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3D Shape Measurement of Objects in Motion and Objects with Complex Surfaces

A thesis submitted in fulfilment of the requirements for the award of the degree

Doctor of Philosophy

from

University of Wollongong

by

Yifan Wei

B. E., Tianjin University, China M. E., University of Wollongong, Australia

School of Electrical, Computer and Telecommunications Engineering October 2021

STATEMENT OF ORIGINALITY

This is to certify that to the best of my belief this thesis is my own work. It contains no materiel previously published or written by other person .The thesis also has not been submitted for qualifications at any other educational institution.

Signature:

Yifan Wei

October 2021

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AUTHOR'S PUBLISHCATIONS

Journals papers:

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- 2. Yifan Wei, Lei Lu and Jiangtao Xi, "Reconstruction of moving object with single fringe pattern based on phase shifting profilometry", Optical Engineering, 60(8), 084106,2021.

Conference paper:

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ACRONYMS

3D: three-dimensional

PSP: phaseshifting profilometry

SNR: signal noise ratio

CMM: coordinate measuring machine

FPP: Fringe projection profilometry

DFD: depth from defocus

TOF: time-of-flight

PSD: position sensitive device

CCD: charge coupled device

LCD: liquid-crystal-display

DMD: digital micro-mirror device

DLP: digital light processing

MIGL: maximum input graylevel

BRDF: bidirectional reflectance distribution functions

RMS: root mean square

SIFT: scale invariant feature transform

ABSTRACT

This thesis aims to address the issues caused by high reflective surface and object with motion in the three dimensional (3D) shape measurement based on phase shifting profilometry (PSP). Firstly, the influence of the reflectivity of the object surface on the fringe patterns is analysed. One of the essential factors related to phase precision is modulation index, which has a direct relationship with the surface reflectivity. A comparative study focusing on the modulation index of different materials is presented. The distribution of modulation index for different material samples is statistically analysed, which leads to the conclusion that the modulation index is determined by the diffuse reflectivity.

Then the method based on optimized combination of multiple reflected image patterns is proposed to address the saturation issue and improve the accuracy for the reconstruction of object with high reflectivity. A set of phase shifted sinusoidal fringe patterns with different exposure time are projected to the object and then captured by camera. Then a set of masks are generated to select the data for the compositing. Maximalsignal-to-noise ratio combining model is employed to form the composite images pattern. The composite images are then used to phase mapping.Comparing to the method only using the highest intensity of pixels for compositing image, the signal noise ratio (SNR) of composite image is increased due to more efficient use of information carried by the images.

The thesis also addresses the errors caused by motion in PSP. As the PSP requires multiple fringe patterns and the object motion among the fringe patterns introduces errors, the thesis proposes to reconstruct the object by projecting single fringe pattern based on PSP. The phase shifted fringe patterns required in PSP are generated by the object motion in the single fringe pattern. By analysing the relationship between the motion and fringe pattern, the moving object is reconstructed successfully.

Experimental results are presented to verify the effectiveness of the work presented above. The thesis is concluded with suggestion forfuture work.

1 INTRODUCTION

1.1 Overview of 3D shape measurement technology

In the past decades, 3D shape measurement has been an active research area due to its wide applications, such as medical science[1, 2], entertainment[3, 4], security [5, 6] and manufacturing [7, 8]. Intensive research efforts have been devoted to this field, and several techniques and approaches have been developed. 3D shape measurement technologies based on digital Fringe projection profilometry (FPP) have the advantages of high speed and accuracy, as well as simple system implementation. With FPP, a set of purposely designed light patterns (normally fringe patterns with sinusoidal light intensive variance along the horizontal or vertical directions) is created by a digital projector, and casted on the surface of the object. The reflections of these patterns are then acquired by a camera from different directions, which are analyzed to yield the 3D shape of the object surface using a set of algorithms related to the geometrical structure of the system. Although significant amount of work has been done in the development of FPP, a number of problems are still impeding its practical applications. More precisely, when the object surface has both dark and high reflective areas (i.e. large dynamic range of reflectivity), fringe patterns acquired from the object will suffer from significant distortion, leading to measurement errors. In addition, in the cases where the objects are in motion,

errors will also occur in the fringe analysis, and thus the 3D measurement results. This thesis aims at developing new approaches to solve these two challenging problems.



Fig. 1.1 Classifications of 3D shape measurement technologies

Existing 3D shape measurement technologies can be classified into several types, as shown in Fig. 1.1. They can be classified as contact and non-contact techniques, according to whether the object is physically contacted or not. A typical contact technology is the Coordinate Measuring Machine (CMM), while the non-contact techniques usually use the light reflected from the object surface in order to obtain the 3D shape. The non-contact technologies can then be divided into passive and active, according to whether a light source is required to probe the subject or not. The passive methods simply obtain the 3D

shape using the object images taken by a camera. On the contrary, the active methods use a light source to probe the object's surface, and simultaneously use cameras to acquire the reflections. The 3D shape is finally obtained from the analysis of the reflections. The structured light is a commonly studied active method, where a set of images with a specifically designed structure is used to probe the object. When theimages have a fringe structure, the method is referred to as Fringe ProjectionProfilometry (FPP).

FPP can then be divided into single shot methods that only use a single image pattern, and multi-shot methods where multiple image patterns are projected. These technologies are discussed as follows.

1.1.1 Contact-based techniques

Contact-based techniques obtain the 3D shape information by physical touch. A CMM is a typical example of the contact-based methods[9, 10]. The CMM consists of three main components, including the main body, the probing system and the data collection system. The main body controls the motion of the probes. The probe touches the object surface to be measured, and the 3D data is then calculated using the data collection system. The CMM is commonly used in manufacturing and can achieve high accuracy measurement. However, this technology has many disadvantages. More precisely, the probe contact with the object surface may change or damage the object, which is not acceptable for deliberate or valuable objects. In addition, CMM is not suitable for fast measurement, because the physical movement of the mounted probe is very slow.

1.1.2 Non-Contact based techniques

Several non-contact methods have been developed to overcome the limitations of the contact-based techniques. Due to their non-contact nature, these deformable approaches be used soft can to measure or objects. Therefore, they can be applied in several application domains. The noncontact 3D shape measurement techniques can be further classified into passive and active methods, according to weather a light source is required to probe the object or not. In the passive methods, the 3D information is captured by analysing images of the objects, taken by cameras or sensors. The active methods use light sources that are cast onto the object surface, and simultaneously employ cameras to acquire the reflected images and to extract the 3D information from these images.

1.1.2.1 Passive Techniques

The passive techniques do not actively emit any kind of radiation, but rather rely on the ambient radiation for the 3D information recovery. Two commonly usedpassive techniques are the Depth from Defocus (DFD) [11]and stereo vision[12-14].

(1) Depth from Defocus

Most of the 3D shape measurement techniques assume that all the depths of a measured scene aresimultaneously in focus. However, in a practical optical system, only finite depths are in focus. Some areas of the captured image are sharp and in focus, while others are blurred or out of focus. In other words, the points in the scene of an object are captured with different amounts of defocusing/blurring. If the blurring due to defocus can be quantified, the defocus information can be used to recover the depth or the shape. This technique is called shape from defocus, or depth from defocus, since the blur extent depends on the scene depth[15]. A single defocused image is not sufficient to obtain a unique reconstruction of the scene, unless additional information is available. Generally, two or more defocused images, obtained with different focus settings, are used. Several real-time systems have been developed owing to the fact that no active illumination is used, and no active control on the focus setting is performed for the DFD technique. However, since this technique requires strong texture information to analyze the blurring effects, its resolution and sensitivity are usually low, which results in limiting its application domains.

(2) Stereo Vision

Stereo vision techniques are based on the analysis of two or more images of the same scene, that are obtained from different perspectives [16, 17]. When two cameras capture a 3D scene from two distinct positions, a number of geometric relations exist between the 3D points and their projections onto the 2D images, which leads to several constraints between the image points. These relations are derived based on the assumption that the cameras can be approximated by the pinhole camera model, while the used geometric constraint is usually referred to asepipolar geometry. To determine the geometric constraint and further obtain the 3D information, the camera parameters should be determined by calibration[16, 18]. These parameters include the extrinsic parameters for position and orientation, the intrinsic parameters for focal length, the optical centre and the distortion parameters. In general, calibration is performed before measurement, using a number of particular calibration scenes, such as the checkerboard, for example. If the corresponding points on different images are known, the 3D point can be reconstructed from two or more 2D images using triangulation. The main advantage of this technique is the low cost of the hardware, since only two cameras are required. However, the determination of the corresponding feature points for 3D reconstruction, requires a high computational load. Due to the fact that large regions with constant luminance exist (e.g. untextured regions or repetitive patterns), problems in uniquely matching two points will occur.

1.1.2.2 Active Techniques

Merely relying on the ambient radiation, passive techniques may fail to provide highaccuracy measurement if the surface texture is not drastically varying from onepoint to another. To overcome these limitations, active techniques have been developed by projecting light onto the objects for correspondence establishment[19]. The coordinates of the points or 3D information can be obtainedby capturing and analyzing the interaction between the object and the radiation. The most used active techniques include the time of flight (TOF), laser triangulation and structured light.

(1) Time of Flight (TOF)

The TOF is an optical technology based on the ultrasonic system of bats. TOF cameras involve active illumination, and deliver the range (or depth) by measuring the time needed for a light signal to travel from the camera light source to the scene and back to the camera sensor[20-22]. Existingactual TOF cameras are based on the continuous emission of a periodic signal. The time can be determined from the phase differenceby modulating the phase at a constant frequency, and then recording it with the detector. The key component is an array sensor that can measure the intensity and distance information to the target, pixel wise, in parallel and without scanning. Since the projection and recorded units are from the same view angle, the TOF technique does not have the

occlusion problem. In addition, the hardware system is very compact compared to other techniques, such as the stereo vision systems where a certain base line distance is required for the two cameras. However, TOF has the limitation of low detector resolution. This is due to the fact that particular sensors should be designed with the requirement of measuring both intensity and distance information.

(2) Laser Triangulation

The laser triangulation system can achieve higher spatial resolutions than the TOF system. In general, a laser triangulation system contains a laser, a detector, as well as a lens placed in front of the detector to focus the laser beam onto the detector[8, 13]. When conducting measurement, the laser emits a beam of light onto the surface of the measured object. The laser beam is then reflected from the surface and falls on the detector through the lens. Based on the beam position on the detector and its emitting location, the depth z from the sensor to the target surface can be calculated using triangulation. In most cases, a laser stripe is swept across the objectinstead of a single laser dot, to speed up the acquisition process. The detector is the most critical element in this system. Two types of detectors exist; the Position Sensitive Device (PSD) and the Charge Coupled Device (CCD). PSD triangulation has been used for more than 20 years. However, it is susceptible to spurious reflections from changing the surface conditions, which can reduce the measurement accuracy. In contrast, the advanced CCD technology can overcome severalPSD limitations The accuracy of the laser triangulation systems is relatively high. More precisely, it can reachvalues less than a micrometer. In addition, it has a large measurement range allowing to fulfill several applications requirements, such as large building measurements, for example. However, using this type of scanning system to scan objects in motion is very difficult, because only one point or one line can be measured at a time.

