Dense distance map reconstruction of deformed surfaces using Moiré pattern analysis

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**DENSE DISTANCE MAP RECONSTRUCTION OF
DEFORMED SURFACES USING MOIRÉ PATTERN
ANALYSIS**

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SCHOOL OF COMPUTER ENGINEERING

2010

DENSE DISTANCE MAP RECONSTRUCTION OF DEFORMED SURFACES USING MOIRÉ PATTERN ANALYSIS

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Summary

Moiré patterns are the results of the interference fringes produced by superimposing two sets of repetitive gratings. These patterns are used in metrology for tasks such as strain measurements, vibration analysis and 3D surface reconstruction. Usually the setup used to generate Moiré patterns requires a grating on the surface to be analyzed and an additional semi-transparent reference grating. In this study, the regular spatial arrangement of sensor cells within a CCD camera is used to simplify this setup. Moiré fringes generated with the simplified setup are extracted with a simple, fast spatial domain algorithm. The relationship between the distances from points on a deformed surface to the imaging plane and the Moiré fringes frequency was derived and verified through a series of experiments. The Least-Squares Truncated Power Series Algorithm (L-STPSA) [1, 2] was adapted to extract the instantaneous frequency of the 1-dimensional Moiré waveform so that a dense distance map of the observed smoothly deformed surfaces can be reconstructed. Two applications were implemented to demonstrate how the proposed surface displacement measurement technique can be used to construct novel human-computer interfaces based on pressure sensitive touch surfaces.

Chapter 1

Introduction

1.1 Moiré Patterns

“Moiré” is a French word referring to *an irregular wavy finish usually produced on a fabric by pressing between engraved rollers*, --Webster’s 1981. Moiré patterns are fringes observed when images with regular patterns superimposed, and these fringes do not exist in any of the original images. As shown in Figure 1.1, Moiré patterns are easily observed when overlapping two similar patterns.

Figure 1.1: (a) Moiré patterns with two similar line patterns (b) Moiré patterns with two similar circular patterns.

Moiré patterns are sensitive to very small relative changes in the geometry of the two superimposed patterns. As shown in Figure 1.2, two different Moiré patterns were generated by overlapping line stripes. 1-pixel shifting of the second line pattern from Figure 1.2(a) to Figure 1.2(b) makes the Moiré patterns significantly wider in black

lines, thinner in white lines. Analysis on changes in the generated Moiré patterns is then used to infer the relative geometrical change of the original superimposed images.

Figure 1.2: (a) Moiré patterns with two similar line patterns with offset by n pixels. (b) Moiré patterns with two similar line patterns with offset by $n+1$ pixels.

In typical Moiré pattern analysis, the pattern on a reference grating is kept constant and the pattern on a specimen surface is allowed to vary based on physical deformation. The observed Moiré patterns variations are then used to analyze the nature of the deformation occurring in specimen surface. A common application of Moiré pattern analysis is strain measurement [3, 4]. Other applications of Moiré patterns analysis include the recovery of the surface geometry on three dimensional objects or vibration analysis. [3, 5], Figure 1.3 illustrates a typical measurement setup with Moiré pattern.

Figure 1.3: A typical Moiré patterns application setup for strain measurement.

An interesting observation is that most modern imaging devices form images with electronic cells arranged in a regular spatial structure, usually in a 2D array, such as computer LCD monitors, CCD cameras, etc. When LCD monitors display images (see Figure 1.4) with patterns that have spatial dimensions which are close to that of the LCD cell spacing, Moiré patterns can be easily observed. Similarly, the captured images from CCD cameras contain Moiré patterns when fine regular patterns have close spatial dimensions to the CCD cells spatial arrangement are in the camera view. Traditionally, these Moiré patterns are considered annoying artifacts of the devices, because the Moiré patterns are getting in the way of the true purpose of the devices.

Figure 1.4: Moiré patterns appear on LCD monitor when displaying tiny dense vertical lines

Figure 1.5: A simplified setup which employs a CCD camera and Moiré pattern analysis to measure surface deformation.

Figure 1.5 illustrates the Moiré patterns formed when a CCD camera captures a fine line grating pattern. Under such a situation, the regular grid arrangement of the

CCD cells in the camera acts as a reference pattern. With this simple setup, no special transparent reference surface is needed to generate the Moiré patterns as shown in Figure 1.3.

1.2 Motivations

It was observed that images from a CCD camera often generated interesting Moiré patterns when surfaces with high frequency patterns come into view of the camera. A question was then asked, “Are these Moiré patterns annoying visual artifacts or can they be useful”? This question led to some basic investigation on the characteristics of Moiré patterns. It was observed that not many research works actually use CCD camera as one of the reference gratings. In 1984, *Y. Morimoto* and *T. Hayashi* used this approach [6] to measure powder compression deformation. These Moiré patterns were from CCD cameras were treated artifacts and a few methods were developed to remove them [7].

It was also observed in early investigations that Moiré patterns generated are sensitive to small relative changes. *Rong-Seng Chang et-al* [8] shows that Moiré pattern can be used to perform micro range measurement with good accuracy. This work suggests that Moiré pattern could be used to measure small deformation caused on the specimen surface. However, their study did not explore the possibilities to reconstruct a deformed surface.

Experiments were then conducted with simple line patterns to explore the characteristics with these Moiré phenomena. A simpler sub-sampling enhancement technique was discovered to extract Moiré patterns for analysis rather than the wavelet transform technique used in [8]. This finding also enables the possibility to perform the same task as the one shown in [8] with simpler setups, because the new technique does not need the frequency of the line patterns to be extremely high. This technique would be presented in detail in Chapter 3.

Based on the new technique, if the deformed surface could be reconstructed, this would enable novel ways of constructing touch-based human computer interactive devices. This goal motivated the subsequent research.

1.3 Objectives and Contributions

The main objective of this thesis is to explore the use of CCD based Moiré patterns for reconstructing a dense distance map of smoothly deforming surfaces. The characteristics of the resulting Moiré pattern are studied to find a reliable method to reconstruct the distance profile of the observed line grating surface. With the ability to reconstruct the dense distance map, a novel input device was built to provide pressure sensitive touch surface for interacting with computer applications.

The contributions of the thesis are listed as follows:

- Developed a mathematical relationship among the Moiré fringe width, the relative pitch width of the observed line gratings, and the cells' spacing of the CCD camera.
- Proposed a simple and fast spatial sub-sampling technique for recovering the Moiré pattern waveform from signals that contain high frequency line grating artifacts.
- Adapted an existing parametric AM-FM signal modeling technique to recover the Moiré fringe width at any point along a 1D profile of the Moiré image. This allows the reconstruction of a dense and varying distance profile of the line grating surface.
- Demonstrated that the distance profile can be robustly extracted in poor and inconsistent lighting conditions such as shadow cast.
- Develop the model to recover the absolute distance profile from the instantaneous frequency variation in the Moiré pattern after the system has been calibrated.
- Extend and develop the model to reconstruct the distance map for a smoothly deforming surface.

- Constructed a simple pressure sensitive touch-based interface to demonstrate novel interaction design based on this type of user interface.

The following diagram (Figure 1.6) summarizes the general flow of the dense distance map reconstruction process, and the topics covered in this thesis.

Figure 1.6: Summary of the process using Moiré-based surface reconstruction technique.

Publications arising from this study:

- T. Tu & W.B. Goh, “*MOIRE PATTERN FROM A CCD CAMERA – Are They Annoying Artifacts Or Can They Be Useful?*” Proc. of the Fourth International Conference on Computer Vision Theory and Applications, *VISAPP2009*, Feb. 2009.
- T. Tu & W.B. Goh, “*Using CCD Moiré Pattern Analysis to Implement Pressure-sensitive Touch Surfaces*” 13th International Conference on Computer Analysis of Images and Patterns, *CAIP2009*, Sept. 2009 (to be presented).

1.4 Thesis Organization

This thesis contains 7 chapters. Each of which is summarized in this section. Chapter 1 describes the main objective and motivations for this works. Main contributions arising from the subsequent investigations are also listed. Chapter 2 is the literature review which briefly summarizes some of the related studies, Moiré pattern applications and surface reconstruction. In Chapter 3, the new 1D Moiré waveform extraction technique is presented. Chapter 4 introduces the mathematical theories related the reconstruction of the smoothly deforming surfaces. It starts with flat surfaces, then explores the incline surfaces and ends with the smoothly deforming surfaces. Chapter 5 presents all relevant results, and it discusses the strength and limitation of this reconstruction technique. Chapter 6 develops a novel pressure sensitive touch-based interface with the proposed dense distance map reconstruction technique. It also demonstrates two simple applications which use the constructed interface. Finally, Chapter 7 concludes the thesis and discusses future work.

Chapter 2

Literature Review

2.1 Moiré Patterns

Moiré patterns were discovered in 1874 by *Lord Rayleigh* [9], Moiré patterns are additional regular fringes generated from overlapping two or more similar patterns. Moiré phenomena are easily observed in daily life, like those from a mesh waste basket shown in Figure 2.1(a). On television, Moiré patterns could be observed on shirts patterned with fine lines or grids (see Figure 2.1(b)). In the digital world, Moiré patterns could be observed in different imaging devices, like camera [6, 8], scanners [10], x-ray microscope [11], and computer monitors [12], etc.

(a)

(b)

Figure 2.1: Observed Moiré patterns in daily life. (a) Mesh waste basket ¹ (b) A shirt with line patterns².

Moiré patterns observed with imaging devices are normally treated as image artifacts. There are hardware and software methods to remove them in the final results produced by these devices. *Kris Zaklika –Jasc Software Inc* has developed the noise removal filters in digital camera. With proper settings, Moiré patterns can be removed

¹ Source: <http://www.organizeit.com/pomeshwast.asp>

² Source: <http://ozark.hendrix.edu/~burch/cs/150/assn/03/index.html>

from the captured images [7]. And tutorials to remove Moiré patterns in photos with software solution like *Adobe Photoshop* [13], or *Ulead PhotoImpact* [14] are also available. Researchers are also developing techniques to remove these artifacts for specific scenarios, like Moiré patterns removed from color flat panel display [12], and Moiré patterns removed from scanned halftone pictures [10].

In the works of [3, 4, 15], Moiré patterns have been well studied using different approaches, either with simple geometry knowledge [3, 15], or complicated signal processing approaches [4].

Regular patterns used to generate Moiré patterns vary, and common ones include dots [16, 17], lines [4, 18, 19] as shown in Figure 2.2. Simple patterns allow us to develop simple mathematical models for the analysis of the resulting Moiré patterns.

Figure 2.2: Common overlapped regular patterns for generating Moiré fringes, (a) dots (b) parallel lines.

