is applied to a Spatial Light Modulator (SLM) having 12000 lines, very large as compared to conventional projectors. This technology can achieve super resolution scans having varied applications. Scans achieved from PMP suffer from a certain type of artifact called “banding” which are periodic bands across the captured target. This leads to incorrect measurement of surfaces. Banding is the most limiting noise source in PMP because it increases with lower frequency and decrease in number of patterns. The requirement for lager number of patterns increases the possibility of motion banding. The requirement for higher frequency leads to the necessity for multi-frequency PMP which, again leads to more patterns and longer scan times. We aim to reduce the banding by correcting the phase of the captured data.

KEYWORDS: Phase Measuring Profilometry, SLM, Banding, Super Resolution, 3D

Akshay Pethe
September, 15th 2008
SUPER RESOLUTION 3D SCANNING USING SPATIAL LIGHT MODULATOR AND BAND CORRECTION

By,

Akshay Gajanan Pethe

Dr. Laurence Hassebrook
---
Director of Thesis

Dr. YuMing Zhang
---
Director of Graduate Studies

September, 15th 2008
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SUPER RESOLUTION 3D SCANNING USING SPATIAL LIGHT MODULATOR AND BAND CORRECTION

THESIS

A thesis submitted in partial fulfillment of the Requirements for the degree of Master of Science in Electrical Engineering in the College of Engineering at the University of Kentucky

By

Akshay Gajanan Pethe
Lexington, Kentucky

Director: Dr. Laurence G. Hassebrook, Professor of Electrical Engineering
Lexington, Kentucky

2008

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Dedicated to the Almighty.
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Chapter 1 Introduction

Structured Light Illumination is a non-contact method of depth measurement and 3D imaging. The applications range from distance measurement to special effects in movies or video games. The technique is based on capturing the fringe patterns deformed due to the surface topology and finding the world coordinates. There are two types of SLI techniques used, 1) 2D pattern and 2) Laser Stripe. Laser stripe systems project one stripe and move it across the object while a camera captures an entire frame per stripe position. The depth is obtained by the spatial position of the stripe in each frame. The 2D pattern techniques, like Phase Measuring Profilometry (PMP) or gray codes only require a few frames but then use decoding across time to obtain the depth across time. Many of the systems using this technique, currently use off the shelf projectors and cameras. These projectors have a maximum resolution of 1280 scan lines. However camera resolution can be much higher at 3000 pixels. The resolution of the 3D image is limited by both the camera and projector resolution. The camera choice determines the lateral resolution. The projector resolution also plays a part in this, but can be lower resolution than the camera if one uses PMP and the projector pixels are blurred together. However if binary patterns are used then the projector resolution is much more limiting because there are no continuous values between projector pixels. There are applications such as fingerprint scanners which would be very effective if high resolution scanning were available. Another limiting factor is the intensity distortion in the projector which gives rise to banding artifact. This is a type of artifact that occurs in the reconstructed image due to error in the calculation of the phase and subsequently the world co-ordinates.
In SLI, some form of known pattern is projected onto the surface. The projected pattern is deformed due to the topology, and this deformed pattern is captured using a camera. Then using triangulation the depth of each point is found. Figure 1-1 shows the triangulation between the projector, an object and the camera. The concept can be better explained using Figure 1-2. The depth variation in the object causes an image to be formed in the sensor, which has lateral distortion corresponding to the depth\(^1\). The most common SLI technique used is the Phase Measuring Profilometry (PMP). In this research we are using the PMP technique to obtain feasibility of super resolution 3D scans. A Spatial Light Modulator (SLM) is used as a projection device. Also the research aims at minimizing the banding using phase error compensation.

![Triangulation between the projector, object and the camera](image)

**Figure 1-1:** Triangulation between the projector, object and the camera
In this research we study and present high resolution projector and camera technology and also a way to reduce the inherent problem of 2D patterns, which is banding. Consider a four million point structured light illumination scanner design. It has a potential single patch projection resolution of 12,288 lines along the phase direction. The Basler CMOS video camera is 2352 by 1726 pixel resolution. The configuration consists of a custom Boulder Nonlinear Systems Spatial Light Modulator for the projection system and a four mega pixel digital video camera. The camera has a potential capture rate of 24 frames per second which can be upgraded to 96 frames per second (fps) for future research.
Recent research work focuses on improving the performance of phase measuring profilometry (PMP) by introduction of multi-frequency PMP techniques. Experimental results have shown accuracy improvements in the 3D data acquired when using the multi-frequency PMP technique. However, like all multi-pattern techniques, the projection of multiple patterns requires the object to remain still during the scan time. If the object moves during the scan process, serious errors are introduced into the final result. To overcome this researchers have tried several approaches. One approach is the encoding of a single pattern with combinations of color, frequency or modulation schemes. However, these single pattern techniques are susceptible to various noise sources and do not perform as robustly or accurately as multi-pattern methods. Another approach is to use a multi-camera configuration; however this adds cost and complexity to the scanning system and loses much of the flexibility of the multi-pattern PMP to be applied at different accuracies. The most successful approach has been to synchronize the camera capture with the digital projection which implements 3-pattern PMP at 90 frames per second. The origin of this idea dates back to the mid 1990s when TI produced its DLP development kits and while we recall seeing synchronized high speed gray coding developed by California Institute of Technology in the early 2000s, we could not find official references. So, Song Zhang research is most representative of the current state of the art.

However, we would argue that the DLP development kits used by these recent groups are not optimum for the SLI application. That is, the patterns used are really 1D in definition and are simply replicated along the orthogonal axis of the projector space. Furthermore, the DLP development kits are limited in resolution by the video display
market. Our approach is based on a completely different Spatial Light Modulator (SLM) technology, originally developed for beam steering using diffractive optic principles. That is, instead of using a mega-pixel DLP 2D device we use a 12,288 (12K) pixel custom made 1D Liquid Crystal Device (LCD) by Boulder Nonlinear Systems as shown in Figure 2-1. The “trick” here is that the device has pixels that are not square, but rather, extremely wide such that the device has a 25mm by 25mm footprint, with 12,288 pixels (lines) in one direction and a single pixel width in the other, as shown in Figure 2-2. This has several significant advantages: (1) a square footprint allows conventional illumination sources to be used resulting in high intensity projection Field of View (FOV), (2) having only 12K pixels along 1D rather than millions within 2D, allows large number of patterns to be stored local to the device for rapid frame rates, (3) the 1D aspect also allows for reduced electronics over the 2D SLMs and (4) the device can be operated in incoherent mode with a polarizer and also phase only and/or amplitude modes for other coherent applications. In the time frame that had, we were not able to achieve the full resolution potential. We believe this may be due to the apparatus set up. The setup was also prone to pixel blurring and had an unfavorable Modulation Transfer Function (MTF).

Along with the projector we also carried out experiments with various cameras having a range of 1 Mega Pixel to 12 Mega Pixel resolutions. We achieved extremely good results with the 4 Mega pixel camera and DLP projector system for more conventional PMP technique. 12 Mega pixel cameras were used to capture detailed texture from different angles to be mapped to a 3D data. Although some work needs to be done on the processing time for the 4Mega pixel system, the quality of data is very promising.
Even though the resolution might be very high, banding can give erroneous 3D measurements. In this research we approach banding by observing the error in the phase. Since phase is used to construct the world co-ordinates, any error in the phase would give rise to an error in the reconstructed coordinates. Hence in this research we aim at finding and correcting the error in the phase domain itself. Our hypothesis is that if a periodic error can be found and corrected in the phase, this step can be added to the calibration and would be needed to be done only once for a given system configuration.

High resolution SLM, cameras and reduction in banding can give extremely high quality super resolution scans.

1.1 Thesis Organization

This thesis is organized in 6 chapters. Chapter 1 gives the introduction and the aim of the thesis. Chapter 2 provides the background on the SLI technique used. It explains in detail the multi-frequency PMP, calibration and SLM. Chapter 3 talks about the SLM device and using PMP with the SLM device. Chapter 4 deals with high resolution digital and video cameras. Banding and band correction is dealt with in chapter 5. The thesis is concluded in Chapter 6. The experimental results for each subsection are presented in the respective chapters itself.
Chapter 2 Background

Phase Measuring Profilometry is one of the oldest range finding methods. It is the most common technique to find 3D surface\textsuperscript{10}. In PMP the deformation of the phase by the surface is used to find the depth of the object. For PMP to work efficiently it is very important to have a calibrated system. Calibration gives the relation between the coordinates in the camera plane, projector plane and the world coordinates.