(3) Structured Light

The structured light method is similar to the stereo vision technique, except that one of the cameras is replaced with a projecting unit. Theprojected lightpatterns can have different structures, while the most commonly used are fringes[23-29]. When observed from a different viewpoint from the projection, the patternsexhibita geometrical distortioncaused by the object surface shape. In order to extract the 3D shape, the same fringe patterns are also projected onto a flat board referred to as the reference plane. The reflection is also picked up by the camera. The points displacement on the reflected image from the object, with respect to the same points on the image from the reference plane, carries the 3D shape information. This then allows the retrieval of the 3D coordinates of the object surface. By carefully designing the fringe patterns, it is easy to identify the correspondence between the two corresponding images, regardless of the natural surface texture. Therefore, this overcomes the difficult correspondence problem in a passive stereo vision system. In addition, the structured light method is able to perform a high-speed 3D shape measurement, as the computational cost is substantially reduced with the help of the projected patterns. Moreover, instead of scanning one point or one line at a time, an entire field of view can be measured at once. This reduces or eliminates the problem of distortion from motion. Furthermore, this technique can provide a relatively high-accuracy measurement, since the correspondence can be accurately determined[30].

Depending on the information used for the correspondence establishment, the structured light techniques can be further divided into two major categories; intensity-based and phase-based techniques. The intensity-based methods use the grayscale values or ratios for the correspondence identification. For instance, binary coding is one of the well-known intensity-based methods that projects multiple binary coded patterns[31]. It is relatively robust to the noise for the codeword identification, since only two illumination levels ('0' and '1') are used. However, itdoes not lead to a high resolution because the projection stripe is always larger than the size of the projector and the camera. Moreover, it requires several patterns to achieve a high resolution measurement, which slows down the measurement speed. Multi-level gray coding and intensity ratios methods have been proposed to reduce the number of required patterns, thus improving the performance [32-34]. The intensity ratio methoduses all grayscale

levels, while the intensity ratio is used for correspondence identification. Although the intensity-based methods can improve the measurement speed, they are highly sensitive to camera noise and image defocus.

In the phase-based and fringe projection techniques, instead of using the intensity information, the 3D information is extracted from the phase values in the image patterns with a fringe structure, where their light intensity sinusoidally varies along the horizontal or vertical direction. Phase-shifting techniques are mostly used to obtain the phase information. They consist in using multiple fringe patterns with certain phase shifts[35]. These methods are robust to the camera noise and illumination variations. There are several approaches to generate and project fringe patterns, such as the laser interference[36], Moir'e contouring[37-39] and digital fringe projection[40-42], for example. The laser interference method uses two wide planar laser beams to generate regular sinusoidal patterns by interference. It has the advantage of generating very fine patterns with unlimited field depth. However, it has a high implementation cost, and the typical laser artifacts such as the speckle noise, are able to affect its measurement quality. Moir econtouring is another approach that allows to generate sinusoidal fringe patterns. Moir'e pattern is generated by shooting light onto two overlaid gratings, that are slightly displaced or rotated from one to another. Although it is widely used in industrial fields, the main limitations of the Moir'e technique are the tedium associated with obtaining

quantitative height information and the requirements of additional accurate controls in the case where the phase shifting technique is used.

Without using any physical gratings or interferometry, digital devices have been recently used to create and project fringe patterns, such as the liquid-crystaldisplay (LCD) projector andthe digital mirror device (DMD) projector based on the Digital Light Processing (DLP) technology. The technique which consists in projecting sinusoidal fringe patterns with a digital video projector is referred to as the digital fringe projection method. Because this technique uses the digital technologies, it provides several advantages compared to the conventional methods. Fringepatternswith different structures can be easily generated using computer software, while the entire system can be implemented by digital devices, i.e. a computer, a projector and a camera. Due to these advantages, the DLPmethod has been widely studied and used in several fields.

1.2 Literature review on the use of FPP for the measurement of shinny surfaces and moving objects

Due to the material characteristics of high reflective objects, the surface of the high light reflection, high light ratio and other problems, resulting in the high reflective area of the whole image is overexposed, other areas are underexposed, image perception and texture detail loss and other phenomena[43-45]. According to the different principles and measurement methods used, this kind

of HDR imaging problems are divided into the following six methods: (1) multiple exposure method; (2) Adjust the projection pattern intensity method;(3) polarization filter method; (4) color invariant method; (5) photometric stereo technology; (6) Other technologies. The following is a detailed review of the research progress of each method.

(1) The multiple exposure method

The multiple exposure technology consists in using multiple fringe patterns with different projection intensities or camera exposure time, and combining their reflections to form a single image, aiming to avoid or reduce the saturation and nulling.

For instance, Zhang and Yau[46]proposed a multiple exposure method that studies the problem of shiny surfaces. In this method, images taken at different exposure times are combined into a group of HDR (high dynamic range)images, i.e. phase-shifted images with a focus on the brightest unsaturated intensity at each pixel. Manually adjusting the lens aperture causes movement between the system components, which changes the calibrated system parameters. Thus, the exposure can be better adjusted by manually adjusting the exposure time rather than adjusting the lens aperture, which leads to a high-quality stripe pattern.Since the ambient light slightly affects the phase shift method, this latter can be used to steadily measure the local surface reflectivity of

objects. Although areas of high or low reflection can be measured without affecting the rest of the areas, images taken at low exposure times contain meaningful information in the surface areasof high reflectivity, and vice versa. It is necessary to control the ambient light at a very low level in the industrial site, because low reflectivity regions have a low SNRin the case of large range reflectivity variation. Otherwise, it is hard to guarantee a high measurement quality. A lack of quantitative calculation exists when determining the appropriate exposure time, because of the subjectively selected exposure times. Multiple long exposures are necessary to synthesize HDR images. For instance, in [46], 23 exposures were needed to gain a high-quality point cloud of a vase. Although the three-step phase-shifting and the three-frequency heterodyne phase unwrapping algorithms are used, 207 images $(3 \times 3 \times 23)$ are needed to synthesize the HDR image. Using two cameras and projectors on different viewing angles, Liu et al. [47] propose a method that incorporates binocular and monocular structured light. This allows to obtain a 3D morphology of highly reflective surfaces, in order to fill in missing data in the dark areas of high light and diffuse reflection. They introduced image segmentation techniques to determine which monocular system is suitable for an accurate reconstruction of the missing points. This method outperforms several methods of the literature in terms of reconstruction, since areas of high reflection highly dependon the illumination and the angle of view. Only with multiple exposures, it is difficult to determine the initial value of the exposure time for an unknown scene. A

single predicted exposure time is not constantly proper for surfaces having a wide range of reflectivity variations. Therefore, it is necessary to make multiple exposures or to choose several different exposure times, based on experience, in order to adapt to the different surface reflectivity.

Feng et al. [48]subdivided the measured surface reflectance into several groups, based on its histogram distribution, in order to avoid the previously mentioned complicated processes. This makes the optimal exposure time of each group adaptively predictable, so that the measured surface bright and dark areas can be properly managed. Finally, these optimal exposure times are used to capture the raw stripe images, in order to synthesize the HDR images. Nevertheless, estimating the response function of the camera with the histogram of the sequence images, may produce a partitioning effect. Therefore, it may be hard to choose the predicted exposure time.

Zhong et al.[49]introduced a similar technique used to adopt the optimal exposure time as large as possible, while avoiding image saturation in the high reflective region. However, using a single exposure time leads to a limited SNR improvement in the regions of low reflectivity. This traditional intensity-based pixel saturation recognition method is easily disturbed, because of the camera blur and random noise. This affects the brightness reaching the highest quantization level. For instance, a brightness level of 255 is reached with an 8-bit camera.

In addition, Jiang et al. [50]proposed a method that adjusts the exposure time of the camera and the intensity of the projected fringe light, in order to generate composite fringe images. The highest modulation intensity is set as the criterion to select pixels from the original fringe image, rather than the brightest unsaturated intensity. This allows to obtain a higher SNR and to minimize the ambient light influence. This method can also automatically fix the exposure time and the projection intensity parameters. However, the practical use of this method is relatively complex. In fact, it requires to add at least 5 times the fringe image, in order to achieve the same measurement as the traditional phase measurements. Rao et al. [51]proposed an automatic multi-exposure technique. This method analyzes the fringe modulation of each pixel and its maximum fringe intensity, in order to automatically calculate several exposure times. It simplifies the reconstructions, which makes the extra manual intervention unnecessary. Experiments show that this method helps to reconstruct surfaces with different textures under the condition of up to 5 exposures.

Aiming at shortening the measuring time, Zhao et al. [52]proposed a fast HDR digital fringe projection methodhaving a frame rate of 700 Hz.This method allows to meet the necessity of fast and effective 3D measurement of highly reflective surfaces with dense point clouds, and reduces the projecting time by 88%. The dynamic range of the projector is extended with three identical Light

Emitting Diode (LED) chips and an intensity modulation technology. The dynamic range of light intensity of one chip can be revised 9 times, i.e. three chips alike can be changed for 27 times. This certainly speeds up the 3D measurement of highly reflective surfaces.

Feng et al. [53]proposed a high dynamic range imaging digital-micromirrorbased approach, which combines the digital micromirror with the camera, and adjusts the intensity of the incident light by pixel level, in order to avoid image saturation.

Suresh et al. [54]proposed a new method for measuring highly reflective surfaces by means of the transitional state of digital micromirrors. A 1-bit binary image is taken twice in each projection period to obtain two stripe images in different brightness. The two images are then combined to solve the saturation problems. A combination of the two 1-bit binary images can be applied fora high-speed measurement. However, if the images are supersaturated, more images with different exposures should be taken to optimize the acquisition of the HDR image. Chang Meng et al. [55]used a single low dynamic range image, in order to correct the exposure and enhance the details. This method leads to a satisfying visual effect at the expense of noise increase in the image. The multiple exposure technology has the advantage of eliminating the need of too many changes to the original technology, and theneed of anextra hardware system. In addition, it leads to a high measuring accuracy and a high SNR. Adjusting the exposure time is the optimal solution when measuring surfaces of multiple textures and colors. However, the exposure time cannot be freely selected for the structured light system, when a fringe pattern is projected with a DLP. In order to accurately capture the grayscale of the projection, the camera and the projector should be totally synchronized, and the exposure time should be set to integer multiples of 1/ FPS.Note that FPS is the refresh rate of the projector, generally equals to 60 Hz).