2.2 Moiré Patterns Applications

Moiré pattern related techniques were developed for various applications, such as remote measurements [4, 20, 18], surface or 3D objects reconstruction [6, 3, 21], micro-range measurements [8], and object recognition [22].

In *Setiawan Hadi's* work [16], Moiré patterns were generated by overlapping two layers with dense random dots, with one of them transformed with a small rotation. In

his experiment, it was discovered that if the two dense random dots are similarly distributed, circular Moiré patterns would appear in the resulting image (see Figure 2.3).

Figure 2.3: Formation of circular Moiré patterns from dots, (a) original dots patterns (b) rotated dots patterns (c) resulting circular moiré patterns.³

The circular moiré patterns were identified visually and with a Hough based technique [16, 22]. In [16], the goal of this study is to match an ‘unknown’ human face to one of the known faces. Hadi, Setiawan has developed a method to turn black and white faces into dense dots. All images including the unknown face and known faces were turned into dots patterns. The dots pattern from the unknown face was then rotated by a small angle. When the rotated unknown face dot pattern was superimposed on top of each known face dots patterns, the face corresponding to the one resulting Moiré pattern contains most obvious circular pattern would be recognized for the unknown face.

An interesting characteristic of Moiré fringes is its sensitivity. A small geometric change in the pattern would result in quite significant change in the Moiré fringe pattern. This is the reason that patterns are widely used to perform remote measures. Usually line patterns would be used [15, 4, 20, 19].

Superimposing line patterns would generate Moiré patterns as lines, as shown in Figure 2.4.

³ Source: paper [16] listed in references

Figure 2.4: Moiré pattern generated with two line gratings. A specimen line grating with equal pitches p_s , which is overlaid with a reference line grating with equal pitches p_r , and generating the Moiré pattern with lines pattern of equal pitches p_m . 2α is the rotation angle between the line patterns.

Applying 2D geometrical relationship between the parallel lines [15] (details shown in Appendix B), the parameters shown in Figure 2.4 obey the following equation.

$$p_m = \frac{p_s \cdot p_r}{\sqrt{p_r^2 \sin^2 2\alpha + (p_r \cos 2\alpha - p_s)^2}} \quad (1)$$

If the two patterns p_s and p_r are the same ($p_s = p_r = c$, c being a known constant), then

$$p_m = \frac{c}{2 \sin \alpha} \quad (2)$$

With this simple equation, the relative rotation angles 2α between the two gratings could be measured through p_m . *Chang* is a pioneer in deploying this method to measure the planar surface rotations [8].

Before p_m could be measured, the Moiré fringes must be extracted by removing artifacts from original line patterns. These artifacts are usually at higher frequencies than the generated Moiré fringes. Naturally a low-pass filter could be used to separate them.

Figure 2.5: Fourier Transform (FT) analysis on a captured image (a) the captured image, (b) the selected 1d waveform in the captured image. (c) the linear scale 1d FT spectrum of the selected scanline in a capture image.

As shown in Figure 2.5, the frequencies of the Moiré pattern and line gratings are poorly separable in the frequency space. In the frequency domain, a simple filter would not work well, because the Moiré fringes may span different frequencies (due to the variation in surface displacements) and they are very close to the frequency of line grating artifacts.

In [23], the authors combined four different phase-shifted moiré patterns to remove noises, as shown in Figure 2.6. The four signals were modeled as

$$I_a(x, y) = I_0(x, y) + I_1 \cos 2\pi f U(x, y) \quad (3)$$

$$I_b(x, y) = I_0(x, y) + I_1 \cos 2\pi f \left[U(x, y) + \frac{1}{4f} \right] \quad (4)$$

$$I_c(x, y) = I_0(x, y) + I_1 \cos 2\pi f \left[U(x, y) + \frac{2}{4f} \right] \quad (5)$$

$$I_d(x, y) = I_0(x, y) + I_1 \cos 2\pi f \left[U(x, y) + \frac{3}{4f} \right] \quad (6)$$

Figure 2.6: Four phase shifted Moiré patterns.⁴

In the four signal models, $I_0(x, y)$ is the component which is not relevant to phase, $I_1(x, y)$ is the phase sensitive component. These two are temporary modeling parameters, solving the above four equations, $U(x, y)$ is obtained,

$$U(x, y) = \frac{1}{2\pi f} \tan^{-1} \frac{I_d(x, y) - I_b(x, y)}{I_a(x, y) - I_c(x, y)} \quad (7)$$

This obtained image $U(x, y)$ is an enhanced phase map of the Moiré patterns, see Figure 2.7. This approaches enhances the noisy Moire patterns, but it requires several

⁴ Source: [23] in the references.

phase shifted images as input, such techniques are not convenient for real-time applications.

Figure 2.7: Enhanced Moiré patterns.⁵

In 1984, *Y. Morimoto* and *T. Hayashi* [6] used skeletons thinning image processing method to find the skeletons of the Moiré fringe images. The binary, skeleton images are considered to be the enhanced Moiré patterns (see Figure 2.8).

Figure 2.8: Strain map reconstruction algorithm used by Morimoto and Hayashi, (a) the captured image with Moiré patterns, (b) the thinned skeleton representing the Moiré patterns, (c) the interpolated displacement map.

With the knowledge of the maximum displacements, (8 mm for their powder compact experiment), a fixed intensity is assigned for all pixels that have value 1 within the binary images, and then a 2D smoothing function is applied to form a strain displacement map. In their Moiré pattern extraction, the skeleton thinning method is an iterative and 2D region operation, which is much more computationally expensive

⁵ Source: (23) in the references.

than the algorithm proposed in this thesis. After thinning the skeleton, most of the input information would be lost, and the subsequent smoothing function would not produce an accurate reconstruction of the dense strain map.

With enhanced Moiré patterns, the pitch, p_m can now be better measured. In [23], fringes were counted. In [8, 19], wavelet transformation were used, wavelet transformation require better separation in frequency domain between Moiré fringe and line patterns. Thus, in their studies, high frequency line patterns were used. For example, in [8], a micro-pitch grating of 300 lines per inch was employed as the specimen grating. This allowed the line pitch of the imaged specimen grating to be close to the actual dimension of the pitch width of the CCD cell spacing. This situation produces Moiré fringes that do not suffer annoying artifacts from the specimen grating pattern, making the extraction of the fringe pitch simple (see Figure 3.3). They subsequently employed the wavelet transform to band-pass the frequency components of the Moiré fringes. This special grating also helps the authors to perform micro range movement for a plane which is perpendicular to the observing camera. However in practice, it is difficult to obtain such dense line gratings except through complex photolithographic processes.

2.3 Surfaces Reconstruction

Moiré patterns were also used to reconstruct 3D surfaces. An example of surfaces reconstruction with Moiré patterns can be found in [21]. In their study, color coded line patterns were used. Each line was composited with two colors, each taking a half width of the line. One color was red, and the other was blue. When the distorted lines were super-imposed by the original lines, Moiré patterns were generated, as shown in Figure 2.9(b). Since the line patterns were color coded, the Moiré patterns were colorful ones. The authors then scanned the entire image horizontally to form a 3D surface map. It was shown that similar height would have similar waveform from the scanned color intensity profile.

Figure 2.9: Three-dimensional surfaces reconstruction with color coded Moiré patterns. (a) line gratings added on to the deformed surface. (b) Moiré patterns generated with a non-deformed surface with same gratings.⁶

This method is simple, however, the authors do not define a specific transformation from color intensity profile to distance, they only showed at different surface heights, different color profiles would be observed. Suppose surface distances vary along scanline B there it would be complex to find such a transformation, (see Figure 2.9(b)).

Another study [24], works on more generic deformed surface. Fine line gratings were printed on an A4 paper with 1200 *dpi* printers, and then the paper was placed on randomly deformed ground. The authors used a point light and a camera. These two devices were placed in different places. With this setup shadow Moiré patterns were presented in the paper [15], as shown in Figure 2.10(a). These Moiré patterns were forming contours in the captured images. The authors suggested using normal mapping from contour to distance maps to reconstruct the surfaces.

⁶ Source: [21] in the references.

Figure 2.10: (a) Shadow Moiré patterns generated for a deformed surface. (b) True 3d distance maps for the deformed surface.⁷

Besides Moiré patterns, there are also other computer vision related methods to reconstruct 3D surface, including coded structure light [25, 26, 27, 28, 29, 30, 31, 32], integrating multiple views [33, 34, 35, 36, 37, 38, 39, 40, 41, 42] and others [43, 44, 45, 46, 47, 48, 49, 50].

For structure lights, the idea is to project specially designed coded patterns, lines or grids onto the surfaces to be reconstruct. By analyzing the distortion of the coded patterns caused by the undulating surface, a corresponding surface map can be established. Simple structure light techniques use static patterns [28, 32].

In study [32], the authors projected a horizontal line structure lights onto a face surface (see Figure 2.11(a)). The face with the distorted line patterns were then captured with a camera (Figure 2.11(b)). After extracting the line patterns and then applying appropriate geometry transformations to the line distortions measured, a 3D face model was generated. This approach is simple to implement, however, there were usually a lot of missing points when classifying which pixels belong to which distorted line. As a result, poorly reconstructed surface patches or holes may appear.

⁷ Source: [24] in references.

Figure 2.11: (a) 3D face reconstruction setup, projector outputs horizontal line grids (b) a sample captured image with distorted patterns (c) extracted and estimated distorted patterns (d) reconstructed 3D face model.⁸

In study [28], uniform dots pattern was projected onto a 3D surface and a distorted dots set were captured. To recreate the 3D surfaces, multiple cameras were used to capture these distorted dots sets in different phase-shifted positions. Combining these phase-shifted dots sets into points. With different models (iso-line modeling in Figure 2.12(b), grid modeling in Figure 2.12(c)) to fit these combined dots sets, different 3D surfaces were then reconstructed.

⁸ Source: (32) in the references.

Figure 2.12: (a) a sample captured image with distorted dots (b) the surface reconstructed with isoline model (c) the surface reconstructed with grid model.

In order to reduce the number of cameras, time-sliced patterns were used [30, 29]. Gray code patterns are patterns whose line width starting with a thick one and then reducing half of the previous line width in each unit time, interaction as shown in Figure 2.13(a) [30]. Another common coding techniques used are phase shifted patterns, see Figure 2.13(b). *Jens Ghring et.al* have combined both codes [33] to reconstruct 3D dense maps. Other patterns were also designed for 3D object reconstructions [27].

Figure 2.13: (a) gray code sequence (b) phase shift sequence.

Structure lights are good at reconstructing 3D surfaces by imposing designed regular patterns onto the surfaces to produce geometry distortions. However, using captured information alone, with multiple views of the same surface from different camera positions, reconstructing the 3D surfaces were implemented with color, edge information [38, 39, 40, 42] instead of geometry distortion of regular patterns.