2.1 Multi frequency Phase Measuring Profilometry (PMP)

In PMP some sinusoidal patterns of known frequency are projected onto the target surface. The frequency is measured in cycles/FOV i.e. number of cycles per field of view. A base frequency is of 1 cycle/FOV. A minimum of 3 phase shifted patterns can give a 3D reconstruction of the target topology\textsuperscript{11}. But it has been shown that addition of an extra frequency improves upon the error and thus gives better depth measure\textsuperscript{12}. If we extend this to N number of higher frequencies keeping the scan time constant, we achieve very high quality 3D reconstruction using the same number of patterns but more frequencies\textsuperscript{13}. Using only the projector phase, one can find all the world coordinates. Hence accurately measuring the deformation in phase is crucial in PMP.

The base frequency gives a non-ambiguous depth range since the phase ranges only from \(-\pi\) to \(+\pi\). Higher frequencies give rise to wrapped phase. Wrapped phase has discontinuity of \(2\pi\). The phase has to be unwrapped in order to remove the phase discontinuity and get a smooth phase map. More the higher number of frequencies less is the error in the phase calculated\textsuperscript{13}. 
A projector projects shifted sine wave patterns and the camera captures the deformed images. The projected image is given by

$$I_n(x^p, y^p) = A^p + B^p \cos(2\pi f y^p - \frac{2\pi n}{N})$$  \hspace{1cm} (2.1)$$

Where $A^p$ and $B^p$ are projector constants, $f$ is the frequency ‘$n$’ is the phase shift index, $N$ is the total number of patterns, and $x^p$ and $y^p$ are the projector co-ordinates.

The captured image is represented as

$$I_c(x^c, y^c) = A^c(x^c, y^c) + B^c(x^c, y^c)\cos(\Phi(x^c, y^c) - \frac{2\pi n}{N})$$ \hspace{1cm} (2.2)$$

The term $\Phi(x^c, y^c)$ gives the phase at a pixel location $(x^c, y^c)$. The phase can be calculated as follows

$$\Phi(x^c, y^c) = \arctan\left(\frac{\sum_{n=1}^{N} I_n(xc, yc) \sin\left(\frac{2\pi n}{N}\right)}{\sum_{n=1}^{N} I_n(xc, yc) \cos\left(\frac{2\pi n}{N}\right)}\right)$$ \hspace{1cm} (2.3)$$

The projector co-ordinate is recovered from the phase as $y^p = \Phi(xc, yc)/2\pi f$.

Thus knowing the phase and thus the projector co-ordinate we can find out the world co-ordinates. PMP gives very high resolution images, but has a limitation of limited depth range.

The PMP algorithm can be described as follows:

1. Project and capture base frequency pattern, i.e. 1 cycle/FOV
2. Find out the value of the phase for each pixel. The value would lie between $-\pi$ to $+\pi$.
3. The following steps are repeated for each higher frequency
   i. Project the higher frequency.
   ii. Capture the deformed fringe pattern
   iii. Calculate the phase; this phase would have $(2\pi/N)$ discontinuities.
iv. Unwrap the phase using the base frequency phase to get a smooth phase map. This would lie in 0 to 2π range.

v. Subtract π from this phase to get it back in –π to +π.

vi. Use this phase to unwrap the next higher frequency.

4. From this phase find the projector coordinate \( y^p \).

5. Using one of the techniques discussed next find the world coordinates.

### 2.2 Calibration

Calibration is a process of finding the mapping between the world coordinates, camera coordinates and the projector coordinates. Since the 3D world coordinates are recorded by the camera, it is required to find the relation between the projector to world coordinates and camera to world coordinates. There are two main types of calibration techniques, Singular Value Decomposition and Least Squares Method. Singular Value decomposition is computationally very demanding. In this research we have used Least Squares Method for calibration.

#### 2.2.1 Single Value Decomposition (SVD)

In Singular Value Decomposition technique\(^{16}\), the camera is treated as a pin hole model. The transformation between the camera and the world coordinates is given by

\[
X^c = \frac{m^{wc}_{11} X^w + m^{wc}_{12} Y^w + m^{wc}_{13} Z^w + m^{wc}_{14}}{m^{wc}_{31} X^w + m^{wc}_{32} Y^w + m^{wc}_{33} Z^w + m^{wc}_{34}}
\]  

(2.4)
\[
y^c = \frac{m_{21}^w X^w + m_{22}^w Y^w + m_{23}^w Z^w + m_{24}^w}{m_{31}^w X^w + m_{32}^w Y^w + m_{33}^w Z^w + m_{34}^w}
\]

(2.5)

The camera parameter matrix is given by

\[
M_{wc} = \begin{bmatrix}
m_{11}^w & m_{12}^w & m_{13}^w & m_{14}^w \\
m_{21}^w & m_{22}^w & m_{23}^w & m_{24}^w \\
m_{31}^w & m_{32}^w & m_{33}^w & m_{34}^w
\end{bmatrix}
\]

(2.6)

The transformation between the world and the projector coordinates is given by

\[
x^p = \frac{m_{11}^w X^w + m_{12}^w Y^w + m_{13}^w Z^w + m_{14}^w}{m_{31}^w X^w + m_{32}^w Y^w + m_{33}^w Z^w + m_{34}^w}
\]

(2.7)

\[
y^p = \frac{m_{21}^w X^w + m_{22}^w Y^w + m_{23}^w Z^w + m_{24}^w}{m_{31}^w X^w + m_{32}^w Y^w + m_{33}^w Z^w + m_{34}^w}
\]

(2.8)

The projector parameter matrix is given by

\[
M_{wp} = \begin{bmatrix}
m_{11}^w & m_{12}^w & m_{13}^w & m_{14}^w \\
m_{21}^w & m_{22}^w & m_{23}^w & m_{24}^w \\
m_{31}^w & m_{32}^w & m_{33}^w & m_{34}^w
\end{bmatrix}
\]

(2.9)

In terms of vector notation the camera and projector matrices can be written as

\[
m_c = [m_{11}^{wc} \quad m_{12}^{wc} \quad m_{13}^{wc} \quad \ldots \quad m_{34}^{wc}]^T
\]

(2.10)

\[
m_p = [m_{11}^{wp} \quad m_{12}^{wp} \quad m_{13}^{wp} \quad \ldots \quad m_{34}^{wp}]^T
\]

(2.11)

The vector \(m_c\) is the solution to the equation \(A_c m_c = 0\), where \(A_c\) is the camera transformation matrix given by
Where $M$ is the total number of calibration points. The perspective transformation matrix $M_{wc}$ has only 11 independent entries. These 11 independent entries can be found through homogeneous linear system using at least six world-camera point matches. The coefficients can be found as follows

$$A_c = UDV^T$$  \hspace{1cm} (2.13)

Where $U$ is a $2M \times 2M$ matrix whose columns are orthogonal vectors, $D$ is the positive diagonal matrix and $V$ is $12 \times 12$ matrix whose columns are orthogonal. The non-trivial solution corresponds to the perspective matrix $M_{wc}$. This is the only non-trivial solution.

The projector coefficients can be found out in similar manner.