(2) The projection pattern intensity adjustment method

A common HDR technique consists in adjusting the gray levels of the projected fringe pattern. In other words, the intensity of the projected pattern is fixed in accordance with the difference between/among the reflectivity of the surface for projection. Waddington and Kofman[56, 57]proposed a method that corrects the sinusoidal stripe pattern of the Maximum Input Gray Level (MIGL) projection. This approachcan be applied to different ambient/background lighting, and it allows to avoid image saturation and errors in the 3D topography measurement. Nevertheless, it only uniformly adjusts the MIGL of the projector to prevent image saturation, which reduces the SNR when measuring surface regions of low reflectivity. The method proposed in [56, 57] combinesthe MIGL reduction

with the per-pixel method, which allows to adjust the intensity of the projected fringe pattern and to select the brightest of the non-saturation technique from the original fringe images, taken under different lighting conditions. The intensity of the projected fringe pattern is recursively adjusted, pixel by pixel, based on the feedback of the camera. The HDR image and the absolute phase map of the measured surface are constructed using the four-step phase shift algorithm. Lin et al. [58] developed a HDR 3D topographic measuring adaptive digital fringe projection technique able to treat the surface of highly reflective the pixel intensity of the objects by adjusting projected fringe pattern.Simultaneously, it allows to improve the measuring accuracy. With the camera response, adjustments are made in terms of surface reflectivity and ambient lighting. Anovel mathematical model for the analysis of the intensity of the interaction between ambient light and surface reflection, allows to accurately calculate the optimal intensity of each pixel in the fringe pattern. This method outperforms the previously proposed methods for the synthesis of HDR images, in different lighting conditions. Furthermore, it only needs 31 images to obtain the point cloud image of an aluminium alloy workpiece in the experiment, while maintaining a high SNR when measuring surfaces of low reflectivity. However, similar to multiple exposures techniques, its measurementis at a slow rate.

According to the reflection characteristics of the measured surface, Chen et al. [59]calculate the optimal projection light intensity using the polynomial fitting algorithm. In the adaptive fringe image, saturation can be diminished and eliminated. Although the SNR remains high, this method can accurately measure the 3D morphology of highly reflective surfaces. By collecting the minimum number of images, the adaptive stripe images are generated to avoid the time-costing work of collecting a large number of images.

Li and Kofman[60]developed an adaptive fringe pattern projection technique that consists inmodifying the MIGL in the projected fringe pattern, according to the local reflectivity of the surface to be measured. Babaie et al. [61]proposed a new method for measuring the 3D morphology of objects having a wide range of reflectivity variations. The intensity of the projected fringe pattern is recursively adjusted at the pixel level, using the feedback of the camera.Lin, et al. [58]developed an adaptive digital fringe projection technique for HDR 3D topography measurement. This technique can deal with the surface of highly reflective objects, by adaptively adjusting the per-pixel intensity of the projected fringe pattern, while improving the measurement accuracy. Based on the camera response function, adjustments are made based on the surface reflectivity, ambient light and surface reflected lighting. The optimal intensity of each pixel in the fringe pattern to be projected can be accurately calculated, using a novel mathematical model allowing to calculate the intensity of the interaction between ambient light and surface reflection. This method outperforms the previously proposed methods for the synthesis of HDR images, using different lighting conditions. In addition, it only needs to take 31 images in order to obtain the point cloud image of the aluminium alloy workpiece, in the experiment.However, when the surface texture highly changes, the saturated pixel in the image leads to a serious phase, and therefore measurement errors occur. Consequently, Li et al. [62]proposed an adaptive digital fringe projection technique which consistsof coordinate mapping and binarization, in order to adaptively generate phase-shifted stripes, while eliminating the saturated pixels in the high reflective regions.

Chen et al.[63]proposed a new color orthogonal fringe pattern projecting method that adaptively revised the pixel-to-pixel projection intensity, according to the reflectivity of highly reflective surfaces. For pixels with a high surface reflectivity, the intensity of the projected pattern is reduced to avoid image saturation, whereas for pixels with low surface reflectivity, the projected pattern intensity is increased to maintain a high SNR. The optimal projection intensity of each pixel is calculated using the light intensity images of different gray levels. The obtained collected adaptive fringe image is free of over-saturation, and it has a high SNR. Only few groups of pre-collected images are needed to measure the highly reflective surface, instead of collecting multiple groups of images with different exposure time and different gray levels. Thus, the
measurement process is more convenient. In addition, this method can effectively avoid the phenomenon of image supersaturation, and accurately reconstruct the 3D morphology of a highly reflective surface.

In contrast to the previously described technique, which consists in using stripe patterns, Zhang, et al. [64] use monochrome white and black stripe patterns for enhancement. An adaptive intensity template is used to dynamically revise the pattern intensity in order to prevent overexposure in high reflectivity regions. This process is generated using the point spread function (PSF) and the camera response function (CRF). In this method, the PSF is based on the homography mathematic matrix from the camera image plane to the projector image plane, and can be pre-calibrated by means of a meter. However, during the measurement process, it is difficult to ensure that the position of the measured object is the same as that of the checkerboard. Therefore, the coordinates mapped by the homography matrix, are not very accurate. The advantage of revising the intensity of the projected pattern, is that it can be adjusted on a pixel-by-pixel basis rather than the overall camera exposure time. To minimize the influence of the ambient light and surface reflection, the lens aperture should be as small as possible when applying this type of HDR technologies in measurements where a strong light projection exists.

(3) The polarization filter method

Another way to manage highly reflective surfaces consists in changing the angle between the transmission axes of the polarizing filter, in order to eliminate the effects of the highlights and saturated areas on the surface. The basic idea is to limit the reflected light incident on the image sensor to a certain angle, thus effectively removing the strong highlights. However, this can be performed at the expense of alower SNR. Riviere[65]uses the polarizing filters technology to reduce the output light intensity of the projector, and the incident light intensity of the camera. Therefore, dark areas of the scene are difficult to measure. On the contrary, parallel polarimors-analyzer calibration can maintain a good fringe quality in dark areas, but not in bright areas.

Salahieh, et al.[66]proposed a multipolar fringe projection imaging system that eliminated the saturation point and enhanced the fringe contrast, by selecting appropriate polarization channel measurements. The projected fringe is linearly polarized before incident on the surface, and then collected after reflection by a camera equipped with a pixelated polarized array with four states. However, the corresponding hardware system is complex.

HaoJinglei, et al. [67]proposed a 3D reconstruction method based on multispectral polarization, which fuses photogrammetry and machine vision. The complete 3D reconstruction of the special surface with high reflection, can be realized by obtaining the precise polarization spectral characteristics of the target. The key of 3D reconstruction using HDR technology based on polarized light plate, is to obtain the polarization state of the reflected light through polarization imaging. This method does not depend on the texture information of the surface.In addition, the polarization imaging can suppress the flare to a certain extent, which effectively solves the problems existing in the traditional 3D reconstruction methods. Although the measurement accuracy is improved, objects and light paths should be carefully adjusted before using polarizing filters, which increases the hardware complexity.

(4) The color invariant method

The change of illumination makes the color unstable, during image retrieval. The color features describing the physical reflection characteristics of the object and extracting information unrelated to illumination, are referred to ascolor invariant description. This method is based on the two-color reflection model proposed by Shafer[68], in which the color of the point is jointly determined by the color of the object surface and the color of the light source. Diffuse reflection represents the color information related to the object surface, while specular reflection represents the color information of the light source.Gever and Smeulders[69] first proposed several color invariants, based on the two-color reflection model. Benveniste and Unsalan[70-72] then used color invariance to solve the problem of highly reflective surfaces. Afterwards, a novel C.I. was introduced to detect red streaks, green streaks and highlights, and

to segment the streaks from the captured image. Using the C.I. in the segmentation process, highlights from ambient light are eliminated in highly reflective surfaces. Recently, with the development of the embedded technology, a new structured light scanner system based on the Digital Signal Processing (DSP) evaluation module has been designed and implemented. This scanner system extracts range data to reduce the computational burden on the computer. Exploiting the color pattern projection and the C.I., the method based on binary, ternary and quaternary color-coded patterns, eliminates the influence of highlight and ambient light during scanning. However, if the underlying surface contains complex textures and multiple colors, the method will inevitably be affected[73].

(5) The photometric stereo technology

The photometric stereoscopic technology can reconstruct 3D morphology and reflectivity of surfaces from multiple images under illumination from different directions at a fixed viewpoint. In the early work of photometric stereoscopic technology, the Lambert reflective surfaces are considered. In the case of non-lambert surfaces, especially for metal surfaces, it is difficult to robustly estimate the reflectivity when dealing with highly reflective regions. Recently, traditional photometric stereoscopic techniques have been proposed to deal with highly reflective regions with varying Bidirectional Reflectance Distribution functions

(BRDF). Researchers have proposed several methodsto detect or isolate the highly reflective parts of the image [74-76].

For instance, Mattino et al.[77] described in detail the way light is reflected on opaque surfaces in BRDF. As for real surfaces, the general BRDF is a complex nonlinear equation involving seven or more parameters [78, 79]. Traditional techniques usually use dense images to measure scale 3D models. However, this results in limiting their application domains. Li et al.[80]proposed an effective photometric stereoscopic method for BRDF parameter estimation, which does not require a 3D geometric object. Since the number of input images is small, the recovered surface normals can be used to select the BRDF parameter from the optimal window of an image.Goldman et al. [81]proposed a photometric stereoscopic method for BRDF surfaces with spatial variation, including surfaces having different diffuse and high reflective properties. They modeled the surface reflectivity as a linear combination of the base materials, and used the famous Ward model to reconstruct the morphology, material BRDF and weight map.

Chung, et al.[82]proposed a new photometric stereoscopic method that focuses on efficiently estimating the BRDF parameters and reconstructing smooth surfaces, in order to address rough and highly reflective surfaces. This method does not use unreliable specular separation and specular reflection estimation. An important visual cue is used to optimally recover the global BRDF parameters. For instance, in the object morphology reconstruction experiment, shadow visual cues are used to estimate global parameters, which reduces the complexity of the normal surface estimation.

(6) Other technologies

To manage the specular reflections that occur in isolated areas of an image, multiple cameras, color sources, color filters, and multiple light projection angles can be used for synthesizing HDR images. For instance,Kowarschik et al.[83]utilizes 15 light projection directions to compensate for the specular reflections or shaded areas. In their method, objects can be rotated to create other views. The camera takes pictures of different colorpatches in local coordinates of the surface, and then synthesizes them into global coordinates. However, several system parameters affect the calibration speed. In addition, hardware, system setup, image templates and composition processing also create varying complexity.

