Development of in-situ measurement systems for capturing free-form and mirror finish surface information

Fu, Shaowei

2019

Fu, S. (2019). Development of in-situ measurement systems for capturing free-form and mirror finish surface information. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/103297>

<https://doi.org/10.32657/10356/103297>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**DEVELOPMENT OF IN-SITU MEASUREMENT
SYSTEMS FOR CAPTURING FREE-FORM AND
MIRROR FINISH SURFACE INFORMATION**

FU SHAOWEI

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

2019

**DEVELOPMENT OF IN-SITU MEASUREMENT SYSTEMS FOR
CAPTURING FREE-FORM AND MIRROR FINISH SURFACE
INFORMATION**

FU SHAOWEI

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

10/01/2019
.....
Date

Fu Shaowei
.....
Fu Shaowei

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

15 / January / 2019
.....
Date

.....
Tegoeh Tjahjowidodo

Authorship Attribution Statement

This thesis contains material from 1 paper published in the following peer-reviewed journal where I was the first author.

Chapter 4 is published as Fu. S, Cheng. F, Tjahjowidodo. T, Zhou. Y, and Butler. D. A Non-Contact Measuring System for In-Situ Surface Characterization Based on Laser Confocal Microscopy. *Sensors* 18, 2657 (2018). DOI: 10.3390/s18082657.

The contributions of the co-authors are as follows:

- Prof David, Dr Cheng and Prof Tegoeh provided the project direction.
- I co-developed the methodology with Dr Cheng.
- I performed all the experimental work at the School of Mechanical and Aerospace Engineering and the Advanced Remanufacturing and Technology Centre. I also developed the software and analyzed the data.
- I prepared the manuscript draft. The manuscript was reviewed and revised by Prof Tegoeh, Prof David, Dr Cheng and Dr Zhou.

10/01/2019
.....
Date

.....
Fu Shaowei

Abstract

Surface finish usually affects the quality, performance and lifetime of engineering products. With the emerging advanced manufacturing technologies developed in last decades, it is also critical to evaluate and control surface characteristics of various products in engineering and manufacturing fields.

Currently, the surface texture of a workpiece is inspected by post-process methods where the finished workpiece is removed from the machine and sent to a metrology laboratory for measurement. The measurement process requires precise alignment which takes considerable time to achieve. These off-line instruments are also difficult to be integrated into an automatic inspection system. In order to improve the manufacturing accuracy and quality control of the advanced manufactured products, an accurate and *in-situ* surface measurement has become increasingly important. This research aims to develop *in-situ* surface inspection solutions for various advanced manufacturing surfaces such as mirror finishing, additive manufacturing and free-form surfaces.

Firstly, an automated surface inspection system is developed using fringe pattern illumination method, the method allows for an *in-situ* surface roughness measurement and through a dedicated surface roughness calculation algorithm, an on-line data acquisition and processing on mirror finish surface can be carried out. In addition, the developed surface inspection system is also able to detect the directions of machining mark and measure the surface uniformity. For defect detection on mirror finish surfaces, a developed system based on light scattering model is able to perform *in-situ* surface defect detection.

Secondly, a displacement measurement system based on image grating technique is developed to improve the robustness and flexibility for displacement measurement using conventional optical encoder and can be integrated into various surface metrology instruments. The performance of the proposed image grating system is compared with a high-accuracy heterodyne laser interferometer. A measurement error compensation method based on optical distortion model is evaluated both theoretically and experimentally. Then, the error compensation method is implemented in the developed image grating system to reduce the optical distortion error. The experimental result shows that the measurement error is less than $0.35\text{ }\mu\text{m}$ within 50 mm measurement range. In addition, a repeatability study of the proposed system is conducted, and the residual errors are within $\pm 0.15\text{ }\mu\text{m}$.

Finally, a surface finish measurement system based on laser confocal method is developed to measure the surface roughness of the different machined and additive manufacturing surfaces. To reduce the inherent disadvantages of confocal sensor such as scattering noise at sharp peaks and background noise caused by specular reflection from the optical elements, the developed system has been calibrated and a linear correction factor has been applied. The proposed system was integrated into a robotic system with the measurement distance and angle adjusted during measurement based on a CAD model of the workpiece in question. Experimental data confirms the capability of this system to measure the surface roughness within the Ra range of $0.2\text{--}7\text{ }\mu\text{m}$, with a relative accuracy of 5%. To overcome the vertical scanning limitation of the laser confocal sensor, an adaptive surface tracing algorithm is developed and tested to measure free-form surfaces. The developed image grating system is also integrated in to the adaptive surface tracing system for validation. Experimental result demonstrates the capability of surface tracing system to measure the free-form surface with surface

height deviation more than 8 mm and the surface texture and profile measurement errors can be controlled within 0.03 μm .

Acknowledgement

First and foremost, I would like to express my gratitude to my supervisors, Associate Professor Tegoeh Tjahjowidodo (Nanyang Technological University) and Dr Cheng Fang (Advanced Remanufacturing and Technology Centre). Thank you for giving me the opportunity to conduct my PhD research in a collaborative environment. Appreciation are given to you for your comprehension, encouragement, and suggestion when I am facing troubles in study and research.

I would also like to extend my special thanks to Dr David Butler, Dr Zhou Yu, Dr Liu Mengjun, Ms Pooja Chaturvedi, Dr Fang Hongchao, Dr Xu Dawei, Ms Lim Pei Xian, Mr Leong Yong Shin, Ms Kristabel Khoo and other colleagues from Nanyang Technological University and the Advanced Remanufacturing and Technology Centre for supporting my research work.

I wish to express a deep sense of appreciation to my family and friends, especially my lovely wife Zhenyan, for their selfless support and encouragement during my PhD study.

Contents

Abstract	4
Acknowledgement	7
List of Tables	13
List of Figures	14
1. Introduction.....	19
1.1 Background	19
1.2 Motivation	19
1.3 Objective	20
1.4 Scope	20
1.5 Outline	21
2. Approach and Methodology	23
2.1 Literature Review	23
2.1.1 An Overview of Surface Texture	23
2.1.2 Characterization of Surface Texture	25
2.1.3 Surface Roughness Measurement Techniques.....	33
2.2 Key Challenges in Surface Finish Measurement	43
2.2.1 In-situ Surface Finish Measurement	43
2.2.2 Mirror Finish Surface Measurement	45
2.2.3 Rough Surface Topography Measurement	49
2.2.4 Free-form Surface Measurement	51

2.2.5	Precision Displacement Measurement	53
2.3	Research Gaps	61
2.4	Methodology	61
2.5	Summary	62
3.	Mirror Finish Surface Inspection based on Machine Vision Methods	64
3.1	Modelling and Software Development	65
3.1.1	Surface Roughness Measurement	65
3.1.2	Surface Defect Detection	69
3.1.3	Software Program Development.....	70
3.2	System Setup and Experimental Materials.....	73
3.2.1	Hardware Details of Inspection System.....	73
3.2.2	Coherence Correlation Interferometer	74
3.2.3	Test Samples	75
3.2.4	System Integration	76
3.2.5	Surface Roughness Measurement Setup.....	77
3.2.6	Surface Scratch Inspection Setup.....	78
3.3	Surface Roughness Measurement	78
3.3.1	Grayscale Contrast Measurement	79
3.3.2	Grayscale Histogram Standard Deviation.....	81
3.3.3	Surface Uniformity Measurement.....	82
3.4	Surface Defect Detection	84

3.4.1	Artefact scratches detection	84
3.4.2	Sample Defect Detection	86
3.5	Summary	88
4.	Position Measurement System Based on Image Grating Technique	89
4.1	Introduction to Image Grating System	89
4.2	Image Registration Techniques	91
4.2.1	Fourier-based Image Registration	91
4.2.2	Subpixel Image Registration in Fourier Domain	94
4.2.3	Subpixel Image Registration Procedure Based on SSDFT method	96
4.3	Image Grating System Validation	101
4.3.1	Image Grating System Setup	101
4.3.2	Error correction caused by optical distortion	103
4.3.3	Choosing up-sampling factor based on environmental conditions	107
4.3.4	1D SSDFT Algorithm Validation	108
4.4	Results and Discussion	109
4.4.1	Measurement results	109
4.4.2	Fifth-degree polynomial fitting	110
4.4.3	Position measurement and error compensation	111
4.4.4	Measurement repeatability study	113
4.5	Conclusion	114
5.	Surface Finish Measurement System Based on Laser Confocal Method	116

5.1	Surface Topography Measurement System based on Laser Confocal Sensor	116
5.1.1	Introduction to Confocal Microscopy	116
5.1.2	Surface Roughness Calculation	118
5.1.3	Internal Scanning Performance of the Laser Confocal Sensor	122
5.1.4	Extended Measurement Range and Profile Data Stitching Algorithm .	123
5.1.5	Step Height Measurement	127
5.1.6	In-Situ Measurement Procedure	128
5.1.7	Measurement Results and Data Analysis for Machined Surfaces	130
5.1.8	Feasibility Study on Area Topography Measurement for Additive Manufacturing Surfaces	135
5.2	Adaptive Surface Measuring System based on Laser Confocal Method	140
5.2.1	System Setup and Surface Tracing Techniques	141
5.2.2	Internal Piecewise Scan	144
5.2.3	Free-form measurement results.....	147
5.3	Summary	153
6.	Conclusions.....	155
6.1	Thesis Conclusions.....	155
6.2	Innovative Contributions.....	156
6.3	Future Work	158
	Appendix A.....	160
	Author's Publications.....	162

Journal Articles	162
Conference Proceedings	162
Patents	163
Reference	164

List of Tables

Table 2-1 Amplitude Parameters	28
Table 2-2 Spacing Parameters	29
Table 2-3 Hybrid Parameters	29
Table 2-4 Height Parameters	31
Table 2-5 Spatial Parameters	32
Table 2-6 Hybrid parameters	32
Table 2-7 Analogue Transducers Based Stylus System	35
Table 2-8 Digital Transducers Based Stylus.....	36
Table 2-9 Summary of differences between the optical and stylus methods.....	43
Table 2-10 Technology comparison for mirror surface texture measurement	47
Table 2-11 Technology comparison for mirror surface defects detection.....	49
Table 2-12 Technology comparison for free-form surface measurement	53
Table 3-1 Typical robotized polishing process	65
Table 3-2 Scratch 1 to 4 dimensions measured by Talysurf CCI	88
Table 4-1 Comparison between different subpixel image registration methods	95
Table 4-2 Registration accuracy comparison between 1D and 2D SSDFT.....	109
Table 5-1 R_a values of the precision roughness reference specimen.	123
Table 5-2 R_a of different surfaces measured using laser confocal system and stylus profilometer.....	132
Table 5-3 Measurement results of different surface texture parameters.....	138
Table 5-4 Measurement results of different surface texture parameters.....	139
Table 5-5 S_a and S_q of free-form surface measured using stylus profilometer and the adaptive surface measurement system.	149
Table 5-6 Comparison of surface roughness parameters	151

List of Figures

Figure 2-1 Major components that constitute a typical surface texture	26
Figure 2-2 Indication of surface lay	26
Figure 2-3 Classification of surface parameters	27
Figure 2-4 Surface profile elements	28
Figure 2-5 Example of measurement loop of a stylus instrument	34
Figure 2-6 Schematic illustration of confocal microscopy	37
Figure 2-7 Intensity curve measured during a vertical scanning	38
Figure 2-8 Schematic illustration of an coherence scanning interferometer	40
Figure 2-9 Coherence correlation interference signal simulation	40
Figure 2-10 Actual and measured profiles using stylus method	41
Figure 2-11 Error due to flank angle	42
Figure 2-12 Surface damage due to stylus	42
Figure 2-13 Data dropout due to high slope	42
Figure 2-14 Error due to sharp edge	42
Figure 2-15 Laser interferometer based on the heterodyne phase-detection principle	54
Figure 2-16 Scheme of optical encoder. (a) Incremental type; (b) Absolute type	55
Figure 2-17 (a) Original image $f(x, y)$; (b) Shifted image $g(x, y)$	59
Figure 3-1 Schematic illustration of the roughness measurement system	66
Figure 3-2 (a) Fringe pattern image captured by machine vision camera; (b) Sample surface roughness measured using Talysurf CCI	66
Figure 3-3 A sharp image and its grayscale histogram	68
Figure 3-4 A blur image and its grayscale histogram	68
Figure 3-5 Schematic of the defect detection model	69
Figure 3-6 Image processing for surface roughness measurement	71

Figure 3-7 Image processing for defect detection.....	72
Figure 3-8 Taylor Hobson Talysurf CCI	75
Figure 3-9 Test samples for roughness measurement.....	76
Figure 3-10 Test samples for defect detection (a) polished surface without defects (b) polished surface with defects (c) polished surface with artefact scratches.....	76
Figure 3-11 System flow of the proposed post-process inspection system	76
Figure 3-12 System configuration for surface roughness measurement.....	77
Figure 3-13 Configuration for surface scratch inspection	78
Figure 3-14 Measured areas on the sample surface	79
Figure 3-15 Roughness measurement result using Talysurf CCI.....	79
Figure 3-16 Grayscale contrast measurement result using proposed system	80
Figure 3-17 S_a -Contrast curve.....	80
Figure 3-18 S_q -Contrast curve.....	80
Figure 3-19 Histogram standard deviation measurement using proposed system.....	82
Figure 3-20 S_a -STD curve.....	82
Figure 3-21 S_q -STD curve.....	82
Figure 3-22 Machining pattern on sample 2 and sample 8.....	83
Figure 3-23 Contrast value in different measurement angles	84
Figure 3-24 Artefact scratches detection	85
Figure 3-25 Artefact scratch 1 measured by Talysurf CCI.....	85
Figure 3-26 Artefact scratch 2 measured by Talysurf CCI.....	85
Figure 3-27 Defect detection results on polished surface without defect.....	86
Figure 3-28 Defect detection results on polished surface with defects	87
Figure 3-29 Scratch 1 to 4 surface topography measured by Talysurf CCI	87
Figure 4-1 Schematic of an image grating system.....	90

Figure 4-2 Schematic of pattern shift between two images	90
Figure 4-3 (a) cross-correlation (b) phase correlation of two aerial images	93
Figure 4-4 1D images for phase correlation calculation	99
Figure 4-5 Phase correlation of two 1D images.....	99
Figure 4-6 Flow chart of image registration based on SSDFT	101
Figure 4-7 Image grating system configuration.....	102
Figure 4-8 Microscope view of the patterned target	103
Figure 4-9 (a) Optical distortion curve (b) position error curve	105
Figure 4-10 100 mm pattern target (a) Full length view (b) Enlarged details	106
Figure 4-11 Points of intersection between the mean intensity of the whole 1D image and the 1D image intensity curve.....	107
Figure 4-12 (a) Pixel numbers between a line pair (b) Cumulated pixel error between line pairs.....	107
Figure 4-13 Stability test of the laser interferometer (5530 dynamic calibrator)	108
Figure 4-14 (a) Pattern shift (mm) in the image grating system (b) Measurement error of the image grating system	110
Figure 4-15 (a) 5th-degree polynomial fitting, (b) Residual errors after fitting	110
Figure 4-16 Residual error after 5th-degree polynomial fitting.....	112
Figure 4-17 Residual error after 5th-degree polynomial fitting (50 mm).....	113
Figure 4-18 Positioning repeatability of image grating system	114
Figure 5-1 Structure of single-point confocal system.....	117
Figure 5-2 Working principle of the laser confocal sensor.....	118
Figure 5-3 Computational flow chart of surface roughness.....	119
Figure 5-4 (a) Precision roughness reference specimen;(b) Measured surface profile.	122
Figure 5-5 Model of n -times of profile data stitching.....	124

Figure 5-6 (a) Laboratory set-up; (b) Extended surface profiles of the precision roughness reference specimen; (c) Enlarged partial profiles of the precision roughness reference specimen.....	127
Figure 5-7 Stitching errors of the laser confocal profile.....	127
Figure 5-8 Measurement results of the depth measurement standards.	128
Figure 5-9 Three-stage movement strategy for surface measurement.	129
Figure 5-10 Experimental system setup.....	130
Figure 5-11 Schematic of Talysurf PGI 800 during measurement of roughness standard samples.....	131
Figure 5-12 Error curve of different machining surface	133
Figure 5-13 Actual and measured profiles using stylus method.....	134
Figure 5-14 Residual relative errors after linear error compensation	135
Figure 5-15 Electron Beam Melting (EBM) test piece	137
Figure 5-16 EBM test piece measured by (a) coherence scanning interferometer; (b) confocal microscope; (c) proposed laser confocal system.....	137
Figure 5-17 DMLS coupons	139
Figure 5-18 System setup in simulation and lab platform	141
Figure 5-19 Relation between the laser confocal sensor reading and the its position on the Z-axis motorized stage	143
Figure 5-20 Motion path for surface tracing.....	143
Figure 5-21 Flow chart showing measurement process of the proposed system.....	145
Figure 5-22 Stitching errors comparison	147
Figure 5-23 Measurement setup (a) Talysurf PGI 800 stylus profilometer; (b) Adaptive surface measurement system.....	148
Figure 5-24 Free-form surface coupon	148

Figure 5-25 Free-form surface measured by Talysurf PGI 800. (a) Original surface topography; (b) Surface topography after form removal	149
Figure 5-26 Free-form surface measured by the adaptive surface measurement system. (a) Original surface topography; (b) Surface topography after form removal.....	149
Figure 5-27 Measurement results (a) Original surface profile measured by the developed system; (b) Original Surface profile measured by Talysurf PGI 800; (c) Surface profile (nominal form removed) measured by developed system; (d) Surface profile after (nominal form removed) measured by Talysurf PGI 800.....	151
Figure 5-28 Free-form surface measurement results (a) Surface profile measured by the developed system; (b) Surface profile measured by Talysurf PGI 800 with sapphire ball contact; (c) Surface profile measurement error	153

1. Introduction

1.1 Background

With the emerging advanced manufacturing technologies developed in the last decades, surface finish measurement plays an increasingly important role in many industries such as optical engineering, additive manufacturing, precision engineering and semiconductor manufacturing [1–4]. A lot of research and development work has been undertaken to improve the quality control of different surface finish products to guarantee a high quality standard [5–8]. During the manufacturing process, an accurate and real-time surface finish measurement has become increasingly important to improve the machining accuracy and efficiency [9]. Ideally, if an error occurs in the machining process, it should be corrected and compensated for instantly. However, this is almost impractical due to the difficulty of real-time measurement and hence correcting machining process parameters [10]. Therefore, it became apparent that the surface finish characteristics needs to be investigated while the product is still in the manufacturing cell (*in-situ*) or even during machining (in-process) [11].

1.2 Motivation

In most manufacturing industries, post-process inspection is the standard mode where the finished workpiece is detached from the machine and sent to a metrology laboratory for measurement. This process, however, results in long production time and it is also cost ineffective when it comes to mass production. Hence, post-process inspection has to be replaced by an automatic surface inspection to reduce the labour cost and to

improve quality control. An automated *in-situ* surface inspection system is, therefore, seen as a potential solution to improve the efficiency of the manufacturing process.

1.3 Objective

The general objective of this research is to solve some key challenges in surface finish measurement that include:

1. Develop an automated *in-situ* inspection system for mirror finish surface roughness measurement and surface defect detection
2. Develop a precision displacement measurement method with high robustness and flexibility compared to conventional optical encoder which can be integrated into various surface metrology instruments
3. Develop a surface finish measurement system based on laser confocal method to measure the surface roughness of different workpiece fabricated by conventional machining, additive manufacturing and free-form surfaces.

1.4 Scope

In order to achieve the objectives mentioned above, several research scopes are indicated as follows:

1. To develop a surface roughness measurement system using machine vision technique. The system needs to offer *in-situ* surface roughness measurement. The developed surface roughness calculation algorithm is able to conduct on-line data acquisition and processing on mirror finish surface.
2. To develop a surface defect detection system using machine vision technique. The system needs to offer *in-situ* surface defect detection. The developed

algorithm for defect detection is able to perform on-line defects recognition and measurement on flat mirror finish surface.

3. To develop a displacement measurement system based on image grating technique. The developed image grating system with subpixel image registration algorithm is able to achieve inline absolute displacement measurement.
4. To develop a surface finishing system based on the laser confocal method. The developed system is able to achieve *in-situ* surface roughness measurement of different machined, additive manufacturing and free-from surfaces.

1.5 Outline

The structure of the thesis is organized as follows:

In Chapter 2, a literature review on overview of surface texture, characterization of surface texture, typical methods for surface roughness measurement is undertaken. Several key challenges in surface finish measurement are also described and discussed.

Chapter 3 presents the developed machine vision inspection system based on patterned area illumination method and surface scattering model, and the in-situ system integration for mirror finish surface roughness measurement and surface defect detection. The experimental results on different polished samples are compared with the reference measuring instrument to validate the measurement accuracy and robustness of the proposed inspection system.

Chapter 4 presents a displacement measurement system based on image grating technique to improve the robustness and flexibility for displacement measurement using conventional optical encoder. Several subpixel image registration algorithms based on spatial domain and Fourier domain approaches are compared and investigated. Then,

the performance of the proposed system is compared with a high-accuracy heterodyne laser interferometer. A measurement error compensation method based on optical distortion model is investigated and hence implemented to improve the measurement accuracy of the proposed displacement measurement system. The proposed system is then tested to measure the displacement of a motorized linear stage and the results are analyzed.