After system calibration the world coordinates are calculated using the perspective matrices. The projector coordinates are known beforehand and the camera coordinates are found from the captured images. Let

$$C = \begin{bmatrix}
    m_{11}^{wc} - m_{31}^{wc} x^c & m_{12}^{wc} - m_{32}^{wc} x^c & m_{13}^{wc} - m_{33}^{wc} x^c & m_{14}^{wc} \\
    m_{21}^{wc} - m_{31}^{wc} y^c & m_{22}^{wc} - m_{32}^{wc} y^c & m_{23}^{wc} - m_{33}^{wc} y^c & m_{24}^{wc} \\
    m_{11}^{wp} - m_{31}^{wp} x^p & m_{12}^{wp} - m_{32}^{wp} x^p & m_{13}^{wp} - m_{33}^{wp} x^p & m_{14}^{wp} \\
    m_{21}^{wp} - m_{31}^{wp} y^p & m_{22}^{wp} - m_{32}^{wp} y^p & m_{23}^{wp} - m_{33}^{wp} y^p & m_{24}^{wp}
\end{bmatrix}$$ \hspace{1cm} (2.14)
\[
D = \begin{bmatrix}
    m_{34}^w x^c \\
    m_{34}^w y^c \\
    m_{34}^w x^p \\
    m_{34}^w y^p
\end{bmatrix}
\]  \tag{2.15}

Then the world co-ordinates are given by
\[
P^w = [X^w \quad Y^w \quad Z^w \quad 1]^T = C^{-1} D \tag{2.16}
\]

The above equation can be used if we have both the projector coordinates. Most of the times only the vertical phase information the projector coordinate \(y^p\) is used along with the camera coordinate. In that case the \(C, D\) and \(P\) matrices can be written as
\[
C = \begin{bmatrix}
    m_{11}^w - m_{31}^w x^c & m_{12}^w - m_{32}^w x^c & m_{13}^w - m_{33}^w x^c & m_{14}^w \\
    m_{21}^w - m_{31}^w y^c & m_{22}^w - m_{32}^w y^c & m_{23}^w - m_{33}^w y^c & m_{24}^w \\
    m_{11}^w - m_{31}^w x^p & m_{12}^w - m_{32}^w x^p & m_{13}^w - m_{33}^w x^p & m_{14}^w
\end{bmatrix}
\]  \tag{2.17}

\[
D = \begin{bmatrix}
    m_{34}^w x^c \\
    m_{34}^w y^c \\
    m_{34}^w x^p
\end{bmatrix}
\]  \tag{2.18}

\[
P^w = [X^w \quad Y^w \quad Z^w]^T = C^{-1} D \tag{2.19}
\]

2.2.2 Least Square Method

An alternative to the SVD technique is the Least Squares Solution\(^\text{17}\). SVD is computationally very demanding and hence takes more time. Least Squares Solution is very easy to implement. Equations 2.4 to 2.11 are the same. To find the perspective
transformation matrices $m_{34}^{wc}$ and $m_{34}^{wp}$ are both set to 1. This approximation is valid since both the matrices are defined up to a scale factor. Thus all the elements of $M_{wc}$ and $M_{wp}$ are found as pseudo inverse.

The matrix $m_c = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & m_{21} & m_{22} & m_{23} & m_{24} & m_{31} & m_{32} & m_{33} \end{bmatrix}^T$ is solution to the equation $Am_c = B$, where $A$ is the camera transformation matrix given by

$$A_{2i-1} = \begin{bmatrix} x_i^w \\ y_i^w \\ z_i^w \\ 1 \\ 0 \\ 0 \\ 0 \\ -x_i^c x_i^w \\ -x_i^c y_i^w \\ -x_i^c z_i^w \end{bmatrix}$$  \hspace{1cm} (2.20)$$

$$A_{2i} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ x_i^w \\ y_i^w \\ z_i^w \\ -y_i^c x_i^w \\ -y_i^c y_i^w \\ -y_i^c z_i^w \end{bmatrix}$$  \hspace{1cm} (2.21)$$

$$B_{2i-1} = [x_i^c]$$  \hspace{1cm} (2.22)$$

$$B_{2i} = [y_i^c]$$  \hspace{1cm} (2.23)
The pseudo inverse solution can be obtained as

$$m_c = (A^T A)^{-1} A^T B$$

(2.24)

The equations 2.18 to 2.21 are used repeatedly to solve the projector perspective matrix.

The 3D world coordinates are calculated using equations 2.17 to 2.19.

**2.3 Spatial Light Modulator (SLM)**

One of the hardware components we have used in our research is a Spatial Light Modulator (SLM). We have used the SLM as a potential super resolution projection system. The SLM is a device which imposes some form of spatially varying modulation on a beam of light\(^2\). The SLM can change the intensity, the phase or both of an incident light beam. The SLM used in this research is a 1x12288 Linear Array Liquid Crystal on Silicon SLM. This SLM converts digitized data into coherent optical information.

![Cross-sectional view of a SLM](image)

*Figure 2-1: Cross-sectional view of a SLM\(^1\).*
The cross-sectional view of a 12K SLM is shown in Figure 2-1: Cross-sectional view of a SLM. Polarized light enters the device from the top and passes through the glass, the liquid crystal SLM and is reflected back through the LC medium. It returns back on the same path. It is possible to electrically control each pixel independently through a programming cable. The induced voltage on each pixel produces an electric field between the electrode and the glass. This field produces a change in the optical properties of the LC layer. C++ code can be written to drive the SLM using any required pattern, and the light is reflected back with its phase having the pattern that the SLM is driven with. The SLM consist of electrically addressable pixels. A pixel in the off state does not affect the phase. The mirror in the on state changes the phase as per the inclination. Since one scan line is one pixel wide this can be potentially a super speed super resolution projector, Figure 2-2 shows the concept.
Chapter 3 Super Resolution Projection Technology

A Spatial Light Modulator (SLM) is a device which can be electronically controlled to change the phase of the light incident upon it. Theoretically the device can be driven at very high speeds on the order of a few hundred frames per second. The SLM in use has 12K scan lines, the largest number of scan lines than any projector has at present.\(^\text{19}\) The SLM is used in conjunction with structured light illumination (SLI) techniques to evaluate the feasibility of obtaining very high resolution 3-D images of an object.

3.1 Concept and Need

Using off the shelf LED projectors having a few hundred scan lines gives rise to a problem known as “banding” and which we will refer to as pixel banding. Due to the very low number of scan lines, high resolution images show periodic bands as shown in Figure 3-1. The figure shows scan of a mannequin made using LED projector. One way to solve this problem would be to increase the number of scan lines.

![Figure 3-1: Images of face and a close up of the nose and eyes showing banding](image-url)
The proposed scanner made using SLM would address this problem. The other advantage is that, even though there are 12k lines, there are only 12k pixels, as one pixel is one line wide. As a result the SLM has a potential of being driven at a very high rate. In SLI technique we project various sine wave patterns of varying frequency and phase on to the object. The depth of the object can be recovered from the deformed fringe patterns captured using the camera.

3.2 Experimental Setup and Measurements

3.2.1 Setup

Figure 3-2 shows the experimental setup of the SLM system. Currently a beam splitter is used to direct light into the SLM. But in the future this would be removed and the light would be made directly incident on the SLM at an angle, giving a factor of 4 times more reflected light intensity than it currently has.

3.2.2 Measurements

In order to determine the quality of the images reconstructed and keep a track of the improvements we measured three quality measures, namely

1. Modulation Index
2. Modulation Transfer function
3. Fourier Transform of the captured data.
1) Modulation Index:

Modulation index gives us an idea of the amount of contrast. Higher the index better the contrast. The modulation index was calculated as follows

\[
M_I = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{I_{p-p}}{I_{\text{max}} + I_{\text{min}}}
\]  

(3.1)

Where

\(M_I\) = modulation index

\(I_{\text{max}}\) = maximum light intensity captured

\(I_{\text{min}}\) = minimum light intensity captured

\(I_{p-p}\) = Peak to Peak intensity.
Figure 3-3: Actual setup of the SLM system

Figure 3-4: Screenshot of the software used to control the SLM system
2) *Fourier Transform*

Fourier transform gives us an idea about the amount of noise and unwanted harmonics. Ideally we want the first harmonic component to be very large as compared to the other harmonics, since the other harmonics lead to banding. So the figures where the first harmonic is much larger indicates better performance. The MTF curves indicate the roll off of the system, i.e. the gain of the system for different frequencies. Larger the band over which the response is flat, better the system. It indicates that higher frequencies can be projected.