Jeong, et al. [84]used a spatial light modulator to manage the camera exposure time of a single pixel. The final exposure-settings for saturated pixels are determined by multiple iterations. The projected fringes are synthesized into HDR images by revising the transmittance level of a modulator located in the conjugate position of the camera plane. However, this process requires additional optics and extra hardware. Feng, et al. [85]proposed an intensity expansion method for cameras using digital micromirror devices, which create HDR images by adjusting the optimal exposure time of each camera pixel.

Compared with sinusoidal patterns based on image intensity, the edges of binary fringe patterns that are susceptible to surface reflection are better defined, although the surface is highly reflective. Therefore, the decoding process is more robust. Song, et al.[86]proposed a structured light coding method for high reflective surface measurements, bypassing the workpiece coating process. The fringe edge is encoded in the projected pattern, instead of the original image intensity. In order to more accurately border fringe edges, a special detector that uses positive and negative fringe patterns is introduced to obtain a sub-pixel accuracy. However, if the saturated areas in the captured image are too large to be contained in a single stripe, no reproducible information is available in these areas.

Jiang, et al. [87]proposed a technique that does not need changes in exposure. The main idea is based on the relation between the inverted stripe patterns and regular stripe patterns. Although this method is not as robust as the previously proposed HDR techniquesthat use multiple exposures, it is promising interms of improving the measurement quality.

Meng, et al. [75] developed a Gonio-Plenoptic imaging system to achieve a single topographic measurement of highly reflective surfaces. Besides the light

field information from the scene, the system consists of a collimating lighting source and a full-light camera to capture BRDF changes on the surface of an object in a single image. In the experiment, the lighting is positioned in 30 different directions. However, the system can only shoot from an angle of almost ± 7 °.Therefore, the system limits the range of surfaces that can be reconstructed. In addition, the system is only suitable for embossed surfaces with small undulations, while it faces problems when dealing with surfaces having larger gradients.

1.3 Outstanding issues and contributions of the thesis

1.3.1 Outstanding issues

It can be seen from the literature review in Section 1.2 that PSP is one of the most popular techniques in 3D reconstruction, due to its advantages of high accuracy, high robustness etc. It can also be seenfrom the fundamental principle of the PSP that the unsaturation image and the static object are the internal requirements of PSP. However, those requirements cannot always be met in practice, because the object of high reflective surface or motion is common. Although some existing methods are proposed to address these issues, none of them provides a universal optimal solution. In summary, the outstanding issues of the PSP can be described as follows:

- (1) There is no useful information when the image has saturation. The way the reflective parameter of the object surface described presents an important question for the thesis.
- (2) The existing method addressing the saturation issues always involves a large number of fringe patterns with different intensity levels. However, it only uses the unsaturation images of the highest intensity and discards other captured images. The possibility of using all the captured fringe patterns to improve the robustness of the reconstruction algorithm, is also a crucial topic in this thesis.
- (3) The traditional PSP requires multiple fringe patterns with phase shift to reconstruct the object. The phase shift is generated using projected multiple fringe patterns with phase shift. In order to achieve high speed reconstruction, we aim at studying the possibility of obtaining the phase shifted fringe pattern by projecting a single fringe pattern.
- (4) Finally, in order to reconstruct the object based on PSP and single fringe pattern, we are also interested in studying the movement influence on the projected single fringe pattern.

1.3.2 Contributions

This thesis addresses the reconstruction of objectshaving a high reflective surface and motion based on PSP. The contributions of this thesis are summarized as follows:

- (1) Improved the SNR using the entire projected fringe pattern with different intensity levels.
- (2) Introduced the PSP algorithm to the signal processing field.
- (3) Proposed a method to reconstruct the moving object by projecting a single fringe pattern, based on PSP.
- (4) Generated the multiple phase shift fringe pattern by the movement.
- (5)Built a 3D shape measurement system allowing to reconstruct the moving object without the synchronization limitation of the camera and the projector.

1.4 Structure of the thesis and conclusion

1.4.1 Structure of the thesis

Chapter 2 presents studyon the surface characteristics influence on the fringe patterns, by selecting some typical materials and making comparative analysis. The fringe modulation index is chosen to represent the reflection of the object surface, while experiments are implemented to verify its efficiency.

In Chapter 3, a new method reconstructingobjects with high reflective surface is presented. By adjusting the projected intensity level, a set of unsaturation imagesare obtained. Afterwards, using the optimized combination, the unsaturation fringe patterns with different intensity levels, are combined to improve the SNR of the reconstruction. Finally, the object with high reflective surface is reconstructed successfully.

Chapter 4 proposes amethodfor reconstructing the moving object by a single fringe pattern, based on PSP. Multiple fringe patterns are required, while the phase shift is generated by the movement among the fringes of the single fringe pattern. The proposed method not only inherits the advantages of PSP, but also projects less fringe patterns.

Finally, conclusions and perspectives are drawn in Chapter 5.

1.4.2 Conclusion

In this chapter, the introduction of the 3D shape measurement techniques has been discussed, and the existing techniques have been reviewed. By analyzingthe principle of the PSP, we find that the PSP reconstruction causes the issues of high reflective surface and object with motion. This thesis first studies the influence of reflectivity on the accuracy of threedimensional measurement. By assessing the influence of the reflectivity of different types of objects on the fringe pattern, and performing statistical analysis and comparison of the modulation index distribution, we can deduce that the modulation index is determined by the diffuse reflectance coefficient. The latter is directly related to the surface reflectivity, and is one of the important factors affecting the three-dimensional measurement accuracy of objects.

By analyzing the combination method of the fringe patterns and the influence of the object movement, this thesis presents some approaches addressing the previously mentioned issues, based on PSP. The proposed methods not only improve the reconstruction SNR using all the unsaturation fringe patterns, but also reconstruct the moving object by projecting a single fringe pattern, based on PSP.

2 Experimental study for the influence of

surface characteristics on the fringe patterns

2.1Introduction

With FPP, ideal sinusoidal patterns are projected onto the object surface which results in deformed fringe patterns. The images of the deformed fringe patterns are captured by a camera and then processed to reconstruct the objects profile. However, the broad application means that the object surface characteristics are complex. The surface may be dark or bright, rough or shiny, which makes the fringe patterns captured by the camera surfer from abnormal intensity. Therefore, it is difficult to accurately reconstruct the object. Although several methods have been developed to deal with the influence of specific surface characteristics, comparative studies for different materials do not exist.

This chapterpresents a studyon the surface characteristics influence on the fringe patterns, by selecting some typical materials and making comparative analysis. The fringe modulation index is chosen to represent the reflection of the object surface, while experiments are implemented to verify its efficiency.

This chapter is organized as follows. Section 2.2 presents the principle of the modulation index. Section 2.3 presents the experimental results. Section 2.4 concludes the chapter.



2.2 Principle of phase shifting profilometry

Fig. 2.1 System structure of the PSP

The proposed algorithms, described in this thesis, are based on the phase shifting profilometry (PSP)[30, 88, 89]. In this section, the PSP principle is presented, while also discussing its limitation.

A typical PSP system consists of a camera and a projector. The projector illuminates the object surface with a set of phase-shifted fringe patterns:

$$s_i(x, y) = a_0 + b_0 \cos\left(2\pi \frac{x}{\lambda_0} + \frac{2\pi i}{N}\right), \quad i = 0, 1, \dots, N-1$$
 (2.1)

where a_0 is the average intensity, b_0 represents the intensity modulation and N denotes the number of steps for phase-shifting. These images are reflected by the object surface and captured by the camera as:

$$d_i(x, y) = a(x, y) + b(x, y) \cos\left(\phi(x, y) + \frac{2\pi i}{N}\right), \quad i = 0, 1, \dots, N-1$$
(2.2)

where a(x, y) and b(x, y) respectively denote the ambient light and projected intensity, $\phi(x, y)$ represents the phase of the captured fringe pattern, which is the modulation of the linear phase in Equation (2.1) by the variance of the object shape, and hence carrying the information of the surface profile.

The well-known phase-shifting algorithm for extracting the phase map of the reflected fringe patterns can be easily demonstrated:

$$\phi(x,y) = \arctan\left[\sum_{i=1}^{N} d_i(x,y) \sin\left(\frac{2\pi i}{N}\right) / \sum_{i=1}^{N} d_i(x,y) \cos\left(\frac{2\pi i}{N}\right)\right]$$
(2.3)

This algorithm has a number of advantages. For instance, it is less influenced by the ambient light and reflectivity variations of the object surface.

It can be seen from Eq. (2.3) that using the arctan() function leads to wrapping the phase value into $(-\pi,\pi)$, which introduces the phase ambiguity between the

projected fringe pattern and the captured fringe pattern. The phase unwrapping method [90-92] is used to obtain the corresponding relationship and remove the above phase ambiguity. The monotonous unwrapped phase can be computed as:

$$\Phi(x, y) = \phi(x, y) + 2\pi \times k(x, y)$$
(2.4)

where $\Phi(x, y)$ is the unwrapped phase and k(x, y) is the fringe order index.

Afterwards, the 3D information can be obtained with the system calibration parameters.



Fig. 2.2 The calibration board used in the thesis

The calibration of the system in this thesis is based on the Zhang's method [25, 93]. The calibration board, shown in Fig. 2.2, is placed in front of the camera for different postures. The calibration board is made in high accuracy, while the

distance between the circles is known. The horizontal and vertical fringe patterns are projected at each posture. The camera captures the images with and without fringe patterns for each posture. The images without fringe patterns are first used to calibrate the camera. The projector is then calibrated by considering it as an inverse camera, with the same algorithm used in camera calibration. The intrinsic parameters (focal length, pixel skew factor etc.) and extrinsic parameters (rotation and translation relationship between the world coordinate system and the camera coordinate system) of the camera and the projector, are obtained. Finally, the 3D information of the object can be calculated based on the phase value and the system parameters.

It can be seen from the principle of the PSP that the 3D information is calculated by the intensity value of the captured fringe pattern. Therefore, when the object has a high reflectivity surface, the captured intensity of the fringe pattern will be saturated, leading to reconstruction failure. On the other hand, the traditional PSP requires that the object remains static during the measurement, as multiple fringe patterns are utilized. Therefore, this thesis addresses the issues caused by high reflectivity surfaces and objects in motion.