Chapter 5 presents a surface finish measurement system based on laser confocal technique. Firstly, a real-time surface roughness calculation software is developed according to ISO standards. Then, the laser confocal sensor (LCS) is validated to measure a precision roughness reference specimen and different depth measurement standards. A profile data stitching algorithm based on least-squares linear regression method is also developed to expand the lateral measurement range of the LCS. Furthermore, an adaptive surface tracing algorithm is proposed and analyzed to improve the vertical scanning range of the LCS. Subsequently, the developed surface finish measurement system is used to measure different additive manufacturing and Free-form surfaces. Finally, the measurement results are analyzed and the feasibility for *in-situ* measurement is discussed.

Chapter 6 summarizes the contribution, followed by future research plan.

2. Approach and Methodology

2.1 Literature Review

2.1.1 An Overview of Surface Texture

During a manufacturing process, machining operations leave characteristic marks on the machined surface. The marks are in the form of fine irregularities (peaks and valleys) generated by the machining tools. Different types of machining tool imprint their specific pattern which can be recognized. These kinds of pattern are referred to as a surface texture [12]. By convention, the surface texture comprises two components, namely short spatial-wavelength part called roughness and longer spatial-wavelength part called waviness [13].

Surface texture usually affects the quality, performance and lifetime of the products. It is also critical to evaluating and controlling surface characteristics of various products in engineering and manufacturing fields. All manufacturing processes involve the generation of surface textures (e.g. turning, milling, grinding and polishing). Furthermore, there is an obvious relationship between the quality of the surfaces generated by different manufacturing processes and the functional requirements of surfaces. The need to understand the relationship has been a common topic in the surface metrology field for many years [14].

Surface texture affects the quality and precision of many types of industrial product, varying from mechanical and biomedical parts to semiconductors and optics [15]. Surface texture has become a vital factor in manufacturing processes, most notably for the following reasons:

- Industry is constantly trying to drive down manufacturing costs and find efficient ways of improving surface quality. This has become an established objective of world-class competing corporations nowadays [16].
- Surface texture defines products quality. The service life of mating surfaces, such as shafts and cylinders are dependent on surface texture. Shaft is often subjected to load reversals, thereby it can worn out and its life span is reduced. On the other hand, surface irregularities are often at the root of product failure, therefore, the more consistently flat surface texture is necessary to prolong the service life of the product [17].
- The lifetime of a product is governed by the wear rate of its component parts. This wear rate depends on the surface in contact and the characteristics of the materials. A rough surface with more sharp surface peaks has less contact surface area, so it wears at a faster rate than the smooth surface with less sharp surface peaks [18].
- There is a growing demand to identify the implications of product's performance. The product reliability is directly related to the technique of the production process and, hence, to surface textures [16].
- The surface manufacturing process selected for a part of the product has been shown to have some influences on the reliability of components [16].

To evaluate and control the surface texture characteristics of products, they first have to be measured. During the manufacturing cycle, measurement can affect the decisions taken on the manufacturing systems and processes. It allows them to be controlled and optimized, thus improving the product quality. Measuring surface texture in the end of the manufacturing cycle helps researchers and engineers to access the components' performance capability.

2.1.2 Characterization of Surface Texture

Essential Definition

The following parts focus on the characterization and illustration of surface texture. It is worth giving some useful definitions here:

- *Nominal surface*: The work piece surface with form and dimensions prescribed in the engineering drawing and no surface irregularities are taken into consideration [12].
- *Real profile*: The surface profile measured by mechanical or optical means. The profile measurements are always carried out in the direction of a characteristic orientation of surface texture. It usually coincides with the direction normal to the surface being measured [19]. A surface reveals maximum evenness parallel to the lay direction, whereas maximum asperity values are established in the normal direction [12].

In general, a surface texture, as illustrated in Figure 2-1, can be divided into its respective components as follows:

- *Roughness*: these are irregularities inherent in the production process left by the machining agent such as tearing, cutting and surface fatigue.
- *Waviness*: the component of surface texture upon which roughness is superimposed. Possible causes are machine or work deflections, vibrations in the manufacturing system, tool wear and material strains.

- *Form Error*: caused by inaccuracies of the machine elements such as elastic deformations, slideway errors, severe tool wear and general machine/ workpiece flexures.
- *Lay*: can be defined as the dominant direction or pattern of the surface texture. It is determined by manufacturing method used to generate the surface, commonly from the accomplishment of a cutting tool. Classification and symbols for surface lay are depicted in Figure 2-2.

Figure 2-1 Major components that constitute a typical surface texture [18]

Lay symbol	Surface pattern	Description
=		Lay is parallel to line representing surface to which symbol is applied.
⊥		Lay is perpendicular to line representing surface to which symbol is applied.
X		Lay is angular in both directions to line representing surface to which symbol is applied.
M		Lay is multidirectional.
C		Lay is circular relative to center of surface to which symbol is applied.
R		Lay is approximately radial relative to the center of the surface to which symbol is applied.
P		Lay is particulate, nondirectional, or protuberant.

Figure 2-2 Indication of surface lay [20]

Surface Profile Parameter Characterization

Surface profile measurement is achieved by measuring a line across the surface and representing that line mathematically as a height function with lateral displacement [21]. According to ISO 4287 [22], a surface profile can be separated into the roughness profile and the waviness profile using a profile filter. Surface roughness is a key parameter for surface characterization in many engineering applications such as friction, contact deformation, tightness of contact joints and position accuracy [23,24]. For this reason, surface roughness has been investigated both theoretically and experimentally for decades. As a result, a wide range of surface roughness parameters have been developed. The majority can be divided into three groups:

- *Amplitude parameters*: Measurement of vertical characteristics of the surface deviations.
- *Spacing parameters*: Measurement of the horizontal characteristics of the surface deviations.
- *Hybrid parameters*: Some combination of amplitude and spacing parameters.

Figure 2-3 Classification of surface parameters [25]

In Figure 2-4, $Z(x)$ is defined as the absolute ordinate values from the center line; l_r is defined as the sampling length; C_1 and C_2 are thresholds used to define the surface peak; X_S is defined as the profile element width.

Figure 2-4 Surface profile elements [25]

In the following tables, some of the available surface roughness parameters are summarized separately.

Table 2-1 Amplitude Parameters

Parameter	Definition
Arithmetic average roughness (R_a)	$R_a = \frac{1}{l_r} \int_0^{l_r} Z(x) dx$
Root mean square roughness (R_q)	$R_q = \sqrt{\frac{1}{l_r} \int_0^{l_r} Z^2(x) dx}$
Maximum height of peaks (R_p)	The maximum height of the profile above the mean line within a sampling length.
Maximum depth of valleys (R_v)	The maximum depth of the profile below the mean line within a sampling length.
Maximum height of the profile (R_t)	$R_t = R_p + R_v$
Skewness (R_{sk})	$R_{sk} = \frac{1}{R_q^3} \left[\frac{1}{l_r} \int_0^{l_r} Z^3(x) dx \right]$
Kurtosis (R_{ku})	$R_{ku} = \frac{1}{R_q^4} \left[\frac{1}{l_r} \int_0^{l_r} Z^4(x) dx \right]$

Table 2-2 Spacing Parameters

Parameter	Definition
Peak count number (P_c)	P_c is defined as the number of local peaks, which intersects the selected band located above and below the mean line.
Mean spacing parameter (R_{sm})	$R_{sm} = \frac{1}{m} \sum_{i=1}^m X_{si}$ <p>where X_s is defined as the spacing distance between each adjacent local peaks and m is the total number of local peaks.</p>

Table 2-3 Hybrid Parameters

Parameter	Definition
Root mean square slope of the profile ($R_{\Delta q}$)	$R_{\Delta q} = \sqrt{\frac{1}{l_r} \int_0^{l_r} \left(\frac{dZ}{dX} \right)^2 dx}$

The Ra value is by far the most universally recognized and well-used parameter for surface roughness. However, Ra has some disadvantages namely that it is insensitive to wavelengths. In addition, it only provides information on the departure of the surface from the mean line but no details about the shape of the surface [26].

Rq can be used to statistically examine a profile, because it is the standard deviation of the profile height distribution. Besides, Rq is more sensitive to peaks and valleys than Ra (due to the squaring function).

Rsk provides information regarding the shape of the distribution of heights. It will distinguish between asymmetrical profiles which exhibit the same Ra . A negative

skewness indicates a predominantly valley-based surface, while a peak-based surface has positive skewness.

Rku provides a means of measuring the sharpness of a profile. It may be relevant in the assessment of surfaces which are subject to sealing or stress fracture.

Rsm , together with the parameter Ra , can be used for evaluating fine plating for its capability of being painted.

$R\Delta q$ is highly related to certain mechanical properties such as elasticity, hardness and the crushability of a surface. Moreover, if the $R\Delta q$ value is small, it indicates that the surface has a good optical reflection property [18]. Together with Rq , $R\Delta q$ provides information on the functional behaviour of the surface such as light reflection, galvanic coatings and tribology conditions.

Areal Surface Parameters Characterization

Since the first roughness measuring instrument appeared at the beginning of the 1930s, the measurement of surface texture has been based on profile surface parameters. The profile surface parameters are useful for showing manufacturing process change, but they are often difficult to determine the exact nature of the surface topographic feature. Much more functional information about the surface can be gained from an analysis of the areal surface texture which has more statistical significance than an equivalent profile measurement [21].

Starting from 1990s, various important work on areal surface texture has been carried out [27–29]. Based on these research outcomes, ISO published a series of international

standards ISO-25178 as a guide for the specification and analysis of areal surface texture. In part 2 of ISO-25178 [30], the prefix S is used for the majority surface texture parameters which can be categorized into height parameters, spatial parameters, hybrid parameters and function related parameters. In the following tables, some of the key parameters are summarized.

Table 2-4 Height Parameters

Parameter	Definition
Root mean square height (S_q)	$S_q = \sqrt{\frac{1}{A} \iint_A z^2(x, y) dx dy}$ <p>A is defined as the evaluation area derived from the primary surface by removing the form and large scale components. $z(x, y)$ is the height of the surface at position (x, y).</p>
Arithmetic mean height (S_a)	$S_a = \frac{1}{A} \iint_A z(x, y) dx dy$
Maximum peak height (S_p)	S_p is defined as the largest peak height value of the surface.
Maximum pit height (S_v)	S_v is defined as the smallest pit height value of the surface.
Maximum height (S_z)	$S_z = S_p + S_v$
Skewness (S_{sk})	$S_{sk} = \frac{1}{S_q^3} \left[\frac{1}{A} \iint_A z^3(x, y) dx dy \right]$
Kurtosis (S_{ku})	$S_{ku} = \frac{1}{S_q^4} \left[\frac{1}{A} \iint_A z^4(x, y) dx dy \right]$

Table 2-5 Spatial Parameters

Parameter	Definition
Autocorrelation length (<i>Sal</i>)	$S_{al} = \min \sqrt{t_x^2 + t_y^2}$ <p>Auto-correlation function is defined as the correlation between a surface and the same surface translated by (t_x, t_y). S_{al} is the horizontal distance of the autocorrelation function which has the fastest decay to a specified value s.</p>
Texture aspect ratio (<i>Str</i>)	$S_{tr} = \frac{\min \sqrt{t_x^2 + t_y^2}}{\max \sqrt{t_x^2 + t_y^2}}$ <p>S_{tr} is defined as the ratio of the fastest to slowest decay to correlation length of the surface autocorrelation function.</p>

Table 2-6 Hybrid parameters

Parameter	Definition
Root mean square gradient (S_{dq})	$S_{dq} = \sqrt{\frac{1}{A} \iint_A \left[\left(\frac{\partial z(x,y)}{\partial x} \right)^2 + \left(\frac{\partial z(x,y)}{\partial y} \right)^2 \right] dx dy}$
Developed interfacial area ratio (S_{dr})	$S_{dr} = \frac{1}{A} \left[\iint_A \left(\sqrt{1 + \left(\frac{\partial z(x,y)}{\partial x} \right)^2 + \left(\frac{\partial z(x,y)}{\partial y} \right)^2} - 1 \right) dx dy \right]$

The Sa and Sq parameters are strongly correlated to each other [29]. The Sq parameter has more statistical significance as the standard deviation and often has a more physical foundation than Sa . Sq is directly related to surface energy and the way light is scattered from a surface. By examining both the Sq value and the Sz value, it may be possible to indicate whether the apparent roughness is due to isolated features or the overall surface roughness. The Ssk parameter correlates well with load carrying ability and porosity. Sku parameter provides a measure of the spikiness of the area and is a useful parameter in predicting component performance with respect to wear and lubrication retention [21,31].

The Sal is the parameter to identify the surface is dominated by low spatial frequency components or high spatial frequency components. The Str parameter is the parameter used to characterize the uniformity of the surface texture [26].

The Sdq parameter is useful for assessing surfaces in sealing applications and for controlling surface cosmetic appearance. The Sdr parameter is used as a measure of the surface complexity, especially in comparisons between several stages of processing on a surface, and it can provide useful correlations in adhesion applications [21].

2.1.3 Surface Roughness Measurement Techniques

In the following paragraphs, the various surface roughness measurement methods are described in two groups (stylus and optical) separately. Then, a comparison discussion will be conducted between stylus and optical methods.

Stylus Based Systems

A typical measurement loop of stylus-based system was shown in Figure 2-5 . The closed loop comprises all mechanical components in the system such as positioning fixture, measuring stand, drive unit, stylus and probe.

Figure 2-5 Example of measurement loop of a stylus instrument [32]

The stylus is loaded against the workpiece and is moved across the stationary workpiece surface using the traverse unit at a constant speed [33]. As the stylus moves, the stylus rides over the workpiece surface detecting surface deviations by the transducer. It converts the vertical movement of the stylus into an analogue signal. This signal is then amplified and digitized for subsequent processing and parameters calculating in the computer. In general, stylus instrument can be further classified into two groups, depending on their operating principles.

- Analogue Transducers

As the stylus follows the workpiece surface, the analogue transducers generate voltage (inductive transducer and moving coil transducer) or electrical charge (piezoelectric transducer) which related to height of the peaks and valleys on the surface. Then, the analogue signal is amplified and passed through an analogue-to-digital convertor. The digital signal is processed and the surface height information is calculated for the measurement. The three typical analogue transducers are presented in Table 2-7.

Table 2-7 Analogue Transducers Based Stylus System [18]

Inductive Transducer (a)	Piezoelectric Transducer (b)	Moving Coil Transducer (c)

- Digital Transducers

The digital transducers utilize a miniature laser interferometer (non-contact laser transducer) or curved phase grating wavelength (phase grating interferometer transducer) to provide the measurement reference. Interference patterns are detected by multiple photodiodes. The digital transducers enable an output signal to be interpolated and gives a high resolution in few nanometers. The two typical digital transducers are presented in Table 2-8.

Table 2-8 Digital Transducers Based Stylus [34]

Non-contact Laser (a)	Phase Grating Interferometer (b)

Optical Techniques

- Confocal Microscopy

The fundamental principle of confocal microscopy is shown in Figure 2-6. Basically, the confocal method measures the best focus position in the microscope to detect the height of a surface point. It is different from the conventional microscope in that it has two additional pinhole apertures; one in front of the photodetector and one in front of the light source. The optical path from the light source to the specimen surface is the same as the path from the specimen surface to the photodetector [35].

If the pinhole aperture is located at the best focus position with respect to the specimen surface, the light reflected from a surface point can pass through the pinhole aperture and focus back on to the detector, therefore, leading to an intensity peak on the photodetector. Then, the height of a point on the specimen surface can be determined by measuring the signal in the intensity curve (see Figure 2-7). As it does not rely on the intensity of the reflected light, the confocal microscopy can measure the surface height without being affected by the material, color, or angle of the target [36].

The lateral resolution of confocal microscope is limited by the Rayleigh criterion. The resolution r is approximately given by

$$r = \frac{\lambda}{2NA} \quad 2-1$$

where λ is the wavelength of the incident light and NA is the numerical aperture of the objective lens. The lateral resolution normally ranges from above 0.3 μ m to about 1.5 μ m. The field of view is limited by the objective magnification. Lower magnification objectives with about 10X magnification provide a larger field of view of approximately 1 mm by 1mm. High magnification objectives with 100X magnification have a field of view of about 0.2 mm by 0.2 mm. But low magnification objectives below 20X are in general not suitable for surface roughness analysis [33,37]. The vertical scanning range of confocal microscope is mainly limited by the working distance of the objective lens. Therefore, it is not possible to make high-resolution measurements with large scanning range. The vertical resolution can be given a standard deviation of repeated axial measurements in tens of nanometer on smooth surfaces in a controlled environment [38].

Figure 2-6 Schematic illustration of confocal microscopy [36]

Figure 2-7 Intensity curve measured during a vertical scanning [39]

- Coherence Scanning Interferometry

According to ISO 25178-604 [40], coherence scanning interferometry (CSI) is a surface topography measurement technique where the interference fringes localization during a scanning of optical path length provides a method to characterize a surface topography. It includes but is not limited to measuring instruments that use spectrally broadband, visible sources (white light) to attain interference fringes localization. CSI is also defined in alternative terms that follow some parts of the above definition [31,41], for example:

- Coherence Correlation Interferometry (CCI),
- Coherence Scanning Microscopy (CSM),
- White Light Interferometry (WLI),
- Vertical Scanning Interferometry (VSI).

Figure 2-8 shows a generic microscopic surface profiler using coherence scanning interferometry. Coherence scanning interferometry often uses a broadband light source (white light). The optical system focuses the light through an objective lens onto the

target surface. An interferometer above the objective lens splits the light into two parts, one directed to the surface and another directed to a smooth reference mirror. As the reflected beams are recombined, the interference fringes are formed around the equal path condition for the two beams. The equal path condition can be detected for each surface area corresponding to each pixel of the CCD camera. Scanning the surface vertically by the microscope and detecting the best equal path condition at every pixel in the CCD camera leads to a topographic image. Coherence scanning interferometry method can provide very high resolution of sub-nanometer over the entire vertical measurement range of about 2 mm [42–44].

A simplified model of signal generation assumes a randomly-polarized, spatially incoherent light source and a smooth surface perpendicular to the incident light beam. The total signal is the sum of all the incoherent interference contributions of the light rays passing through the objective and reflecting from the object surface and reference mirror. For example, the light rays at an incident angle α corresponds both to a specific image point (x', y') and to a specific position in the objective pupil. These light rays are separated at the beam splitter into the measurement path to the target surface at a particular point (x, y) and the reference path to the reference mirror. If (x, y) is the scan position of the surface with respect to the microscope, and the interference fringe spatial frequency can be expressed as:

$$K = 4\pi \frac{\beta}{\lambda} \quad 2-2$$

for a directional cosine $\beta = \cos(\alpha)$ and a wavelength λ . The summation over a range of frequencies cause a peak signal where all the individual contributions are equally in phase. This position is often defined as the stationary phase point and stand for the peak

of the signal envelope shown in Figure 2-9. The incoherent superposition model using mathematical prediction of signal shape and can be used to determine surface heights from the coherence scanning interferometry signals [40].

Figure 2-8 Schematic illustration of an coherence scanning interferometer [45]

Figure 2-9 Coherence correlation interference signal simulation [41]

Comparison between Stylus and Optical Methods

Several studies have been reported in the literature to compare the contact stylus with the non-contact optical methods for measurement of surface texture. Shahabi et al. [46] proposed a method of roughness measurement using the 2D profile extracted from an edge image of the workpiece surface and compared the accuracy with the conventional stylus profilometer. Vorburger et al. [15] drew attention to optical methods and presented a remarkable comparison in the performance between recent optical measurement techniques, which were confocal microscope, phase-shifting interferometers, coherence scanning interferometer and the traditional stylus profilometers for a wide range of roughness values. Whitehouse [18] expressed some of the characteristics as well as the comparison of surface-profiling results obtained from the optical methods and stylus profilometer.

The limitations of stylus type devices can be summarized below:

- The spherical shape of the stylus tip causes the peaks and steps to become rounded, as well as the depth of valleys to be reduced (Figure 2-10).
- The stylus flank angle (Figure 2-11) also affect the measurement accuracy. The stylus cannot penetrate completely into the groove or valley.
- Repeated use of the device can cause wear of the stylus tip, hence affecting the readings. Meanwhile, the wear stylus tip may scratch the workpiece surface (Figure 2-12).

Figure 2-10 Actual and measured profiles using stylus method [46]

Figure 2-11 Error due to flank angle [18]

Figure 2-12 Surface damage due to stylus [35]

Optical roughness measurement methods have several advantages compared to the stylus methods, such as the ability for in-process, rapid measurement capability, no wear due to the noncontact nature and the ability to provide area measurement. However, optical methods also have their limitations:

- Optical methods are limited to moderate slopes consistent with the range of acceptance angles for the numerical aperture of the objective [15].
- Surface colour and reflectivity can also affects the measurement quality of the optical methods [47].
- Sharp edges, inclusions, defects, and other peculiarities of the surface can scatter light away from the objective (Figure 2-13 and Figure 2-14).

To compare the advantages and disadvantages between stylus-based methods and optical method, a summary is given in Table 2-9.