3) *Modulation Transfer Function (MTF):*

The modulation transfer function gives us an idea of the amount of attenuation for different frequencies. It is typically a graph resembling a low pass filter transfer function. Ideally there should be no roll off except at very high frequencies. MTF is calculated as a percentage as follows\(^2\)

- \( V_b \): The minimum luminance (or pixel value) for black areas at low spatial frequencies.
- \( V_w \): The maximum luminance for white areas at low spatial frequencies.
- \( V_{\text{min}} \): The minimum luminance for a pattern near spatial frequency \( f \) ("negative peak").
- \( V_{\text{max}} \): The maximum luminance for a pattern near spatial frequency \( f \) ("positive peak").

\[
C(0) = \frac{V_w - V_b}{V_w + V_b}
\]

\[
C(f) = \frac{V_{\text{max}} - V_{\text{min}}}{V_{\text{max}} + V_{\text{min}}}
\]

is the low frequency (black-white) contrast.

\[
\text{MTF}(f) = 100\% \times \frac{C(f)}{C(0)}
\]  

(3.2)
### 3.3 Experimental Data

The above indices were measured for different configurations, namely using different filters and polarizer. The results are listed in Table 1. The graphs for the MTF and FFT are shown for the first three cases. The FFT graphs are for a typical pixel and should only have energy in the k=1 frequency bin. Energy in the other frequency bins indicates either noise or harmonic distortion. Figure 3-3 and Figure 3-4 show the actual setup and the interface for the software used to control the SLM.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Frequency in Cycles/FOV</th>
<th>Imax</th>
<th>Imin</th>
<th>M₁</th>
<th>MTF (figure #)</th>
<th>FFT (figure#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough wall, Red Filter, No Polarizer</td>
<td>1</td>
<td>207</td>
<td>120</td>
<td>0.266</td>
<td>Figure 3-5</td>
<td>Figure 3-9</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>200</td>
<td>124</td>
<td>0.234</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>199</td>
<td>131</td>
<td>0.206</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smooth White Board Red Filter, No Polarizer</td>
<td>1</td>
<td>138</td>
<td>74</td>
<td>0.301</td>
<td>Figure 3-6</td>
<td>Figure 3-10</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>138</td>
<td>76</td>
<td>0.272</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>130</td>
<td>83</td>
<td>0.220</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarizer, Red Filter Smooth White Board</td>
<td>1</td>
<td>84</td>
<td>34</td>
<td>0.423</td>
<td>Figure 3-7</td>
<td>Figure 3-11</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>80</td>
<td>39</td>
<td>0.344</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>79</td>
<td>43</td>
<td>0.295</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarizer, Green Filter Smooth White Board</td>
<td>1</td>
<td>35</td>
<td>19</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>35</td>
<td>22</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>34</td>
<td>20</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarizer, IR filter Smooth White board</td>
<td>1</td>
<td>100</td>
<td>47</td>
<td>0.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>98</td>
<td>53</td>
<td>0.298</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>97</td>
<td>54</td>
<td>0.284</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Megapixels camera And LED projector</td>
<td>1</td>
<td>132</td>
<td>8</td>
<td>0.885</td>
<td>Figure 3-8</td>
<td>Figure 3-12</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>130</td>
<td>11</td>
<td>0.844</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>126</td>
<td>11</td>
<td>0.839</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>128</td>
<td>13</td>
<td>0.815</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>148</td>
<td>35</td>
<td>0.617</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>128</td>
<td>118</td>
<td>29</td>
<td>0.605</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>256</td>
<td>76</td>
<td>43</td>
<td>0.277</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3-5 MTF of 12K SLM configuration

Figure 3-6 MTF of SLM with smooth surface.
Figure 3-7 MTF of SLM system

Figure 3-8 MTF of LED projector system
Figure 3-9 FFT of single pixel response across patterns for 12K SLM.

Figure 3-10 FFT of single pixel response across patterns for 12K SLM.
Figure 3-11 FFT of single pixel response across patterns for 12K SLM.

Figure 3-12 FFT of single pixel response for LED based projection.
Figure 3-13: 3D Scan of “Alice” using the SLM system. Approx. dimensions 190 mm x 160 mm.

Figure 3-14: Zoomed in image showing the point cloud detail of 12K SLM scan.
Comparing Figure 3-5 and Figure 3-8 we see that the MTF of the LED system is much better than the SLM system for the current setup. The results of the SLM system are disappointing, we think primarily due to the optical apparatus. Fixing the limitations in the apparatus so as to achieve the full resolution potential of the SLM should be number priority for future research. We think remarkable improvements would be seen by increasing the amount of light is incident on the target. Currently only 1/4\textsuperscript{th} of the total light energy is incident on the target. If we can boost this by 400\% we will see immediate improvements in the results.

Figure 3-13 shows 3D scan of mannequin Alice. One can see some distortion near the ears and the nose. But the smooth facial surface shows promising result if more work is done on the apparatus. Figure 3-14 shows the zoomed in section of Alice. One can see the high density of pixels.
Chapter 4 High Resolution Video and Digital Camera

4.1 Four mega pixel camera system

The actual performance of the SLM was low so to evaluate the camera performance we used a 4 Mega pixel camera and LED projector system. As before structured light illumination technique was used. The result was a high resolution 3D scan. Figures 13 to 16 show the 3D scans of mannequin “Fred” and a model of an astronaut. The approximate dimensions of “Fred” are 290 mm x 150 mm and that of the astronaut are 135 mm x 65mm.

Figure 4-1: High Resolution scan of “Fred” using 4Meg system. Approx. dimensions 290 mm x 150 mm
Figure 4-2: Zoomed in section of the eye of Fred showing the dense point cloud using 4Meg system.

Figure 4-3: High Resolution scan of an astronaut model using 4Meg system. Approx. dimensions 135 mm x 65mm.
4.2 Hand scanner Project

One of the current projects that is going on in our group is the Hand Scanner. This scanner aims at capturing the entire palm from one side of the nail to the other along with all the ridge details. This is a state of the art scanner and would give very high resolution images of the palm. The system consists of 3 Canon G9 cameras, one MV BluFox camera, two still pattern projectors, and one digital projector. The G9s are used to capture the texture of the palm in super detail which can then be overlaid on the 3D data. The 3 G9 cameras are 12Mega Pixel digital cameras with ability to capture RAW data.
A full tether control of the G9 cameras was achieved. Different parameters such as, flash, auto focus, zoom, aperture can be controlled by software. The application was written in VC++

Figure 4-5: Interface for software to control the Canon G9 cameras

Figure 4-5 shows the user interface of the software. The three cameras are controlled in three separate threads, thus giving control over when to capture an image using which camera.
4.2.1 Conversion to RAW format

The software developed to control the cameras also does JPEG to RAW conversion of the captured images. RAW image contains much more detail and resolution than a JPEG image. The image is processed through a series of conversions to finally get a BMP image. First the image is converted from a JPEG to DNG. The DNG is then converted to a PPM and then finally the PPM to a BMP image.
Chapter 5 Banding and Band Correction

Banding is a kind of artifact that is inherent in the SLI technique. Banding gives rise to appearance of periodic bands in the 3D reconstructed data. Essentially it is an error in the calculated phase and hence the calculated world co-ordinates, mainly the Z coordinate.

5.1 Classification

Banding arises due to more than one reason. Banding can be classified into these 3 broad categories

5.1.1 Inherent Banding

This is the inherent banding in PMP technique. Scanning the target with only base frequency and only 3 patterns gives rise to this. Figure 5-1: Inherent banding due to use of only 3 patterns shows an example of the same.

Figure 5-1: Inherent banding due to use of only 3 patterns
One can clearly see the three bands in the form of sinusoidal variations. One form of banding can be affected by more than one parameter. For example, shows how gamma affects the inherent banding. Due to the error induced by gamma, the bands become prominent.

![Figure 5-2: Inherent banding affected by gamma](image)

### 5.1.2 Gamma Banding

The sinusoidal patterns that are projected by the projector are not exactly same as the ones that are fed into it. Every projector has a gamma which distorts the output sinusoidal patterns. This gives rise to another form of banding called ‘Gamma Banding’. In gamma banding, the number of bands appearing are given by the product of the highest frequency of scanning and the number of patterns used. In case of dual frequency PMP
the number of bands varies depending upon whether 3 or more patterns are used. This is discussed more in detail later in the chapter.