Among other reconstruction methods [43, 44, 45, 47, 46, 49, 50, 48], shadows were used to generate 3D surfaces [45, 50], complex statistic modeling and knowledge modeling [47, 48] were studied as well.

These surface reconstruction studies are aiming to build virtual objects or virtual environment observed by the camera. Comparing with all the above mentioned research, my work has a relatively simpler setup; no intensively dense line grating patterns are required as in [8]. The spatial domain Moiré waveform extraction algorithm proposed in my work does not require any frequency domain operations such as the wavelet transform in works like [8, 19]. The algorithm is also sensitive to small surface displacements.

Chapter 3

Moiré Pattern Analysis

This chapter introduces the basic Moiré analysis theory used in this work. The regular patterns used to generate Moiré patterns are line patterns of different pitches. However, within the scope of the work presented in this thesis, the angle between the two line gratings is always zero. In other words, the angle between reference and specimen line gratings shown in Figure 2.4 is equal to zero, ($\alpha = 0$). With $\alpha = 0$, the Eqn. (1) can be simplified to,

$$p_m = \frac{p_s \cdot p_r}{|p_r - p_s|} \quad (8)$$

This equation is the basis for the subsequent work in this chapter, p_m is the observed Moiré fringe pitch, p_s is the pitch of the specimen line grating and p_r is the pitch of the reference grating, which in this work is given by the distance between the imaging cells of the CCD camera. This equation is only valid when $|p_r - p_s| < p_r$. Chapter 4 discusses the extension of this relationship for cases where the specimen line grating pitches p_s is much larger than the reference grating pitch p_r .

3.1 Moiré patterns from a CCD Camera

A CCD camera forms 2D images through the CCD sensors, which are physically arranged in a grid structure. Each sensor cell gathers the light falling on it with a designed integration function about its center location. The integrated light intensity from each sensor cell would contribute to the corresponding pixel intensity in the final captured image as shown in Figure 3.1.

Figure 3.1: The CCD sensor cells image capturing principle.

As implied by Eqn. (8), the ability to measure the Moiré fringe pitch p_m is essential to all Moiré-based measurement problems. However, the Moiré patterns are mixed with the original patterns, so it is critical for us to remove the artifacts arising from the original pattern in order to extract the Moiré pattern in the image.

The specimen line grating in this study has a relatively larger pitch (approximately 33 lines per inch), which means that these gratings can be easier generated from a 300 or 600 *dpi* laser printer. Using such coarse pitch specimen gratings results in Moiré fringes that are not well separated in the frequency domain (see Figure 2.5). Traditional frequency domain-based techniques like wavelet transform [8, 19] cannot be easily applied to extract the pitch of these Moiré fringes. The subsequent sections discuss some interesting property that results from employing the CCD array as a reference grating and a fast time domain algorithm for measuring the pitch of the Moiré fringes is introduced.

3.2 Moiré pattern pitch with two line gratings in Parallel

When the CCD reference line grating and the specimen line grating are in parallel ($\alpha=0$). We have the scenario illustrated in Figure 3.2. This scenario would be the focus of the Moiré pattern extraction algorithm.

Figure 3.2: Moiré fringes are formed when two line gratings of different pitch are superimposed.

3.2.1 Moiré Fringes from Gratings with Near Similar Pitch

Figure 3.2 shows two overlapping line gratings, whose pitches are roughly of the same dimensions, the pitch of the reference and specimen gratings are p_r and p_s respectively. In Figure 3.2, the situation where the pitch of $p_s > p_r$ is illustrated, however, p_s is only slightly larger than p_r . As a result of the two gratings being superimposed, lower frequency Moiré fringes (light) with period p_m results due to the repeated and regular maximum overlap of the two sets of dark lines. Dark fringes are observed in zones of minimum overlap. The Moiré fringe pitch, p_m is given by the well known Eqn. (8).

For cases where $p_s > p_r$, the absolute value of Eqn. (3) is used to give the fringe pitch p_m . Let us assume that the reference line grating is now replaced by a regular-pitched CCD imaging cells, which have approximate point spread integration function

over each of their cell pitch, in later discussions it would be shown that the model of CCD cell response would not affect our analysis. Figure 3.3 (a) shows the resulting 1-D image intensity profile. Notice that the extracted period p_m of the Moiré fringe pattern can be obtained easily since there are little artifacts from the specimen grating.

Figure 3.3: Moiré fringe patterns obtained when using point spread function of the specimen grating intensity falling on regularly-spaced CCD cells. The image intensity profile obtained when the CCD pitch (reference grating) and the specimen grating pitch are (a) $p_r=40$, $p_s=46$ spatial units respectively and (b) $p_r=40$, $p_s=48$ spatial units respectively.

It is shown in Figure 3.3 that the pitch According to Eqn. (8), the closer the reference grating pitch p_r is to the specimen grating p_s , the wider is the pitch p_m of the observed Moiré fringes. Figure 3.3 (b) confirms this observation as the Moiré fringe pitch p_m begins to reduce in value as the pitch p_s of the specimen grating is increased slightly relative to the CCD cell pitch. p_m measured agree with Eqn. (8).

3.2.2 Moiré Fringes from Gratings with Dissimilar Pitch

What happens when the pitch of the specimen grating, p_s is much larger than that of the reference grating, p_r , as shown in Figure 3.4(b)? This section derives a new expression for the Moiré fringe pitch, p_m' for the situation shown in Figure 3.4(b) where $|p_s - p_r| > p_r$ since the fringe pitch expression given in Eqn. (8) is only valid for

the situations shown in Figure 3.3(a), where $|p_s - p_r| < p_r$. In order to make use of Eqn. (8), subtract the largest integer multiple of the reference pitch p_r from the large specimen grating pitch p_s' . The remaining pitch value after subtraction, given by $\hat{p}_s$ is less than p_r and can therefore be substituted into Eqn. (8) to compute the Moiré fringe period p_m . In Figure 3.4(b), an example is illustrated where this remaining pitch $\hat{p}_s$ has a value of p_s . As shown in Figure 3.4(a), if the width of the Moiré fringe pitch p_m is made up of $k \times p_s$ width (in the example shown in Figure 3.4, $k = 3$), then the fringe pitch p_m' of the wide specimen grating will also be given by $k \times p_s'$.

Figure 3.4: Resulting pitch for the Moiré fringes generated when the specimen grating pitch is (a) only slightly larger than the reference grating pitch and (b) much larger than the reference grating pitch. Notice the Moiré fringe pitch is made up of $k = 3$ specimen grating pitches in both cases (see text for details).

From Eqn. (8), the number of specimen grating, p_s making up the Moiré fringe pitch with p_m is given by

$$k = \frac{p_m}{p_s} = \frac{p_r}{p_r - p_s} \quad (9)$$

Now consider a specimen grating pitch p_s' that is much larger than the reference grating pitch p_r . Find the maximum number of integer multiples of p_r within p_s' and this integer multiply m is given by

$$m = \left\lfloor \frac{p_s'}{p_r} \right\rfloor \quad (10)$$

where $\lfloor \cdot \rfloor$ is the floor function. The remaining pitch $\hat{p}_s$ after removing integer multiples of the reference pitch, p_r is therefore given by

$$\hat{p}_s = p_s' - mp_r \in [0, p_r] \quad (11)$$

The number of specimen grating pitch width contained within the Moiré fringe pitch can be obtained by substituting (11) into (9), and is given by

$$k' = \frac{p_r}{p_r - \hat{p}_s} \quad (12)$$

The Moiré fringe pitch, p_m' for the large specimen grating with pitch p_s' and this is given by

$$p_m' = k' \times p_s' = \frac{p_r p_s'}{p_r - \hat{p}_s} \quad (13)$$

Substituting (9) into (13) gives

$$p_m' = \frac{p_r p_s'}{(1+m)p_r - p_s'} \quad (14)$$

From this general expression of the Moiré fringe pitch, we can observe that the presence of the $(1+m)$ factor ensures that the absolute value of the denominator of both Eqns. (8) and (14) will not exceed 1.

Figure 3.5: Moiré fringe patterns obtained with different specimen gratings of different pitch widths. The reference grating in both cases has $p_r=40$. Specimen grating pitch in (a) $p_s=48$ and in (b) $p_s=88$. In both cases, the remaining pitch width $\hat{p}_s=8$.

This means the increase in specimen grating pitch p_s' will produce a fringe pitch p_m' that is equally magnified, as shown in Figure 3.5.

3.3 Removing Specimen Grating Artifacts using Sub-sampling

The resulting Moiré pattern produced when $m > 1$ (see Figure 3.4(b)) contains significant high frequency artifacts from the specimen line grating, which makes automatic fringe pitch detection difficult.

Since the reference grating pitch p_r is the pitch of the CCD cell and therefore the pixel width, these high frequency artifacts can be quickly removed by down-sampling (sub-sampling) the Moiré pattern waveform as shown in Figure 3.6. For situations where $m = 1$, down-sampling is done by selecting every other pixel in the original $N \times N$ sized image to form new image of size $N/2 \times N/2$. It is not important whether the even or the odd pixels are removed as this only causes a phase shift in the resulting down-sampled waveform. Notice in Figure 3.6, the pitch width (in terms of pixel

count) of the Moiré fringe remains unchanged after down-sampling (i.e. 11 pixels in the given example).

Figure 3.6: Removing the high frequency specimen line grating artifacts by sub-sampling.

When the value of $(1+m)$ in Eqn. (14) is 3, an artifact-free waveform could be obtained by sub-sampling every other 3rd point. When $(1+m)$ is 4, sub-sample every other 4th point and so on (as shown in Figure 3.7, Figure 3.8 and Figure 3.9). In the experimental setup presented in Chapter 5, every other 4th pixel in the full resolution image was sampled in order to remove the high frequency artifacts of the specimen line grating. This would suggest that a value of $m = 3$ exist due the imaging distance and lens magnification factor used to observe the specimen line gratings.

Figure 3.7: No sub-sampling needed as $m+1=1$, $m=0$. (a) line grating signal and CCD cell integration function. (b) generated Moiré pattern.

Figure 3.8: Sub-sampling once with every 2 pixels needed as $m+1=2$, $m=1$. (a) line grating signal and CCD cell integration function. (b) generated Moiré pattern after sub-sampling once every 2 pixels.

Figure 3.9: Sub-sampling once every 3 pixels needed as $m+1=3$, $m=2$. (a) line grating signal and CCD cell integration function. (b) generated Moiré pattern after sub-sampling once every 3 pixels.

This sub-sampling method is very efficient and fast in extracting the Moiré patterns from the observed signal from the CCD camera, since only selection operations are performed on the entire image pixels set.