Figure 2-13 Data dropout due to high slope [31]

Figure 2-14 Error due to sharp edge [18]

Table 2-9 Summary of differences between the optical and stylus methods.

Criteria	Stylus	Optical
Possible damage during measurement	Possible damage to surface	No damage to surface
Quantitative information	Less (line profile)	More (areal topography)
Working distance	0 (contact)	2 - 40 mm
Lateral resolution	0.125 – 0.5 μm	0.3 - 0.5 μm
Lateral scanning range	Up to 200 mm	Up to 200 mm
Vertical resolution	5 - 10 nm	0.1 - 10 nm
Vertical scanning range	Up to 20 mm	Up to 20 mm
Sensitivity to workpiece tilt	Insensitive to tilt of workpiece	Limited tilt only allowed (approximately 30° for 50x objective)
Measuring speed	Relatively slow speed (up to 1mm/s)	Can achieve fast scan (up to 10 mm/s)
In-situ measurement capability	No	Yes
Time for analysing	Rapid	Slow

2.2 Key Challenges in Surface Finish Measurement

2.2.1 In-situ Surface Finish Measurement

In-situ measurement for surface finish on a workpiece is increasingly demanded in many advanced manufacturing products such as mirror finishing [48,49], additive manufacturing [50,51] and free-form products [52,53]. *In-situ* measurement requires that the actual measurement needs to be carried out while the machined product is still positioned in the manufacturing cell [54]. If an error occurs in the manufacturing process, the *in-situ* measurement results can be used to rectify the process parameters, and

consequently reduce rejections as well as manufacturing costs [49,55]. The conventional method for surface finish measurement is to scan surfaces with a contact stylus and capture surface height deviations in the form of a surface profile [32]. However, Stylus-based method is susceptible to environmental disturbance due to its contact nature and it is a relatively slow process attributed to the point-to-point measuring mode and the risk of 'stylus flight' [35]. Hence, it is not a suitable technique for *in-situ* surface finish measurement [56].

Non-contact systems based on optical techniques are considered more suitable for *in-situ* measurement as they are able to provide high scanning speed and measurement accuracy [57]. Umberto et al. [58] developed a novel system based on confocal sensor which is capable of measuring dimension, waviness and roughness simultaneously. The developed system was proved to provide robust and reliable surface roughness measurement, but limited repeatability of 0.2 μm for measuring surfaces roughness R_a between 0.3 to 0.7 μm . Yann et al. [57] have integrated a chromatic confocal sensor on a 5-axis milling machine to achieve *in-situ* surface roughness measurement. The experimental results showed that the roughness measurement errors are less than 10% and probably due to the spot size effect of the chromatic confocal sensor. Jiang X Q et al. [59] and Lin D et al. [60] have investigated some critical aspects of spatial light-wave scanning techniques and attempted to replace conventional stylus-based methods for *in-situ* surface measurement. However, the practical surface roughness measurements have not been performed and no accuracy analysis has been conducted.

More recently, many machine vision based methods have been developed to measure surface roughness in the indirect ways. Wong P L et al. [56] proposed an measurement method based on a new optical technique using the combine effects of light scattering

and interference. The developed system is implemented in a cylindrical grinding process to demonstrate the applicability for in-process surface roughness measurement. Tian et al. [61] have proposed a hybrid inspection system which applied two digital cameras to capture laser speckle pattern and scattering images simultaneously. By using advanced image processing and feature fusion algorithm, *in-situ* surface roughness characterization with high measurement range can be obtained. However, the developed system has not been systematically validated and tested on wide range of samples. Fuh et al [11,62] developed an in-process system for surface roughness measurement by combining laser-scattering technique and adaptive optics. The developed adaptive-optics-assisted system showed equivalent measurement accuracy to the stylus method, and relative error values of less than 8.7% are obtained for average surface roughness (R_a).

2.2.2 Mirror Finish Surface Measurement

In the American Society for Testing and Materials (ASTM) standard A480 [63], the surface finish of stainless steel is defined at eight grades. The highest grade, mirror finish, is defined as a highly smooth finish typically manufactured by polishing process with finer grit abrasives and finally with buff polishing. Recent years, mirror finish surface products have been widely used in many industries. The aerospace industry has a strong demand for high finish quality in the aircraft leading edges to help to reduce drag (air resistance) in-flight [64]. In the optical industry, prism arrays [65], polygon mirror [66] and projection lens of optical lithography [67] which are key parts of advanced machines or optical instruments need to be fabricated with a high quality of surface finishing. Semiconductor wafer, a basic component used in integrated circuit (IC) fabrication, is

required to be mirror polished to improve the IC chip performance [68–70]. In medical industry, orthopaedic implants such as knees or hips prostheses need to be polished to mirror finish to reduce friction and increase lifespan [71,72].

A mirror finish surface can be achieved by different machining processes such as chemical mechanical polishing [73–75], magnetorheological finishing [76,77], abrasive flow machining [78] and elastic emission machining [79]. In semiconductor manufacturing, chemical mechanical polishing or planarization is the most widely used method to produce mirror finish surface since early 1990s. Polishing is usually conducted without allowing the fine abrasive particles create brittle fractures on the workpiece surface, while subtracting these materials in minute steps to finally fabricate a mirror finish surface [80].

According to different national standards [63,81], the quality of the mirror finish surface is specified in only a qualitative way like “a non-directional finish that is reflective and has good image clarity”. However, the industry needs to qualify the mirror finish surface in quantifiable ways to differentiate among different products. The mirror finish surface texture and local defects are the most important surface geometry and physical properties for mirror finish components [49,82].

For mirror finish surface measurement, optical techniques have great potential due to their non-contact mechanism to avoid surface damage and contamination. Interferometers are widely used both in academic and industry for surface characterization of mirror surfaces [83,84]. Extremely high measurement accuracy down to sub-nanometer can be achieved with heterodyne or phase modulation techniques [85,86]. However, most commercial interferometers are usually expensive and must be operated in a clean and vibration-free laboratory environment. Some

research has been carried out to develop fast and *in-situ* methods to measure the mirror finish surface. Gao et al [9] developed an optical probe by combining a displacement sensor and an angle meter to measure the profile of mirror surfaces. Fuh et al [87] developed an in-process measurement of surface roughness by combining an optical probe and adaptive optics. Speckle metrology [69,88,89] has been tested and used to measure surface roughness of semiconductor wafer through light scattering method and has shown feasibility to be integrated into a manufacturing cell for *in-situ* measurement [55]. Recently, Tadanori et al [90,91] proposed a patterned area illumination method to measure the specular reflection of the polished metal surfaces and study the relationship between the surface texture and gloss values. A summary and comparison of the reviewed technical methodologies for mirror surface finish measurement is presented in Table 2-10.

Table 2-10 Technology comparison for mirror surface texture measurement

Criteria Technology	Measuring speed	In-situ measurement	Surface texture measurement	Environmental vibration effects
Coherence Scanning Interferometer	Low	No	Yes	High
Optical probe based on displacement and angle meter	Low	Yes	No	High
Optical probe based on adaptive optics and laser scattering	Low	Yes	Yes	Low
Laser speckle microscope	High	Yes	Yes	High
Patterned area illumination system	High	Yes	Yes	Low

Apart from the surface texture, the defects on the mirror finish surface such as scratches, dents and pitting corrosion can also influence the appearance and functionality of mirror finish products [78,92]. The defects detection on mirror finish components is usually conducted manually by skilled workers in industry. In this method, the skilled workers inspect the work piece using an optical microscope and decide by experience whether certain defects exist on the surface and which types of defect they are. If any defect is discovered on the surface, the work piece will be either scrapped or repaired according to the condition of the defect [93]. In recent years, some research has been reported which use vision inspection methods to replace the manual inspection. Rosati et al [94] proposed a real-time defect inspection system for highly reflective curved surface. This system employed a non-flat mirror to illuminate and inspect the sample surface and collect the reflected light rays from the sample surface using a CCD camera. Zhang et al [93] presented an inspection system based on machine vision to measure and classify defects on ground and polished surfaces by adopting different extraction methods, e.g. Gabor filter, Laws filter and statistical features from co-occurrence matrix. Bobby et al [95] developed a defect detection system for highly reflective rings used in a textile machine and compared four different algorithms based on auto-median, single-step thresholding, Fourier transform based filtering and image convolution techniques. Tsai et al [96,97] developed several algorithms (Fourier transform, independent component and probability density function) for defect detection on randomly textured surfaces. Kim et al [98,99] developed a fully automated system for scratch detection on silver halide film by defining the texture and shape properties from spatial domain. A technology comparison and summary of defects inspection on mirror surface is presented in Table 2-11.

Table 2-11 Technology comparison for mirror surface defects detection

Criteria Technology	Inspection speed	In-situ inspection	Minimum measurable defects	Environmental vibration effects
Vision system using backlight effect	High	Yes	0.06 mm	Low
Vision system using feature extraction and Support Vector Machine	Low	No	0.05 mm	High
Machine vision system based on dark-field illumination	High	Yes	0.06 mm	Low
Automated surface inspection using global image reconstruction	Low	No	No information	High
Fully automated surface scratch detection system	Low	No	No information	High

2.2.3 Rough Surface Topography Measurement

With the recent research and development of additive manufacturing and advanced surface engineering processes such as direct metal laser sintering [100], electron beam melting [101] and laser shock peening [102], surface topography measurement for relatively rough surfaces have attracted much attention.

Industry adoption of metal additive manufacturing (AM) has increased dramatically in the past few years due mainly to the advantages it offers over conventional processes such as the freedom to design more complex shaped components as well as a reduction in the number of manufacturing stages [103,104]. One challenge which arises from these new processes is the measurement and characterization of the surfaces [105]. Surfaces made by AM processes normally present higher surface roughness and more irregular surface microstructures than conventional machined surfaces [4,106]. This can be attributed to a number of factors including loose particle adhesion [107], incomplete

melting of the powder [108] as well as the actual process parameters [109]. With so many various factors, it is important to be able to link the AM surface to the final application and ultimately back to the process parameters [110,111].

Triantaphyllou et al. [107] have measured AM surfaces produced by selective laser melting (SLM) and electron beam melting (EBM) using both contact and optical methods. They found that Sa and Sq were suitable areal measurement parameters for AM surfaces. Besides, the optical methods using focus variation technique is able to provide accurate surface roughness results, but much faster measurement speed than stylus-based method. Calignano et al. [112] have investigated the surface roughness of aluminum workpieces manufactured by direct metal laser sintering (DMLS). Scan speed was observed to have the greatest impact on the surface roughness compared to other process parameters such as laser power and hatching distance. Grimm et al. [113] have studied area surface parameters of laser-sintered surfaces measured by a confocal microscope. The measurement results showed strong correlations between the surface orientation and the areal parameters Sdr and Sdq . Launhardt et al. [110] have conducted a systematic comparison between contact and optical surface roughness measurement methods on Selective Laser Sintering (SLS) samples. It has been observed that the contact measurement methods allow a fast and repeatable measurement of the SLS surface profile. In contrast, optical measurement methods are able to provide 3D-visualization of the SLS surface topography, however measurement results vary significantly using different optical techniques and measurement parameters.

2.2.4 Free-form Surface Measurement

Free-form surfaces can be defined as the surfaces which have no axes of rotation and may have almost any designed shape [53]. The geometry of free-form surfaces cannot be determined by a simple mathematic equation, as is the case for spherical and cylindrical surfaces, but a set of equations including: toroidal, biconic, non-uniform rational b-spline, etc [114]. Free-form surfaces manufacturing has been used in various industries due to their advantages such as reduced geometrical aberrations in optics field [114], drag reduction for aero engines [115], and improved manufacturing accuracy for knee implants in biomedical industry [116]. Several advanced manufacturing technologies have been developed to fabricate designed free-form surfaces, such as ultra-precision cutting, single-point diamond turning, CNC multi axis polishing and injection molding [117,118]. However, a major problem, relating to the expanding application of free-form surface products, is how to measure and characterize free-form surfaces with high accuracy [114].

The most widely used instrument in industry for free-form surface roughness measurement is stylus profilometer. However, the stylus profilometer usually has very fragile stylus tip and limited vertical gauging range less than 15 mm [119]. Optical profilers such as coherence scanning interferometer and confocal microscope are able to provide non-contact surface measurement solutions, but the lateral and vertical measurement range are limited. Vertical scanning technique and lateral image stitching are able to enlarge the scanning range but it is very time-consuming.

Fan [120] has integrated a laser triangulation sensor into a coordinate measuring machine (CMM) for measuring free-form surface profile. The developed non-contact measurement system is able to automatically trace the free-form surface and measure

the surface profiles with error less than 5 μm . Bradley [121] has designed an automated roughness measurement system integrated with a fiber optic interferometer and a computer-controlled CMM. However, the system encounter vibration noise from CMM during scanning movement and cause a lot of work on data filtering. The Ultrahigh Accurate 3-D Profilometer (UA3P) [122] developed by Panasonic Corporation uses a laser-based interferometric three axis positioning system and atomic force microscopy (AFM) technology in the stylus. The UA3P system is able to provide the measurement range of a CMM with the measurement accuracy of AFM technology. Guo et al. [115] developed a reference-free beam-sampling system for measuring optical freeform surfaces. The developed system is tested to measure different toroidal samples and achieved a tens of nanometers measurement accuracy.

However, the work mentioned above has mainly focused on the development of measuring instruments suitable for laboratory measurements, in a clean and vibration-free environment, instead of in-process or *in-situ* measurements in a manufacturing cell.

Li et al. [52] have invented a measuring system based on laser gauging head and high-pressure jet device to perform in-process surface roughness measurement. Based on the measurement results in the polishing process, this system has been proved to provide measurement accuracy of sub-micron level and feasibility to feedback control the polishing tool. Chang et al. [123] presented a fuzzy-logic controlled system for on-line free-form surface measurement using a scanning contact probe integrated into a CNC machine. The fuzzy logic control scheme reduced the scanning probe's lateral shift and made the measuring process continuous, but the measuring errors on certain curved surface went up to 20 μm . Recently, Xue et al. [124] developed a novel spatial light modulator that can be inserted into a commercial wavefront interferometer to extend the

measurement and dynamic range of the conventional interferometry. The developed system has been tested on a 4-axis CNC ultra-precision lathe and the measurement error is about 0.2 μm over a free-form aperture sample of 150 mm radius. A technology comparison and summary of free-form surface measurement is presented in Table 2-12.

Table 2-12 Technology comparison for free-form surface measurement

Criteria Technology	Measuring speed	In-situ measurement	Vertical measurement rage	Vertical resolution
Stylus profilometer	High	No	≤ 20 mm	5 – 10 nm
Optical profiler	Low	No	≤ 20 mm	0.1 – 10 nm
Laser triangulation sensor integrated with CMM	High	No	≥ 100 mm	5 μm
Fiber optic interferometer integrated with CMM	High	No	5 mm	0.1 μm
Ultrahigh Accurate 3-D Profilometer	High	No	100 mm	0.05 μm
Reference-free beam-sampling system	Low	No	1.5 mm	0.05 μm
In-process surface roughness measuring system using laser gauging head	High	Yes	≤ 1 mm	0.1 μm
Scanning contact probe integrated into CNC machine	High	Yes	≥ 50 mm	20 μm
Adaptive wavefront interferometer using novel spatial light modulator	Low	Yes	≤ 0.1 mm	0.2 μm

2.2.5 Precision Displacement Measurement

2.2.5.1 Overview of Displacement Measurement Techniques

As a key technical enabler, displacement sensing technology plays a very important role in many activities in product quality assessment such as geometric measurement [125,126], surface finish measurement [10,127]. Laser interferometer based on the heterodyne phase-detection principle is a widely accepted non-contact metrology instrument for long displacement measurement with sub-nanometer resolution [128].

Figure 2-15 illustrates the typical schematic of a heterodyne interferometer configuration. The two frequency components of the laser source obtained from an acoustic optical modulation or from a Zeeman split, have linear polarization and orthogonal to each other, which are then separated by the polarizing beam splitter (PBS) [129]. The measurement and the reference beams have frequencies f_1 and f_2 respectively. Due to the moving of the target mirror, the measurement beam is Doppler shifted by Δf_1 . The two beams recombine after the polarizing beam splitter (PBS) and interference occurs. The recombined signal has a beat frequency of $f_2 - (f_1 \pm \Delta f_1)$. The result is a phase shift of the measurement signal compared to the reference signal. A phase detector is then used to measure the phase between the reference and the measured signals. Displacement of the movable target mirror could be deduced from this phase shift [130]. However, it is difficult to integrate a laser interferometer for in-situ measurement due to its low robustness and high sensitivity to manufacturing environmental conditions [131]. Hence, it is usually used as a reference instrument instead of a feedback sensor for motorized stage calibration.

Figure 2-15 Laser interferometer based on the heterodyne phase-detection principle [129]

Optical encoders are widely equipped for precision positioning systems. An optical encoder generally consists of an optical grating scale used as the measurement reference,

an optical reading head for measuring the graduations scale, and electronics for data acquisition and processing [131]. With continuous improvement of optical scanning algorithms and signal processing technologies, optical encoders are able to achieve submicron to nanometer accuracy nowadays. In Figure 2-16, two types of optical encoders, namely incremental type and absolute type, are presented as two commercially available examples [132,133]. The incremental optical encoder moves the scanning reticle with an index grating and the linear scale relative to each other. The incident light is modulated and received by the photovoltaic detector, then these light fluctuations are subsequently converted into electrical signals. By using pulse counting and subdivision technologies, the optical encoders are able to achieve submicron to nanometer accuracy [134]. Compare with incremental optical encoder, the absolute optical encoder is not required to move the optical reading head to the home position or reference position. An additional serial code track is added to the incremental track on the scale. The serial code structure has a unique pattern over the whole moving length of the optical encoder. The main advantage of the absolute optical encoder is providing the absolute position value immediately after switch-on and can be retrieved at any moment during the encoder movement [132].

Figure 2-16 Scheme of optical encoder. (a) Incremental type; (b) Absolute type [132,133]

Time grating encoder is a newly developed alternative approach to optical grating encoder for displacement measurement. By accurately measuring the time and the phase of a constant-speed electric field, the displacement can be calculated [135,136]. However, most grating-based displacement sensors have some inherent disadvantages that limit their inline applications: (1) The short standoff distance limited the installation flexibility. (2) Sealing or packaging process may be needed for condemnation concerns. (3) Accumulated computation needs continuous signal sampling. In case of any unexpected signal discontinuity, the measurement will fail.

Digital image correlation (DIC) has been widely accepted and generally used as a high-robustness technology for displacement and deformation measurement [137] and suitable for applications in harsh manufacturing environments [138]. By analysing the correlation of digital images taken for the same object before and after deformation and movement, the displacement can be determined by subpixel interpolation [139,140]. Currently the measurement range of DIC is limited to sub-millimeter or less and usually only used for surface deformation analysis [141,142].

In order to overcome the limitation of measurement range in DIC using a 2D area scan camera, a line scan camera with large image sensor is an ideal option for long displacement measurement. Line scan camera create an image as a row of single pixel at using a CMOS or CCD array detector [143]. Line scan camera is particularly suitable for machine vision applications which need high speed, high spatial resolution and simple illumination conditions for image capture [144].

2.2.5.2 Image Registration Methods

Image registration is defined as the process of geometrically aligning the reference and sensed images of the same scene taken from different viewpoints at different times [145]. Image registration approaches are generally classified in area-based methods and feature-based methods. Area-based methods using pixel-to-pixel matching algorithm are widely implemented in the applications for deformation and displacement measurement such as digital image correlation (DIC) [142]. Since area-based methods count each pixel in the image into measurement, the main advantage is that they use the whole image during the image registration process without losing any information [146]. Feature-based methods extract distinctive features in the sensed and reference images to estimate the geometric transformation between them. In contrast to the area-based methods, the feature-based methods do not work directly with image intensity values [147] and have been mostly used in remote sensing [148], stereo vision matching [149], geometric contour registration [150] and image mosaicking applications [151].

Image registration methods with pixel level accuracy can be computed directly and may be sufficient in many applications [152], but some important problems including displacement measurement require the image registration algorithms with subpixel level accuracy [138].

In recent years, the most widely used techniques for subpixel image registration are based on searching the peak location in the cross-correlation of the two aligned images [152]. These techniques have significant registration accuracy and robustness to background lighting changes and image noises [153–155]. These techniques can be categorized into two groups: spatial domain methods and Fourier domain methods.

The spatial domain approaches usually calculate the up-sampled cross-power spectrum [156,157] or cross-correlation [158,159] between the reference and sensed images. The most commonly used approaches for up-sampling are based on interpolation algorithms, such as bilinear interpolation, bi-cubic interpolation and B-spline interpolation. It has been investigated that these methods are always sensitive to noise [154] and the accuracy depends highly on the quality of the interpolation algorithms [146]. Besides the interpolation methods, the commonly used approaches without interpolation are based on gradient optimization function [160,161]. This kind of methods iteratively search for the maximum value of in the formulated function such as cross-correlation and retrieve the shifted subpixel values and avoid the interpolation need for a large up-sampling factor [162]. The main shortage of these methods is that they highly depend on the assumption of image intensity conservation and might fail when large illumination differences are present between reference and sensed images [163].