2.3Modulation index

In order to analyse the influence of the object surface with different reflectivities, the modulation index is selected to represents the information of

the surface reflectivity by lots of researchers[94]. The average intensity a(x, y) and the intensity modulation b(x, y) can be determined from the fringe pattern captured by the camera (cf. Eq. (2.2)) as[94]:

$$a(x, y) = \frac{1}{N} \sum_{i=1}^{N} d_i$$
 (2.5)

$$b(x,y) = \frac{2}{N} \sqrt{\left[\sum_{i=1}^{N} d_i \sin\left(\frac{2\pi i}{N}\right)\right]^2 + \left[\sum_{i=1}^{N} d_i \cos\left(\frac{2\pi i}{N}\right)\right]^2}$$
(2.6)

The fringe modulation index $\gamma(x, y)$ is given by:

$$\gamma(x, y) = b(x, y) / a(x, y) \tag{2.7}$$

Because the SNR has a positive correlation with the modulation index $\gamma(x, y)$, the PSP tends to make the captured fringe patterns have modulation index as high as possible, in order to acquire phase $\phi(x, y)$ with high precision. Investigating the expression of $\gamma(x, y)$ from another viewpoint helps to demonstrate the factors influencing the modulation index. The projector illumination can be rewritten as an ideal distribution:

$$I_i^p = a + b\cos\left(\phi + \frac{2\pi i}{N}\right), \quad i = 1, \cdots, N$$
(2.8)

where constants *a* and *b* can be set in the computer to adjust the intensity of the fringe patterns.

The fringe patterns, captured by the camera, can then be express as:

$$I_{i} = s(r(x, y)I_{i}^{p} + I^{a}(x, y)), \quad i = 1, \cdots, N$$
(2.9)

where *s* denotes the camera's sensitivity to light, r(x, y) is the surface reflectivity and $I^{a}(x, y)$ is the ambient light.

Comparing with Eq. (2.5) and Eq. (2.6), we obtain:

$$A = s(r(x, y)a + I^{a}(x, y)), \quad B = sr(x, y)b$$
(2.10)

Thus, the modulation index can be expressed as:

$$\gamma(x, y) = \frac{B}{A} = \frac{b}{a + I^{a}(x, y) / r(x, y)}$$
(2.11)

It can be noticed that the surface reflectivity r(x, y) highly affects the modulation index. Therefore, the influence of the object surface characteristics (mainly related to r(x, y)) on the fringe patterns, can be evaluated with the modulation index.

2.4 Experimental study on the reflection of different materials

To evaluate the influence of different materials on the fringe patterns, some typical samples are selected. A commercial projector (Hitachi CP-X260, 1024×768 pixels) is used for structural illumination. Five-steps phase-shifted fringe patterns are generated and then projected onto the samples surfaces. Afterwards, the deformed fringe patterns are captured with the camera (DUNCANTECH MS3100, 1280×959 pixels). The modulation index is then calculated by the same method described in section 2.3. As the modulation index corresponding to different samples has values on the same scale ($\gamma(x, y) \in [0,1]$), its analysis and comparison should be convenient and convincing.

2.4.1 Sample selection

The materials choice should mainly take into account the universality, typicality for PSP. Moreover, in order to ensure that the study is practically useful, all the materials involved in the experiment should be widely used in industry. Five types of materials and corresponding samples that are widely used in industry, medical applications and daily life, are selected. In order to ignore the interreflection of the surface, only the samples with simple shape are selected.

The selected materials and samples are:

(1)Plastics. In the experiment, a plastic card is chosen as the sample.

(2)Metal. In the experiment, a piece of Aluminium alloy is chosen as the sample.

(3)Ceramic. In the experiment, a ceramic cup is chosen as the sample.

(4) Leather. In the experiment, a notebook with leather cover is chosen as the sample.

(5) Paper. In the experiment, a piece of white paper is chosen as the sample.

2.4.2 Experiment & results

The experiment was done in a constant light condition, in order to ignore the fluctuation of the ambient light. 5-step PSP is used to calculate the γ value, for different object samples (captured fringe images). For each sample, the distribution of γ in a selected area as well as its histogram, are demonstrated. Instead of use *B* as the modulation directly, the γ is calculated by B/A as shown in Eq 2.11. The influence on the fringe pattern intensity for the object saturation part, is firstanalysed. The intensity values of different positions among the 5-step PSP fringe patterns, are presented in Fig. 2.3.



Fig 2.3. The intensity of the 5 fringe patterns at different positions.

It can be seen that, in the shadow area, the intensity value is always 0. In the most saturation area, the intensity value is always 255. In the part saturation area, some intensity valuesare 255, and the saturation happens. In the unsaturation area, the intensity value is related to the reflectivity of the object surface.

Afterwards, the five objects are tested to present the relationship between the modulation index and reflectivity of the object surface. The results are shown in Fig. 2.4-2.8.



Fig 2.4. Experiment results for plastic (an access card): (a) the captured fringe image and the selected area; (b) the 3D distribution of γ in the selected area; (c) the histogram of (b).



Fig 2.5. Experiment results for metal (Aluminium alloy): (a) the captured fringe image and selected area; (b) the 3D distribution of γ in the selected area; (c) the histogram of (b).



(a)



Fig 2.6. Experiment results for ceramic (a cup): (a) the captured fringe image and selected area; (b) the 3D distribution of γ in the selected area; (c) the histogram of (b).



(a)



Fig 2.7. Experiment results for leather (a notebook): (a) the captured fringe image and selected area; (b) the 3D distribution of γ in the selected area; (c) the histogram of (b).







Fig 2.8. Experiment results for paper: (a) the captured fringe image and selected area; (b) the 3D distribution of γ in the selected area; (c) the histogram of (b).

2.4.3 Analysis

As previously mentioned, to acquire phase ϕ with a high precision, PSP tends to make the captured fringe patterns have modulation index as high as possible. It can be clearly seen from the experiment results that most of the samples have distinct modulation index γ , while the plastic card and the paper have similar γ distribution. The plastic card, the leather cover and the paper have high γ values in the selected areas, while the cup presents low γ values in the shiny area. The piece of Aluminium alloy has relatively low γ values, especially in the shiny area.

It can also be seen that different materials may present a similar γ distribution.In other words, the plastic and the paper may both have high γ values, while the metal and the ceramic both have low γ values in the shiny area. We deduce that the materials type is not a determinative factor. The difference of γ distribution is more depended on the diffuse reflectivity (shiny or not) of the surface.

2.5 Conclusion

This chapter presents a comparative study focusing on the characteristics of objects with different materials. In order to get comprehensive data, the experiment is performed for different materials in the FPP system. The obtained influence properties could be used for the development of effective de-noising algorithms, in order to improve the measurement accuracy. In future work,we will focus on the influence of other characteristics such as the color, shape and ambient for example, and then develop an algorithm to compensate the distortion for different material surface conditions.

3 RECONSTRUCTION OF THE OBJECT WITH SHINY SURFACE, BASED ON OPTIMIZED COMBINATION

3.1Introduction

PSP is an effective method for non-contact 3D imaging and measurement with a wide range of applications. With PSP, sinusoidal fringe patterns are projected onto the object surface and deformed by the height of the object. The deformed fringe patterns are captured by a camera, and then analysed to reconstruct the objects profile. However, the surface of the object should be diffusive. This requirement limits the application of PSP. In practice, this requirement cannot always be met as the surface may be dark or bright, rough or shiny, leading to distortion of the captured fringe patterns. In the cases of shiny surfaces, reflection saturation can happen, resulting in significant errors in the extracted phase maps, and consequently the 3D shape measurement.

In this chapter, a method addressing the saturation issue for the objects with a dynamic range of reflectivity variation, is proposed. The proposed method utilizes all the unsaturation images. Therefore, it is more efficient for measuring the shiny surfaces by FPP with low-cost cameras. Compared with existing methods that only use the highest intensity of pixels for compositing images, the proposed method is able to significantly improve the measurement accuracy. It

is important to mention that the proposed method only works for the cases where an unsaturated reflection can be obtained, by reducing the projection intensity.

This chapter is organized as follows. Section 3.2 presents the principle of the existing method. Section 3.3 describes the proposed method based on optimized combination, where the errors caused by the shiny surface are removed. In Section 3.4, experimental results are presented to verify the efficiency of the proposed algorithm. Finally, the chapter conclusion is drawn in Section 3.5.

3.2 Principle of the existing method

For the reason of easy reference and understand for the reader, we describe the equations of the fringe patterns again. With PSP, a set of phase-shifted fringe patterns are generated by a digital projector, described as:

$$s_i(x, y) = a_0 + b_0 \cos\left(2\pi \frac{x}{\lambda_0} + \frac{2\pi i}{N}\right), \quad i = 1, \cdots, N$$
 (3.1)

where $s_i(x, y)$ is the intensity of the projected fringe patterns, *i* denotes the index number, λ_0 represents the spatial wavelength of the fringe pattern, a_0 , b_0 and Nrespectively denote the average intensity, intensity modulation and number of steps for phase shifting. These images are reflected by the surface of the object and captured by the camera:

$$d_i^0(x,y) = a(x,y) + b(x,y)\cos\left(\phi(x,y) + \frac{2\pi i}{N}\right), \quad i = 1, \cdots, N$$
(3.2)

where a(x, y) denotes the ambient or background light captured by the camera, b(x, y) is the intensity modulation and $\phi(x, y)$ represents the phase map of the captured fringe pattern, which is the modulation of the linear phase by the variance of the object shape, and hence carrying the information of the surface profile.

Note that, in many practical applications, the background light exists when the measurement is not conducted in a dark room. The phase value can be obtained by:

$$\varphi(x,y) = \tan^{-1}\left[\sum_{i=1}^{N} d_{i}^{0}(x,y)\sin(\frac{2\pi i}{N})/\sum_{i=1}^{N} d_{i}^{0}(x,y)\cos(\frac{2\pi i}{N})\right]$$
(3.3)

In order to avoid the sign ambiguity on the phase value, the double-argument atan2 function is used when the algorithm is implemented. Eq. (3.3) represents the well-known phase-shifting algorithm for extracting the phase map of the reflected fringe patterns. This algorithm has a number of advantages.For instance, it is less influenced by the ambient light and reflectivity variations of the object surface. However, if the object surface contains shiny areas, the acquired fringe patterns may include saturation areas, and they cannot be correctly described by Eq.(3.2). In this case, Eq. (3.3) is not able to yield the correct phase map $\phi(x, y)$, which leads to a significant error in the 3D reconstruction of the surface.

In order to remedy this saturation issue, two separate pieces of work were carried out based on the same scenario [46, 57]. More precisely, for each phase-shifted fringe pattern $s_i(x, y)$, a set of the same pattern with different intensity levelsis generated by varying the camera exposure time [46] or the projection intensity [57]. These patterns are projected onto the object, and the reflections are captured by the camera as:

$$d_{i,i}(x, y) = p_i d_i(x, y), \quad j = 1, 2, ..., M$$
 (3.4)

where M is the number of the intensity levels and p_j denotes the influence of the camera exposure time in [46] or the projection intensity in [57], which decreases with j.