3.4 CCD Cell Summation Model and the Shape of the Moiré Pattern Waveform

The observed Moiré pattern is formed from the individual CCD cell summation of specimen line grating intensities across the uniform 2D cell arrangements. For each cell, an integral function could be used to model how a CCD cell captures its associate pixel intensity value. A 1D cross section taken perpendicularly to the black and white line grating image will produce an image intensity profile resembling a rectangle pulse train (as depicted in Figure 3.3). However, the CCD integral function is most likely to approximate a point spread function which is not entirely known to us. The question here is how would the point spread function of CCD cell influence the shape of the

resulting Moiré waveform? In previous discussions of the Moiré pattern extraction, the simulation treated the line gratings as perfect square signals and the CCD cell's integration function as one that approximate a normal distribution across the width of the cell. Simulation results were obtained for 3 hypothetical summation models as shown in Figure 3.10. These models were the impulse summation at the centre of the CCD cell; the centered Gaussian point spread summation and the ideal uniform summation over the entire CCD cell width.

Figure 3.10: Three different intensity summation models for the hypothetical CCD cell.

Figure 3.11 shows the resulting 1D Moiré pattern waveform for each of the three summation models. Notice that the shape of the waveform is dependent on the CCD integration function but the fundamental frequency, which is related to the Moiré fringe pitch width, remains unchanged.

Figure 3.11: The resulting Moiré waveform using (a) Gaussian point spread, (b) impulse and (c) uniform CCD cell intensity summation model. These results were obtained with a specimen line grating pitch where the value of m in Eqn. (14) is 0.

In summary, from our experiments, I observed that the Moiré pattern pitch is not affected by how the CCD integrates the light intensity falling on each of its individual cell. And it is shown in Chapter 4; the dense distance information of a line grating surface can be derived from the instantaneous pitch widths of the Moiré waveform.

Chapter 4

Surface Distance Map Estimation

Figure 4.1: Distance reconstruction technique flow with thesis organization.

As shown in Figure 4.1, this chapter would be focusing on details on modeling the extracted 1D Moiré waveform using an adapted L-STPSA algorithm [1, 2]. The instantaneous frequencies for all points along the 1D Moiré waveform are better estimated.

4.1 Relationship between Fringe Pitch and Distance from Specimen Line Grating

Given that the true pitch of the specimen grating is given by S . We assume a thin lens (pin-hole) camera model, because d is relatively larger than the focal length of the camera given by F , as shown in Figure 4.2. A grating with length S would be mirrored as p_s' in the captured image from the camera.

Figure 4.2: Pin-hole camera model geometry relating the line grating's pitch S to p_s' .

Using simple geometry, the specimen grating pitch p_s' can be approximated by

$$p_s' = \frac{FS}{d} \quad (15)$$

Putting (10) into (9) and rearranging, the well-known equation was formed,

$$d = \frac{FS}{(1+m)} \left(\frac{1}{p_m'} + \frac{1}{p_r} \right) \quad (16)$$

Given that F , S , and p_r are constants, the estimated distance from the camera d has an inversely proportional relation to the measure Moir éfringe pitch, p_m' . To reconstruct the surface distance map, it is essentially to estimate the Moir épattern fringe pitches. One simple way to estimate the fundamental frequency is to use peak to peak pitch estimation.

4.2 Peak to Peak Pitch Estimation

Figure 4.3: Moiré pattern pitch with peak to peak estimation.

By definition, the pitch is the distance from one peak to the nearest peak of the Moiré fringe waveform. The simplest and most common approach is to estimate the displacement of the specimen grating neighboring peaks in the Moiré fringe pattern (see Figure 4.3). This approach requires little computation time.

This approach is problematic because there are only a few peak to peak pitches in any given Moiré pattern image. With only a few peak-to-peak pitch values, the reconstruction of the entire surface using bi-linear interpolation results in large errors in the distance measurement. The only exception is the estimation of the distance to a non-inclined planar surface. In this case, all measured peak to peak pitches should result in approximately the same value, making interpolation unnecessary.

A better approach is therefore required to estimate the instantaneous frequencies along all the pixels values in the Moiré pattern waveform.

4.3 Instantaneous Frequency Estimation

For a periodic signal, the inverse of the pitch gives the frequency of the signal. According to Eqn. (16), the pitch period of the sub-sampled Moiré pattern waveform provides a reciprocal description of the surface displacement d from the camera. By

estimating the instantaneous frequency (i.e. reciprocal of pitch period) of the fundamental sinusoid of any of the waveforms shown in Figure 4.3, a dense distance profile of the surface along a selected 1D cross-section across the Moiré pattern image can be reconstructed. This should be achieved independently of the assumed CCD cell summation model (see Section 3.4). The observed Moiré waveforms suggest that a Gaussian CCD cell summation model is most likely but the exact spread of this model remains an unknown. This fact is unimportant for recovering the depth profile of the specimen line grating surface provided a technique can be found to estimate the instantaneous frequencies of the fundamental sinusoidal component in the Moiré pattern waveforms.

Figure 4.4(c) shows the sub-sampled waveform resulting from a 1D cross-section of a Moiré pattern image obtained from a curved line grating surface that has a varying intensity profile. The varying intensity could be due to shadows or uneven ambient lighting during imaging.

Figure 4.4: (a) Moiré pattern image of a curved line grating surface acquired under uneven lighting condition. (b) The full resolution intensity profile along the dotted (red) cross-section. (c) The waveform with the line grating artifacts removed after sub-sampling every 4th pixel.

Notice that the sub-sampled waveform $s(n)$ in Figure 4.4(c) can be viewed as a multi-component time-varying amplitude and frequency modulated (AM-FM) signal that is riding on a time-varying bias. In order to extract the varying pitch period of the signal, extracting the instantaneous frequency of the fundamental sinusoid is necessary

and this must be done, taking into account the varying bias and amplitude of the signal at different pixel position. In order to model this fundamental AM-FM sinusoid, the least-squares truncated power series approximation (L-STPSA) model approach of [1, 2] was modified with an additional time-varying bias.

Firstly, with n denotes different pixels along the waveform, the sub-sampled waveform $s(n)$ is converted into a positive-negative swinging zero-mean signal $x(n)$ using the following operation.

$$x(n) = s(n) - \frac{1}{N} \sum_{k=1}^N s(k) \quad (17)$$

4.4 The L-STPSA AM-FM Model

The model has been used in works [1, 2] to estimate instantaneous frequency of AM-FM modulated sound signals. The same model is applied here with an additional element for modeling the slowly-varying intensity bias across the image that may be caused by uneven lighting conditions.

An AM-FM sinusoidal signal $\tilde{x}(n)$ with a varying bias given by $v(n)$ can be represented by

$$\tilde{x}(n) = A(n) \cos[w_c n + \theta(n)] + v(n) \quad (18)$$

, where w_c is a fixed carrier frequency with varying amplitude $A(n)$. The instantaneous frequency $f(n)$ is the derivative of the varying phase $\theta(n)$ and is given by

$$f(n) = \frac{w_c + [d\theta(n)/dn]}{2\pi} \quad (19)$$

The signal $x(n)$ can be expanded to its in-phase and quadrature sinusoidal components given by

$$\tilde{x}(n) = a(n) \cos[w_c n + \theta(n)] + b(n) \sin[w_c n + \theta(n)] + v(n) \quad (20)$$

where $a(n)$ and $b(n)$ are given by

$$a(n) = A(n)\cos(\theta(n)) \text{ and } b(n) = -A(n)\sin(\theta(n)) \quad (21)$$

Assume the functions that describe the varying amplitude $A(n)$ and phase $\theta(n)$ are analytic, then such functions can be approximated by a power series. As an example, $\cos x$ is given by the series

$$\cos x = 1 - x^2/2! + x^4/4! - x^6/6! + \dots \quad (22)$$

Adopting this assumption, we can now model the in-phase and quadrature components of $\tilde{x}(n)$ and the varying bias $v(n)$ as general truncated power series (with centre at 0) of orders P and R respectively, given by

$$a(n) = \sum_{k=0}^P n^k a_k, \quad b(n) = \sum_{k=0}^P n^k b_k, \quad v(n) = \sum_{j=0}^R n^j v_j \quad (23)$$

Start the modeling process by assuming that there are no phase variations (i.e. $\theta(n)=0$), then given a signal $x(n)$ of sample length N , the modeled signal $\tilde{x}(n)$ in Eqn. (18) can be estimated by minimizing the mean square-error ε in Eqn. (24) with respect to the $(P+1)$ pairs of amplitude coefficients, the $(R+1)$ bias coefficients and a predetermined carrier frequency w_c .

$$\varepsilon = \sum_{n=1}^N \{\tilde{x}(n) - x(n)\}^2 \quad (24)$$

Further details of the coefficients estimation can be found in [2] with the simple extension of a further $(R+1)$ linear simultaneous equations to solve for the varying bias $v(n)$.

Since the varying phase is estimated iteratively, it is not important what the predetermined carrier frequency w_c is as long as it is a frequency component present in the waveform. Since the waveform being analyzed is observed to be near sinusoidal (due to the CCD cell's Gaussian intensity summation model), we chose w_c by picking the frequency corresponding to the highest peak frequency in the power spectrum of the waveform $x(n)$.

It can be shown in [1] that the current estimate of the varying phase is given

$$\hat{\theta}(n) = \arctan \left[\frac{-b(n)\cos(\theta(n)) + a(n)\sin(\theta(n))}{a(n)\cos(\theta(n)) + b(n)\sin(\theta(n))} \right] \quad (25)$$

From Eqn. (18), both $a(n)$ and $b(n)$ can be estimated from the $(P+1)$ a_k and b_k coefficients using the least-square truncated power-series approximation (L-STPSA) model of order P . Since the initial values of $\theta(n) = 0$, we can now make an initial estimate of the varying phase $\hat{\theta}(n)$ using Eqn. (25).

Unwrap the varying phase by tracking the 2π jumps in the phase values obtained in Eqn. (25) and smooth this function using another L-STPSA model of order Q given by

$$\theta(n) = \sum_{k=0}^Q c_k n^k \quad (26)$$

The smooth L-STPSA reconstructed phase function $\theta(n)$ in Eqn. (26) is then substituted back into the AM-FM signal model in Eqn. (21) to obtain another new estimate of $a(n)$ and $b(n)$, which in turn is substituted, along with $\theta(n)$, into Eqn. (25) to compute a new estimate of the varying phase $\hat{\theta}(n)$. This iterative parameter-substitution process is repeated until the waveform model in the M^{th} iteration deviates little from that estimated in the $(M+1)^{\text{th}}$ iteration. The results from this progressive sinusoidal signal estimation technique are shown in Figure 4.5. In the case of the waveform shown in Figure 4.4(c), reasonable convergence occurred after the 6th iteration, with $P=12$, $Q=5$, $R=3$ and $w_c=0.393$.