If the computational speed is concerned or if the images were acquired under the frequency-dependent noise, then Fourier domain approaches are preferred rather than the spatial domain approaches [147]. The foundation principle of Fourier domain methods is based on the well-known Fourier shift theorem. Given two images $f(x, y)$ and $g(x, y)$, assumed that horizontal shift x_0 and vertical shift y_0 between the two images as shown in Figure 2-17, $f(x, y)$ and $g(x, y)$ are related by the following transformation:

$$f(x, y) = g(x - x_0, y - y_0) \quad 2-3$$

Figure 2-17 (a) Original image $f(x, y)$; (b) Shifted image $g(x, y)$

According to the Fourier shift theorem, the Discrete Fourier Transform (DFT) of $f(x, y)$ and $g(x, y)$ satisfy:

$$F(u, v) = G(u, v) \exp \left[-i2\pi \left(\frac{ux_0}{M} + \frac{vy_0}{N} \right) \right] \quad 2-4$$

where $F(u, v)$ and $G(u, v)$ are DFT of $f(x, y)$ and $g(x, y)$ respectively, M and N stand for the image dimensions. The normalized cross-correlation spectrum is defined as following:

$$R(u, v) = \frac{F(u, v)G^*(u, v)}{|F(u, v)G^*(u, v)|} = \exp \left[-i2\pi \left(\frac{ux_0}{M} + \frac{vy_0}{N} \right) \right] \quad 2-5$$

where $*$ indicates the complex conjugation. The inverse Fourier Transform (IFT) of the normalized cross-correlation spectrum $R(u, v)$ is a Dirac Delta function [154] centered at (x_0, y_0) as following:

$$\text{IFT}[R(u, v)] = \delta(x - x_0, y - y_0) \quad 2-6$$

It can be observed the accuracy of Fourier domain methods fully depends on calculation of the peak in the Dirac Delta function as in Equation 2-6.

Since the Fast Fourier Transform (FFT) can be implemented with very high speed, a conventional method is to compute the up-sampled cross-correlation by zero-padding the normalized cross-correlation spectrum in Fourier domain and use the inverse Fast Fourier Transform (IFFT) to locate its peak [164]. This method preserves high registration accuracy and robust results, but the computational time and memory consuming are huge, especially for large-size images and high up-sampling factor [152]. To troubleshoot the problem of low computational efficiency in the conventional FFT method, many researchers have proposed various methods. Hassan Foroosh et al. [154] proposed a method using a Sinc function to approximate the Dirac Delta function in frequency domain, which has less computation complexity but limited registration accuracy (0.05 pixel resolution) compared to the conventional FFT method. Murat Balci et al. [165] have demonstrated that the discrete phase difference of two shifted images is a two-dimensional sawtooth signal. Hence, subpixel registration can be carried out directly in the Fourier domain by counting cycles' number of the phase difference on each frequency axis. Guizar Sicaire et al. [166] proposed a new method that uses matrix-multiply Discrete Fourier Transform (DFT) algorithm to compute the up-sampled cross-correlation between the reference and sensed images. This method is able to achieve subpixel registration accuracy equivalent to that of the conventional FFT method in much reduced computation time and memory requirements. In addition, this method has also been implemented in many machine vision applications by other researchers [152,167,168] and been validated with high registration efficient and robustness to noise.

2.3 Research Gaps

Based on the literature review and key challenges in surface finish measurement, it can be concluded that there are clear research gaps in the following area:

1. In-situ inspection solution for mirror finish surface roughness measurement and surface defect detection in harsh industrial environment.
2. Precision position measurement sensor with high robustness and flexibility which can be integrated into various surface metrology instruments.
3. In-situ surface finish measuring system to access the surface topography of different workpiece fabricated by conventional machining, additive manufacturing and free-form surfaces.

2.4 Methodology

To measure mirror finish surface roughness measurement, an automated surface inspection system is developed using fringe pattern illumination method, the method allows for an *in-situ* surface roughness measurement and through a dedicated surface roughness calculation algorithm, an on-line data acquisition and processing on mirror finish surface can be carried out. In addition, the developed surface inspection system is also able to detect the directions of machining mark and measure the surface uniformity. To detect defects on mirror finish surfaces, an automated inspection system based on Rayleigh criterion in surface scattering model is developed to perform *in-situ* measurement.

To improve the robustness and flexibility for displacement measurement using conventional optical encoder in many surface metrology instruments, a displacement measurement system based on image grating technique is developed. Sub-pixel image

registration algorithm based on Fourier domain approach is proposed to improve the registration accuracy from pixel-level to sub-pixel level. The performance of the proposed image grating system is compared with a high-accuracy heterodyne laser interferometer. An error compensation method based on optical distortion model is also proposed to reduce the measurement error of the developed system.

To achieve *in-situ* surface roughness measurement on different machined and additive manufacturing surfaces, a surface finish measurement system based on laser confocal method is developed. To reduce the inherent disadvantages of confocal sensor such as scattering noise at sharp peaks and background noise caused by specular reflection from the optical elements, the developed system has been calibrated and a linear correction factor has been applied. In addition, to overcome the vertical scanning limitation of the laser confocal sensor, an adaptive surface tracing algorithm is developed to measure free-form surfaces. The developed displacement measurement system based on image grating technique is also integrated in to the adaptive surface tracing system to improve the positioning accuracy.

2.5 Summary

In this chapter, a brief overview of surface texture as well as the importance of surface texture measurement are given in the first section. Then, some essential definitions of surface characterization were described. Different surface profile parameters and areal surface parameters are introduced and discussed in separate groups (height, spatial, hybrid). The next section of the chapter illustrated different surface roughness measurement methods in stylus and optical techniques respectively. A detailed comparison has also been conducted among them.

Then, several key challenges in surface finish measurement are reviewed and summarized in the next section. Firstly, *in-situ* surface finish measurement requires that the actual measurement needs to be carried out while the machined product is still positioned in the manufacturing cell. Non-contact systems based on optical techniques such as confocal microscopy and white light interferometry have been implemented in manufacturing system to provide high scanning speed and measurement accuracy. More recently, many machine vision based methods have been developed to measure surface roughness in the indirect ways and demonstrated good compromise between measurement speed and accuracy.

The next part of this section has reviewed the recent research and development of surface measurement techniques in three advanced manufacturing surfaces, which are mirror finish surfaces, additive manufacturing surfaces and free-form surfaces. The non-contact measurement method based on different machine vision and optical profiling techniques have been proved to provide comparable measurement accuracy to stylus-based contact method, but faster scanning speed, non-destructive measurement and feasibility for *in-situ* measurement.

Lastly, a review of different techniques for precision displacement measurement is presented. Accurate displacement measurement is a critical requirement in all surface metrology instruments. Laser interferometer has been widely used as a reference metrology instrument for long displacement measurement with sub-nanometer resolution. Optical encoders are widely equipped for precision positioning systems, but have some inherent disadvantages. Digital image correlation using subpixel interpolation algorithm is an ideal option for accurate deformation and displacement measurement, but the measurement range is limited to sub-millimeter or less.

3. Mirror Finish Surface Inspection based on Machine Vision Methods

During a typical robotized polishing process as Table 3-1 indicated below, the quality control needs to be conducted from the initial stage (after CNC machining) with Ra around 2 μm to the final mirror polish stage with Ra down to 0.01 μm . The polishing process for the production of mirror finish surfaces is costly due to long manufacturing time and high probability of polishing errors. The surface texture and local defects are the most important surface geometry and physical properties for mirror finish components [49]. An *in-situ* surface texture and defect measurement system is highly demanded to reduce the rejections and costs. The *in-situ* measurement system should achieve fast and non-contact inspection and send measurement results to the polishing operator to make decision for further processing. The *in-situ* measurement for the mirror finish surfaces has several requirements:

- The inspection system should be flexible and portable and be able to fit into a compact industrial robot cell.
- The weight of the inspection system should be less than 5 kg to meet the payload of a compact industrial robot.
- The inspection system should be simple to be integrated into the industrial robot. The developed software should be able to provide on-line data processing.
- The inspection speed needs to be fast enough to meet the demands from robotized surface finishing industry.

Table 3-1 Typical robotized polishing process

Polishing process	Dry process using abrasive adhesive disc with grit size from 30 μm to 15 μm .		Wet process using diamond slurry compound with particle size from 3 μm to 0.25 μm and cushioned backing pad.
Polished sample
R_a (μm)	2 – 0.2		0.2 - 0.01

3.1 Modelling and Software Development

3.1.1 Surface Roughness Measurement

A patterned area illumination system is developed using a programmable illumination source and a monochrome machine vision camera. Figure 3-1 shows the system configuration. A black and white fringe pattern is generated by the illumination source. In specular reflection, the incidence angle is equal to the reflection angle. Hence, when the fringe patterns are projected on the mirror finish surface, a mirror-like reflected image of the fringe patterns can be captured by the machine vision camera. The sharpness of the fringe patterns in the image provides information related to specular reflection on the surface and surface roughness [91]. For analyzing the sharpness and contrast of the fringe patterns, the image processing task includes fringe pattern generation, pattern recognition and fringe pattern analysis.

As an illustration, Figure 3-2 shows the black-and-white fringes projected on samples surface and surface topography plots measured by Talysurf CCI with different roughness level. It can be clearly seen that from sample 1 to sample 4, image of black-and-white fringes become blur and surface roughness increases refer to the surface height scale bar. Then, by comparing the sharpness of the black-and-white fringes and the surface roughness measured by Talysurf CCI HD, a mathematical correlation can be determined.

Figure 3-1 Schematic illustration of the roughness measurement system

Figure 3-2 (a) Fringe pattern image captured by machine vision camera; (b) Sample surface roughness measured using Talysurf CCI

3.1.1.1 Grayscale Contrast

As discussed in Section 3.1.1, the sharpness of the fringe patterns in the image provides information about the surface specular reflection. The surface roughness and the surface specular reflection can be related [169]. Luminance contrast [170] of the fringe patterns can be used to evaluate the specular reflection on mirror finish surface. Luminance contrast is a measure of the perceived lightness or brightness difference between two colours [171]. Michelson contrast is widely used for simple periodic patterns where both bright and dark features are equivalent [172]. The Michelson contrast is defined as:

$$C = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \quad 3-1$$

Where L_{max} and L_{min} are the maximum and minimum luminance in the image.

However, the Michelson contrast is often influenced by the location of the distribution of grayscale level and the maximum or minimum value of brightness which is sometimes noise. In order to reduce the noise level, the luminance contrast C in the developed imaging processing algorithm was modified as:

$$C = \frac{AW - AB}{AW + AB} \quad 3-2$$

where AW and AB are the average intensity of the white fringes and black fringes.

3.1.1.2 Grayscale Histogram Standard Deviation

Grayscale histogram is an important tool for image analysis, which plots the number of pixels as a function of their brightness values in the range from 0 to 255 [173]. Two images with different sharpness and their corresponding histograms are presented in

Figure 3-3 and Figure 3-4. It can be observed that the width of the two histogram distribution plots are significantly different. The standard deviation is often used to evaluate the extension of a distribution in the field of statistics [169]. By evaluating the standard deviation of the histogram distribution of grayscale histogram, the intensity variation between different images can be quantified.

Figure 3-3 A sharp image and its grayscale histogram

Figure 3-4 A blur image and its grayscale histogram

For this study, areal surface texture parameters S_a and S_q were chosen for system evaluation and comparison. Then the contrast ratio values and grayscale histogram standard deviation were separately compared to the roughness values measured by the Talysurf CCI HD which will be demonstrated in Section 3.3.

3.1.2 Surface Defect Detection

According to Rayleigh criterion in surface scattering [174], a sample surface can be considered as smooth which mainly cause specular reflection if it meets the following condition:

$$\Delta h < \frac{\lambda}{8 \cos \alpha} \quad 3-3$$

Where Δh is RMS roughness (R_q), α is the incidence angle and λ is the wavelength of the lighting source (Figure 3-5).

Figure 3-5 Schematic of the defect detection model

If α and λ decrease, $\frac{\lambda}{8 \cos \alpha}$ will be smaller, so Δh will be larger than $\frac{\lambda}{8 \cos \alpha}$. When the surface scattering happens, the imaging device can capture the scattering lights mainly caused by the surface defects. The most widely used monochrome lighting source is red and green light. Because the wavelength of green light is smaller than wavelength of red light, the proposed system is integrated with a green LED light source for preliminary study. By setting the system configuration with 90° imaging and 30° lighting angles as shown in Figure 3-5, surface defects with Δh (R_q) larger than 76.5 nm will scatter light based on Rayleigh criterion.

3.1.3 Software Program Development

The proposed software program consists of image acquisition part and image processing part. LabVIEW™ vision development module was chosen to conduct the software program development in order to achieve *in-situ* inspection. LabVIEW™ vision development module has a wide applicable library to access different types of machine vision cameras. The image acquisition part of the software program was completed using the IMAQ function inside the vision development library. Besides, the machine vision camera can be controlled through computer and the captured image can be subsequently post-processed. The image processing part was separated into two individual programs for surface roughness measurement and defect detection as below.

- Image processing for surface roughness measurement:
 1. Create region of interest on the acquired image.
 2. Extract intensity plane of the image to get the grayscale image.
 3. Dilate the grayscale image to increase contrast and sharpness.
 4. Using median filter to remove the background noises.
 5. Locate measurement areas and calculate the average intensity of the black and white fringes.
 6. Calculate the contrast and surface roughness based on the proposed empirical equations.
 7. Display contrast and roughness measurement results in the inspection front window.

Figure 3-6 shows a preliminary image process result for surface roughness measurement of a tested sample. It can be observed that the image contrast and sharpness increased and background noises reduced after image processing. The contrast and surface roughness calculated based on empirical equations can be displayed in the inspection front window.

Figure 3-6 Image processing for surface roughness measurement

- Image processing for surface defect detection:
 1. Create region of interest on the acquired image.
 2. Extract green plane of the image to get grayscale image.
 3. Dilate the grayscale image to increase contrast and sharpness.
 4. Using median filter to remove the background noises.
 5. Using local threshold with background correction method to convert the grayscale image to binary image and isolate the defects.
 6. Adapt Sobel edge detection to further separate the defects.

7. Locate all the defects and display results in the inspection front window.

In order to verify the proposed defect detection model, some inspection images of the validation experiments were conducted. Figure 3-7 shows the image processing procedure from original image to the final results display for three different samples. It can be seen that most incident lights were reflected away from the image field. The surface defects which scatter the light can be detected by the machine vision camera, while the other parts of the image field remain dark. The preliminary results show good capability and feasibility of the proposed image processing program for detecting the surface defects.

Figure 3-7 Image processing for defect detection

3.2 System Setup and Experimental Materials

3.2.1 Hardware Details of Inspection System

The main components in the proposed inspection system are:

- Machine vision camera and lens

An industrial machine vision camera (EXG50c, Baumer, Friedberg, Germany) with 1/2.5" progressive scan CMOS sensor and 2592x1944 pixel resolution was integrated into the inspection system. It has a sensor pixel size of $2.2\ \mu\text{m} \times 2.2\ \mu\text{m}$ and frame rate of 13 fps at full resolution.

Two ultra-low distortion lenses (M1620 and M5028, Computar, Cary, NC, USA) were selected for surface roughness measurement and defect detection. The M1620 lens with EXG50c camera is able to provide a spatial resolution about $1.5\ \mu\text{m}$ at the field of view of 3.08cm x 4.11cm. Its minimum working distance of 0.2 m is suitable for surface roughness measurement. The M5028 lens with EXG50c camera is able to provide a spatial resolution about $3.3\ \mu\text{m}$ at the field of view of 6.40cm x 8.53cm. Its long working distance of 0.4 m is suitable for surface defects detection.

- Patterned area illumination source:

A programmable pattern illuminator (Ipad mini 3, Apple Inc., Cupertino, CA, USA) equipped with 7.9" liquid crystal display which has 2048 x 1536-pixel resolution at 326 pixels per inch. This high resolution illumination display is able to generate different kinds of high quality fringe patterns.

- Collimated illumination source:

This collimated light (M530L3-C1, Thorlabs, Newton, NJ, USA) with high-power mounted LED and adjustable light intensity will be used to illuminate the workpiece surface for defect detection. Its nominal wavelength is 520 nm and maximum power is 3200 mW.

- Industrial Robot:

A six-axis multipurpose industrial robot (ABB IRB 140, ABB Group, Zurich, Switzerland) is integrated with the inspection module to achieve automated and *in-situ* surface measurement. It has a payload of 6 kg with a reach of 810 mm and position repeatability of 0.03 mm.

3.2.2 Coherence Correlation Interferometer

The test samples used for roughness measurement modelling were calibrated by using a coherence correlation interferometer (Talysurf CCI HD, AMETEK Inc, Berwyn, PA, USA) with 50X objective lens as shown in Figure 3-8. The principles and detailed characteristics of coherence correlation interferometer are described in Section 2.1.3. It basically uses coherence scanning interferometry to measure the surface texture and is able to provide spatial resolution of 0.5 μm and vertical resolution of 0.1 nm using 50X objective lens.

Figure 3-8 Taylor Hobson Talysurf CCI

3.2.3 Test Samples

For roughness measurement, a set of sixteen stainless steel samples labelled from 1 to 16 (Figure 3-9) were ground and polished to achieve different roughness values to represent different surface conditions of fan blades and turbine blades which have been widely used in aerospace and power generation industries. These sixteen tested samples were finished using tissue, felt, soft wood, copper, hard wood and grit separately. These six finishing materials have been commonly used sequentially to achieve mirror finish quality in surface finishing industry. For defect detection, three mirror finished flat test sample shown in Figure 3-10 were manufactured. The first sample has been well polished to achieve a surface without obvious defects. The second sample has been semi-polished to leave different kinds of defects like scratches, pits and rust stains. The third sample has been scratched to fabricate two artefact scratches on the surface to validate the developed algorithm and the proposed inspection system.

Figure 3-9 Test samples for roughness measurement

Figure 3-10 Test samples for defect detection (a) polished surface without defects (b) polished surface with defects (c) polished surface with artefact scratches

3.2.4 System Integration

Figure 3-11 System flow of the proposed post-process inspection system

The inspection system includes two modules, a sensor module and an image processing module. The system setup, including imaging distance and angle, lighting source distance and angle, and camera settings were determined based on the results of the modelling described in Section 3.1 and hardware characteristics in Section 3.2.1. The robot carried the inspection unit to approach the target area at a fixed distance and angle

to capture images. Next, the captured images were sent to the processing unit for roughness measurement and defect detection.

3.2.5 Surface Roughness Measurement Setup

Figure 3-12 System configuration for surface roughness measurement

Figure 3-12 shows the configuration for surface roughness measurement and the whole inspection unit was installed on a robot arm to demonstrate the capability of *in-situ* measurement. The robotized inspection system will be used to achieve the automatic surface inspection for the future research work. A black and white fringe pattern was generated by the tablet screen. Reflected by the mirror finish surface, the image of the pattern can be captured by the machine vision camera. After analyzing the contrast value or histogram standard deviation of the fringe pattern image, the roughness can be quantified. The 16 mm focal lens were used under this configuration. The camera and patterned backlight were angled 45° from horizon and the distance between camera and workpiece was set to be 0.1 m.

3.2.6 Surface Scratch Inspection Setup

Figure 3-13 Configuration for surface scratch inspection

Figure 3-13 shows the configuration for surface defect detection and the whole inspection unit integrated within an industrial robot system. A collimated LED light was employed to illuminate the workpiece surface and enhance the visibility of the surface defects. The distance between camera and workpiece was set to be 0.4 m. With a collimated light, most incident light will be reflected away from the view of vision camera, but the scattering light generated by the surface defects will be captured by the machine vision camera. The 50 mm focal lens were used under this configuration. The camera was set at 90° angle to the sample surface and the collimated LED light was settled at 30° incident angle to the sample surface.

3.3 Surface Roughness Measurement

As discussed in previous chapter, sixteen test samples with different surface roughness were used for measurement. Sample size is 30mm diameter and each sample has been measured in five areas as shown in Figure 3-14.

The calibrated roughness values S_a and S_q were measured by the Taylor Hobson Talysurf CCI. Each measurement area is 2 mm by 2 mm. The roughness measurement results are presented in Figure 3-15. It can be observed that the sixteen samples have different S_a and S_q values in the range of 1 nm to 120 nm and 2 nm to 165 nm respectively.

Figure 3-14 Measured areas on the sample surface

Figure 3-15 Roughness measurement result using Talysurf CCI

3.3.1 Grayscale Contrast Measurement

The grayscale contrast (C) measurement results and the average values with standard deviation were shown in Figure 3-16. The S_a -contrast curve in Figure 3-17 and S_q -contrast curve in Figure 3-18 show good feasibility of the proposed system for surface roughness measurement. As widely accepted, the coefficient of determination R^2 value

indicates how well data points agree with the fitted line. The closer the R^2 value is to one, the better the linear relationship between two sets of data points. The high R^2 value of 0.9707 in S_a -contrast curve and R^2 value of 0.9819 in S_q -contrast curve indicate that linear regression of the data set is reliable.