Note that $d_i(x, y)$ in Eq. (3.4) may not be the same as that in Eq. (3.2) due to the influence of the saturation $d_{i,1}(x, y)$ is the fringe pattern with the highest intensity, and hence it has the largest saturated areas $d_{i,M}(x, y)$ is the fringe pattern with the lowest intensity and containing no saturation areas. The techniques proposed in [46] and [57]consist in constructing a fringe pattern without having any

saturation area. This is achieved on a pixel-by-pixel basis by selecting the brightest but unsaturated corresponding pixels from the M patterns. In other words, the new fringe pattern is constructed by combining the following areas:

The unsaturated areas on $d_{i,1}(x, y)$;

The unsaturated areas on $d_{i,2}(x, y)$, excluding the unsaturated areas on $d_{i,1}(x, y)$;

The unsaturated areas on $d_{i,3}(x, y)$, excluding the unsaturated areas on $d_{i,2}(x, y)$;

• • •

The unsaturated areas on $d_{i,M}(x, y)$, excluding the unsaturated areas on $d_{i,M-1}(x, y)$.

A new fringe pattern without saturation can be obtained using this method. However, the method is not efficient, because for each of the fringe patterns in Eq. (2.4), only a small portion (area) is used, while the remaining areas, either saturated or unsaturated(e.g. the second brightest intensity but unsaturated image), are simply discarded. In fact, as the discarded areas also contain the 3D information of the surfaces, they can be used to improve the robustness and accuracy of the reconstruction.

3.3 The principle of the proposed method

As previously mentioned, the performance of measurement can be improved if all the unsaturated areas in the acquired fringe patterns are utilized. Without loss of generality, we assume that the saturation occurs when the intensity exceeds T_s . Therefore, to describe the saturated and unsaturated areas on the image in Eq. (2.4), the following is introduced:

$$P_{i,j}(x,y) = \begin{cases} 1, & d_{i,j}(x,y) < T_s \\ 0, & d_{i,j}(x,y) = T_s \end{cases}$$
(3.5)

This can be used as a mask to retrieve the unsaturated (or the saturated) areas of the relevant images. For example, $P_{i,3}(x, y)d_{i,3}(x, y)$ picks all the unsaturated areas of $d_{i,3}(x, y)$ by setting the pixels on the saturated areas to zero. As the number and size of the saturated areas decrease with j, it can be assumed that:

$$P_{i,1}(x,y) \subset P_{i,2}(x,y) \subset P_{i,3}(x,y) \cdots \subset P_{i,M}(x,y)$$
(3.6)

Consequently, the following can be built:

$$A_{i,j}(x,y) = \begin{cases} P_{i,1}(x,y), & when \quad j=1\\ \overline{P}_{i,j-1}(x,y)P_{i,j}(x,y), & when \quad j=2,3,...,M \end{cases}$$
(3.7)

where $\overline{P}_{i,j}(x, y) = 1 - P_{i,j}(x, y)$.

Note that $A_{i,1}(x, y) = P_{i,1}(x, y)$ is the mask used to extract all the unsaturated pixels on $d_{i,1}(x, y)$. The areas on all the other images corresponding to this mask are all saturated. Hence, when this mask is applied to all the other images, unsaturated pixels are always obtained.

 $A_{i,2}(x, y) = \overline{P}_{i,1}(x, y)P_{i,2}(x, y)$ gives the mask used to extract the pixels that are saturated on $d_{i,1}(x, y)$ but unsaturated on all the other images.

 $A_{i,j}(x, y) = \overline{P}_{i,j-1}(x, y)P_{i,j}(x, y)$ is the mask used for the pixels that are saturated on $d_{i,1}(x, y)$, ..., and $d_{i,m-1}(x, y)$ but unsaturated on all the other images.

 $A_{i,M}(x, y) = \overline{P}_{i,M-1}(x, y)P_{i,M}(x, y)$ gives the mask used for the pixels that are saturated on $d_{i,1}(x, y)$, ..., $d_{i,M-1}(x, y)$ but only unsaturated on $d_{i,M}(x, y)$.

Afterwards, we propose to construct the fringe pattern based on the following:

In the areas defined by $A_{i,1}(x, y)$, the corresponding areas of all the *M* image patterns are unsaturated, and hence they will all be utilized.

In the areas defined by $A_{i,2}(x, y)$, the corresponding areas of M-1 image patterns $d_{i,j}(x, y)$ (j=2, ...,M) are unsaturated, and hence employed.

In the area defined by $A_{i,j}(x, y)$, the corresponding areas of M - m + 1 image patterns $d_{i,j}(x, y)$ (j=m, ...,M) are unsaturated, and hence employed.

In the area defined by $A_{i,M}(x, y)$, only the corresponding areas of $d_{i,M}(x, y)$ are unsaturated and utilized.

Consequently, all the data associated with the unsaturated areas on all the acquired images are employed. Therefore, all the information carried by them is utilized. Letting $U_i(x, y)$ denote the constructed fringe pattern, the areas masked by $A_{i,m}(x, y)$ should be constructed as:

$$U_{i}(x, y)A_{i,m}(x, y) = \sum_{j=m}^{M} k_{m,j}d_{i,j}(x, y)A_{i,m}(x, y)$$
(3.8)

where $k_{m,j}$ is a scaling factor which should be selected in a way to yield the maximal SNR for the area masked by $A_{i,m}(x, y)$.

In order to determine $k_{m,j}$, we assume that all the acquired fringe patterns contain additive random noise, i.e. $d_{i,j}(x, y) = p_j d_i(x, y) + n(x, y)$.By replacing it in Eq. (3.8), we obtain:

$$U_{i}(x, y)A_{i,m}(x, y)$$

$$=\sum_{j=m}^{M} k_{m,j} \left\{ p_{j}d_{i}(x, y) + n_{j}(x, y) \right\} A_{i,m}(x, y)$$

$$=\sum_{j=m}^{M} k_{m,j}p_{j}d_{i}(x, y)A_{i,m}(x, y) + \sum_{j=m}^{M} k_{m,j}n_{j}(x, y)A_{i,m}(x, y)$$

$$=d_{i}(x, y)A_{i,m}(x, y)\sum_{j=m}^{M} k_{m,j}p_{j} + A_{i,m}(x, y)\sum_{j=m}^{M} k_{m,j}n_{j}(x, y)$$
(3.9)
The first term in Eq. (3.9) corresponds to the synthesized pattern without noise, while the second term is the resulting noise component. Assuming that the additive noise has a zero mean, a variance σ^2 , and is independent with respect to j, the power of the noise component is given by:

$$\left[A_{i,m}(x,y)\right]^{2}\sigma^{2}\sum_{j=m}^{M}k_{m,j}^{2}$$
(3.10)

Hence, the SNR is expressed as:

$$SNR = \frac{\left[d_{i}(x, y)A_{i,m}(x, y)\right]^{2} \left(\sum_{j=m}^{M} k_{m,j}p_{j}\right)^{2}}{\left[A_{i,m}(x, y)\right]^{2} \sigma^{2} \sum_{j=m}^{M} k_{m,j}^{2}} = SNR_{0} \frac{\left(\sum_{j=m}^{M} k_{m,j}p_{j}\right)^{2}}{\sum_{j=m}^{M} k_{m,j}^{2}}$$
(3.11)

where SNR_0 is the SNR associated with the fringe pattern $d_i(x, y)$ and additive noise n(x, y).

Base on Cauchy inequality, it reaches its maximum value when $k_{m,j} = p_j t_m$, where t_m is a constant with respect to m. Therefore, Eq. (3.9) becomes:

$$U_{i}(x,y)A_{i,m}(x,y) = d_{i}(x,y)A_{i,m}(x,y)\sum_{j=m}^{M}t_{m}p_{j}^{2} + n(x,y)A_{i,m}(x,y)\sum_{j=m}^{M}t_{m}p_{j}$$
(3.12)

This gives the reconstructed area masked by $A_{i,m}(x, y)$. In order to construct a complete fringe pattern having the same shape as $d_i(x, y)$, the weight $\sum_{j=m}^{M} t_m p_j^2$

should be a constant with respect to j. Letting $\sum_{j=m}^{M} t_m p_j^2 = 1$, we have:

$$t_m = \frac{1}{(M - m + 1)p_j^2}$$
(3.13)

$$k_{m,j} = p_j t_m = \frac{1}{(M - m + 1)p_j}$$
(3.14)

and the SNR is given by:

$$SNR = SNR_{0} \frac{\left(t_{m} \sum_{j=m}^{M} p_{j}^{2}\right)^{2}}{t_{m}^{2} \sum_{j=m}^{M} p_{j}^{2}} = SNR_{0} \sum_{j=m}^{M} p_{j}^{2}$$
(3.15)

It can be clearly seen that the *SNR* can be enhanced by carefully setting the weight.Consequently,the fringe patterns can be constructed as:

$$U_{i}(x, y) = \sum_{m=1}^{M} U_{i}(x, y) A_{i,m}(x, y)$$
(3.16)

The procedure can be summarized as follows:

Step 1: Acquire M fringe patterns with different intensity values, i.e. $d_{i,j}(x, y) = p_j d_i(x, y), \quad j = 1, 2, ..., M$; Step 2: Obtain the mask functions $P_{i,m}(x, y)$, m = 1, 2, ..., M;

Step 3: Construct the mask functions $A_{i,m}(x, y)$, m = 1, 2, ..., M using Eq. (3.7);

Step 4: Use Equation (3.8) to obtain areas of fringe pattern masked by $A_{i,m}(x, y)$. Note that the scaling factor $k_{m,i}$ should be computed as in Eq. (3.14);

Step 5: Construct the fringe pattern $U_i(x, y)$ using Eq. (3.16);

Step 6: Repeat the above steps for all the N phase-shifted fringe patterns;

Step 7: Calculate the phase map using the reconstructed fringe patterns, and reconstruct the 3D shape of the object surface.

3.4 Experiments

In order to demonstrate the efficiency of the proposed method, a FPP system is constructed using components of affordable price, including a DELL X1501 projector with a resolution of 1024×768 pixels, and a webcam GUKE HD91 of 1920×1080 pixels. Note that the webcam is much cheaper than industrial cameras.However, it results in captured images having a much higher noise. The object to be measured is a plastic carton face shown in Fig.3.1(a). A five-step PSP is used to extract the phase map. When the object is projected by a

fringe pattern with full intensity (the projector maximum intensity is set to 255), saturation areas are clearly seen, as shown in Fig. 3.1(b).



Fig. 3.1. The object used in the experiment. (a) The carton face object; (b) the captured fringe pattern of the object to be measured.

In order to apply the proposed method, eight levels of the fringe pattern intensity are produced and projected onto the object, while the intensity value gradually decreases by 10 percent. The intensity levels are then: 255, 229, 204, 178, 153, 127, 102 and 76. Note that, when the minimum fringe pattern intensity is applied, there should be no saturation on the whole object. The captured fringe patterns are shown in Fig. 3.2. It can beclearly seen that the saturation areas reduce with the intensity decrease. Note that the images of high intensity have a high SNR. However, they suffer from large saturation areas. On

the other hand, images with low intensity are characterized by a small saturation. However, they are disadvantageous in terms of low SNR, which makes the object reconstruction hard.