Figure 4.5: (a) The estimated L-STPSA AM-FM sinusoid of the fundamental frequency at (a) iteration #1 and (b) at stable full signal reconstruction at iteration #6. The original waveform and estimated varying bias is shown in dotted (red) and dashed lines (black) respectively. [2]

Once a stable AM-FM sinusoid has been iteratively estimated, the varying phase $\theta(n)$ from Eqn. (26) can yield an instantaneous frequency as given in Eqn. (19). Since we are interested in the varying pitch period of the Moiré pattern as it has an inversely proportional relationship to the distance, d of the line grating surface to the CCD camera, we can relate the varying phase $\theta(n)$ in Eqn. (26) to the reciprocal of the Moiré pattern pitch width p_m' in Eqn. (16) using the instantaneous frequency given in Eqn. (19).

$$\frac{1}{p_m'(n)} = f(n) = \frac{w_c + \theta(n) - \theta(n-1)}{2\pi} \quad (27)$$

Notice the derivative of the varying phase in Eqn. (19) can be approximated using simple backward difference. Figure 4.6 shows the recovered depth profile of the 1D cross section of the line grating surface shown in Figure 4.4(a) from the plot of $1/p_m'(n)$ in Eqn. (27). The instantaneous frequency use was derived using the estimated phase change of the fundamental sinusoid shown in Figure 4.4(b).

Figure 4.6: The cross-sectional shape of the surface distance from the camera computed from the instantaneous frequency estimate of the recovered L-STPSA sinusoidal signal in Figure 4.4(b).

4.5 Simple Planar Surface Distance Estimation

Given that the Moiré fringe pitch, p_m' now can be estimated across a 1D profile. With The L-STPSA AM-FM Model, each pixel in the scanline has an estimated $p_m'(n)$, and Eqn. (16) can be rewritten as

$$d(n) = \frac{FS}{(1+m)} \left(\frac{1}{p_m'(n)} + \frac{1}{p_r} \right) = kf(n) + b \quad \text{where} \quad \frac{1}{p_m'(n)} = f(n) \quad (28)$$

Figure 4.7: The setup for simple planar surface distance estimation. The paper was placed in flat and level on the horizontal base of the camera stand.

In the experimental setup used (see Figure 4.7), the spatial distance between the CCD camera imaging cells p_r is an unknown. The focal lens F though given as 5 mm may not be reliably confirmed due to possible variation in the lens mounting distance. This means the system constants k and b in Eqn. (28) are unknown. In order to measure $d(n)$, a calibration process is necessary. This can be simply done by adjusting the camera stand to two different positions at $D1$ and $D2$ (illustrated in Figure 4.7), to obtain two known distances $d(n)$. The two unknowns, k and b can be estimated by solving the equations with $D1$, $D2$ substituted into Eqn. (28). This setup could be used for simple planar surface distance estimation. For simple flat surfaces, the distances would be the same for all the pixels in a captured image assuming negligible barrel distortion effects as is the case for the setup used here.

For the calibrated Eqn. (28) to work, the $d(n)$ must have a bounded range to ensure that m would stay unchanged in order to retain the same k and b value. This value of m is the sub-sampling factor introduced in Chapter 3, which is used to remove high frequency artifacts within Moiré pattern images. If the m is changed, the system needs to be recalibrated.

4.6 Incline Planar Surface Distance Estimation

To explore further, let us consider the case where the surface is an incline planar surface with a constant gradient along a 1D scanline, as illustrated in Figure 4.8. In this setup, the line grating surface was inclined at an angle θ . Obviously the distances d is no longer the same for all the pixels along the 1D scanline unlike the case of the flat surface in the previous section,

Figure 4.8: The setup for incline planar surface distance estimation, the paper was placed on a rigid board, which was inclined by an angle θ .

With this new angle θ , the pitch of line gratings S would effectively become $S \cos \theta$ to the calibrated system, as illustrated with Figure 4.9.

Figure 4.9: The line grating pitch as viewed by the camera is effectively shortened by the presence of a local inclination of θ .

Revising the Eqn. (28) based on the inclination θ gives d_i , the distance of an inclined surface to the camera,

$$d_i = \frac{FS \cos \theta}{(1 + m)} \left(\frac{1}{p_m'} + \frac{1}{p_r} \right) \quad (29)$$

Accordingly, the distances measured for a pixel along the incline surface would become,

$$d_i(n) = d(n) \cos \theta = [kf(n) + b] \cos \theta \quad (30)$$

However, the angle θ is an unknown value. To get the distance measures, the value θ needs to be found. This is done with the help of two known end points along the incline, and their distance apart as shown in Figure 4.10.

Figure 4.10: The right angled triangle with measure L to solve angle θ for the incline.

As shown in Figure 4.10, if the two end points of the line gratings have a same horizontal offset L , the inclination angle θ is given by

$$\tan \theta = \frac{|OA|}{|OB|} = \frac{\Delta d_i}{L} = \frac{d_i(A) - d_i(B)}{L} = \frac{d(A) - d(B)}{L} \cos \theta \quad (31)$$

The distance measures $d(A)$ and $d(B)$, at the end points can be computed if the system constants k and b given in Eqn. (28) are known and the instantaneous frequencies of the Moiré fringe waveform $f(A)$ and $f(B)$ at the end points A and B respectively can be estimated. System constants k and b can be obtained by the calibration process described in Section 4.5. Moiré fringe waveform instantaneous frequencies $f(A)$ and $f(B)$, Eqn. (31) can be solved as follows,

$$\theta = \sin^{-1}(x) = \sin^{-1} \left[\frac{-L + \sqrt{L^2 + 4\Delta d_i^2}}{2\Delta d_i} \right] \quad (32)$$

where,

$$\Delta d_i = d_i(A) - d_i(B)$$

With this θ value solved, from Eqn. (31) all the distances measures for each pixel along the 1D scanline can also be found.

4.7 Curved Surface Distance Estimation

In order to handle more generic surfaces such as smooth curved surfaces, we can model such surfaces as a composition of piecewise incline surfaces. As shown in Figure 4.11(a), the short segment of a smooth curve ACB along a 1D scanline can be approximated by the incline AB . The distance of pixel C (see Figure 4.11(b)) to the camera can be approximated using its neighboring pixels A and B .

Figure 4.11: (a) An incline shortens the line gratings pitch S by a factor $\cos\theta$. (b) The inclination on any point on a smooth curve can be approximated using the inclination produced by its two adjacent pixel points. (c) The parameters related to an incline measurements.

The algorithm in Section 4.6 was extended to measure absolute distance values for an incline planar surface. An instantaneous incline angle value θ_i was computed for to each point C along the 1D scanline. Using distance measures d_A and d_B of its two adjacent neighbor points A and B repeat. The θ_i value is local to each point C . It encapsulates the characteristic of the local surface distance change. With this local θ_i value, the distance $d_i(n)$ of each incline point from the camera can be estimated by substituting θ_i into Eqn. (30).

In this proposed approach, an important condition must be met. The surface involved must be smoothly deforming, because sharp angular changes in the surface will result in self-occlusions as Shown in Figure 4.12.

Figure 4.12: Sharp deformed surface would cause the gratings get overlapped after projected in captured images, which will result a new different grating pitch.

A more limiting constraint of this technique is the need for sub-sampling factor m given in Eqn. (14) to remain unchanged over the entire observed undulating surface. This is because the system constants k and b give in Eqn. (25) obtained through the proposed calibration procedure are only valid for a give m value. In short, the curvature of the observed line grating surface must be smoothly changing and shallow. These constraints are not a problem for the pressure-sensitive touch interface application implemented in Chapter 6.

4.8 3D Surface Distance Map Estimation

So far, all previous discussions were focused on the relationship between the surface distances and the Moiré fringe waveform instantaneous frequencies along a 1D scanline. By combining the dense distance maps obtained from each of the Moiré

fringe waveform along the parallel consecutive 1D scanlines, a 3D surface dense distance map can be obtained.

Figure 4.13 shows the setup for measuring 3D dense distance map for a surface in 3D. Multiple 1D scanlines shown in dotted red lines were consecutively extracted and its 1D distance profile stitched together to form the dense 3D distance map shown in Figure 4.14.

Figure 4.13: A 3D incline concept surface.

Figure 4.14: Reconstructed 3D surface of the incline plane described in Figure 4.12, and color shows different distances of the points away from the camera.

The distances values are illustrated in different colors. From the intensities, the reconstructed dense distance maps reflected the original incline setup.

Chapter 5

Experimental Results

This chapter presents various experimental results to verify the theories proposed in Chapter 3 and Chapter 4. Towards the end of this chapter, several advantages of the proposed Moiré fringe measurement techniques such as insensitivity to ambient lighting variation and sensitivity to small surface displacements are discussed.

Figure 5.1: Typical experiments setup (a) Camera and supporting table (b) computer used to analyze Moiré patterns (c) Sample Moiré pattern demonstration.

Figure 5.1 shows a typical setup used for the experiments presented in this chapter. It consists of a CCD camera mounted on a crank-based height-adjustable stand, a personal computer (PC) and an A4-sized white paper printed with uniform black-white

line gratings. The resolution of these lines, 33 lines per inch, was printed with a 600 *dpi* laser printer. The camera used is the *Dragon Fly Express* monochrome model [51] from *Point Grey Research Inc.*, with a C-mount lens of focal lens 5mm. The resolution of the captured image is 640×480 pixels.

5.1 Level Planar Surface Measurement

Figure 5.2: (a) internal states of a distance measurement at $d = 72$ cm. (b) A plot to show the relationship between the distance, d , between the line grating surface and the CCD camera and the estimated instantaneous frequency, f , of the Moiré pattern waveform.

The first set of experiments was performed to build a model to measure distances of level surfaces from the camera. The camera distances to the surface were adjusted from 70.0 cm to 75.0 cm in steps of 1.0 cm. Because the surface is horizontally flat, all points on the surfaces have the same instantaneous frequency measure for each camera height. The plot showing the relationship between the instantaneous frequency measure f and the surface-to-camera distance d is shown in Figure 5.2. At this distance and with the printed line grating pitch used, the value of sub-sampling factor m in Eqn. (10) is 3 and artifact-free 1D Moiré waveform is obtained by sampling every other 4th pixel of the original resolution waveform.