Figure 3-16 Grayscale contrast measurement result using proposed system

Figure 3-17 S_a -Contrast curve

Figure 3-18 S_q -Contrast curve

Based on the S_a (S_q) and contrast values in Figure 3-17 and Figure 3-18, a linear relation can be modelled as Equation 3-4 and 3-5 as below. These empirical equations are based on the preliminary measurement results of the sixteen samples. More samples need to be measured to get additional data points to validate the proposed empirical equations.

$$S_a = -131.3C + 120.66 \quad 3-4$$

$$S_q = -175.24C + 165.84 \quad 3-5$$

3.3.2 Grayscale Histogram Standard Deviation

The grayscale histogram standard deviation (STD) measurement results and the average values with standard deviation were shown in Figure 3-19. The S_a -STD curve in Figure 3-20 and S_q -STD curve in Figure 3-21 showed there are a linear relationship between grayscale histogram standard deviation (STD) and surface roughness (S_a and S_q). The R^2 value of 0.9813 in S_a -STD curve and R^2 value of 0.9694 in S_q -STD curve indicate that linear regression of the data set is dependable. By comparison these R^2 values with the contrast measurement results with R^2 value of 0.9707 in S_a -contrast curve and R^2 value of 0.9819 in S_q -contrast curve, the correlation between grayscale contrast (C) and surface roughness is similar to the correlation between histogram standard deviation (STD) and surface roughness.

By comparing Figure 3-17 and Figure 3-20 as well as Figure 3-18 and Figure 3-21, it can be observed that the error bar in S_a -STD and S_q -STD curves is much larger than the error bar in S_a -contrast and S_q -contrast curves. Based on the above observations, the results based on contrast algorithm were more reliable than the histogram standard deviation algorithm.

Figure 3-19 Histogram standard deviation measurement result using proposed system

Figure 3-20 S_a -STD curve

Figure 3-21 S_q -STD curve

3.3.3 Surface Uniformity Measurement

According to ISO 25178-2 [30], Str is defined as the ratio of the fastest to slowest decay to correlation length of the surface autocorrelation function. For evaluating the surface texture, Str is the parameter to characterize the surface uniformity.

Sample 2 and Sample 8 were chosen to study the effect of machining pattern on mirror surface isotropy. Figure 3-22 shows the microscopic images of the two samples. It can be clearly seen that these two samples represent two typical mirror finish surfaces with unidirectional machining pattern and multi-directional machining pattern. They have a very close Sq value (mean $\pm$ st.dev) of 59.4 ± 1.5 nm and 60.1 ± 1.8 nm respectively. But the Str value of sample 2 and sample 8 is 0.072 ± 0.006 and 0.426 ± 0.013 . In principle, Str has a value between 0 and 1. Larger values, say $Str > 0.5$, indicates uniform texture in all directions. Smaller values, say $Str < 0.3$, indicates an increasingly strong directional structure or machining pattern.

Figure 3-22 Machining pattern on sample 2 and sample 8

The contrast values are measured using the image processing algorithm described in Section 3.1.3. The contrast results at different measurement angles for sample 2 and sample 8 were plotted in Figure 3-23 to compare the grayscale contrast difference. The grayscale contrast value at 0 degree and 180 degree is much larger than those at the other measurement angles for sample 2. As a comparison, sample 8 has random and similar grayscale contrast value from 0 degrees to 180 degrees. Other samples will be investigated to check whether they have a similar trend that the samples with Str value close to zero have two peaks in 0 degree and 180 degree.

In conclusion, the grayscale contrast ratio has correlation with directions of the machining marks and the projected fringes at different measurement angles. The surface texture aspect ratio parameter Str which provides information about the strength of the machining marks was experimentally evaluated and compared with grayscale contrast change.

Figure 3-23 Contrast value in different measurement angles

3.4 Surface Defect Detection

3.4.1 Artefact scratches detection

Based on developed system configuration and using the proposed image processing program, the inspection results are presented in Figure 3-24. The camera captured the original image, then the image was processed and the two artefact scratches were detected and displayed.

To test the resolution of the proposed system, the artefact scratches 1 and 2 were also measured using Talysurf CCI and the results are presented in Figure 3-25 and Figure 3-26. The average width and depth of the artefact scratch 1 is 18.5 μm and 3.0 μm

separately. The average width and depth of the artefact scratch 2 is 10.4 μm and 0.7 μm separately.

Based on the inspection results of the artefact scratches, the proposed system and image processing algorithm is able to detect the scratches which are difficult for manual inspection.

Figure 3-24 Artefact scratches detection

Figure 3-25 Artefact scratch 1 measured by Talysurf CCI

Figure 3-26 Artefact scratch 2 measured by Talysurf CCI

3.4.2 Sample Defect Detection

The developed system was tested on the polished sample without defect on the surface to validate the inspection accuracy. The inspection results are presented in Figure 3-27. After the original image being processed through the proposed image processing algorithm, the results displayed zero defects on the sample surface. The proposed system was also tested to inspect the polished sample with different kinds of defects on the surface. Figure 3-28 shows the inspection results of the middle and bottom area on the sample surface. From the results display images, the proposed system is able to detect and count different defects such as scratches, pits and rust stains.

In order to test the resolution of the proposed system, four detected scratches labelled from 1 to 4 in Figure 3-28 were also measured using Talysurf CCI and the results are presented in Figure 3-29 and Table 3-2. The average width and depth of the four scratches are similar to the artefact scratches measured in last section. Based on the inspection results of the surface defects, the proposed system and image processing algorithm is able to detect the surface defects with width above $10\text{ }\mu\text{m}$ and depth above $0.2\text{ }\mu\text{m}$ which are difficult for manual inspection.

Figure 3-27 Defect detection results on polished surface without defect

(a) Original image

(b) Results display

Figure 3-28 Defect detection results on polished surface with defects

Figure 3-29 Scratch 1 to 4 surface topography measured by Talysurf CCI

Table 3-2 Scratch 1 to 4 dimensions measured by Talysurf CCI

Scratch Number Scratch dimension	1	2	3	4
Average width (μm)	12.59	17.19	10.94	12.38
Average depth (μm)	0.25	0.66	0.28	0.23

3.5 Summary

In this chapter, a surface roughness measurement system using the fringe pattern illumination method is developed to address *in-situ* roughness measurement on mirror finish surface. By analyzing the grayscale contrast ratio of the fringe pattern reflection image and comparing to the measurement results from the referenced coherence scanning interferometer, the experimental results showed that the developed system was able to measure different mirror finish surfaces with Sa and Sq values in the range of 1 nm to 120 nm and 2 nm to 165 nm respectively. The experimental results demonstrated a good correlation between the grayscale contrast value and the surface roughness parameters (Sa and Sq). In addition, the grayscale contrast ratio was also correlated with directions of the machining marks and the projected fringes at different measurement angles. The surface texture aspect ratio parameter Str which provides information about the strength of the machining marks was experimentally evaluated and compared with grayscale contrast change. Besides, a surface defect inspection system based on Rayleigh criterion in surface scattering was developed. The defect inspection system was integrated into the robotic cell to achieve *in-situ* defect detection on mirror finish surface. The experimental results showed that the developed system is able to detect surface defects with width above 10 μm and depth above 0.2 μm .

4. Position Measurement System Based on Image Grating Technique

4.1 Introduction to Image Grating System

The position measurement system was developed using the concept of image grating technique which is based on 1D subpixel image registration algorithm. As discussed in Section 2.2.5.1, line scan camera creates an image as a row of single pixel (1D image) and particularly suitable for measurements which require high speed, high spatial resolution and simple illumination conditions. In order to focus on 1-dimensional precise measurement and achieve high efficiency, a line scan camera with large image sensor is selected instead of a conventional 2D area scan camera in the developed system as the displacement reader.

As shown in Figure 4-1, an image grating system includes a patterned target attached or printed on the motorized stage and a stationary line scan camera as the displacement reader. By applying different optics, the standoff and measurement range can be adjusted. When the system is properly aligned, position of the moving object will be correlated to the pixel translation of the patterned target on the image.

This system can be pre-calibrated using a visible feature with known dimension. In this study, line patterns with known interval distance was used. Through calibration, the pixel-to-dimension ratio can be determined. After calibration, the focusing mechanism of the optical lens shall be locked. During the measurement practice, the first image captured at the starting position is used as the reference. As shown in Figure 4-2, pattern shift can be calculated in pixels between the first image and subsequent images using

image registration approach. Then, the displacement can be computed according to the pixel-to-dimension ratio.

Figure 4-1 Schematic of an image grating system

Figure 4-2 Schematic of pattern shift between two images

In order to implement the image grating system into practical position measurement, the measurement accuracy needs to be determined. Most commercial surface topography measuring instruments are integrated with motorized stages configured with stepper or DC motor with lead screw. The positioning accuracy of these types of cost-effective motorized stages are within the range from $0.5\ \mu\text{m}$ to $5\ \mu\text{m}$ [175–177]. Therefore, the target of our developed image grating system is to achieve position measurement accuracy less than $0.2\ \mu\text{m}$. However, the image sensor in a typical line scan camera has the pixel size in millimeter level. To break through the pixel-level resolution of the line scan camera, subpixel image registration algorithm was introduced in the image grating system.

4.2 Image Registration Techniques

Due to the requirement for real-time position measurement, computational speed is a main concern for the image registration techniques. Hence, as discussed in Section 2.2.5.2, the Fourier domain approaches are preferred to spatial domain approaches.

4.2.1 Fourier-based Image Registration

The foundation principle of image registration in Fourier domain is based on the well-known Fourier shift theorem [146]. Given two images $f(x, y)$ and $g(x, y)$, assumed that horizontal shift x_0 and vertical shift y_0 between the two images, $f(x, y)$ and $g(x, y)$ are related by the following transformation:

$$f(x, y) = g(x - x_0, y - y_0) \quad 4-1$$

According to the Fourier shift theorem, the Discrete Fourier Transform (DFT) of $f(x, y)$ and $g(x, y)$ satisfy:

$$F(u, v) = G(u, v) \exp \left[-i2\pi \left(\frac{ux_0}{M} + \frac{vy_0}{N} \right) \right] \quad 4-2$$

where M and N stand for the image dimensions, $F(u, v)$ and $G(u, v)$ are DFT of $f(x, y)$ and $g(x, y)$ respectively, as given by the relation:

$$\begin{aligned} F(u, v) &= \frac{1}{\sqrt{MN}} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x, y) \exp \left[-i2\pi \left(\frac{ux}{M} + \frac{vy}{N} \right) \right] \\ G(u, v) &= \frac{1}{\sqrt{MN}} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} g(x, y) \exp \left[-i2\pi \left(\frac{ux}{M} + \frac{vy}{N} \right) \right] \end{aligned} \quad 4-3$$

A widely used method to perform image registration is to compute the cross-correlation function of the two images [161,178]. The cross-correlation function of $f(x, y)$ and $g(x, y)$ [167] is defined as:

$$c(x_0, y_0) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x, y) g^*(x - x_0, y - y_0) \quad 4-4$$

where * indicates the complex conjugation. By using Fourier shift theorem and inverse Fourier Transform (IFT), Equation 4-4 can be rewritten as:

$$c(x_0, y_0) = \sum_{u=0}^{M-1} \sum_{v=0}^{N-1} F(u, v) G^*(u, v) \exp \left[i2\pi \left(\frac{ux_0}{M} + \frac{vy_0}{N} \right) \right] \quad 4-5$$

So transformation x_0 and y_0 can be obtained by locating the peak of cross-correlation $c(x_0, y_0)$ in the Fourier domain. The Fast Fourier Transform (FFT) algorithm can be implemented to speed up the calculation.

Recently, image registration using phase correlation method in the Fourier domain has been a hot research topic [153,155]. Compared to cross-correlation function, phase correlation function normalizes (whitens) the cross power spectrum [179] which is defined as following:

$$R(u, v) = \frac{F(u, v) G^*(u, v)}{|F(u, v) G^*(u, v)|} = \exp \left[-i2\pi \left(\frac{ux_0}{M} + \frac{vy_0}{N} \right) \right] \quad 4-6$$

The phase correlation function $r(x, y)$ is the inverse Fourier Transform (IFT) of the normalized cross power spectrum $R(u, v)$ which is a Dirac Delta function [154] centered at (x_0, y_0) as following:

$$r(x, y) = \text{IFT}[R(u, v)] = \delta(x - x_0, y - y_0) \quad 4-7$$

Compared with the cross-correlation method, the most outstanding advantage of the phase correlation method is that the peak of the correlation function can be more accurately located. Figure 4-3 shows an example of cross-correlation function and phase correlation function of two aerial images [154]. As can be seen, the cross-correlation method produces a few broad peaks among the main peak whose maximum may not be correctly centered at the registration point. In contrast, the phase correlation method yields a more distinctive peak at the correct registration point.

A second significant advantage is due to the normalizing process, which makes the phase correlation method particularly robust to the images degraded with background noise, gain error owing to calibration and illumination variations [145]. This advantage also makes phase correlation method especially suitable for image registration across various spectral bands [154].

Figure 4-3 (a) cross-correlation (b) phase correlation of two aerial images [154]

4.2.2 Subpixel Image Registration in Fourier Domain

Based on the phase correlation function as Equation 4-7 in Section 4.2.1, it can be observed the accuracy of phase correlation methods fully depends on calculation of the peak in the Dirac Delta function. The basic phase correlation method can only be used for pixel-level registration as a coarse estimation. To improve the coarsely registered images to higher accuracy, subpixel image registration methods need to be introduced. A conventional approach to calculate the image translation within a fraction, $1/k$, of a pixel is to embed the cross power spectrum in a zero-padded matrix in Fourier domain and compute an inverse FFT to obtain the k -times up-sampled phase correlation and locate its peak [180]. This approach provides high registration accuracy and robust results, but the computational time and memory consuming are huge, especially for large-size images and high up-sampling factor (k) [152]. To solve the problem of low computational efficiency in the conventional FFT approach, some commonly used approaches are based on interpolation algorithm such as iterative intensity interpolation [155] and correlation interpolation [181]. However, these methods are usually sensitive to image noise [163] and their accuracy largely depend on the quality of the interpolation algorithms [154].

In recent years, many researchers have proposed different new methods to obtain fast and highly accurate image registration. Foroosh et al. [154] proposed a phase correlation method on downsampled images using a Sinc function to approximate the Dirac Delta function in frequency domain, which has less computation complexity but limited registration accuracy (0.05 pixel resolution) compared to the conventional FFT method. Murat et al. [165] have demonstrated that the discrete phase difference of two shifted images is a two-dimensional sawtooth signal. Hence, subpixel registration can be performed directly in the Fourier domain by counting cycles' number of the phase

difference on each frequency axis. Guizar et al. [166] proposed a single-step Discrete Fourier transform (SSDFT) that uses matrix-multiply Discrete Fourier Transform (DFT) algorithm to compute the up-sampled cross-correlation between the reference and sensed images. This method is able to achieve subpixel registration accuracy equivalent to that of the conventional FFT method in much reduced computational complexity.

Wang et al. [163] have done some comparison experiments between Foroosh's method [154], Murat's method [165], and SSDFT method [166] for accurate translation calculation on two classical images and the comparison results of different registration methods are shown in Table 4-1. It can be observed that among the three subpixel registration methods, the registration accuracy of SSDFT method exceeds the Foroosh's method, and has a little superiority compare to the Murat's method.

Table 4-1 Comparison between different subpixel image registration methods [163]

Image	True translation	Foroosh's method	Murat's method	SSDFT method Up-sampling factor k
Pentagon	(0.500, -0.500)	(0.480, -0.510)	(0.496, -0.493)	$k = 100$ (0.500, -0.500)
	(0.250, 0.500)	(0.280, 0.490)	(0.255, 0.498)	(0.240, 0.500)
	(-0.250, -0.500)	(-0.250, -0.520)	(-0.250, -0.520)	(-0.250, -0.500)
	(0.000, 0.750)	(0.000, 0.800)	(0.000, 0.744)	(0.000, 0.750)
Paris	(0.167, -0.500)	(0.152, -0.490)	(0.163, -0.510)	$k = 200$ (0.165, -0.500)
	(0.670, -0.500)	(0.690, 0.330)	(0.679, 0.242)	(0.670, 0.250)
	(-0.330, -0.167)	(-0.320, -0.150)	(-0.331, -0.159)	(-0.330, -0.165)
	(0.330, 0.330)	(0.325, 0.320)	(0.333, 0.329)	(0.330, 0.330)

Yousef et al. [179] and Douini et al. [152] proposed a phase correlation registration algorithm based on Guizar's method by using a down-sampled Fourier Transform to

reduce the computation time and memory requirements. However, this algorithm is limited to register images that differ by a small shift otherwise its performance significantly degrades.

Therefore, in this research, single-step Discrete Fourier transform (SSDFT) method is chosen as the subpixel image registration algorithm for position measurement.

4.2.3 Subpixel Image Registration Procedure Based on SSDFT method

The single-step Discrete Fourier transform (SSDFT) approach has two steps. The first step finds a coarse estimation for the peak location of the phase correlation between two images using the conventional zero-padding FFT approach with up-sampling factor of $k = 2$. In the second step, the SSDFT approach refines the estimation for the accurate peak in a 1.5×1.5 pixel neighbourhood around the coarse estimation based on matrix-multiply DFT.

Based on our application for position measurement using a line scan camera which create a 1D image as a row of single pixel, the 2D SSDFT algorithm is simplified to 1D SSDFT algorithm and explained in the following.

A 1D image can be defined as a 1D discrete signal $f(\mathbf{X})$ and the Fourier Transform (FT) of the signal in matrix form can be written as:

$$F(\mathbf{U}) = E(\mathbf{UX}) \cdot f(\mathbf{X}) \quad 4-8$$

where $\mathbf{X} = (x_0, \dots, x_{N_A-1})^T$, $\mathbf{U} = (u_0, \dots, u_{N_B-1})^T$ and

$$E(\mathbf{UX}) = \begin{pmatrix} e^{-i2\pi x_0 u_0} & \dots & e^{-i2\pi x_k u_0} & \dots & e^{-i2\pi x_{N_A-1} u_0} \\ \dots & \dots & \dots & \dots & \dots \\ e^{-i2\pi x_0 u_k} & \dots & e^{-i2\pi x_k u_k} & \dots & e^{-i2\pi x_{N_A-1} u_k} \\ \dots & \dots & \dots & \dots & \dots \\ e^{-i2\pi x_0 u_{N_B-1}} & \dots & e^{-i2\pi x_k u_{N_B-1}} & \dots & e^{-i2\pi x_{N_A-1} u_{N_B-1}} \end{pmatrix} \quad 4-9$$

Equation 4-8 is the FT in matrix form deduced from the representation by Riemann sum of continuous FT and if N_A is equal to N_B , Equation 4-8 become the DFT of the signal [182]. Based on the matrix Fourier Transform (FT) described in Equation 4-8 and 4-9, the up-sampling matrix inverse FT can be defined similarly. Firstly, the initial normalized cross power spectrum $R(u, v)$ from Equation 4-6 is modified as $R(u)$ in Equation 4-10.

$$R(u) = \frac{F(u)G^*(u)}{|F(u)G^*(u)|} = \exp \left[-i2\pi \frac{ux_0}{M} \right] \quad 4-10$$

We define m as the pixel size of up-sampled region around the coarse estimation ($m = 1.5$ in SSDFT algorithm), and k as the up-sampling factor in spatial domain, and $\hat{S}$ as the coarse estimation of the peak location of $R(u)$ from Equation 4-10. The up-sampling range L is defined as:

$$L = \left\{ x', \quad k \cdot \hat{S} - \frac{km}{2} \leq x' \leq k \cdot \hat{S} + \frac{km}{2} \right\} \quad 4-11$$

It is known that the discrete spectrum in Fourier domain corresponds to a continuous periodic signal in spatial domain. Therefore, increasing sampling rate of the signal can obtain a higher resolution of the spatial domain signal. Given a normalized cross power spectrum $R(\mathbf{U})$, the up-sampling matrix inverse FT on L is defined based on the matrix-multiply FT:

$$r(\mathbf{X}') = \begin{cases} e^{i2\pi\mathbf{X}'\mathbf{U}^T} \cdot R(\mathbf{U}), & \mathbf{X}' \in L \\ 0, & \mathbf{X}' \notin L \end{cases} \quad 4-12$$

where $\mathbf{X}'$ is spatial distribution of the up-sampled phase correlation $r(\mathbf{X}')$.

It is assumed that the sampling step of x' is $1/k$ pixel. The up-sampling matrix inverse FT operator restricts the region of the $R(\mathbf{U})$ and $[-m/2, m/2]$ is the region of the coarse estimation. The accurate phase correlation peak is located within this region. Firstly, after the coarse estimation $\hat{S}$ is obtained in the conventional zero-padding FFT approach and the up-sampling region is set according to m , the region $[\hat{S} - m/2, \hat{S} + m/2]$ is up-sampled with factor k to get vector $\mathbf{X}'$. Finally, the up-sampled phase correlation $r(\mathbf{X}')$ can be calculated based on Equation 4-12. By searching the maximum in vector $\mathbf{X}'$, the fine estimation $\Delta\hat{S}$ can be obtained. Then, the final estimation of the translation S between the two images is achieved by Equation 4-13.

$$S = \hat{S} + \Delta S \quad 4-13$$

Figure 4-4 shows an example of two 1D images for translation calculation. The normalized cross power spectrum between the reference image and shifted image can be obtained by Equation 4-10 which is shown in Figure 4-5 (a). The enlarged view around the peak location is shown in Figure 4-5 (b). It can be seen that the peak location on the spectrum is in pixel-level accuracy. Then the normalized cross correlation spectrum is up-sampled by SSDFT method in the neighborhood around the peak location in Figure 4-5 (b), and the up-sampled cross correlation spectrum is depicted as in Figure 4-5 (c). Comparing Figure 4-5 (b) and Figure 4-5 (c), it can be concluded that the location of the peak is more accurate after up-sampling using SSDFT algorithm.