Figure 5-3: Gamma banding with F=8, N=3 and gamma=0.5

Figure 5-3 and Figure 5-4 show the examples of gamma banding. Gamma banding affects all the other forms of banding too, i.e. it adds to them. Gamma banding can be considerably reduced by using an appropriate gamma correction. It can be seen that in Figure 5-4 the amplitude of the bands is much smaller than Figure 5-3. This is because the gamma correction value is closer to 1.9 which was the correction factor in the system used.
5.1.3 Motion Banding

Figure 5-5 shows an example of motion banding. Motion banding occurs when the target object being scanned moves during the scanning process. We have observed that in motion banding, the number of bands appearing across the data are equal to the highest frequency with which the scanning was carried out. In this case, the highest frequency used was 16 cycles/FOV; hence, one can observe 16 bands.
Figure 5-5: Example of motion banding on a flat white board

5.2 Banding Measure

Band energy is defined as the ratio of wavelength of the ripples to the peak to peak distance of ripples.

\[ b_e = \frac{h}{\lambda} \]  

(5.1)

Where \( b_e \) is the band energy, \( \lambda \) is the wavelength of the ripples and \( h \) is the peak to peak distance of ripples.
Figure 5-6: Band Measurement

Where,

\[ A, B = \text{Peaks of the ripple} \]
\[ C = \text{Valley of the ripple} \]
\[ a, b, c = \text{corresponding lengths of the sides of the triangle} \]

The wavelength of the ripple is nothing but ‘c’. Heron’s formula is used to find the area of the triangle and after that the peak to peak distance is calculated. Area of the triangle using Heron’s formula is given by

\[
Area = \sqrt{s(s-a)(s-b)(s-c)}
\]  \hspace{1cm} (5.2)

\[ s = \frac{a+b+c}{2} \]
Where semi-perimeter \( s = \frac{a+b+c}{2} \) \hspace{1cm} (5.3)

The peak to peak distance of the ripple is calculated as

\[ h = \frac{2 \times \text{Area}}{\lambda} \] \hspace{1cm} (5.4)

where \( \lambda \) is the base of the triangle.

### 5.3 Algorithm to Solve Gamma Banding

In gamma banding the number of bands are given by Highest Frequency * Number of Patterns for multi-frequency PMP. We can clearly see the appearance of bands in the phase. Instead of correcting the world coordinates we correct the phase itself. The results for a flat board and a hand are shown below.

The algorithm works as follows:

- Find flat bands in the phase, the size of which can be variable.
- Interpolate between the two points to fit a line which closely matches the slope of the phase in that area.
- Based on the value of slope and the difference between the intensity values of two consecutive points differentiate data from the plane background and do not alter the data.
5.3.1 Correction of Dual frequency PMP

A set of 3D data was captured using only 2 frequencies. 32 Patterns were used for the base frequency and 4 patterns of the next higher frequency. In dual frequency PMP if only 3 patterns of the second frequency are used, then the number of bands is the product of frequency and number of patterns. If more than 3 patterns are used then the number of bands half of the product of frequency and number of patterns. The data for $F = 16, 8, 4, 2$ and 1 has been corrected using the above algorithm. It was observed that as the second frequency was closer to 1, the dependence of banding on the phase decreased, i.e. the banding was present even after correcting the phase. Similar results were obtained for
F = 16, 8 and 4. For F=1 and F=2, although the phase map was smoothened it did not give any improvement in the banding.

Figure 5-8: Zoomed in phase cross section for F= 16 before and after correction

Figure 5-9: Distribution of Z coordinates for F=16
Figure 5-10: 3D view of for F=16 before (left) and after (right) correction

Figure 5-11: 3D view of for F=8 before (left) and after (right) correction
Figure 5-12: 3D view of for F=4 before (left) and after (right) correction

Figure 5-13: 3D view of for F=2 before (left) and after (right) correction
Table 2: Band Measures for Dual frequency PMP (Camera Space Correction)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>h(before correction)</th>
<th>h(after correction)</th>
<th>be(before correction)</th>
<th>be(after correction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>12.9161</td>
<td>5.4167</td>
<td>0.8555</td>
<td>0.6743</td>
</tr>
<tr>
<td>8</td>
<td>34.2011</td>
<td>11.5247</td>
<td>1.1825</td>
<td>0.6543</td>
</tr>
<tr>
<td>4</td>
<td>44.7899</td>
<td>27.22</td>
<td>0.7082</td>
<td>0.7575</td>
</tr>
<tr>
<td>2</td>
<td>128.079</td>
<td>50.2581</td>
<td>1.0126</td>
<td>0.7914</td>
</tr>
<tr>
<td>1</td>
<td>116.117</td>
<td>83.0355</td>
<td>0.49747</td>
<td>0.6562</td>
</tr>
</tbody>
</table>

Table 3: Number of bands due to gamma banding (NUM_BANDS)

<table>
<thead>
<tr>
<th>PMP Type</th>
<th>Patterns = 3</th>
<th>Patterns &gt;3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi Frequency</td>
<td>Highest freq * # patterns</td>
<td>Highest freq * # patterns</td>
</tr>
<tr>
<td>Dual Frequency</td>
<td>Highest freq * # patterns</td>
<td>(Highest freq * # patterns)/2</td>
</tr>
</tbody>
</table>
5.3.2 Correction of Multi Frequency PMP

Figure 5-15: Original and Corrected phase of a flat white board

Figure 5-16: Original and Corrected Z Coordinate of the flat white board
Figure 5-17: Original 3D image of the flat board

Figure 5-18: 3D image of the board after band correction
Figure 5-19: Original and Corrected phase of a palm image

Figure 5-20: Original 3D image of the palm, with banding
Table 4: Band measures for Multi Frequency PMP (Camera Space Correction)

<table>
<thead>
<tr>
<th>Target Object</th>
<th>h(before correction)</th>
<th>h(after correction)</th>
<th>be(before correction)</th>
<th>be(after correction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat board</td>
<td>4.1571</td>
<td>3.7310</td>
<td>0.6846</td>
<td>0.5864</td>
</tr>
<tr>
<td>Palm</td>
<td>4.3301</td>
<td>3.4254</td>
<td>0.7014</td>
<td>0.5623</td>
</tr>
</tbody>
</table>

Using this technique to directly correct 3D data is less efficient. Instead, this method can be effectively used by correcting a flat board for a given calibrated setup of instruments, and then using the mapping between the original and corrected phase as a LUT for future scans of 3D objects. Another disadvantage of correcting in the camera space is that the bands get spread out in space depending on the inclination of the camera, thus making them non-periodic.
5.3.3 Correction in the Projector Space

A more efficient way to solve banding would be if we do not have to search for the bands. Such an approach would be computationally very efficient. This can be achieved if we perform the same correction in the projector space rather than the camera space. One more advantage of working in the projector space is that no matter what the inclination of the camera with respect to the projector is the stripes in the projector space are always aligned, equidistant.

The captured images can be converted to projector space as follows

- Choose a phase value yp from the camera space.
- Scale the yp to form the index in projector space such that
  \[ YP = yp \times (My - 1) / (2\pi) \]
  where My = number of columns of the image.
- Now form the projector image as
  \[ Ip(xc, YP) = yp(n) - yp(n-1) \]

Using this mapping preserves the bands in the projector space. Now consider an ideal phase ranging from 0 to 2\(\pi\) in the camera space. If this was also converted to the projector space then it would give us a straight line, let us call it proj_ideal. Now the corrected phase in the camera space is given as follows

\[
\begin{align*}
    yp_c(1) &= yp_o; \\
    yp_c(2) &= yp_o(2) - proj_ideal(2); \\
    yp_c(n) &= yp_c(n-1) + Ip(xc, YP) - diff(xc, YP);
\end{align*}
\]
Where subscript ‘c’ stands for corrected and ‘o’ for original and \( \text{diff} = I_p - \text{proj}_{\text{ideal}} \).