As expected, the distance d is linearly proportional to the estimated instantaneous frequency f , which confirms the relationship suggested by Eqn. (28). Using least squared error line fitting for the results obtained, (shown as dotted line in Figure. 5.2), the calibrated linear system obtained was

$$d(n) = kf(n) + b = -11.487 \times f(n) + 76.933 \quad (33)$$

With the system constants k and b estimated in Eqn. (33), the computed distance of the flat surface, whose range is within 70.0 cm and 75.0 cm, was calculated from the estimated Moiré fringe frequency and is given in Table 5.1 using another set of surfaces. Error was observed to be small for distance of flat surfaces, the average error of 0.05625 cm.

Table 5.1: Experimental results for other level surfaces

Actual Distances d (cm)	Calculated Distances d' (cm)	Errors (%)
73.5	73.56	0.0816
73	73.00	0.0000
72.5	72.53	0.0414
72	71.90	-0.1389
71.5	71.48	-0.0280
71	70.90	-0.1408
70.5	70.59	0.1277
70	70.05	0.0714

5.2 Incline Surfaces Measurement

For the calibrated system in Section 5.1, incline surfaces were then placed under the camera. The same line grating patterns were applied on the incline surface. The inclination angle θ (see Figure. 4.8) was adjustable within a range. Big angles were avoided to prevent changing the sub-sampling factor, m to invalidate the calibrated parameters k and b in Eqn. (33).

The experimental results in Table 5.2 were computed with the system constants $b=76.933$ and $k= -11.487$. The experiments were designed to check the inclination angles, θ values computed

Table 5.2: Summary of actual incline angles and estimated incline angles

Actual angle($^{\circ}$)	1.3639	2.4540	4.7636	6.7890	8.3973	8.9306	11.0474	12.3554
Estimated angle θ_m ($^{\circ}$)	2.9027	2.8455	4.8217	6.7233	8.3863	8.6470	11.1490	11.7951
Error($^{\circ}$)	1.5387	0.3915	0.0581	-0.0656	-0.011	-0.2836	0.1016	-0.5602

With theory proposed in Section 4.6. Two end points of observable were used as points A and B . L parameter, which is the projected distance from point A to point B in Eqn. (32) used for all measures were $21cm$, (see Figure 4.10).

In these experiment results, the errors were reasonable small, with a maximum value of 1.5 degrees. However, the first 1.5 degrees error could be introduced by actual angle measurement used for these results.

Figure 5.3: Actual incline angles measurement by ruler readings a and b .

The actual angles were measured using rulers with triangular geometry. Two length readings a and b (see Figure 5.3) were recorded for an incline angle within a right triangle. The angle θ_m values was given by

$$\theta_m = \tan^{-1} \frac{a}{b} \quad (34)$$

According to Eqn.(34), a small ruler reading error was in a or b , a great error would be introduced for θ_m .

With an estimated angle θ for an incline planar surface, the distances $d_i(n)$ could be calculated via Eqn. (31), using the calibrated system constants b and k obtained in Section 5.1.

Figure 5.4: Experiment results comparing the actual incline and estimated incline planar surface.

Since an incline surface is well determined and easy to measure physically, it is used again to study proposed algorithm used to reconstructed smooth curve surface. The results shown in Figure 5.4 comparing the estimated distance for each point are reasonably close to the actual distances. The error between the actual incline angle and measured angle is about 0.678 degrees, which is comparable to the results in Table 5.2.

5.3 Smooth Curved Surfaces

To verify the reconstruction accuracy of a more generic surface, the following experiment was designed. An arc shape surface was placed on the supporting table as shown in Figure 5.5. The surface captured by the camera was between point A and point B . The distance from table to the camera, H was at 73.5 cm . The surface was printed with the same line gratings used in previous experiments.

Figure 5.5: Experimental setup for curve surface measurement. (a) experimental setup. (b) the bended surface (c) ruler reading for measuring ΔL

In the previous section the incline surface was reconstructed using a single horizontal offset L between two image points that were 21 cm apart (see Figure 4.10). In order to estimate the camera-to-surface distance of a smooth curved surface, this horizontal offset ΔL is reduced to a local distance of two pixel width about the point of interest C as described in Section 4.7. As shown in Figure 5.5(a), the horizontal span of the visible curved surface is given by w , which was measured to be 12.1 cm by the ruler shown in Figure 5.5(c). In order to compute ΔL , the span w is divided by the number of pixels within a scanline. ΔL was computed to be 0.075625.

A sampling of physical measurements was used to approximate the actual curve. This sampling method placed 13 points at equally distance (1 cm), from A to B, labeled in sequence numbers 1 to 13. For each point, a distance measure h was performed from the surface to the camera, and then an interpolation was used in-between to construct the actual curve. These measure results are summarized in Table 5.3 together with estimated measures h' .

Table 5.3: Summary of actual curve and estimated curve distances at sample points.

Labels	1	2	3	4	5	6	7	8	9	10	11	12	13
Measured h (cm)	72.60	72.30	71.98	71.80	71.65	71.55	71.52	71.50	71.60	71.80	72.06	72.30	72.70
Estimated h' (cm)	72.71	72.35	72.04	71.78	71.61	71.50	71.47	71.5	71.61	71.79	72.03	72.34	72.6
Error (%)	0.152	0.069	0.083	-0.028	-0.056	-0.070	-0.070	0.000	0.014	-0.014	-0.042	0.055	-0.138

The measured distances h' were reconstructed for all points on a scanline from between the visible range of A to B using the Moiré pattern method described in Section 4.7. These results were plotted as two curves in Figure 5.6. The distances were presented in negative numbers to retain the same curvature as shown in Figure 5.5(a). The approximation orders used in the modified L-STPSA AM-FM model algorithms for this experiment were $P=12$, $Q=4$, $R=3$.

(a)

(b)

Figure 5.6: (a) Reconstructed curve compares with the measured curve measured. (b) Dense 3D distance map for the reconstructed surface.

The curve reconstructed was a slightly deformed surface. The results were observed to have good accuracy. The errors were slightly larger at two ends of the curve, because the L-STPSA AM-FM model may result in unstable fitting (larger error) for end points. In Figure 5.6(b) the dense 3D distance map was reconstructed with 40 scanlines in the center. The reconstructed 3D dense maps reflects the real curve surface used in the experiments, (see Figure 5.5).

5.4 Impact of Uneven Lighting Conditions

The L-STPSA AM-FM Model used in the distance estimation algorithms was designed to model both sinusoidal signal's amplitude and varying intensity bias along the 1D Moiré waveforms. In theory this should allow the distance estimation algorithm to be invariant to changes in ambient lighting conditions along the 1D profile.

In this experiment, the effects of ambient lighting variations on the accuracy of the extracted depth using the proposed CCD Moiré waveform analysis technique were studied. Figure 5.7 shows the setup used in which a curved A4-sized paper with evenly spaced vertical line gratings was imaged twice. Firstly, under normal lighting conditions and secondly, with portions of the line grating surface covered by shadows.

Figure 5.7: Experimental setup for testing effects of lighting variations. (a) Normal light source and (b) Shadows cast on line grating surface due to partially occluded light source.

Figure 5.8 shows the two Moiré pattern waveforms obtained after sub-sampling the intensity value of every other 4th pixel of a 1D cross section (perpendicular to lines) of the Moiré pattern image. The fundamental sinusoidal waveforms along with their respective instantaneous frequencies were extracted for both the waveforms using $P=10$, $Q=5$ and $R=3$. The carrier frequencies used for the waveforms in Figure 5.7(a) and Figure 5.7(b) were $w_c=0.668$ and $w_c=0.628$ respectively.

Figure 5.8: The 1D intensity profiles of the sub-sampled zero-mean Moiré pattern waveforms obtained under (a) normal lighting condition and (b) with shadows. Notice the shadows resulted in uneven intensity attenuation. The estimated amplitude modulation envelopes of the fundamental sinusoids are shown dotted (red) and the varying biases are shown in dashed lines (black).

The resulting 1D depth profiles of the surface cross section under different lighting conditions were plotted together as shown in Figure 5.8. Hardly any noticeable variations in depth profiles were observed. This shows that the proposed technique for measuring the depth profile of a line grating surface is robust to lighting variations. The ability of the L-STPSA technique to simultaneously extract the varying

instantaneous frequency and amplitude modulation envelopes in a waveform allows us to handle changes in the Moiré pattern intensity, which does not fundamentally change the pitch of the Moiré fringes.

Figure 5.9: The plot of the two estimated 1D depth profiles of Moiré pattern waveforms in Figure 5.7(a) and 5.7(b). The two overlapping profiles are almost identical despite the significant variation in the intensity profile.

5.5 Sensitivity of distance measurement

To study whether the Moiré patterns were suitable for measuring small deformations, the experimental setup shown in Figure 5.10(b) was used to create very small mm-scaled displacements on a stretched canvas by applying horizontal pressure via a blunt-headed plunger. The deforming patterned surface of 18 lines per inch line grating was imaged from about 1.5 meters away, which gave a sub-sampling factor m value of 3.

Figure 5.10: (a) Moiré pattern image (pseudo-colored for clarity) with line artifacts removed by sub-sampling every other $m=4$ samples. The 1D cross-section analyzed is shown in a red dashed line. (b) Setup used to investigate sensitivity to small displacements on a stretched canvas.

Figure 5.11: The extracted instantaneous frequencies along the 1D Moiré waveform for different plunger displacement positions.

Figure 5.11 shows plots of the extracted instantaneous frequencies, $f(n)$ along the 1D Moiré waveform at the cross-section line shown in Figure 5.10(a). The results

suggest that small monotonic displacements of $<1mm$ can be clearly separated by the proposed Moiré analysis technique using images captured from a distance of about $>1.5m$ away. With a large imaging distance and small surface deformations, like in this case, the simple measure given by $d(n)$ in Eqn. (28) would be a reasonable approximate of the camera-to-surface distance. If similar calibration procedures as describe in Section 5.1 were carried out to determine the new system constants b and k in Eqn. (28), the measured instantaneous frequency $f(n)$ in Figure 5.11 can be used to determine the exact displacement of the canvas. However, if the task is merely to detect a measure proportional to the pressure applied on the canvas, then the frequency measure $f(n)$ would suffice. This is assuming the useful working range of the finger pressure to be detected by the proposed vision-based interface displaces the canvas in a proportional manner.

The ability of the proposed CCD-based Moiré pattern analysis technique to estimate small surface displacements led to the development of a novel pressure sensitive touch user interface. This new input device was used in two simple demo applications described in the next chapter.