(a)

(b)

Figure 4-4 1D images for phase correlation calculation (a) Reference image (b) Shifted image

(a)

(b)

(c)

Figure 4-5 Phase correlation of two 1D images (a) Full phase correlation plot; (b) Enlarged phase correlation plot; (c) Up-sampled phase correlation (up-sampling factor $k = 10$)

The image registration process based on SSDFT method is presented in Figure 4-6 and described as follows:

- (1) Input reference and sensed images.
- (2) The normalized cross power spectrum $R(u)$ is constructed and then the coarse estimation of the peak location of $R(u)$, $\hat{S}$, is calculated by conventional inverse FFT method.
- (3) Identify the up-sampling factor k , if $k > 1$ then continue, else if $k < 1$, $\hat{S}$ is set to zero and go to step (6).
- (4) Construct an up-sampling kernel function based the coarse estimate $\hat{S}$ and up-sampled region m .
- (5) Calculate the locally up-sampled cross power spectrum $R(u)$ and then the fine estimation $\Delta\hat{S}$ using matrix-multiply Fourier Transform.
- (6) Compute the final estimation S by adding up the coarse estimate $\hat{S}$ and the fine estimation $\Delta\hat{S}$.

Figure 4-6 Flow chart of image registration based on SSDFT

4.3 Image Grating System Validation

4.3.1 Image Grating System Setup

The image grating system for measuring motorized stage position was set up as shown in Figure 4-7. A heterodyne laser interferometer 5530 (Agilent, California, USA) with linear measurement resolution of 0.5 nm was used as the reference instrument for position measurement. A linear interferometer and a linear retroreflector are assembled for linear measurement. A line scan camera (raL12288-8gm, Basler AG, Ahrensburg,

Germany) with 43 mm sensor size and 12288-pixel resolution was integrated in the system. Its sensor pixel size is $3.5\ \mu\text{m}$ and sampling line rate is 8 kHz. A consumer lens (NIKKOR 60mm F2.8G, Nikon Inc., Melville, NY, USA) was selected to provide magnification ratio from 1:1 to 1:10.

The patterned target (Hong Cheng Optical Products, Dongguan, China) used in the developed image grating system includes a set of 40 line pairs with $50\ \mu\text{m}$ interval printed on an optical glass. The measurement uncertainty of the line feature is $\pm 1\ \mu\text{m}$. A microscope view of the line features on the patterned target is shown in Figure 4-8. In order to enhance the contrast and shorten the exposure time for the line scan camera, a LED illumination backlight (CV-NFL-100X96W, Moritex Corporation, Asaka, Japan) was placed as the substrate of the patterned target. A motorized stage (TSA100-B, Zolix Instruments Co., Ltd., Beijing, China) was selected for position measurement. It has a travel range of 100 mm, a minimum incremental motion of $1.25\ \mu\text{m}$ and a positioning repeatability less than $5\ \mu\text{m}$.

Figure 4-7 Image grating system configuration

Figure 4-8 Microscope view of the patterned target

4.3.2 Error correction caused by optical distortion

The image registration algorithms discussed in Section 4.2 are all based on an assumption that the optical magnification is uniform over the full field of view, which is unrealistic for actual optics. Most lenses have either barrel or pincushion distortion [183,184]. This section will provide the discussion of measurement errors caused optical distortion.

Theoretical modeling:

With an ideal optical lens, the magnification of which is uniform over the whole image field, the displacement of the target in the object field D_o is proportional to that in the image field D_i :

$$D_o = kD_i \quad 4-14$$

where k is the reciprocal of lens magnification. If the lens has either barrel or pincushion distortion, leading to a variable magnification, the relationship between D_o and D_i can be expressed:

$$D_o = \int_{x_0}^{x_t} k(x) dD_i \quad 4-15$$

where $k(x)$ is the reciprocal of the lens magnification with respect to x . With Equation 4-14 and Equation 4-15, the measurement error can be expressed as:

$$E = \int_{x_0}^{x_t} k(x) dD_i - \bar{k} \cdot (x_t - x_0) \quad 4-16$$

where $\bar{k}$ is the undistorted reciprocal of lens magnification; x_0 and x_t are the starting and stopping locations of the patterned target in the image. In a digital image, where the positioning information is discretized by pixilation, Equation 4-16 can be replaced by:

$$E = \sum_{i=m}^n k(i) \cdot d - \bar{k} \cdot (n - m)d \quad 4-17$$

where $k(i)$ is the reciprocal of magnification at i th pixel and d is the dimension of one pixel; m and n are the pixel indexes of the starting and stopping locations of the target in the image. The unevenness magnification of the lens can be fitted by a 4th-degree polynomial equation [147,183,185] and written as:

$$k(i) = a + bx^2(i) + cx^4(i) \quad 4-18$$

where $x = 0$ represents the center of camera and $k(0) = \bar{k}$ which is the undistorted reciprocal of magnification.

To simulate the optical distortion in the consumer lens (NIKKOR 60mm F2.8G) integrated in the developed image grating system, we assume the image starting position $m = -4500$ and stopping position $n = 4500$; the pixel size $d = 3.35 \mu m$ and the

reciprocal of magnification $\bar{k} = k(0) = 1$, $k(2500) = 1.001$, $k(4500) = 1.01$. Substitutes m , n , d , $\bar{k}$, $k(0)$, $k(2500)$ and $k(4500)$ into Equation 4-17 and 4-18, the simulated optical distortion curve and position error curve can be plotted as Figure 4-9. It is obvious that the position error curve can be fitted by a 5th-degree polynomial equation which is consistent with the integral of 4th-degree polynomial equation $k(x)$ in Equation 4-16.

Figure 4-9 (a) Optical distortion curve (b) position error curve

Experimental verification:

In order to verify the theoretical modeling of the optical distortion in the consumer lens (NIKKOR 60mm F2.8G) at its closest focus distance (magnification 1:1), a 100 mm patterned target with line pairs of 100 μm interval which covers the whole field of view in the line scan camera, was used to quantify the optical distortion. The full length view and enlarged details of the 100 mm patterned target are shown in Figure 4-10.

(a)

(b)

Figure 4-10 100 mm pattern target (a) Full length view (b) Enlarged details

Due to the optical distortion, the pixel numbers in each line pair (Figure 4-10 (b)) are not identical. By counting the pixel numbers in each line pair, the optical distortion and the position error of pattern shift can be analysed. In this experimental verification, a linear interpolation method is used to find the points of intersection between the mean grayscale intensity of the whole 1D image and the 1D image intensity curve (Figure 4-11).

Then, the pixel numbers within one line pair can be calculated in sub-pixel level shown as in Figure 4-12 (a). To reduce the measurement and interpolation error, a 4-th degree polynomial equation is used to fit the measured data points. It can be seen that the pixel number within one line pair at the image center (line pair index = 150) is lesser than the pixel number at the image edges (line pair index = 0, 300). It can be also concluded that the consumer lens (NIKKOR 60mm F2.8G) has a pincushion distortion that the image magnification increases with distance from the image center. By integrating the 4-th degree polynomial equation and then subtracting the integration of the pixel number within one line pair at the image center, the error curve of cumulated pixel between line pairs can be plotted as Figure 4-12 (b).

Figure 4-11 Points of intersection between the mean intensity of the whole 1D image and the 1D image intensity curve

Figure 4-12 (a) Pixel numbers between a line pair (b) Cumulated pixel error between line pairs

4.3.3 Choosing up-sampling factor based on environmental conditions

Concerning the linear measurement resolution of the laser interferometer is in the nanometer scale, the stability of the ground vibration and ambient temperature are very critical to the measured measurement accuracy. A stability test was carried out to see the readings of the laser interferometer at every 10 second for 500 seconds. Figure 4-13 shows that the laser interferometer fluctuates between 40 nm and -30 nm. The line scan camera used in the developed image grating system has a pixel size of $3.5\text{ }\mu\text{m}$, so the

subpixel registration resolution of 0.01 pixel is suitable for the position measurement. Hence, the up-sampling factor k defined in Section 4.2.3 is selected to be 100 for the all experiments.

Figure 4-13 Stability test of the laser interferometer (5530 dynamic calibrator)

4.3.4 1D SSDFT Algorithm Validation

In order to validate the image registration accuracy and computational cost of the proposed 1D SSDFT method, a comparison study has been carried out between the proposed 1D SSDFT method and the 2D SSDFT method.

To test 2D SSDFT method, 8 line images has been captured sequentially to form an 8×9000 pixel 2D image. The 1D SSDFT method takes average of each column in the 8×9000 pixel 2D image to obtain a 1×9000 pixel 1D image. Each image registration has been repeated 100 times in MATLAB software platform to reduce the random computational fluctuation of the CPU and RAM. The image translation and computational time of image registration using 1D and 2D SSDFT method are shown in Table 4-2. It can be observed that 1D SSDFT method obtained equal registration accuracy, but less computational time compared to the 2D SSDFT method.

Table 4-2 Registration speed and accuracy comparison between 1D and 2D SSDFT

SSDFT method	Image translation (pixel)	Computational time (s)
1D	2984.180	2.9693
2D	2984.180	4.9092

4.4 Results and Discussion

4.4.1 Measurement results

In the 25mm travel length of the motorized stage, measurement results of both the reference instrument (Agilent laser interferometer 5530) and the developed image grating system were recorded with 0.1 mm interval as shown in Figure 4-14 (a). Then the measurement deviation values were plotted into the measurement error curve, as shown in Figure 4-14 (b).

The trend of measurement error from experimental tests is consistent with the theoretical analysis presented in Section 4.3.2. From both theoretical analysis and experimental tests, it can be concluded that the measurement error is pixel-location-dependent. When the optical lens is fixed on the camera, a preloaded error curve can be used for error compensation.

(a)

(b)

Figure 4-14 (a) Pattern shift (mm) in the image grating system (b) Measurement error of the image grating system

4.4.2 Fifth-degree polynomial fitting

As discussed in Section 4.3.2, the measurement error curve shown in Figure 4-14 (b) can be fitted to a 5th-degree polynomial equation using least squares algorithm. Five repeated measurements were conducted with 1 mm interval in 25 mm travel range. So, five sets of 26 data points and a 5th-degree polynomial curve fitting the data points are plotted in Figure 4-15 (a). The residual errors after 5th-degree polynomial fitting are shown in Figure 4-15 (b) which are in the range of $\pm 0.15 \mu\text{m}$.

(a)

(b)

Figure 4-15 (a) 5th-degree polynomial fitting, (b) Residual errors after fitting

4.4.3 Position measurement and error compensation

The position measurement of the motorized stage was carried out with 0.1 mm incremental step in 25 mm travel range and the moving speed was set to 1 mm/s. The measurement was repeated five times, and the 5-degree polynomial fitting curve plotted in Figure 4-15 (a) was used to compensate the optical distortion and misalignment error of the image grating system. The five sets of measurement error curves are shown in Figure 4-16. It can be concluded that after correcting the optical distortion and misalignment, most of the measurement residual errors from the developed image grating system can be controlled within $\pm 0.2 \mu\text{m}$.

In order to test the versatility of the developed image grating system, the camera lens magnification was changed from 1:1 to 1:2 to measure a longer travel distance. The reconfigured image grating system was used to measure 50 mm displacement of the motorized stage with 0.2 mm incremental step. The five sets of measurement error curves are plotted in Figure 4-17. It can be observed that the measurement residual error is in the range of $\pm 0.35 \mu\text{m}$ after 5th-degree polynomial fitting.

Figure 4-16 Residual error after 5th-degree polynomial fitting

Figure 4-17 Residual error after 5th-degree polynomial fitting (50 mm)

4.4.4 Measurement repeatability study

To test the measurement repeatability of the image grating system, the whole system was reassembled, and five locations (5 mm, 10 mm, 15 mm, 20 mm and 25 mm) were taken for the comparison study. The laser interferometer 5530 was used as the reference instrument. For each location, the position measurement was repeated 10 times. The

measurement error curve plotted in Figure 4-18 shows a good repeatability after error compensation using the 5-degree polynomial equation, and the residual errors are within $\pm 0.15 \mu\text{m}$.

Figure 4-18 Positioning repeatability of image grating system

4.5 Conclusion

The position measurement results presented in Section 4.4 have demonstrated that the developed image grating system has measurement error of $\pm 0.2 \mu\text{m}$ within 25 mm measurement range compared with the measurement results of the laser interferometer. When the optical lens is working with 1:1 magnification, the standoff distance is around 100 mm. If optics with longer focal length is applied, maintaining the same magnification, the standoff can be enlarged. This is helpful in the applications when long clearance is needed. When the camera is moved further from the object, the field of view will be enlarged. When the optical lens is working with 1:2 magnification, the measurement error of $\pm 0.35 \mu\text{m}$ within 50 mm measurement range is still acceptable.

Conventional position measurement technologies, such as optical grating and laser interferometry, rely on continuous signal sampling. Signal discontinuity due to sensor contamination or optical path blocking will lead to measurement failure. The proposed image grating system is able to determine the absolute position of the targeted object whenever the patterned feature is detectable. This advantage helps to improve the system robustness for *in-situ* position measurement.

5. Surface Finish Measurement System Based on Laser Confocal Method

5.1 Surface Topography Measurement System based on Laser Confocal Sensor

5.1.1 Introduction to Confocal Microscopy

Figure 5-1 illustrates the typical optical structure of a single-point confocal system. Most reflected light will pass through the pinhole only when the target point is on the focal plane. In the range of confocal system's Depth of Field (DOF), the reflected light intensity detected by the photodiode forms a Depth Response Curve (DRC). The peak point of the DRC detected by the photodiode indicates the focus plane of the target point on the measured surface [186,187]. With a high-resolution encoder of the confocal system, the height of the target point on the surface can be measured. Thus through the recording of the heights, a surface profile can be obtained and roughness derived [38,188].

Apart from the pinhole scanning technique, some confocal microscopes use the slit scanning method. The slit scanning method has an advantage of increasing the signal intensity and speed, but its vertical resolution is significantly deteriorated by the lateral cross-talk [189]. Another critical consideration for surface measurement is the lateral resolution. Compared to white light, as a point light source, laser can achieve a smaller spot size. In addition, laser has more concentrated power than that of the white light. This allows higher light intensity levels at the focal point [190].

Figure 5-1 Structure of single-point confocal system. (a) Target point is on focus; (b) Target point is out of focus.

With respect to the above consideration of vertical and lateral resolution, in this study a single-point laser confocal sensor, Keyence LT-9010M (KEYENCE, Osaka, Japan), is employed for developing an *in-situ* roughness measurement system. The sensor utilizes a red semiconductor laser with a wavelength of 655 nm. The laser beam spot diameter is 2 μm and the vertical resolution of the laser confocal sensor is 0.1 μm . In addition to the basic optical system, the laser confocal sensor has two embedded scanning mechanisms, which determine a vertical measurement range of 0.6 mm and a lateral scanning length of 1.1 mm.

Figure 5-2 shows the working principle of the laser confocal sensor. The tuning fork is implemented in the LT-9010M as an oscillation unit. The tuning forks have several advantages such as high amplitude and phase sensitivities, high mechanical quality factor and corresponding high gain, which make the system able to achieve accurate sensor tip positioning in scanning probe microscope and confocal microscope[191,192]. While vibrating the objective lens up and down using tuning fork, the focusing point moves accordingly. The detector will receive the highest light intensity when the target surface is located at the focal distance. Then, the internal sensor attached to the tuning

fork determines the target height by measuring the position of the turning fork. The embedded lateral scanner helps to achieve a measuring length of 1.1 mm by using a high accuracy oscillating mechanism. A 2D surface profile, in the form of (X, Z) data points, is sent to the control station via serial communication and then processed in real-time by an algorithm to compute the surface roughness. The sampling frequency of the laser confocal sensor is able to achieve 1.5 kHz, which is suitable for surface profile measurement.

Figure 5-2 Working principle of the laser confocal sensor. (a) Vertical scanning mechanism; (b) Lateral scanning mechanism.

5.1.2 Surface Roughness Calculation

In general, any surface profile comprises of roughness, waviness and form features. Roughness is an irregularity as a result of any production processes such as tearing, cutting and surface fatigue. Waviness is a periodic texture, usually caused by vibration, chatter or machine deflections. Form often results from inaccuracies of the machine elements such as elastic deformations, linear guide errors and long-term thermal effects.

A surface roughness calculation software program was developed for the proposed laser confocal system to achieve *in-situ* surface measurement. The computational flow chart of the software program is presented in Figure 5-3.

Figure 5-3 Computational flow chart of surface roughness

Firstly, in order to obtain the roughness profile, the surface form needs to be separated from the surface profile. To eliminate the surface form from the measurement result, best-fit least-squares methods are recommended in ISO 4287 [22]. A second order polynomial fitting method using least squares algorithm was introduced for illustration purpose. The surface roughness standards set (FLEXBAR SKU-16008, Flexbar, Islandia, NY, USA) used in experiments are machined by grinding, turning and milling processes. The form errors introduced by these machining processes are relatively simple, such as lines and curvatures, which make a second order polynomial fitting suitable for form error removal. The second order polynomial regression algorithm is described by Equation 5-1:

$$f(i) = a_0 + a_1x(i) + a_2x^2(i) \quad 5-1$$

Where $f(i)$ represents the output element after polynomial regression, $x(i)$ represents the i^{th} data point in longitudinal direction of the assessed profile. The polynomial regression function finds the polynomial coefficients a_i by minimizing the residue (RSS) according to Equation 5-2.

$$RSS = \frac{1}{n} \sum_{i=0}^{n-1} w(i) \times [f(i) - Z(i)]^2 \quad 5-2$$

where n is the number of data points acquired in measurement; $w(i)$ is the i^{th} element of weight; $Z(i)$ is the i^{th} data point in height direction of the assessed profile. After removal of the surface form error, the leveled surface profile $Z_L(x)$ is obtained by Equation 5-3.

$$Z_L(i) = Z(i) - f(i) \quad 5-3$$

To separate short wave components such as micro-fracture marks and a waviness profile from the roughness profile, a Gaussian profile filter has been introduced following ISO 16610-21 [193]. The Gaussian profile filter is a phase correct filter that does not result in phase shift and asymmetrical profile distortion [194]. The weighting function for the Gaussian profile filter is given by Equation 5-4.

$$s(x) = \frac{1}{\alpha \times \lambda} \times \exp \left[-\pi \left(\frac{x}{\alpha \times \lambda} \right)^2 \right] \quad 5-4$$

where x is the distance from the center of the weighting function; α equals to $\sqrt{\ln 2 / \pi}$ to provide 50% transmission characteristic of the Gaussian profile filter at the cut-off wavelength λ . The long cut-off wavelength λ_c is determined based on ISO 4288 [19] to

separate the waviness profile. The short cut-off wavelength λ_s defines the intersection between roughness and even shorter wave components. The cut-off wavelength ratio λ_c/λ_s should be determined based on ISO 3274 [32]. The primary surface profile $Z_p(x)$ can be obtained by applying short wavelength filter of λ_s on leveled surface profile $Z_L(x)$.

The waviness profile $Z_W(x)$ is the discrete convolution of the primary profile $Z_p(x)$ and weighting function $s(x)$ given by Equation 5-5:

$$Z_W(x) = \sum_{i=x-L_c\lambda_c}^{x+L_c\lambda_c} Z_p(i)s(x-i) \quad 5-5$$

where, L_c is the truncation constant of the weighting function. For general use following ISO 16610-21 [193], L_c equals to 0.5 and results in a 0.76% implementation error.

The roughness profile $Z_R(x)$ is the deduction between the leveled surface profile $Z_L(x)$ and the waviness profile $Z_W(x)$ given by Equation 5-6:

$$Z_R(x) = Z_L(x) - Z_W(x) \quad 5-6$$

In this study, the surface roughness parameter used to validate the developed surface measurement system is the arithmetical mean roughness (Ra), the most widely used surface texture parameter. The definition of Ra parameter following ISO 4287 [22] is expressed by Equation 5-7:

$$Ra = \frac{1}{n} \sum_{i=1}^n |Z_R(i)| \quad 5-7$$

where $Z_R(i)$ is the i^{th} data point in height direction of the roughness profile $Z_R(x)$.

The surface roughness calculation algorithm presented in Equations 5-1 to 5-7 is implemented in the developed data processing software for *in-situ* surface roughness measurement.

5.1.3 Internal Scanning Performance of the Laser Confocal Sensor

In this study, a precision roughness reference specimen (Mitutoyo 178-602, Mitutoyo Corporation, Kawasaki-shi, Japan) with calibrated Ra value of $2.97\text{ }\mu\text{m}$ is used to verify the measurement capability of the laser confocal sensor (LCS). The surface pattern of this reference specimen has a harmonic form and the surface profile measured from the LCS is illustrated in Figure 5-4. This reference specimen was measured five times on the same spot using the LCS and the Ra values listed in

Table 5-1 give a mean value of $3.07 \pm 0.05\text{ }\mu\text{m}$ (mean $\pm$ 1 std. dev). The measurement results show a good correlation with the stated Ra value and demonstrate the feasibility of surface roughness measurement using the LCS.