After recovering the corrected phase the world coordinates are recalculated. The following figures show the algorithmic flow chart and the results on a flat board.

\[
\begin{align*}
\text{Read in the phase image} \\
\text{Convert to projector space using the conversion} \\
Y_P &= y_p \times (M_y - 1)/(2*pi) \\
I(x_c, Y_P) &= y_p(n) - y_p(n-1) \\
\text{Find the projector image of an ideal ramp in the projector space, let it be called} \\
\text{proj}_{\text{ideal}} \\
\text{Form } \text{diff} = I - \text{proj}_{\text{ideal}} \\
\text{Correct the phase in camera space using} \\
y_{p,c}(1) &= y_{p,o}(1) \\
y_{p,c}(2) &= y_{p,o}(2) - \text{proj}_{\text{ideal}}[2] \\
y_{p,c}(n) &= y_{p,c}(n-1) + I(x_c, Y_P) - \text{diff}(x_c, Y_P) \\
\text{Calculate new world coordinates}
\end{align*}
\]

Figure 5-22: Flowchart for Projector Space correction method
Figure 5-23: Banding in the projector space

Figure 5-24: Corrected phase in camera space
Figure 5-25: Phase in projector space after correction

Figure 5-26: 3D metallic view before (top) and after (bottom) correction
Correction values of a flat board can be used as a LUT for correcting the phase of 3D scans made on the same calibrated setup of instruments. One of the problems in this technique arises due to noise. Since the band positions are predetermined and not searched for, there can be an error introduced due to noisy signals which reduces the effectiveness and accuracy of the algorithm. For example, noise might make a pixel value become zero where it should have been something else. This would cause the predetermined band values to be not in an increasing order. This in turn would make the corrected phase to be in error.

<table>
<thead>
<tr>
<th>Target Object</th>
<th>h(before correction)</th>
<th>h(after correction)</th>
<th>be(before correction)</th>
<th>be(after correction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat board</td>
<td>10.1703</td>
<td>2.6526</td>
<td>0.4922</td>
<td>0.2493</td>
</tr>
</tbody>
</table>

Future work in this method would include correcting a 3D object. One could do this in two ways, one is to use the data used for correcting a flat board as a look up table and use it in the calibration step. Figure 5-27 and Figure 5-28 show a sphere and its phase in the projector space. The second method would be to use a notch filter to only pass the high frequency components of a phase of a 3D object, like the sphere, since the banding is high frequency component. Then we would need to fit a high degree polynomial in order to closely follow the data but not the banding. Then we would correct it in the way, similar to the flat board.
Figure 5-27: 3D view of a Sphere (Bowling Ball)

Figure 5-28: Cross section of the phase in the projector space
Chapter 6 Conclusion and Future Work

The existing SLM system that we have indicates that our high resolution multi-frequency PMP technique delivers excellent results with scalability from orders of microns to meters. We believe the final bottle neck in performance will be the optical spatial response. We know this from experiments performed for other projects. To minimize the impact of this on our 1D SLM approach, we have incorporated standard F-mounts so that optical optimization can be readily applied and the F-mount standard allows us larger selection and access to higher quality lenses. Furthermore, these SLM are usually used in phase only modality so using them for polarization control may not be a linear relationship. This research provides us a baseline for further improvement and development of the 12K SLM based scanner. Our goal was to get the 12K SLM integrated with a camera system to be able to scan objects in 3-Dimensions. Our conclusion at this point is that this appears quite feasible but needs further development to reduce the inter-pixel interference of the pixels. We would also need a higher speed device which can potentially go to 700Hz for future designs. Currently we are at 70Hz.

The potential of this technology is high, in part, because BNS is a custom chip designer and willing to develop systems on a 1 chip per development stage. We believe the problems to overcome are more engineering than research. At present, the LED projector with 4 mega pixel camera is achieving considerably higher performance in terms of harmonic distortion, higher SNR, higher modulation index and higher MTF. Our conclusion at this point is that 4 mega pixel is a competitive configuration as is. Its performance is extremely high and would be a good candidate for commercialization. We believe the bottleneck in performance is the lens setup. More specifically we need to
install a thinner F-mount device to bring the lens closer to the SLM, yet allowing for space for the beam splitter. We are also using the trigger mechanism included with the BNS SLM to achieve higher frame rates. The next big step will be to configure an angled direct path system where there is no beam splitter. This will increase the projection efficiency by 400% but will require a different, type of lens that has longer focal distances to allow the incident light paths to achieve the full aperture of the SLM\textsuperscript{22}.

In banding although we were able to show improvements more work needs to be done on finding the non-ideal phase. The technique for searching the bands and fitting a straight line can only give limited improvements. The approach of correcting in the projector space is a really novel and efficient way to perform phase correction. The approach to use the data for a flat board as a part of calibration seems very promising.
Appendix A: MATLAB Codes

A.1 Search and Correct algorithm for camera space to solve gamma banding

%%% University of Kentucky, Summer 2008
Akshay Pethe
Banding Correction in Camera Space
This code gets rid of the bands by finding the flat bands, peaks and fitting straight lines between these bands.

B=double(imread('C:\BandingData\gamma_0.7_16x3\test0P.bmp'));
B_r=B(:,:,1);
[My Nx]=size(B_r);
fid=fopen('C:\BandingData\gamma_0.7_16x3\test0YP.byt','rb');
phase=fread(fid,inf,'float32');
fid=fopen('C:\BandingData\gamma_0.7_16x3\test0Z.byt','rb');
zco=fread(fid,inf,'float32');
I=double(imread('C:\BandingData\gamma_0.7_16x3\test0I.bmp'));
C=double(imread('C:\BandingData\gamma_0.7_16x3\test0C.bmp'));
for x=1:Nx
    for y=1:My
        index=y*Nx+x;
        if(index>Nx*My)
            index=Nx*My;
        end
        phaseuw(y,x)=phase(index);
        z_co(y,x)=zco(index);
    end
end
col=phaseuw(:,500);
col_mod=col;

N=3;
F=16;
flat_period=round(Nx/(N*F))-20;
% initializations for the for loop
for j=1:Nx
    col=phaseuw(:,j);
col_mod=col;
    for k=1:15
        x1=1;
x2=2;
y1=col(x1);
y2=col(x2);
first_flag=0;
second_flag=0;
counter=0;
still_not_growing=0;
for i=1:My
    %take two consequetive values;
    val1=col(i);
    if(i<My)
        val2=col(i+1);
    else
        val2=col(i);
    end

    %used for counting whether the flat band is reached
    if((val2-val1)<0.005)
        counter=counter+1;
    else
        counter=0;
    end

    %to prevent data from being over_written
    if(abs(val2-val1)>0.2 & first_flag==1)
        first_flag=0;
        second_flag=0;
        counter=0;
        still_not_growing=0;
    end

    %detect the second band and store the starting point and then form the
    %equation of the line for correction
    if(counter>=flat_period & first_flag==1 & still_not_growing==1)
        x2=i-counter;
        y2=col(x2,1);
        second_i=x2;
        second_flag=1;
    end

    %detect the first flat band and store the starting point
    if(counter>=flat_period & first_flag==0)
        x1=i-counter;
        if(x1==0)
            x1=1;
        end
    end
y1=col(x1,1);
first_flag=1;
first_i=x1;
end

%check whether the band is still growing after having detected the %first minimum flat band length
if(i>x1+counter & first_flag==1 & still_not_growing==0)%i.e. next iteration
    if(counter==0)
        x1=i-counter;
y1=col(x1,1);
        first_i=x1;
        still_not_growing=0;
    else
        still_not_growing=1;
    end
end

%check whether the band is still growing after having detected the %second minimum flat band length
if(i>x2+counter & second_flag==1)%i.e. next iteration
    if(counter==0)
        x2=i-counter;
y2=col(x2,1);
        second_i=x2;
    else
        slope=(y2-y1)/(x2-x1);
        if(slope<=(2*pi)/My)
            x=first_i:1:second_i;
            intercept=y1-slope*x1;
            y=slope*x+intercept;
            col_mod(first_i:second_i,1)=y;
        end
        first_flag=0;
        second_flag=0;
        counter=0;
        still_not_growing=0;
    end
end
end

col=col_mod;
flat_period=3;
end
C_r(:,j)=col_mod;
end

figure;
imagesc(phaseuw);
colormap('GRAY');
title('Original Phase');

figure;
imagesc(C_r);
colormap('GRAY')
title('Corrected');