Chapter 6

Applications

Touch surfaces enable computer interaction using natural finger gestures. Their use has increased significantly due to the growing mobile phone market with products like *iPhone* [52], HTC windows mobile enabled phone devices [53], etc. More recently, touch surface interaction has migrated to the desktop computing world, with the introduction of *Microsoft Surface* [54], and *Microsoft Windows 7* operating system [55]. Current technologies behind these touch-sensitive surfaces include electronic [52, 53, 56] or vision-based [54, 57, 58, 59, 60] approaches. Vision-based touch surfaces are relatively pervasive due to the affordability of imaging devices like CCD cameras and the improved vision algorithms and its computational speed. Such systems normally detect finger touches using reflection from non-visible infrared light sources [59, 60] or shadows [58]. However few systems are able to accurately detect the pressure levels of the touch interaction. Some like [59] rely on uncorrelated finger contact time or unreliable increase in the diameter of the detected finger contour to infer increasing pressure. Others like [56] require special deformable surface with embedded color markers. Additionally, most touch surfaces give little or no physical feedback on the pressure-induced deformation of the interaction surface. They normally provide activation feedback through visual or auditory means.

This chapter presents a vision-based user interface that consist of a stretched deformable canvas that is printed with regular fine pitched line grating on one side and an interactive pressure sensitive touch surface on the other. Physical pressure-based feedback is provided by the deformable surface; the more pressure is applied by the user's finger, the more the surface will deform. This small local surface deformation that is strongly correlated to the applied pressure is measured by our system with the aid of an off-the-shelf CCD camera. The pressure measurement is performed by analyzing the changes in the Moiré fringe patterns observed by the CCD camera that is imaging the other side of the interaction surface. The imaged surface contains fine printed line grating patterns that would have been displaced towards the camera due to the local deformation of the canvas. This chapter presents some experimental results

showing the viability of using this proposed technique to extract pressure-induced local surface deformation across an appropriately located 1D profile across the interaction surface. Two simple real-time example applications were implemented to demonstrate the computational efficiency of this Moiré pattern analysis algorithm. These applications also illustrate the potential of how pressure-sensitive user interface that employ deformable surfaces can be effectively used to develop engaging and physically intuitive interfaces for computer games and multimedia applications.

Figure 6.1: Experimental setup. (a) Side-view of the deformed interaction surface and the imaging area of the CCD camera on the stretched canvas. (a) Frontal view of the interaction surface and the locations of the three ‘pushbutton’ areas where pressure was applied. The black dotted line is the 1D cross-section where the Moiré fringe waveform was extracted and analyzed.

An experimental setup as shown in Figure 6.1 was used to study the surface deformation extracted by the Moiré fringe pattern analysis algorithm when varying finger pressures were applied to the stretched canvas at various positions. Three areas (**A**, **B** and **C**) on the canvas (as shown in Figure 6.1(b)) were marked out where ‘pushbuttons’ interaction could take place. The black dotted line in Figure 6.1(a) is the 1D cross-section that is centered about and stretches across all the three defined pushbutton areas.

The viability of using the proposed technique to implement pressure-sensitive pushbutton-type touch interaction requires us to verify the following. Firstly, increasing pressure applied at each location **A**, **B** and **C** can be measured and determined to be correspondingly increasing. This would permit interaction design

based on an additional user specifiable parameter (i.e. finger pressure) that is variable in nature unlike the discrete on and off interpretation of a mouse click or a keyboard entry. Secondly, the depression of the canvas at different pushbutton positions **A**, **B** and **C** can be easily and uniquely separated.

All images were acquired using a Dragon Fly Express monochrome CCD camera from *PointGrey Research Inc*, and a lens with a 25 mm focal lens. The distance of the canvas to the camera was about 1.8m and the line grating pattern used was about 66 lines per inch. The PC used has Intel® Core™ 2 Duo CPU clocking at 2.2GHz.

6.1 Detecting Pushbutton Activation

The interaction surface is usually not flat as there are already small latent deformations even when no pressure is applied. Figure 6.2(a) shows the initial distances (neutral state) of the surface to the camera (along the 1D cross-section shown in Figure 6.2(b)). In order to remove the neutral state bias, all measured distances were subtracted from the initial distance measure. This also helps remove any misalignment between the camera and canvas. As shown in Figure 6.2(b), with the neutral state now ‘flat’, a more distinctive differentiation between weak and strong applied pressures can now be observed.

In pushbutton control, an important requirement is to be able to determine distinctively separate thresholds when a button is considered to have been pressed, and when the button is considered to be released. As shown in Figure 6.2(b), there is substantial differentiation between the strong and weak pressures applied. This permits use to set two suitable thresholds that is reasonably separated to determine when the button press and release events occur.

Figure 6.2: (a) The extracted distance measures between the camera and canvas along the 1D cross-section shown in Figure 6.1(b) for different finger pressures on pushbutton B. They are the neutral state with no pressure applied (dotted blue line), weak pressure (dashed green line) and strong pressure (solid red line). (b) Distance measures for different applied pressures measured relative to the neutral state. The minimum value for distance measures would be where the maximum force is applied. The possible thresholds for button press and release detection are indicated in black arrows.

6.2 Detecting Pushbutton Locations

The pushbutton press positions are determined by pixel coordinates l , where the maximum pressure occurred. On the interaction canvas, we want to be able to distinguish between three pushbutton positions, **A**, **B** and **C**. In our setup, the imaging area of the CCD camera is defined by the range, $l \in [1, 160]$. Three equal-sized areas were used to separate the three pushbuttons. Pushbutton **A** was defined by $l \in [1, 50]$, pushbutton **B** defined by $l \in [56, 105]$, and pushbutton **C** defined by $l \in [111, 160]$. The unassigned pixels $l \in [51, 55]$ and $l \in [106, 110]$ are considered ambiguous areas that do not belong to any of the three pushbuttons.

As shown in Figure 6.3(a), the location where each of the three pushbuttons **A**, **B** and **C** were pressed is identified by the locations of maximum canvas displacement measure (i.e. where maximum finger pressure was applied). The results show that the pressing of each of the pushbutton was correctly detected within their respectively defined pushbutton zone.

An additional experiment was done by applying finger pressure at pushbutton **A**'s position and slowly sweeping the pressing finger in one continuous motion towards pushbutton **C**. A video of this sweeping action was captured and analyzed. Figure 6.3(b) shows the position of maximum pressure obtained (as in Figure 6.3(a)) for different image frames as the video progress. The results suggest that the pushbutton position as defined by the extracted maximum canvas displacement shows the expected monotonically increasing position change. This shows that the proposed technique is able to reliably track the direction where maximum pressure sweep is being applied. Such capability for direction tracking may be useful for applications that require 'move left' or 'move right' commands using simple depress finger gestures.

Figure 6.3: (a) The measured canvas displacements (pressure) when the user's finger pressed the pushbutton at locations **A** (dashed green line), **B** (solid red line) and **C** (dotted blue line). The three arrows marks the estimated pushbutton centers where maximum canvas displacements were detected. (b) A plot of the position of maximum canvas displacement as finger pressure was swept from position of button **A** to button **C** (see text).

6.3 Detecting Varying Applied Pressure

The next experiment verifies if the variations of finger pressure at different pushbutton locations can be reliably measured. To allow user applications to make use of the measured pressure values at each of the respective pushbutton positions, a normalized pressure measure between $[0, 1]$ is obtained. This pressure is assumed to be inversely proportional to the surface distance measure, $d(n)$ computed by the Moiré pattern analysis algorithm and is given in Chapter 4 and Chapter 5.

In our experimental setup, many parameters are unknown. These include the system constants b and k given in Eqn. (8), the distance between camera and canvas, the precise spacing between lines in the line grating pattern used, etc. Since no absolute measurements are used by our applications, this set of information is not necessary. However, a simple calibration procedure is required to be done each time the canvas is mounted and the camera is aligned to view the interaction area of the canvas. This calibration is to find out the maximum force the setup is capable to detect. Only two pieces of information are required. The first is the distance measure profile along the 1D cross-section (see Figure 6.1(b)) for the initial neutral state of the stretched canvas surface, d_0 . This would be used to calculate the relative pressure measures, P given by

$$P(n) = d_0(n) - d(n) \quad (34)$$

The other is the maximum pressure measure P_{max} . This is measured when the user presses one finger on the canvas at pushbutton location **B** with the maximum amount of working force her or she wishes to apply during the course of interacting with the surface. The largest value of $P(n)$ registered along the 1D profile is assigned to P_{max} .

Figure 6.4: The measure normalized pressure profiles for different increasing finger pressure applied at (a) pushbutton **A**, (b) pushbutton **B** and (c) pushbutton **C**.

Given the pressure measure defined in Eqn. (29), the normalized pressure $p(n)$ is given by

$$p(n) = \begin{cases} 0.0 & P(n) \leq P_0 \\ \frac{P(n) - P_0}{P_{\max} - P_0} & P_{\max} > P(n) > P_0 \\ 1.0 & P(n) \geq P_{\max} \end{cases} \quad (35)$$

where $p(n) \in [0.0, 1.0]$. P_0 is the threshold of pushbutton press activation pressure measure. It is necessary to prevent false detection of pushbutton activation and pressure due to minor deformation in the canvas due to exploratory finger touch (touching the canvas but not yet selecting button activation) and those resulting from frame vibration. In our work, the value of the press activation threshold P_0 is heuristically set to 25% of the $P_{\max}$ and was found to be effective for most user interaction. The button release threshold is set at 10% of $P_{\max}$.

Figure 6.4(a)-6.4(c) show the different pressure measures obtained on the 1D cross-section along the pushbutton locations **A**, **B** and **C** for different increasing pressure applied at location **A**, **B** and **C** respectively. Noticed that for all the position, increasing applied pressure produced an increasing value of normalized pressure $p(n)$ given in Eqn. (35). These results suggest that we can indeed use the pushbutton in a pressure-sensitive manner and each pushbutton one different locations of the canvas can be expected to exhibit this property.

The next section details two example applications that take advantage of this pressure-sensitive characteristic of the push button to redefine how a user can interact with a computer in new ways that are more intuitive than what can be afforded with the current mouse and keyboard interfaces.

6.4 Example Applications

Two example applications were implemented using the proposed pressure-sensitive interactive canvas interface. The first illustrates an example application where the pressure-sensitive user interface maps well to the game design. The applied pressure, with its physical feedback controls the amount of force being exerted on a virtual deformable stretched rubber band. The effect of the amount of force applied by the user to the canvas has a direct outcome on the behavior of the virtual object in the game.

6.4.1 Bouncing Ball

In this simple application, a virtual bouncing ball was placed in the center of a simulated rubber band. When the virtual rubber band was depressed by an applied force at its center (as shown in Figure 6.5(c)), the ball would follow, and when the rubber band was released, it will return to its neutral position and in so doing cause the ball to bounce up in the air (as shown in Figure 6.5(d)). As shown in Figure 6.5(a), the amount of bending in the virtual rubber band was controlled by the interactive deformable canvas. In this example, only pressure-sensitive pushbutton **B** was used. The normalized pressures $p(n)$ in Eqn. (35) was configured to give the ball different initial velocities. The harder the user presses the pushbutton **B** and releases the button, the higher the ball will bounce up into the air.