Figure 5-4 (a) Precision roughness reference specimen; (b) Measured surface profile.

Table 5-1 *Ra* values of the precision roughness reference specimen.

	1	2	3	4	5	Mean	Std. Dev.
<i>Ra</i> (μm)	3.11	3.03	3.01	3.14	3.08	3.07	0.05

5.1.4 Extended Measurement Range and Profile Data Stitching Algorithm

A The measurement length achieved by the embedded scanner was 1.1 mm, which can only cover one cut-off length of 0.8 mm when the surface *Ra* value is in the range of 0.1–2 μm (following ISO 4288 [19]). However, measurement of five cut-off lengths is the default recommendation according to ISO 4288. In order to expand the lateral measurement range and improve the vertical positioning accuracy of the laser confocal sensor (LCS), a compact XZ-configured 2-axis motorized linear stage (New Focus 9066-XY-PP-M, Newport Corporation, Irvine, CA, USA) is integrated to improve the lateral scanning range. The XZ-configured linear stage has a travel range of 12.7 mm and a minimum incremental motion of 30 nm in both X and Z axis. By accessing the Dynamic Link Library (DLL) in the driver of the XZ-configured linear stage, the in-house developed software is able to set the speed, acceleration and PID control parameters of the linear stage.

The Z-axis linear stage carries the LCS and moves to its working distance of 6 mm from the sample surface. The LCS performs a local scan of 1.1 mm length to measure the surface profile and outputs the surface profile data to the developed data processing software. Then, the X-axis linear stage moves a distance equal to 80 percent of the local scan length in order to overlap 20 percent of the two adjacent surface profiles.

Due to the misalignment between the LCS scanning axis and linear stage movement axis, jump errors were observed at the overlapping surface profile. To reduce this misalignment error, a data stitching algorithm was introduced, which was based on the iterative least-squares method. Figure 5-5 shows the model of n-times of surface profile data stitching, where $f(x)$ and D represent the entire profile to be measured and its length, $f_i(x)$ and L represent part of the whole profile to be measured and its length in each measurement, $0.2L$ represents a 20 percent overlapping length between two adjacent surface profiles. Several publications [195–197] report that a 20 percent overlapping surface will give a good trade-off between having good stitching accuracy and obtaining large measurement range with minimum data sets.

Assuming that the local surface roughness information is consistent in the overlapping area of the two adjacent surface profiles, the mismatch is only caused by slope and offset differences during measurement. The error propagation of the stitching algorithm has been analyzed in [198–200] and was shown that the stitching error was in the tens of nanometer level for a range longer than 50 mm stitched length.

Figure 5-5 Model of n -times of profile data stitching.

In Equation 5-8, $\Delta f_i(x)$ denotes the difference between $f_{i-1}(x)$ and $f_i(x)$ within the overlapping section. In Equation 5-9, a_i and b_i represent the slope and offset coefficients in the least-squares linear regression equation, respectively:

$$\Delta f_i(x) = f_{i-1}(x) - f_i(x) ; x \in [0.8iL, 0.8iL + 0.2L] \quad 5-8$$

$$\Delta f_i(x) = a_i x + b_i ; x \in [0.8iL, 0.8iL + 0.2L] \quad 5-9$$

In this n th iterative stitching algorithm, $f'_i(x)$ corresponds to the shifted profile in the i th iteration derived in in Equation 5-10.

$$f'_0(x) = f_0(x) ; x \in [0, 0.8L]$$

$$f'_1(x) = f_1(x) + a_1 x + b_1 ; x \in [0.8L, 1.8L]$$

$$f'_2(x) = f_2(x) + a_2 x + b_2 + a_1 x + b_1 ; x \in [1.6L, 2.6L] \quad 5-10$$

•
•
•

$$f'_n(x) = f_n(x) + \sum_{i=1}^n (a_i x + b_i) ; x \in [0.8nL, 0.8nL + L]$$

By adding both sides of Equations 5-10, the whole stitched profile $f(x)$ can be written as Equation 5-11.

$$f(x) = f_0(x) + \sum_{i=1}^n f'_i(x) \quad 5-11$$

With the integration of the XZ-configured linear stage and data stitching algorithm, the proposed system could achieve a surface profile measurement up to 12.7 mm in length. The laboratory set-up of the proposed system and the precision roughness reference specimen are shown in Figure 5-6a. To verify the extended data stitching algorithm, the

precision roughness reference specimen was measured using the proposed laser confocal system and the Talysurf PGI 800 stylus profilometer (AMETEK Inc, Berwyn, PA, USA) separately. The measured surface profiles are plotted in Figure 5-6b. As can be seen from this figure, a good match between the laser confocal profile and the stylus profile was observed.

To compare the discrepancies between the two profiles in Figure 5-6b, the enlarged partial surface profiles are plotted in Figure 5-6c. It can be observed that the laser confocal profile has higher peak-to-valley amplitudes compared to that from the stylus profile. It also indicates noise-like spikes at the profile peaks and valleys. In addition, the laser confocal profile is not as symmetric as that from the stylus profile, which is mainly attributed to the light scattering effect at the steep slope section in the surface profile. These observations are consistent with the results from previous studies [15,53,201], which showed that the area of high curvature at surface peaks and valleys may produce severe measurement distortions and noises.

The Mean Squared Error (MSE) of five overlapped sections in the stitched profile are presented in Figure 5-7. The stitching error in the form of MSE is $0.024 \pm 0.010 \mu\text{m}$ (mean $\pm$ std. dev). The stitching error is considered acceptable referring to the sample's R_a value of $3 \mu\text{m}$.

Figure 5-6 (a) Laboratory set-up; (b) Extended surface profiles of the precision roughness reference specimen; (c) Enlarged partial profiles of the precision roughness reference specimen.

Figure 5-7 Stitching errors of the laser confocal profile.

5.1.5 Step Height Measurement

Step heights of six depth measurement standards (type A1) were measured following the guidelines in ISO 5436-1 [202]. Five measurements have been distributed evenly over each depth measurement standard as attached in Appendix A. Figure 5-8 shows the calculated step heights of six depth measurement standards measured by Talysurf PGI 800 stylus profilometer and the proposed laser confocal system. It can be observed that although all measurement results are in good correlation, the confocal measurement results have slightly higher values compared to the stylus measurement results. This may be due to the measurement distortions [15] and noises at the high curvature surface area which is explained in Section 5.1.4.

Figure 5-8 Measurement results of the depth measurement standards.

5.1.6 In-Situ Measurement Procedure

The proposed system is also integrated with a 3-stage motion control to minimize vibration caused by the positioning system or scanning mechanism. For *in-situ* measurement, the motion system, which could be a robot or other motion stages, may cause notable vibration. Lateral scanning is also another source of vibration, which is an important consideration for conventional off-line measurement systems. In this

research work, in order to minimize the vibration, the proposed system only actuates the embedded scanning mechanism simultaneously with data collection. The robot arm is used only for approaching and alignment operations, roughly adjusting the measurement distance and angle.

In this process the measurement system is positioned based on the CAD model of the component. The Z-axis linear stage is used to precisely move the laser confocal sensor (LCS) to its working distance of 6 mm from the work piece surface. The X-axis linear stage is used to shift the LCS for every 0.88 mm interval. When placement of the LCS is completed, the motion function of the robot arm and XZ-configured linear stage will be disabled.

In every positioning interval, surface scanning of 1.1 mm is done by the embedded lateral scanner in the LCS. During the surface data collection, the embedded lateral scanner, where the vibration is negligible, is the only moving unit. Upon the completion of the measurement procedure, the profile data in every interval will be stitched together using the developed algorithm described in Section 5.1.4. The motion control algorithm for *in-situ* surface roughness measurement can be summarized as shown in the flowchart in Figure 5-9.

Figure 5-9 Three-stage movement strategy for surface measurement.

5.1.7 Measurement Results and Data Analysis for Machined Surfaces

It has been discussed in Section 5.1.2 that following ISO 4288 [28], surface roughness can be calculated based on the surface profile collected by the developed laser confocal measurement system. In order to determine the accuracy of the proposed confocal system, the Talysurf PGI 800 stylus profilometer is used as a reference. A series of roughness standard data from several samples representing different machining processes with nominal Ra value in a range of 0.2–6.3 μm were used for calibration purpose. The error curve of the proposed system and error compensation are presented in this section.

5.1.7.1 Experimental Setup and Roughness Measurement

The experimental setup in a robot cell is illustrated in Figure 5-10. The developed laser confocal measurement system is integrated with an industrial robot (ABB IRB 2400, ABB Group, Zurich, Switzerland) for roughly positioning and alignment. This industrial robot provides a payload of 12 kg and position repeatability of 0.05 mm.

Figure 5-10 Experimental system setup.

The Talysurf PGI 800 stylus profilometer shown in Figure 5-11 is used as a reference instrument. The stylus profilometer is a high accuracy instrument and widely used as a standard instrument for surface roughness measurement. It employs a phase grating interferometer to trace the diamond tip stylus that is in contact to the target surface to achieve nanometer resolution. The roughness standard samples have been repeatedly measured five times using both Talysurf PGI 800 and the proposed laser confocal measurement system. By comparing the averaged roughness measurement results, the accuracy and measurement range of the proposed laser confocal system is assessed.

Figure 5-11 Schematic of Talysurf PGI 800 during measurement of roughness standard samples

5.1.7.2 Data Analysis

Table 5-2 shows the roughness standard samples measurement results of the stylus profilometer Taylor Hobson PGI 800 and the proposed laser confocal measurement system. As a major contributor to the overall measurement uncertainty of the stylus profilometer, the repeatability, expressed as two standard deviations from five repeats, is also stated for each measurement. Other factors, such cut-off wavelength and stylus tip radius may have nanometer-level contribution to the overall uncertainty [203–205].

Table 5-2 *Ra* of different surfaces measured using laser confocal system and stylus profilometer.

Machining	Stylus Profilometer Measured	Laser Confocal System Measured	Error
	<i>Ra</i> (μm) (Reference)	<i>Ra</i> (μm) (To Be Evaluated)	(μm)
Grinding	0.20 ± 0.01	0.22	0.02
	0.36 ± 0.01	0.38	0.02
	0.83 ± 0.01	0.88	0.05
	1.55 ± 0.02	1.63	0.08
	3.20 ± 0.04	3.33	0.13
Milling	0.40 ± 0.00	0.41	0.01
	0.58 ± 0.01	0.59	0.01
	1.40 ± 0.00	1.46	0.06
	3.00 ± 0.02	3.16	0.16
	4.06 ± 0.03	4.19	0.13
	6.91 ± 0.02	7.17	0.26
Turning	0.26 ± 0.01	0.27	0.01
	0.54 ± 0.01	0.55	0.01
	1.52 ± 0.02	1.57	0.05
	2.70 ± 0.02	2.85	0.15
	3.25 ± 0.04	3.39	0.14
	6.35 ± 0.02	6.63	0.28

The measurement errors of the laser confocal system in Table 5-2 are plotted as the error curve in Figure 5-12. For very smooth surfaces with *Ra* values less than 0.4 μm, the laser confocal system shows unpredictable errors, due to two typical inherent disadvantages of confocal technology namely the spot size limit and the background

noise. The laser spot size limits the lateral resolution of the proposed measurement system which cannot resolve surface feature less than 1 μm . The background noise of the laser confocal sensor is mainly caused by laser power saturation, stray light and scattering effect at sharp edges [206]. In Figure 5-12, unique markers represent the different data of grinding, milling and turning for reference. Unfortunately, in practical measurement, machining patterns and Key Performance Indicators (KPIs) are sometimes unknown. In this study, therefore, a combined linear function was provided for error correction.

Figure 5-12 Error curve of different machining surface

Accommodating a fixed intercept value will cause a notable relative error when the Ra value is very small. In this case, a zero-pass linear function $y = 0.041x$ is forced to fit the measurement errors, as shown in Figure 5-12. The coefficient of determination R^2 value, as usual, indicates how well the data points agree with the fitted line. The high R^2 value of 0.9459 suggests that the data set can be regressed linearly.

As observed in Figure 5-12, the measurement error increases linearly with increasing roughness Ra . This might be caused by two factors. Firstly, rough surfaces usually have

sharper edges, defects and other small surface imperfections than smooth surfaces. These surface features can scatter the laser light away from the sensor objective and can lead to larger errors and more non-measured data points. Secondly, the stylus tip acts as a mechanical filter to reduce the peak-to-valley distance in surface profile (see Figure 5-13). This mechanical filter has more significant effect on the surface with higher roughness due to more small and narrow surface features.

Figure 5-13 Actual and measured profiles using stylus method [46]

After linear correction, the residual relative errors can be calculated as the results shown in Figure 5-14. It can be seen that most of measurement relative errors can be controlled within 5%, regardless of the machining process. It is also shown that for small Ra values, the relative error is comparatively large, which means random errors contributed by spot size and noises are more influential for smooth surfaces. In this study, therefore, $0.2\ \mu\text{m}$ has been observed to be the lower limit of the measurable Ra values due to the inherent limitations of laser confocal sensor.

Figure 5-14 Residual relative errors after linear error compensation

5.1.8 Feasibility Study on Area Topography Measurement for Additive Manufacturing Surfaces

Industry adoption of metal additive manufacturing (AM) has increased dramatically in the past few years due mainly to the advantages it offers over conventional processes such as the freedom to design more complex shaped components as well as a reduction in the number of manufacturing stages. One challenge which arises from these new processes is the measurement and characterisation of the surfaces. This can be attributed to a number of factors including loose particle adhesion, incomplete melting of the powder as well as the actual process parameters. With so many various factors, it is important to be able to link the AM surface to the final application and ultimately back to the process parameters.

In this section, the AM test coupons were fabricated by Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM) without post-processing. These two AM technologies are essentially similar in their principle, the energy source (electron beam

or laser beam) melt and fuse a layer of loose powder onto the previous layer. The AM coupons are measured using three instruments: coherence scanning interferometry (Talysurf CCI HD, AMETEK Inc, Berwyn, PA, USA), confocal microscopy (Smartproof 5, ZEISS, Oberkochen, Germany) and the developed laser confocal system.

Based on the literature review in section 2.1.2, the areal surface texture parameters have more statistical significance than 2D profile parameters especially for AM surfaces with low surface integrity. Several areal surface texture parameters including height, spatial and feature information are chosen to evaluate the AM surfaces and explained as below:

- S_a and S_q are strongly correlated, but S_q has more statistical significance and can be used instead of S_a .
- S_z is highly sensitive to outliers and noise and S_{10z} can be used instead as a robust parameter.
- S_{sk} can identify the surface is peak-dominated or valley-dominated.
- S_{ku} measures the spikiness of surface.
- S_{tr} measures the surface isotropy and is very useful linking to manufacturing process.
- S_{td} indicates the dominated surface texture direction, but very sensitive to the sample positioning direction.

An AM test piece manufactured by Electron Beam Melting (EBM) shown in Figure 5-15 was repeatedly measured five times using coherence scanning interferometry, confocal microscope and the proposed laser confocal system. The surface topography measurement results with standard deviations are listed in Figure 5-16. Table 5-3 shows the measurement results of different areal surface texture parameters. The experimental results show that the coherence scanning interferometry, confocal microscopy and the

developed laser confocal system have comparable performance for EBM surface texture measurement. The developed laser confocal system is more capable of *in-situ* surface measurement and can be used for the development of AM surface measurement techniques.

Figure 5-15 Electron Beam Melting (EBM) test piece

Figure 5-16 EBM test piece measured by (a) coherence scanning interferometer; (b) confocal microscope; (c) proposed laser confocal system

Table 5-3 Measurement results of different surface texture parameters

	Coherence scanning interferometer	Confocal microscope	Proposed laser confocal system
<i>Sa</i> (μm)	2.50 ± 0.10	2.42 ± 0.13	2.41 ± 0.12
<i>Sq</i> (μm)	3.26 ± 0.16	3.09 ± 0.19	3.04 ± 0.17
<i>S10z</i> (μm)	24.95 ± 0.16	23.02 ± 0.27	22.09 ± 0.17
<i>Ssk</i>	-0.18 ± 0.01	-0.14 ± 0.01	-0.17 ± 0.02
<i>Sku</i>	3.40 ± 0.04	3.58 ± 0.04	3.37 ± 0.08
<i>Str</i>	0.19 ± 0.01	0.21 ± 0.00	0.18 ± 0.02
<i>Std</i> (°)	69.97 ± 0.14	71.04 ± 0.10	70.58 ± 0.13

Two coupons fabricated by Direct Metal Laser Sintering (DMLS) with different building layer thickness of the DMLS process were measured using the developed laser confocal system. Coupon A (20 μm layer thickness) and Coupon B (20 μm layer thickness) and their surface topography measurement results are shown in Figure 5-17. Table 5-4 presents the measurement results of different areal surface texture parameters and their repeatability, expressed as two standard deviations from five repeats. The measurement results show that both coupons have extreme high values for *Ssk* and *Sku*, meaning they have peak-dominated surfaces with high spikiness. Coupon A has larger values for *Sa*, *Sq*, *S10z* and *Str* compared to Coupon B, which means that Coupon A has a rougher surface but better surface uniformity. It can be concluded that *Sq*, *S10z* and *Str* can be used to correlate with the process parameters providing information regarding the layer thickness of the DMLS process.

Figure 5-17 DMLS coupons (a) Coupon A (20 μm layer thickness); (b) Coupon B (40 μm layer thickness); Surface topography measurement results (c) Coupon A; (d) Coupon B

Table 5-4 Measurement results of different surface texture parameters

Build layer thickness	A (20 μm)	B (40 μm)
Sa (μm)	17.15 ± 0.09	4.93 ± 0.08
Sq (μm)	17.15 ± 0.21	6.76 ± 0.18
$S10z$ (μm)	99.25 ± 1.64	47.35 ± 0.84
Ssk	1.90 ± 0.06	1.29 ± 0.06
Sku	7.48 ± 0.14	7.63 ± 0.09
Str	0.95 ± 0.02	0.45 ± 0.02
Std ($^\circ$)	2.84 ± 0.12	2.84 ± 0.10

5.2 Adaptive Surface Measuring System based on Laser Confocal

Method

Compared to conventional surfaces, free-form surfaces have no axes of rotation and may have almost any designed shapes. The geometry of free-form surfaces cannot be determined by a simple mathematic equation, as in the case of spherical and cylindrical surfaces, but by a set of nondeterministic equations, e.g. toroidal, biconic, non-uniform rational b-spline, etc [114]. Free-form surfaces are common in some industries, for instance in aerospace industries which manufacture turbine blades. Several advanced manufacturing technologies are available to machine parts with free-form surfaces, where among those are ultra-precision cutting, single-point diamond turning and CNC multi-axis polishing. However, a major problem that becomes a concern in any relevant industrial application of free-form surface products, e.g. in advanced optics, aerospace and biomedical industries, lies more on how to measure and characterize free-form surfaces with high accuracy.

To respond to the problem, an adaptive surface measuring system is developed based on the laser confocal approach described in Section 5.1 for automatic surface tracing of any free-form surfaces. The system is capable of overcoming the measurement range limitation of the laser confocal sensor, which is typically performed for a short-distance surface measurement. Owing to a hybrid surface scanning concept, a global scanning system is introduced to the system to trace the surface, ensuring the laser confocal sensor to stay within its measurement range and at its reference distance (the stand-off distance).

5.2.1 System Setup and Surface Tracing Techniques

The proposed adaptive surface measurement system comprises a laser confocal sensor (LCS) and an XYZ-configured positioning system. The LCS serves as a local scanning unit, to perform short distance surface scanning measurements, while the XYZ positioning system is functioned as a global scanning unit to trace the surface form and to keep the local scanning unit stays within the measurement range from the workpiece surface. The adaptive surface measurement system, both in simulation and lab platform setup, is shown in Figure 5-18.

Figure 5-18 System setup in simulation and lab platform

The XYZ positioning system holds the LCS and positions it to the reference measurement distance at 6 mm from the measurement area of interest on the workpiece. Based on the specifications, the measurement range of the confocal sensor is about 0.6 mm from the reference distance. However, in real practice, the variation of the free-form surface height of the measured part might exceed the measurement range. Therefore, the Z axis positioning stage needs to be continuously adjusted to allow the relative LCS position to be within the measurement range during the whole

measurement process. In order to satisfy the need, a surface tracing technique was developed based on a continuous tracing path algorithm [120].

An illustrated configuration of the laser confocal sensor reading and the Z-axis motorized stage is shown in Figure 5-19, where the measuring quantity is described in Equation 5-12.

$$Z_{abs} = Z_{st} - (Z_{ref} - Z_{lc}) \quad 5-12$$

In the equation, Z_{abs} is the absolute position of the measured surface height to the datum of the Z-axis motorized stage, Z_{st} represents the position of the laser confocal sensor on the Z-axis motorized stage, Z_{ref} denotes the reference measuring distance of the laser confocal sensor and Z_{lc} indicates the output height result from the laser confocal sensor.