Fig. 3.2. The captured fringe patterns with 8 maximum intensity levels. (a)-(h): the captured fringe patterns of 8-levels fringe intensity.

Based on the fringe patterns shown in Fig.3.2, the masks identifying the saturation area can be obtained using Eq. (3.5), and are shown in Fig. 3.3. The threshold T_s is set to 255. Note that the specific pixel is saturated when its intensity value is equal to 255. In Fig. 3.3, the black points are the unsaturation pixels while the white points present the saturation area. Figure 3.3(a) illustrates the mask for Fig. 3.2(a), and Fig. 3.3(b) presents the mask for Fig. 3.2(b). It can be observed that the saturation areas also reduce with the decrease of the maximum fringe intensity level.



Fig. 3.3.The mask identifying the saturation area. (a) the mask for Fig. 3.2(a); (b) the mask for Fig. 3.2(b).

Based on the proposed method, a new fringe pattern is constructed for each step of the PSP, as shown in Fig. 3.4(a). Using the merged result, the wrapped phase value, shown in Fig. 3.4(b), is retrieved.



Fig. 3.4. The merged fringe pattern and wrapped phase obtained by the proposed method. (a) the merged fringe pattern; (b) the wrapped phase value obtained by the proposed method.

As the other phase shifting profilometry methods, phase unwrapping is applied to the wrapped phase, and the 3D information of the object is reconstructed. The obtained results are shown in Fig. 3.5 and Fig. 3.6. Fig. 3.5(a) is the front view of the reconstructed result. In order to clearly observe the details of the reconstructed surface, an object area is shown with a zoom in view. Fig. 3.6(a) is the mesh display of Fig. 3.5(a),while Fig. 3.6(c) is the cross line of Fig. 3.6(a) when x=75. It can be seen that all the areas, including the saturated ones, are well reconstructed and the obtained surface is smooth.



Fig. 3.5.The reconstructed results. (a) The front view of the reconstructed result obtained by the proposed method; (b) the front view of the reconstructed result obtained by [47,48].



Fig. 3.6. Comparison of the reconstruction results. (a) the mesh display of the result in Fig. 3.5(a); (b) the mesh display of the result in Fig. 3.5(b); (e) the cross line for Fig. 3.6(a) when x=75; (f) the cross line for Fig. 3.6(b) when x=75.

Fig. 3.5(b), Fig. 3.6(b) and Fig. 3.6(d) present a comparison between the results obtained by the proposed method and those obtained by the method presented in

[46]. Compared with the proposed method, the results obtained by the method in [46]contain significant errors. This is due to the fact that the latter does notuse all the unsaturation fringe patterns, and significant errors are introduced when the SNR is low. Note that the shadows are removed in the results shown in Fig. 3.5 and Fig. 3.6.

In the second experiment, a metal object with a higher reflectivity is reconstructed. Eight intensity levels are employed. The captured fringe pattern with the highest and lowest intensity values is shown in Fig. 3.7. It can be observed that the image of Fig. 3.7(b) does not present saturation, compared with the image in Fig. 3.7(a).



Fig. 3.7.The captured fringe pattern image of a metal object.(a) The fringe pattern image with the highest intensity value; (b) the fringe pattern image with the lowest intensity value.

The reconstructed results of the metal object are shown in Fig. 3.8. It can be clearly seen that the proposed method significantly improved the reconstruction accuracy.



Fig. 3.8. The reconstructed results of a metal object. (a)-(b) The front view of the reconstructed result obtained by the proposed method and the method in [47,48]; (c)-(d) The mesh display of Fig. 3.8(a) and Fig.3.8(b).

In order to evaluate the anti-noise performance of the proposed method, the root mean square (RMS) errors are calculated for the reconstruction results of Fig. 3.5 and Fig. 3.8. With the proposed method, the RMS error of the image in Fig. 3.5(a) is 0.068 mm, and that of the image in Fig. 3.5(b) is 11.07 mm. With the metal object, the RMS error for the results in Fig. 3.8(a) and Fig. 3.8(b) are 0.071 mm and 9.58 mm, respectively. Hence, the proposed method can significantly improve the measurement accuracy under low SNR.

The above experiments are implemented using the Matlab software, with an Intel i7-7700 (2.81 GHz) processor and 16 GB RAM. The calculation time for the first experiment and second experiment is 10.8 s and 9.2 s, respectively. Note that the calculation time can efficiency be decreased using C++ coding and parallel computing in GPU.

Please note that the required frame number of the proposed method is $M \times N$. When the object has no saturation, only one intensity level (M = 1) is enough to reconstruct the object. On the other hand, when the object has saturation, Mintensity levels are employed to remove the saturation influence, and therefore the frame number will be $M \times N$.

3.5 Conclusion

This chapter presents a method addressing the saturation issue for the objects with a dynamic range of reflectivity variation. The proposed method utilizes all the unsaturation images. Therefore, it is more effective for measuring the shiny surfaces by FPP with low-cost cameras. Compared with existing methods that only use the highest pixels intensity for compositing image, the proposed method is able to significantly improve the measurement accuracy. It is important to mention that the proposed method only works for the cases where unsaturated reflection can be obtained by reducing the projection intensity. As for the objects having very shinny surfaces, we may not be able to acquire a saturation-free fringe pattern, and therefore the proposed method will not work.

4 RECONSTRUCTION OF MOVING OBJECTS WITH SINGLE FRINGE PATTERN BASED ON PSP

4.1 Introduction

In PSP, at least three sinusoidal fringe patterns with known phase shifting are projected onto the object surface by the projector. The camera then captures the reflected fringe patterns from another angle successively[91]. As the object is detected by multiple fringe patterns, PSP has the advantages of high accuracy and high robustness. However, the multiple fringe patterns condition also requires the object to be kept static during the capture of the fringe patterns. Errors will be introduced in the reconstruction result when the object is moved between the multiple fringe patterns[95-97].

The traditional PSP projects multiple fringe patterns onto the object surface to create the phase shift, which is the essential condition of PSP. When the moving object is reconstructed, the phase shift can be obtained from the object movement. This chapter proposes to reconstruct the moving object by projecting a single fringe pattern. One static fringe pattern is projected and the camera captures multiple fringe patterns of the moving object. As the object moves among the fringes, the phase is shifted between the captured images. Afterwards, the object movement is tracked and the phase shift caused by the movement is analyzed. Finally, the correct phase value is retrieved, based on the known phase shifting value.

Thischapter is organized as follows. In the section 4.2, the phase shift caused by the motion is analyzed, and a new method to retrieve the phase value is proposed. Section 4.3 presents the movement limitation of the proposed method. Section 4.4 shows the simulated and experimental results to verify the efficiency of the proposed algorithm. Finally, Section 4.5 concludes the chapter.

4.2 The principle of the proposed method

The principle of the traditional PSP, previouslydescribed in Chapter 1, relies on obtaining the 3D information of the object based on the phase information and the system calibration parameters. The traditional PSP can reach a high accuracy when dealing with a static object. However, when the moving object is measured, we can deduce that: (1) for the traditional PSP, the phase shift is generated by changing the initial phase value of the fringe pattern; (2) when the object is moved among the fringe patterns, errors will be introduced to the phase value if Eq. (2.3) is directly used[98].

In the proposed method, only one fringe pattern is projected. The object movement is employed to generate the phase shift. The camera captures at least three fringe patterns for the moving object. Asfor the static fringe pattern projection, the captured object fringe pattern can be expressed as:

$$I_{n}(x, y) = a + b\cos(\phi(x, y) + \Phi(x, y))$$
(4.1)

In Eq. (4.1), the phase shift in the traditional PSP is removed. If the object is static, same fringe patterns will be captured. When the object has a 2D movement and point (x, y) is moved to (u, v), the relationship between (x, y) and (u, v) can be described by the rotation matrix and translation vector:

$$\begin{bmatrix} x \\ y \end{bmatrix} = R \begin{bmatrix} u \\ v \end{bmatrix} + T, \begin{bmatrix} u \\ v \end{bmatrix} = \overline{R} \begin{bmatrix} x \\ y \end{bmatrix} + \overline{T}$$
(4.2)

where R, \overline{R}, T and \overline{T} are the rotation matrix and translation vector, respectively. Assume $\tilde{h}(\bullet)$ is the object height distribution after movement. When the object only has 2D movement, its height does not change with the movement. Therefore, we have:

$$\tilde{h}(u,v) = h(x,y) \tag{4.3}$$

As the height distribution has a corresponding relationship with the phase variation $\Phi(x, y)$, the latter remains constant for all the object situations, before movement and after movement. Therefore, the fringe pattern after movement can be expressed as:

$$\tilde{I}_{n}(u,v) = a + b\cos(\phi(u,v) + \Phi(x,y))$$
(4.4)

With the coordinator after movement, the object intensity value at (u,v) is generated by phase variation $\Phi(x,y)$, and the phase value of the reference plane at (u,v). In order to uniform the parameter, Eq. (4.4) can be rewritten as:

$$\hat{I}_{n}(f(x,y),g(x,y)) = a + b\cos(\phi(f(x,y),g(x,y)) + \Phi(x,y))$$
(4.5)

$$u = f(x, y), \quad v = g(x, y)$$
 (4.6)

where f(x,y) and g(x,y) are the functions defined by the rotation matrix and transfer vector. Eq. (4.5) is the reconstruction model describing the moving object fringe pattern, based on the single fringe pattern projection. Compared with the traditional reconstruction model, the phase variation is generated by the object movement, while the phase shift amount is not uniform and it depends on the movement distance. Therefore, a new phase retrieval algorithm should be applied.