%pi_fact is the proper scaling factor rather than just taking 2pi, since the
%maximum value might not be 255
pi_fact=max(max(C_r))/255*(2*pi);
D_r=C_r*pi_fact/max(max(C_r));

pi_fact=max(max(B_r))/255*(2*pi);
error=(B_r*pi_fact/max(max(B_r)))-D_r;

albedo=uint8(C(:,:,1));
B_c(:,:,1)=albedo;
B_c(:,:,2)=albedo;
B_c(:,:,3)=albedo;

albedo=uint8(I(:,:,1));
B_i(:,:,1)=albedo;
B_i(:,:,2)=albedo;
B_i(:,:,3)=albedo;

result=CPlleastsqmethod();
out=getWorldCoordsB(I(:,:,1),C_r,16);
xw=out(:,:,1);
yw=out(:,:,2);
zw=out(:,:,3);
mat5file='board';
result = mat5write(mat5file,B_c,B_i,xw,yw,zw);

figure;
subplot(2,1,1)
plot(z_co(:,550),r');
title('Original Z Coordinate');
subplot(2,1,2);
plot(zw(:,550),b');
title('Corrected Z Coordinate');
figure
x=1:1:My;
plot(x,phaseuw(:,500),r',x,C_r(:,500),b');
xlabel('Pixel value');
ylabel('Phase value');
legend('Original Phase','Corrected phase');

A.2 Projector Space Correction for solving gamma banding
%
University of Kentucky, Summer 2008
Akshay Pethe
Banding Correction in Projector Domain
This code converts the phase into projector domain, then it gets rid of the bands by finding the period and fitting straight lines between these bands. The phase is then again mapped back to the camera domain.
%
%Read the I, C and YP images
I=double(imread('C:\Users\pethe\Desktop\data\BandtestB\BandtestI.bmp'));
C=double(imread('C:\Users\pethe\Desktop\data\BandtestB\BandtestC.bmp'));
fid=fopen('C:\Users\pethe\Desktop\data\BandtestB\BandtestYP.by','rb');
B=fread(fid,inf,'float32');
fid=fopen('C:\Users\pethe\Desktop\data\BandtestB\BandtestZ.by','rb');
zco=fread(fid,inf,'float32');
[My Nx]=size(I(:,:,1))

%Converting to Projector Space
proj=zeros(My,Nx);
YP_values=zeros(My,Nx);
LUT_co_cam=zeros(My,2);

%Original Phase image
for xc=1:Nx
    for yc=1:My
        index=yc*Nx+xc;
        if(index>Nx*My)
            index=Nx*My;
        end
        B_r(yc,xc)=B(index,1);
    end
end

for xc=1:Nx
    for yc=1:My
        index=yc*Nx+xc;
        if(index>Nx*My)
            index=Nx*My;
        end
        B_r(yc,xc)=B(index,1);
    end
end
index=Nx*My;
end

yp=B(index,1);
YP=round(yp*(My-1)/(2*pi));
if(YP==0)
    YP=1;
end
if(YP>My)
    YP=My;
end

% Projector space phase image
if(yc==1 || xc==1)
    proj(YP,xc)=0;
else
    proj(YP,xc)=B_r(yc,xc)- B_r(yc-1,xc);
end

% YP values
YP_values(yc,xc)=YP;

% Zcoord
z_co(yc,xc)=zco(index);

% Finding average of the image to remove the noise
avg=zeros(My,1);
for j=1:Nx
    avg=avg+proj(:,j);
end
avg=avg/Nx;

% average=average*mean(avg(min(min(YP_values)):max(max(YP_values)),1));
average=average*mean(avg());

diff=proj-average;
alpha=1.45;
new_phase=zeros(My,Nx);
for xc=1:Nx
    for yc=1:My
        % Fetch the phase values
        yp=B_r(yc,xc);
        % Map it to projector domain
        YP=round(yp*(My-1)/(2*pi));
        % Make sure it is in correct bounds
        if(YP==0)
            YP=1;
        end

end
end

diff=proj-average;
alpha=1.45;
new_phase=zeros(My,Nx);
for xc=1:Nx
    for yc=1:My
        % Fetch the phase values
        yp=B_r(yc,xc);
        % Map it to projector domain
        YP=round(yp*(My-1)/(2*pi));
        % Make sure it is in correct bounds
        if(YP==0)
            YP=1;
        end

end
end
end
if(YP>My)
    YP=My;
end
%Fetch the corrected value
if(yc==1)
yp_corrected=B_r(yc,xc);
else
    yp_corrected = new_phase(yc-1,xc)+ alpha*(proj(YP,xc)-diff(YP,xc));
end
%Correct the value
new_phase(yc,xc)=yp_corrected;
end
end

%Rescale the Yp coordinate
clear bmp;
clear albedo;
albedo=uint8((new_phase*255)/(2*pi));
bmp(:,:,1)=albedo;
bmp(:,:,2)=albedo;
bmp(:,:,3)=albedo;
imwrite(bmp,'rescaled_YP.bmp','BMP');

%Reconstruction of the 3D data
result=CPlleastsqmethod();
out=getWorldCoordsB(I(:,:,1),new_phase,16);
xw=out(:,:,1);
yw=out(:,:,2);
zw=out(:,:,3);
mat5file='projcorrect';
clear albedo;
albedo=uint8(C(:,:,1));
B_c(:,:,1)=albedo;
B_c(:,:,2)=albedo;
B_c(:,:,3)=albedo;
clear albedo;
albedo=uint8(I(:,:,1));
B_i(:,:,1)=albedo;
B_i(:,:,2)=albedo;
B_i(:,:,3)=albedo;
result = mat5write(mat5file,B_c,B_i,xw,yw,zw);
A.3 Second Method to solve in Projector Space

The captured images can be converted to projector space as follows

- Choose a phase value \( Y_p \) from the camera space.

- Scale the \( Y_p \) such that

  \[ yp = Y_p \times \frac{My}{2\pi}, \]  
  where \( My = \) number of columns of the image.

- Now form the projector image as

  \[ I(xc,yp) = Y_p \]

In gamma banding since the number of bands is the product of highest frequency of
scanning and the number of patterns used, we can know beforehand what will be the
period of the bands and what would be the start and end point of each band. Thus this
would completely eliminate the searching. The period of the bands in the projector domain is given by

\[ BAND\_PERIOD = \frac{\text{Max}(YP) - \text{min}(YP)}{\text{NUM\_BANDS}} \]  

Where

\( YP = \) scaled value of the phase in the projector space

\( \text{NUM\_BANDS} = \) number of bands as specified in table 3.

Now once we get the exact band locations, these are mapped back to the camera space. All that is left to be done is to fit a straight line which passes through all these points, thus linearizing the phase. This approach can be used to calibrate the system, so that it would have to be done only once for a given system configuration.
Figure A-1: Flow chart for Projector space correction algorithm

1. Read in the phase image
2. Convert to projector space using the conversion
   \[ YP_{\text{proj}} = yp \times (M_y - 1)/(2 \times \pi). \]
   Form a LUT such that
   \[ \text{LUT}(YP) = yc \]
3. Calculate
   \[ \text{num}_b = \text{freq} \times \text{pattens} \]
   \[ \text{Period} = (\max(YP_{\text{proj}}) - \min(YP_{\text{proj}}))/\text{num}_b \]
4. Find the X and Y coordinates in projector space. X coordinates will be periodic such that
   \[ x_2 = x_1 + \text{period} \]
5. Find the pixel values in the camera space such that
   \[ X_{\text{cam}} = \text{LUT}(X(i)) \]
   Find the phase values such that
   \[ Yp_{\text{cam}} = \text{Phase image}(X_{\text{cam}}) \]
6. Find the slope and the intercepts in camera space.
7. Fit splices between X coordinates thus correcting the phase
8. Calculate new world coordinates
Figure A-2: Zoomed in image of phase before and after correction