In this experiment, after calibration, $P_{max} = 0.04$, $P_0 = 0.01$ for the press threshold and $P = 0.004$ for the release threshold. Observations show that when greater force was applied to pushbutton **B**, the higher the ball will bounce into the air. The interactive experience of using the deformable canvas interface was significantly more intuitive than the version using repetitive keyboard presses to increase the bend in the rubber band. It is also much faster to specify to the interactive system the desired initial velocity to be applied to the ball as this is directly mapped to the amount of force applied to pushbutton **B** compared to the number of repetitive keyboard presses needed to specify a high initial velocity.

The CD attached to this thesis contains demonstrations of the bouncing ball application. See Appendix A.1 for description of this video demo (*BouncingBall.wmv*).

Figure 6.5: (a) Bouncing ball application setup. A CCD camera (out of view) was on the other side of the canvas viewing the line grating pattern associated with the interaction surface. Pushbutton B is being pressed by the user. (b) Neutral state, no force is applied on the canvas, the number shown is the value of the instantaneous maximum value of normalized pressure $p(n)$, (c) A force was applied on the canvas, and the virtual rubber band depresses as expected with a pressure value of 0.83. (d) The finger is released from the canvas and the ball starts bouncing up into the air and the pressure returns to 0.

6.4.2 Movie Player Scene Search Function

Traditionally video players (e.g. DVD players) have digital video scene search controls, the player have 3 buttons, play/pause, fast reverse and fast forward. The fast reverse button and fast forward buttons are toggling buttons. Each time the button

pressed, it switches the speed among a few different speeds, for example, normal speed, 2 times, 4 times and 8 times. However to make the control simple, the repetitive toggling can only increase the search speed. This makes it troublesome for the user to have find control over the speeding up and slowing down operations when searching a specific scene in the video sequence.

In this example application, we attempt to show how the use of a pressure-sensitive pushbutton can make such a task of fast forward or reverse video scene searching radically easier and more intuitive. We mapped pushbuttons **A**, **B** and **C** in our setup to the movie player commands, fast-reversing, play/pause, and fast-forward commands. **B** toggles the movie player state between playing and paused. Button **A** controls fast reversing with mapping the normalized pressure $[0.0, 1.0]$ to playing speed $[1.0, 6.0]$, and button **C** uses the same mapping to control fast forwarding. For this setup, the distance between the camera and canvas was changed, so a recalibration was performed. New values of $P_{max} = 0.08$, $P_0 = 0.02$ for the press threshold and $P = 0.008$. The test movie used was stitched from looping three simple ten seconds video sequences.

The CD attached to this thesis contains demonstrations of the video scene search application. See Appendix A.2 for detailed descriptions of this demo video, *VideoSceneSearch.wmv*.

Figure 6.6: (a) This application setup consists of three pushbuttons, they are placed vertical, and the camera was rotated clockwise 90 degrees as well. (b) A video scene was paused after activation of button **B** (Play/Pause) was activated. Different pressure was applied to either button **A** for (c) fast forwarding at 3.8 times speed or (d) button **C** for fast reversing at 1.6 times speed.

Chapter 7

Conclusions

This thesis proposed a spatial domain based Moiré pattern based technique for reconstructing dense distance maps of line grating surfaces which are placed in front of a CCD camera. No complex *Ronchi* grating or pattern super-positioning techniques are required like in typical Moiré based measurement techniques. The line patterns used in generating the Moiré fringes are also easy to produce by simply printing from a standard 600 *dpi* laser printer.

7.1 Principle Results

The proposed Moiré pattern based surface distance estimation process contains four steps. The first step is to align the line patterns and camera CCD grid properly to generate analyzable Moiré patterns. This ensures the generated Moiré patterns have no or little distortion caused by relative rotation. The second step is to perform the spatial domain sub-sampling to enhance the Moiré pattern, remove original high frequency line artifacts in the Moiré pattern. The sub-sampling factor is determined by the camera lens and line grating pattern pitch. The third step is to use a modified L-STPSA algorithm to approximate the instantaneous frequencies for all the points on each selected scanline. The dense 3D distance maps can then be reconstructed by merging all the consecutive scanlines. Finally, a simple transform is made to the estimated Moiré frequencies to obtain the actual camera-to-surface distance measures. Experimental results suggest that this proposed approach for reconstruction smoothly deformed surface is reasonably accurate, insensitive to variation in ambient lighting and relatively sensitive to small surface deformations.

In the last part of the thesis, the proposed Moiré pattern based technique was used with a deformable line patterned canvas to support user interaction. Two simple applications were implemented to demonstrate how this novel user interface can be deployed to enhance user interaction with computer applications.

7.2 Future Work

Constrained by the camera lens used, only a 28cm by 28cm imaging area can be actively used by the users to interact with the deformable canvas. This also constraints us from exploring the possibility of implementing pressure-sensitive multi-touch interaction, since the canvas active area is too small. Any two presses at the same time but at different locations in the imaged area would interfere with each other and would most likely to be recognized as a single button press. To overcome this, we could get a wide-angle camera to observe a larger area, and get elastic material to serve as the deformable surface. With a larger canvas area, it is natural for us to do more scan lines to enable user interact with the canvas in a full 2D space. The elasticity of deformable surface reduces interference between close touch points on the surface. A bigger canvas also brings more with more scanlines. This imposes a challenge in optimize the algorithm further for real-time performance.

A real-time pressure-sensitive touch display surface could be implemented. The general idea for this interactive display is to have a stretched opaque vinyl canvas act as the interactive display on one side (with front projection). And on the other side that is printed with line grating, a vision-based system for pressure-sensitive multi-touch detection. Unfortunately, one of the side effects of employing frontal projection is that the projected imagery will annoyingly appear on the user's hands and this will also result in shadows on the display surface. A more complicated strategy would be to use an occlusion-free back-projection display that employs the imperceptible pattern projection technique of *Cotting et-al.* [61] to time-slice the line grating pattern into pre-allocated synchronized temporal slots of the video frames. Unlike [61], the Moiré-based surface reconstruction technique proposed here is faster as there is no need to project a sequence of Gray-coded structured light pattern during surface depth reconstruction.

Figure 7.1: A possible implementation of a front projection pressure-sensitive multi-touch display surface using the proposed Moiré pattern-based technique for touch pressure measurement.

One constrain that was used throughout this work is the requirement that the line grating is aligned with camera CCD grids and no relative rotation between these lines and CCD cells exist. As shown in Figure.7.2, relative rotation between two line gratings will generate regular Moiré patterns. However the analysis of the nature of these Moiré patterns is more complex. By incorporating relative rotation, more information would be revealed about the change in the deformable surfaces, and richer, more flexible user interactivity could be designed.

(a)

(b)

Figure 7.2: Two different Moiré patterns with different relatively rotated angles for the reference pattern.

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Appendix

A.1 Bouncing Ball Video Demo

[Video on the CD: *BouncingBall.wmv*]

This demo illustrates how a simple pressure sensitive push button works with our proposed touch canvas. This kind of control is good for analogue inputs for any application. The resistance force from the canvas provides good feedback for users to know how much is the pressure on the canvas.

Scene 1: Experimental Setup

This Scene shows the experimental setup, including a PC running the application, a touch canvas with labeled push buttons on one side and printed line gratings on the other side facing a CCD camera. The CCD Camera was connected to the PC. A fan was used to enhance the elasticity of the canvas.

Scene 2: Controlling the ball with weak forces.

Scene 3: Controlling the ball with strong forces.

Scene 4: More testing with random forces.

A.2 Video Scene Search Demo

[Videos on the CD: *WMP.wmv*, *RealPlayer.wmv*, *VideoSceneSearch.wmv*]

This demo shows how the proposed pressure-sensitive touch canvas can be used for a common task of video player such as scene seeking.

Traditionally, applications like *Windows Media Player*, implement one dedicated button to seek videos in a desired direction. If the button was pressed, a constant speed would be applied for the seeking (see *WMP.wmv*)

And many DVD players extend this behavior with a few pre-fixed seeking speeds. Repeat press the button would toggle from the various fixed speeds in a ring order (see *RealPlayer.wmv*).

In this demo, we extended the DVD player behavior by allowing users to control the seeking speed with the variable touch pressure applied on the designed canvas (see *VideoSceneSearch.wmv*)

This demo contains the following 5 scenes

Scene 1: Introduction of experimental setup, which includes a PC running the application, a touch canvas with labeled push buttons on one side and printed line gratings on the other side facing a CCD camera. The CCD Camera was connected to the PC. A fan was used to provide wind-based pressure will return the canvas to its neutral position after repeated depressions. There are three buttons labeled, from top to bottom, **A**: Reverse Seeking, **B**: Play/Pause **C**: Forward Seeking.

Scene 2: Play/Pause using center push button **B**, demonstrates button activation and deactivation. The states of the video player were highlighted.

Scene 3: Forward Seeking with the bottom button **C**, demonstrates the variable pressure detected. The variable seeking speeds were highlighted.

Scene 4: Reverse Seeking with the top button **A**, demonstrates the variable pressure detected. The variable seeking speeds were highlighted.

Scene 5: Random seeking, demonstrate the location detection for different buttons.

B. Derivation of Eqn (1)

The following presents the details how Eqn. (1) is derived.

$$AB = \frac{p_s}{\cos 2\alpha}$$

$$AC = \frac{p_r}{\cos 2\alpha}$$

$$\angle BAC = 2\alpha$$

$$\therefore BC = \frac{1}{\cos 2\alpha} \sqrt{p_s^2 + p_r^2 - 2p_s p_r \cos 2\alpha} \quad (\text{Law of cosines})$$

$$\begin{aligned} p_m &= \frac{2\text{Area}}{BC} = \frac{AB \cdot AC \cdot \sin 2\alpha}{BC} \\ &= \frac{p_s \cdot p_r}{\sqrt{p_r^2 \sin^2 2\alpha + (p_r \cos 2\alpha - p_s)^2}} \end{aligned}$$

C. Publications

The following section presents the publications which are listed in Chapter 1.

Publications arising from this study:

- T. Tu & W.B. Goh, “*MOIRE PATTERN FROM A CCD CAMERA – Are They Annoying Artifacts Or Can They Be Useful?*” Proc. of the Fourth International Conference on Computer Vision Theory and Applications, *VISAPP2009*, Feb. 2009.
- T. Tu & W.B. Goh, “*Using CCD Moir éPattern Analysis to Implement Pressure-sensitive Touch Surfaces*” 13th International Conference on Computer Analysis of Images and Patterns, *CAIP2009*, Sept. 2009 (to be presented).