Eq. (4.5) is then extended to N fringe patterns:

$$\begin{cases} \tilde{I}_{1}(x, y) = a + b\cos(\phi(x, y) + \Phi(x, y)) \\ \tilde{I}_{2}(f_{2}(x, y), g_{2}(x, y)) = a + b\cos(\phi(f_{2}(x, y), g_{2}(x, y)) + \Phi(x, y)) \\ \vdots \\ \tilde{I}_{n}(f_{n}(x, y), g_{n}(x, y)) = a + b\cos(\phi(f_{n}(x, y), g_{n}(x, y)) + \Phi(x, y)) \end{cases}$$

$$(4.7)$$

In Eq. (4.7), the captured intensity values on the left side and the phase value on the reference plane $\phi(\bullet)$ are the known parameters, while *a*, *b* and $\Phi(x, y)$ are the unknown parameters. Therefore, when $N \ge 3$, the phase variation $\Phi(x, y)$ can be obtained by solving Eq. (4.7). $\Phi(x, y)$ can be calculated as:

$$\Phi(x, y) = \arctan \frac{D_a - D_b}{D_c - D_d}$$
(4.8)

where:

$$D_{a} = \sum_{n=1}^{N} \tilde{I}_{n}(f_{n}(x,y),g_{n}(x,y))\cos(\frac{2\pi(n-1)}{N})\sum_{n=1}^{N}\cos(\phi(f_{n}(x,y),g_{n}(x,y)))\cos(\frac{2\pi(n-1)}{N})$$
(4.9)

$$D_{b} = \sum_{n=1}^{N} \tilde{I}_{n}(f_{n}(x, y), g_{n}(x, y)) \sin(\frac{2\pi(n-1)}{N}) \sum_{n=1}^{N} \cos(\phi(f_{n}(x, y), g_{n}(x, y))) \sin(\frac{2\pi(n-1)}{N})$$
(4.10)

$$D_{c} = \sum_{n=1}^{N} \tilde{I}_{n}(f_{n}(x, y), g_{n}(x, y)) \cos(\frac{2\pi(n-1)}{N}) \sum_{n=1}^{N} \sin(\phi(f_{n}(x, y), g_{n}(x, y))) \sin(\frac{2\pi(n-1)}{N})$$
(4.11)

$$D_{d} = \sum_{n=1}^{N} \tilde{I}_{n}(f_{n}(x, y), g_{n}(x, y)) \sin(\frac{2\pi(n-1)}{N}) \sum_{n=1}^{N} \sin(\phi(f_{n}(x, y), g_{n}(x, y))) \cos(\frac{2\pi(n-1)}{N})$$
(4.12)

In Eqs. (4.9)-(4.12), when n = 1, we have:

$$f_1(x, y) = x, \quad g_1(x, y) = y$$
 (4.13)

4.3Movement type limitation

Although only a single fringe pattern is projected, the proposed method still utilizes multiple fringe patterns with phase shifting, in order to reconstruct the 3D information. Rather than projecting multiple phase shifting fringe patterns, the phase variation is generated by the object movement. However, not all the movement types can generate the phase variation. Two movement situations, shown in Fig. 4.1, may cause failure of the proposed method.



Fig. 4.1 Two types of movement that may cause failure of the proposed method. (a) the fringe pattern for a static object; (b) the fringe pattern when the object movement direction is parallel to the fringes; (c) the fringe pattern when the object movement direction is vertical with the fringes and the movement distance is one period.

The proposed method can only reconstruct the objects motion. When the object is static during the capture of the fringe patterns, the captured fringe

patterns are the same (cf. Fig. 4.1(a)). Therefore, the proposed method cannot work properly.

When the movement direction is parallel to the fringe patterns (cf. Fig. 4.1(b)), although the object is in motion, no phase variation is introduced. When the object is moved along the vertical direction of the fringes, and the movement distance is equal to one period (or integer multiples of a period) of the fringe pattern (cf. Fig. 4.1(c)), the phase variation is 2π (or integer multiples of 2π), and the captured object fringe patterns will be same as in Fig. 4.1(a). For the above two situations, the captured fringe pattern cannot be used for phase calculation and should be discarded, while anew image with appropriate phase variation should be captured.

From the above analysis, it can be deduced that it is crucial to determine the relationship between the movement direction and the fringe pattern direction. As the object movement is limited to a 2D movement with respect to the reference plane, the fringe pattern direction of the reference plane can be identified in advance. Assuming that the fringe pattern of the reference plane is captured, as shown in Fig. 4.2, the parallel direction to the fringe pattern is first determined. The phase map of the reference plane is obtained by the traditional PSP method. Two points with the same phase value and same period are then identified, such as point *O* and *A*, for example. Using the coordinates of points *O* and *A*, vector \overline{OA} is calculated. This vector is parallel to the direction of the

fringe pattern. It can be seen that, when the object movement direction is parallel to \overrightarrow{OA} , no phase variation is introduced (cf. Fig. 4.1(b)).



Fig. 4.2 The identification of the fringe pattern direction.

As for the situation illustrated in Fig. 4.1(c), the movement direction is vertical with the fringe pattern and the movement distance is equal to the integer multiples of the fringe pattern period. The vertical direction of the fringe pattern and the movement distance along this direction, should be identified. As vector \overline{OA} has been obtained, the vertical vector of \overline{OA} (\overline{OB} in Fig. 4.2) can be calculated. \overline{OB} has the same vertical direction of the fringe pattern. Afterwards, by analyzing the phase map along \overline{OB} , the period of the fringe pattern is obtained. When the object has a translation movement along \overline{OB} , and the movement distance is equal to the integer multiples of the fringe pattern period, the captured image should be discarded.

Note that the object movement may be the combination of the situations in Fig. 4.1 or the rotation movement. The movement component along \overrightarrow{OB} is used to retrieve the phase variation caused by the movement. In order to avoid the inconspicuousness phase variation, a threshold should be applied to ensure that the phase variation caused by the movement is large enough.

4.4. Simulation and experiment

The efficiency of the proposed algorithm is first verified by the simulation. Three object fringe patterns, shown in Fig. 4.3, are captured. Only one fringe pattern is projected and the phase variation is introduced by the object movement. From Fig. 4.3(a) to Fig. 4.3(b), the object is rotated by 0.02 rad in clock-wise direction, and has a translation movement in the upward direction for 10 pixels.From Fig. 4.3(b) to Fig. 4.3(c), the object has a translation movement in the downward direction for 35 pixels. In the images of the fringe pattern, significant phase variations are caused by the movement.



Fig. 4.3. Three fringe patterns generated by simulation. (a) the original object fringe pattern; (b) the second object fringe pattern with rotation and translation movement; (c) the third object fringe pattern with translation movement.

With the known movement information, the phase variation caused by the movement can be easilyobtained. The reconstruction result of the proposed method is shown in Fig.4.4. It can be observed that the object is wellreconstructed.



Fig. 4.4. The reconstruction result obtained by the proposed algorithm.

Afterwards, the experimental verification with the earphone object, is carried out. One colour camera (Allied Vision Manta 504C, resolution 2452×2056) and one projector (Wintech DLP PRO 4500, resolution 912×1140) are used to evaluate the efficiency of the proposed method. The projector projects the fixed sinusoidal fringe pattern onto the object surface. The object is moved among the fringes, while three fringe patterns are captured to reconstruct the object. Note

that, in order to track the object movement, the red fringe patterns are projected. The red component of the captured fringe pattern (cf. Fig. 4.5) is used to retrieve the phase information.The blue component of the captured fringe pattern is used to track the object movement, as described in [99].



Fig. 4.5.The red component of the captured fringe pattern.

Same as the object tracking method in [99], the Scale Invariant Feature Transform (SIFT) algorithm is used to obtain the feature points from the blue channel of the image. The corresponding relationship of these feature points is shown in Fig. 4.6.



Fig. 4.6. Feature points and corresponding relationship, obtained by the SIFT algorithm

The rotation matrix and translation vector describing the object motion, are then obtained [99]. The correct phase is calculated by the proposed method. The three-dimensional object reconstruction is shown in Fig. 4.7.



Fig. 4.7. Reconstruction results obtained by the proposed algorithm. (a) the front view of the reconstructed result in mesh display; (b) the mesh display of the reconstructed result.

It can be seen that the proposed method can successfully reconstruct the moving object by single projection. In order to evaluate the accuracy performance of the proposed method, the RMS error is calculated using the result obtained by the three-step PSP when the object is static. Compared with the result obtained when the object is not in motion, the RMS error of the proposed method for the moving object reconstruction is 0.087 mm.

4.5 Conclusion

This chapter proposed a novel method that reconstructs the moving object by projecting a single fringe pattern, based on PSP. The object movement is

utilized to generate the phase variation in the traditional PSP. The method determining the relationship between the static fringe pattern and the movement direction, is also detailed.In addition, the limitation of the movement type is discussed. As the proposed method does not need to change the projected fringe pattern, it has the potential of increasing the reconstruction speed.

5 CONCLUSION AND FUTURE WORK

The work focusing on the reconstruction of shiny surface objects and moving objects, has been presented in the previous chapters. The main contributions of this thesis are summarised in Section 5.1.The future work presented in Section 5.2.

5.1 Conclusion

This thesis focuses on the reconstruction of objects with high reflective surface and moving objects, based on the phase shifting profilometry. As for the high reflective surface issues, the proposed method not only adjusts the projecting intensity of the fringe pattern to avoid saturation, but also uses all the unsaturation images to improve the SNR of the reconstruction result. When dealing with moving objects reconstruction, the proposed method only requires to project a single fringe pattern in order to reconstruct the moving object. The phase shift is introduced by the object movement among the fringes. At least three fringe patterns are required. The influence caused by the movement is also analysed. The main contributions of this thesis can be summarized as follows:

(1) The reconstruction of objectshaving a shiny surface, has been improved.This is verified by the increase of the calculated SNR.

In the traditional methods addressing objects of shiny surface, the fringe patterns of different intensities are projected onto the object surface. They are then combined with the highest intensity value of the unsaturation parts, while the other fringe patterns are discarded. On the contrary, the proposed method utilizes all the unsaturation fringe patterns to improve the reconstruction accuracy.

The proposed method utilizes all the unsaturation fringe patterns, and combine them with different weights. When the weight is defined, the optimized combination signal processing algorithm is used. The optimized combination method is one of the popular methods in signal processing. The success of this method in several signal processing applications promising for its efficiency in 3D reconstruction.

(2) The phase shift is introduced by the movement, based on the single fringe pattern projection.

As the single fringe pattern is employed and multiple fringe patterns with phase shift are required, the proposed method introduces the phase shift by object movement. When the object moves among the fringes, the phase shift is generated on the fringe pattern of the object surface.

The influence of the object on the static fringe pattern is analyzed, with the mathematical description of the object movement. However, not all the

movement types can generate the phase shift. Therefore, the limitation of the movement type is also discussed.

(3) The synchronization limitation of the system is removed.

In the proposed method, only a single fringe pattern is projected, which means the projector does not need to change the fringe pattern during the measurement. The camera captures the fringe pattern individually. The measurement system does not require the synchronization between the camera and the projector.

5.2 Future work

Although the algorithms proposed in this thesis succeed in well reconstructing objects of high reflective surface as well as moving objects, several issues should be addressed in future work.

- (1) The method mentioned in Chapter 3 is able to significantly improve the measurement accuracy. However, it is time consuming due to the fact that it requires the information from multiple patters. Therefore, a method which not only improves the accuracy but also reduces the time consumption, is of our interest.
- (2) When dealing with objects having very shinny surfaces, a saturation-free fringe pattern may not be acquired, which leads to failing the proposed

method. Therefore, the measurement of extremely shiny surfaces should be further studied.

(3) The new applications, such as the automatic intelligent driving, automatic recognition and 3D printing, are quickly emerging in the past decades. The requirements of three-dimensional visual data acquisition are also significantly boosting. Therefore, the specific characteristics of these new applications should be considered when developing the foreseen algorithm.

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