Figure A-3: Z coordinate distribution
%\{  
University of Kentucky, Summer 2008  
Akshay Pethe  
Banding Correction in Projector Domain  
This code converts the phase into projector domain, then it gets rid of the bands by finding the period and fitting straight lines between these bands. The phase is then again mapped back to the camera domain.  
\%

\%Read the I, C and YP images  
I=double(imread('C:\Users\pethe\Desktop\data\BandtestB\Bandtest0I.bmp'));  
C=double(imread('C:\Users\pethe\Desktop\data\BandtestB\Bandtest0C.bmp'));  
fid=fopen('C:\Users\pethe\Desktop\data\BandtestB\Bandtest0YP.byf','rb');  
B=fread(fid,inf,'float32');  
fid=fopen('C:\Users\pethe\Desktop\data\BandtestB\Bandtest0Z.byf','rb');  
zco=fread(fid,inf,'float32');  
[My Nx]=size(I(;;,1))

\%Converting to Projector Space  
proj=zeros(My,Nx);  
YP_values=zeros(My,Nx);  
LUT_co_cam=zeros(My,2);  
for xc=1:Nx  
    for yc=1:My  
        index=yc*Nx+xc;  
        if(index>Nx*My)  
            index=Nx*My;  
        end  
    end  
end  

\% Figure A-4: 3D image reconstruction before (left) and after (right) correction
end
yp=B(index,1);
YP=round(yp*(My-1)/(2*pi));
if(YP==0)
    YP=1;
end
if(YP>My)
    YP=My;
end
% Projector space phase image
proj(YP,xc)=yp;
% Original Phase image
B_r(yc,xc)=B(index,1);
% YP values
YP_values(yc,xc)=YP;
% Zcoord
z_co(yc,xc)=zco(index);
% Creating the LUT
if(LUT_co_cam(YP,1)==0)
    LUT_co_cam(YP,1)=YP;
    LUT_co_cam(YP,2)=yc;
end
end
end

% Store the projector domain image in two more variables
A_r=proj;
A_r_ori=proj;

% Finding average of the image to remove the noise
% not used anywhere in this code
avg=zeros(My,1);
for j=1:Nx
    avg=avg+A_r(:,j);
end
avg=avg/Nx;

% Rough estimate of the period
freq=8; % highest frequency of scanning
pat=3; % number of patterns of the highest frequency used

% For dual frequency
num_bands=(freq*pat)/2; % number of bands appearing

% For Multi frequency
%num_bands=freq*pat; %number of bands appearing

% period of the bands in the projector domain (generic)
period = round((max(max(YP_values))-min(min(YP_values)))/num_bands);

for j=1:Nx
    col=A_r(:,j);
    x_coord=zeros(num_bands+2,1);
    y_coord=zeros(num_bands+2,1);
    x_coord(1)=min(YP_values(:,j));
    y_coord(1)=col(x_coord(1));
    % finding the x, y coordinates
    for i=2:num_bands+1
        x_coord(i)=x_coord(1)+round((i-1)*period);
        if(x_coord(i)>My)
            x_coord(i)=My;
        end
        y_coord(i)=col(x_coord(i));
    end
    % fix for y
    for i=2:num_bands+1
        if(y_coord(num_bands+1)==0)
            y_coord(num_bands+1)=max(col);
        end
        if(y_coord(i)==0)
            y_coord(i)=(y_coord(i-1)+y_coord(i+1))/2;
        end
    end
    % finding the slope
    slope=zeros(num_bands+1,1);
    for i=1:num_bands+1
        slope(i)=(y_coord(i+1)-y_coord(i))/(x_coord(i+1)-x_coord(i));
    end
    % Finding the intercepts
    intercept=zeros(num_bands+1,1);
    for i=1:num_bands+1
        intercept(i)=y_coord(i)-slope(i)*x_coord(i);
    end
% Fitting a line
for i=1:num_bands+1
    x=x_coord(i):1:x_coord(i+1);
    y=x*slope(i)+intercept(i);
    col(x_coord(i):x_coord(i+1),1)=y;
    clear x;
    clear y;
end

% for j=1:Nx
    A_r(:,j)=col;
    clear col;
end

figure;
imagesc(A_r_ori);
colormap('GRAY');
title('Original phase image in projector space');

figure;
imagesc(A_r);
colormap('GRAY');
title('Corrected phase image in projector space');

clear bmp;
clear albedo;
albedo=uint8((A_r)*255/(2*pi));
bmp(:,:,1)=albedo;
bmp(:,:,2)=albedo;
bmp(:,:,3)=albedo;
imwrite(bmp,'corrected_YP.bmp','BMP');

% Correction in Camera space September 2nd 2008
x_co_cam=zeros(num_bands+2,1);
y_co_cam=zeros(num_bands+2,1);
for i=1:num_bands+2;
    if(x_coord(i,1)==0)
        x_co_cam(i,1)=LUT_co_cam(1,2);
    else
        x_co_cam(i,1)=LUT_co_cam(x_coord(i,1),2);
    end
    if(x_co_cam(i,1)==0)
        x_co_cam(i,1)=1;
    end
end
y_co_cam(i,1)=B_r(x_co_cam(i,1),500);
end

slope_cam=zeros(num_bands+1,1);
intercept_cam=zeros(num_bands+1,1);
for i=1:num_bands+1
    if((x_co_cam(i+1)-x_co_cam(i))==0)
        slope_cam(i)=slope_cam(i-1);
    else
        slope_cam(i)=(y_co_cam(i+1)-y_co_cam(i))/(x_co_cam(i+1)-x_co_cam(i));
    end
end

for i=1:num_bands+1
    intercept_cam(i)=y_co_cam(i)-slope_cam(i)*x_co_cam(i);
end

final_slope_cam=mean(slope_cam)
final_intercept_cam=mean(intercept_cam)

x_cam=1:1:My;
y_cam=final_slope_cam*x_cam + final_intercept_cam;
for i=1:Nx
    new_phase(:,i)=y_cam;
end

%Rescale the Yp coordinate
clear bmp;
clear albedo;
albedo=uint8((new_phase*255)/(2*pi));
bmp(:,:,1)=albedo;
bmp(:,:,2)=albedo;
bmp(:,:,3)=albedo;
imwrite(bmp,'rescaled_YP.bmp','BMP');

%Reconstruction of the 3D data
result=CPlleastsqmethod();
out=getWorldCoordsB(I(:,:,1),new_phase,16);
xw=out(:,:,1);
yw=out(:,:,2);
zw=out(:,:,3);
mat5file='projcorrect';
clear albedo;
albedo=uint8(C(:,:,1));
B_c(:,:,1)=albedo;
B_c(:,:,2)=albedo;
B_c(:,:,3)=albedo;
clear albedo;
albedo=uint8(I(:,:,1));
B_i(:,:,1)=albedo;
B_i(:,:,2)=albedo;
B_i(:,:,3)=albedo;
result = mat5write(mat5file,B_c,B_i,xw,yw,zw);
figure;
subplot(2,1,1)
plot(z_co(:,500),'r');
title('Original Z Coordinate');
subplot(2,1,2);
plot(zw(:,500),'b');
title('Corrected Z Coordinate');
figure
x=1:1:My;
plot(x,proj(:,550),'r',x,A_r(:,550),'b');
xlabel('Pixel value');
ylabel('Phase value');
legend('Original Phase(projector domain)','Corrected phase(projector domain)');
figure
x=1:1:My;
plot(x,B_r(:,550),'r',x,new_phase(:,550),'b');
xlabel('Pixel value');
ylabel('Phase value');
legend('Original Phase(camera space)','Corrected phase(camera space)');
References


Vita

Akshay Pethe was born on 2\textsuperscript{nd} February 1983 in Mumbai, India. He was awarded the Bachelors of Engineering in Electronics from Mumbai University in 2005. He worked as a mainframe programmer in TATA Consultancy Services Pvt. Ltd from June 2005 to June 2006. He was a Research Assistant at University of Kentucky from February 2007 to May 2008. Currently he is working in Intel Corporation.

Akshay Gajanan Pethe