During the surface measurement process, each internal scanned segment was continuously fitted by a second degree polynomial function to define the subsequent vector M_i to position the sensor to the following to-be-scanned surface profile. The motion path for surface tracing is shown in Figure 5-20, while the motion vector M_i is expressed by Equation 5-13.

$$M_i = \overline{Z_{abs}}(i + 1) - \overline{Z_{abs}}(i) \quad 5-13$$

where $\overline{Z_{abs}}(i)$ denotes the mean value of the measured absolute positions at the i th internal scanning.

Figure 5-19 Relation between the laser confocal sensor reading and the its position on the Z-axis motorized stage

Figure 5-20 Motion path for surface tracing

5.2.2 Internal Piecewise Scan

The measurement process flow chart of the proposed system is shown in Figure 5-21. Firstly, the XYZ positioning system is controlled to move the laser confocal sensor to the starting position. The laser confocal sensor will perform a local scan of 0.1 mm to 1.1 mm length to measure the surface profile and output the surface profile data to the developed data processing program.

Subsequently, the X axis stage will travel up to 80% of the local scan length capacity to provide 20% overlap on the two adjacent surface profiles. In parallel, height information will be extracted from the surface profile data and is fed to the system for the vertical reference to adjust the distance to the sensor in Z axis in the subsequent positioning step. After the X axis stage completes the predefined scan length, Y axis stage moves to the predefined step.

Later, after the height of laser confocal sensor is adjusted to the reference measurement distance, the surface profile measurement will be repeated for the next predefined length. Each local scan in the X axis direction, as well as in the Y axis position will be stitched using the developed algorithm discussed in Section 5.1.4 to reconstruct the surface profile that can be used for surface roughness evaluation.

Figure 5-21 Flow chart showing measurement process of the proposed system

Since all free-form surfaces should follow the C^2 continuity (second order continuity) [120], a second degree polynomial regression algorithm described in Equations 5-14 and 5-15 is chosen to best fit the current measured surface profile and predict the next surface profile to be scanned.

$$z_i(x_j) = a_i x_j^2 + b_i x_j + c_i \quad 5-14$$

$$z_{i+1}(x_j) = a_i (x_j + 0.8L)^2 + b_i (x_j + 0.8L) + c_i \quad 5-15$$

where $z_i(x_j)$ represents the surface profile height after polynomial regression, x_j is the j^{th} data point in the scanned profile and $z_{i+1}(x_j)$ represents the predicted subsequent surface profile to-be-scanned.

The Z axis movement in each step is given in Equation 5-16.

$$\Delta h_i = \frac{1}{n} \sum_{j=1}^n [z_i(x_j) + z_{i+1}(x_j)] \quad 5-16$$

where Δh_i represents the displacement in i^{th} measurement, while n is the number of data points acquired in each internal scan.

After measurement, a data stitching algorithm presented in Section 5.1.4 is introduced to reduce the misalignment error between adjacent scanned sections.

Figure 5-22 shows a comparison between surface profile measurement with and without stitching algorithm. Significant height differences can be observed between two adjacent piecewise scans on the reconstructed surface profile without stitching technique, while the stitching algorithm is able to eliminate the erratic errors.

(a)

(b)

Figure 5-22 Stitching errors comparison (a) Surface profile measurement (after form removal) without using stitching algorithm; (b) Surface profile measurement (after form removal) with stitching algorithm

5.2.3 Free-form measurement results

In order to evaluate the quality and accuracy of the resulting surface profile data, another measurement using Talysurf PGI 800 stylus profilometer was used as a benchmark, where the setup is shown in Figure 5-23 (a). The positioning system based on image grating technique developed in Section 4 is integrated into the adaptive surface measurement system, as shown in Figure 5-23 (b).

The performance evaluation of the proposed system was carried out on a free-form surface coupon as shown in Figure 5-24. Since Talysurf PGI 800 stylus profilometer has a limited vertical movement of 8 mm, only a certain segment of the workpiece surface was measured as indicated by red area in Figure 5-24. The area indicated by red colour on the coupon is 30mm×10mm and has been repeatedly measured five times using both Talysurf PGI 800 and the adaptive surface measurement system. The measured surface topographies from both systems are shown in Figure 5-25 and Figure 5-26, respectively.

Two typical surface texture parameters Sa and Sq were chosen to quantify the surface topography measurement. The Sa and Sq values calculated according to ISO 25178-2 [30] and the repeatability, expressed in standard deviation, are presented in Table 5-5.

Figure 5-23 Measurement setup (a) Talysurf PGI 800 stylus profilometer; (b) Adaptive surface measurement system

Figure 5-24 Free-form surface coupon

Figure 5-25 Free-form surface measured by Talysurf PGI 800.

(a) Original surface topography; (b) Surface topography after form removal

Figure 5-26 Free-form surface measured by the adaptive surface measurement system.

(a) Original surface topography; (b) Surface topography after form removal

Table 5-5 Sa and Sq of free-form surface measured using stylus profilometer and the adaptive surface measurement system.

	PGI 800 Stylus Profilometer	Adaptive Surface Measurement System	Error (μm)
Sa (μm)	1.09 ± 0.00	1.12 ± 0.01	0.03 ± 0.01
Sq (μm)	1.42 ± 0.00	1.44 ± 0.01	0.02 ± 0.01

In order to better visualize the measurement results from the both systems, one surface profile data has been extracted from the respective area surface topography, as shown in Figure 5-27.

Aligned with the Sa and Sq parameters chosen for the surface texture assessment, the roughness parameters Ra and Rq were chosen to evaluate the measurement accuracy of the surface texture. One hundred and one surface profiles were extracted from the measured surface topography after nominal form removal. The calculated Ra and Rq values according to ISO 4287 [22] and the repeatability, expressed in standard deviation, are presented in Table 5-6. The errors of Ra and Rq are about $0.03\ \mu\text{m}$, which are consistent to the measurement error in surface topography measurements.

(a)

(b)

(c)

(d)

Figure 5-27 Measurement results (a) Original surface profile measured by the developed system; (b) Original Surface profile measured by Talysurf PGI 800; (c) Surface profile (nominal form removed) measured by developed system; (d) Surface profile after (nominal form removed) measured by Talysurf PGI 800.

Table 5-6 Comparison of surface roughness parameters

	PGI 800 Stylus Profilometer	Adaptive Surface Measurement System	Error (μm)
<i>Ra</i> (μm)	0.99 ± 0.05	1.02 ± 0.08	0.03 ± 0.09
<i>Rq</i> (μm)	1.21 ± 0.06	1.24 ± 0.11	0.03 ± 0.012

A feasibility of measuring profile with large surface height deviation was also studied to validate the capability of the adaptive surface measurement system. A stylus arm of 120 mm length with sapphire ball (1 mm tip radius) was equipped for Talysurf PGI 800 stylus profilometer for surface form measurement. It was selected as the reference measuring instrument which can achieve a vertical measurement repeatability of $0.1\text{ }\mu\text{m}$ and vertical measurement range of 16 mm. The free-form surface profile measured by Talysurf PGI 800 stylus profilometer and adaptive laser confocal system are shown in Figure 5-28. Based on the figure, it can be observed that the adaptive laser confocal system has a measurement error of $\pm 10\text{ }\mu\text{m}$ within 100 mm measurement distance compared with the measurement results of the Talysurf PGI 800 stylus profilometer.

(a)

(b)

Figure 5-28 Free-form surface measurement results (a) Surface profile measured by the developed system; (b) Surface profile measured by Talysurf PGI 800 with sapphire ball contact; (c) Surface profile measurement error

5.3 Summary

Firstly, a laser confocal based measurement system for non-contact and *in-situ* surface topography measurement has been developed. The motivation of this development is to exploit a roughness measurement technology to be used in manufacturing environment, instead of using the traditional desktop measurement in laboratories. A laser confocal sensor has been integrated with a precise 2-axis linear stage and robot arm. Experimental data demonstrates the capability of the proposed system to measure surfaces with Ra from 0.2–7 μm . This covers a typical roughness of milling, turning and grinding products. In this range with linear error compensation, measurement relative errors can be controlled within 5%.

Secondly, a novel displacement sensor, as the so-called image grating encoder, is presented. It is featured by adjustable measurement range, flexible standoff and in-line measurement capability. An image grating system comprises a target feature that is attached to the moving stage and a line scan camera as the stationary displacement

reader. By observing the position of the target feature in the image and applying subpixel interpolation, the displacement of the moving stage can be determined. In order to improve the measurement efficiency, a computation for pattern correlation and subpixel interpolation are performed in frequency domain. The calibration and error correction method were also developed to compensate for the measurement error caused by optical distortion. Experimental data shows that the image grating technology is able to reach measurement accuracy of $\pm 0.2 \mu\text{m}$ in a measurement range of 50 mm. By applying different optics, the standoff distance and the measurement range can be customized for different applications.

Lastly, an adaptive surface measurement system was developed to measure free-form surfaces by integrating a laser confocal displacement sensor and the image grating system. The laser confocal displacement sensor serves as a local scanning unit to perform short distance surface scanning and the XYZ positioning stage is programmed as a global scanning unit to trace the surface form and to ensure that the local scanning unit is always within the measurement range from the reference measurement distance. The adaptive surface measurement system is able to overcome the inherent measurement range limitation of laser confocal sensors for free-form surfaces with large surface height deviation. Experimental data shows that the developed system is able to measure surfaces with surface height deviation more than 8 mm and the surface texture and profile measurement errors can be controlled within $0.03 \mu\text{m}$.

6. Conclusions

6.1 Thesis Conclusions

In this thesis, two automated *in-situ* surface measurement systems have been developed to characterize various manufactured surfaces that include mirror finished, conventional machined, additive manufactured and free-form surfaces.

Firstly, a patterned area illumination method and an *in-situ* measurement system have been developed to replace manual inspection of mirror finish surface. The experimental results show that the developed system is able to measure different mirror finish surfaces with Sa between 1 nm to 120 nm and Sq ranging from 2 nm to 165 nm, respectively. The surface texture aspect ratio parameter Str , which provides information about the strength of the machining marks, was experimentally evaluated and compared with grayscale contrast change. In addition, a robotized surface defect inspection system based on Rayleigh criterion in surface scattering was developed. The experimental results show that the developed system is able to detect surface defects with width less than 10 μm and depth above 0.2 μm .

Secondly, a novel image grating system has been developed to improve the robustness and flexibility for position measurement. When the optical lens is working with 1:1 magnification, the standoff distance is around 100 mm. The measurement results show that the developed system is able to achieve 0.2 μm measurement accuracy within 25 mm measurement range compared with the measurement results of the laser interferometer. If optics with longer focal length is applied, maintaining the same magnification, the standoff can be enlarged. When the camera is moved further from the object, the field of view will be enlarged. When the optical lens is working with 1:2

magnification, the measurement error of $\pm 0.35 \mu\text{m}$ within 50 mm measurement range is still acceptable.

Finally, a non-contact and *in-situ* surface topography measurement system has been developed using laser confocal technology. A profile data stitching algorithm based on least-squares linear regression method is also developed. Experimental data shows that the proposed system is able to measure surfaces with Ra from $0.2\text{--}7 \mu\text{m}$. After applying linear error compensation, relative measurement errors are less than 5%. Subsequently, an adaptive surface measurement system has been developed to overcome the measurement limitation of the laser confocal sensor. The experimental data shows that the developed system is able to measure free-form surfaces with surface height deviation more than 8 mm and the surface texture and profile measurement errors are less than $0.03 \mu\text{m}$.

6.2 Innovative Contributions

In most manufacturing industries, the post-process inspection is a standard mode, where typically the finished workpiece is detached from the manufacturing cell and transported to the metrology laboratory for measurement. This process, however, results in long production time and it is also cost ineffective when it comes to mass production. Hence, an automatic surface inspection is seen to be a potential alternative for post-process inspection to reduce labour costs and to improve quality control procedures.

A surface roughness measurement system based on fringe pattern illumination method has been developed to address the engineering problem statement of *in-situ* roughness measurement on mirror finish surface. By analysing the grayscale contrast ratio of the

fringe pattern reflected image and comparing it to the measurement results from the referenced coherence scanning interferometer, the experimental results show that the developed system is able to measure different mirror finish surfaces with Sa in the range of 1 nm to 120 nm and Sq values between 2 nm to 165 nm, respectively (as published in [A3], [A5] and [A7]).

A novel position measurement system based on image grating sensor has been developed to improve the robustness and flexibility for displacement measurement using conventional optical encoder. The measurement results showed an error of $\pm 0.35 \mu\text{m}$ within 50 mm measurement range after calibration using the laser interferometer (as published in [A2] and [A4]). Conventional displacement technologies, such as optical grating and laser interferometry, rely on a continuous signal sampling. Signal discontinuity due to sensor contamination or optical path blocking will lead to measurement failure. The proposed image grating system is able to determine the absolute position of the targeted object whenever the patterned feature is detectable. This advantage will help to improve the system robustness for *in-situ* displacement measurement.

In order to measure manufactured surfaces other than mirror finish surfaces, a non-contact and *in-situ* surface topography measurement system has been developed owing to laser confocal technology. A laser confocal sensor was integrated to a precise 2-axis linear stage and robot arm. Experimental data shows that the proposed system is able to measure surfaces with Ra from 0.2–7 μm , which covers a typical range of milling, turning and grinding products (as published in [A1]). In this range with linear error compensation, measurement relative errors can be controlled within 5%. The proposed system was also used to measure additive manufacturing surfaces fabricated by Direct

Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM). The measurement results showed that the proposed system has comparative performance to the stylus profilometer and optical profilers (as published in [A6] and [A8]).

To improve the vertical scanning range of the laser confocal sensor, an adaptive surface measuring system is developed to measure free-form surface by integrating the laser confocal sensor system and the image grating system (as published in [A9]). The adaptive surface measurement system is able to trace the surface form and keep the local scanning unit always within the measurement range from the reference measurement distance. Experimental data showed that the developed system is able to measure surfaces with surface height deviation more than 8 mm and the surface texture and profile measurement errors can be controlled within 0.03 μm .

6.3 Future Work

In this thesis, the proposed fringe pattern illumination system is able to measure the surface roughness on flat mirror finish surfaces. Moving forward, the challenge is to characterize non-flat mirror finish surfaces, which have an underlying form and waviness topography in free-form surfaces. In addition, the image grating system and the adaptive surface measurement system need to be improved to reduce measurement error and time.

The future work will involve the following.

- Use optics simulation software to validate the fringe pattern illumination method for measuring curved mirror finish surfaces.

- The defects detection system based on machine vision technology will be systematically evaluated with industrial components with different surface defects.
- Design a new patterned target with reference mark and improve the sub-pixel image registration algorithm to be integrated into the image grating system for position measurement larger than 100 mm.
- Develop a single-point continuous measurement algorithm for the adaptive surface measurement system to integrate single-point confocal sensor and eliminate the profile stitching process.
- Compensate the abbe error of the adaptive surface measuring system by introducing a XYZ configured positioning system with three image grating sensors.

Appendix A

Chapter 3.3 Roughness measurement result using Talysurf CCI

Sample No.	Sa (nm)							Sq (nm)						
	1	2	3	4	5	Average	Standard Deviation	1	2	3	4	5	Average	Standard Deviation
1	17.2	18.2	17.7	18.4	17.1	17.7	0.5	31.8	33.5	33.1	34.1	31.5	32.8	1.0
2	39.4	37.2	39.1	37.5	39.7	38.6	1.0	59.9	61.2	58.4	57.1	60.5	59.4	1.5
3	50.8	50.6	49.1	46.4	47.8	48.9	1.7	71.7	72.3	72.4	65.6	70.2	70.4	2.5
4	78.2	78.8	75.6	76.9	78.8	77.7	1.2	110.5	108.1	103.5	104.1	109.5	107.1	2.8
5	96.5	98.7	90.3	99.4	92.6	95.5	3.5	128.4	131.7	120.6	133.1	121.9	127.1	5.1
6	121.7	113.6	114.6	119.5	122.9	118.5	3.7	161.1	174.9	165.5	160.8	163.5	165.2	5.2
7	14.9	14.4	13.9	15.4	14.3	14.6	0.5	28.9	28.1	27.6	30.6	26.4	28.3	1.4
8	38.8	42.6	41.2	38.3	41.0	40.4	1.6	58.4	62.3	60.8	57.6	61.4	60.1	1.8
9	59.7	60.8	55.9	55.1	57.3	57.8	2.2	88.3	94.2	84.0	82.9	86.1	87.1	4.0
10	106.2	99.1	100.5	101.6	97.8	101.0	2.9	147.7	134.2	137.1	139.0	133.3	138.3	5.1
11	104.4	109.5	107.1	105.2	111.7	107.6	2.7	143.5	152.4	148.1	145.2	158.7	149.6	5.5
12	116.1	126.5	118.8	116.7	118.1	119.2	3.8	155.1	169.8	158.8	154.3	156.9	159.0	5.6
13	1.1	1.4	1.2	1.3	1.1	1.2	0.1	1.8	2.1	1.8	2.2	2.1	2.0	0.2
14	4.3	3.3	4.4	3.7	4.2	4.0	0.4	6.1	5.0	6.4	5.1	5.8	5.7	0.5
15	2.7	4.1	3.1	3.3	3.8	3.4	0.5	5.5	7.8	6.1	6.7	7.9	6.8	0.9
16	19.3	18.6	20.2	23.6	22.5	20.8	1.9	33.2	31.5	34.8	38.5	37.7	35.1	2.6

Chapter 3.3.1 Grayscale contrast measurement result using proposed system

Sample No.	Contrast (C)						
	1	2	3	4	5	Average	Standard Deviation
1	0.756	0.762	0.752	0.753	0.762	0.757	0.004
2	0.559	0.565	0.558	0.559	0.564	0.561	0.003
3	0.535	0.516	0.515	0.524	0.538	0.526	0.009
4	0.274	0.285	0.278	0.294	0.262	0.279	0.011
5	0.257	0.275	0.258	0.275	0.281	0.269	0.010
6	0.071	0.045	0.051	0.069	0.053	0.058	0.010
7	0.787	0.792	0.790	0.796	0.799	0.793	0.004
8	0.520	0.508	0.515	0.518	0.510	0.514	0.005
9	0.379	0.392	0.388	0.381	0.395	0.387	0.006
10	0.154	0.161	0.164	0.160	0.169	0.162	0.005
11	0.089	0.089	0.091	0.083	0.097	0.090	0.004
12	0.106	0.085	0.095	0.102	0.090	0.096	0.008
13	0.957	0.954	0.954	0.953	0.951	0.954	0.002
14	0.941	0.937	0.939	0.934	0.932	0.937	0.003
15	0.942	0.942	0.942	0.941	0.944	0.942	0.001
16	0.766	0.784	0.775	0.782	0.769	0.775	0.007

Chapter 3.3.2 Histogram standard deviation measurement result using proposed system

Sample No.	Grayscale Histogram Standard Deviation (STD)						
	1	2	3	4	5	Average	Standard Deviation
1	105.817	103.517	105.689	105.435	105.371	105.166	0.840
2	86.562	79.698	84.602	85.171	79.468	83.100	2.943
3	81.706	71.084	71.801	73.972	81.744	76.061	4.721
4	37.382	32.937	41.016	35.569	41.181	37.617	3.175
5	36.190	41.529	29.689	28.561	28.145	32.823	5.235
6	13.474	19.356	8.065	27.123	23.944	18.392	6.911
7	106.902	105.711	106.395	106.161	107.606	106.555	0.651
8	81.602	78.679	79.103	78.020	78.760	79.233	1.235
9	65.453	62.431	69.752	63.503	67.565	65.741	2.663
10	22.259	23.919	21.100	27.596	22.627	23.500	2.237
11	19.754	18.425	18.600	18.998	20.526	19.261	0.781
12	20.372	16.892	16.112	16.419	20.185	17.996	1.881
13	109.602	109.990	109.712	109.442	109.452	109.640	0.202
14	104.746	104.100	103.986	103.393	104.446	104.134	0.457
15	105.128	104.015	107.065	106.341	105.133	105.536	1.061
16	101.491	101.485	99.436	98.730	104.269	101.082	1.935

Chapter 5.1.4 Stitching errors of the laser confocal profile.

	1	2	3	4	5	Mean	Std. Dev.
MSE (μm)	0.034	0.023	0.022	0.027	0.016	0.024	0.010

Chapter 5.1.5 Measurement results of the depth measurement standards.

Instrument	Nominal Value (μm)					
	5	10	15	20	25	30
Stylus (μm)	5.09 ± 0.02	9.95 ± 0.01	15.10 ± 0.02	19.98 ± 0.01	24.62 ± 0.05	29.99 ± 0.01
Confocal (μm)	5.24 ± 0.04	10.12 ± 0.05	15.21 ± 0.04	20.15 ± 0.11	24.78 ± 0.07	30.22 ± 0.05

Author's Publications

Journal Articles

- [A1] Fu. S, Cheng. F, Tjahjowidodo. T, Zhou. Y, and Butler. D. A Non-Contact Measuring System for In-Situ Surface Characterization Based on Laser Confocal Microscopy. *Sensors* 2018, 18, 2657.
- [A2] Fu. S, Cheng. F, and Tjahjowidodo. T. Image Grating: A New Technology for In-line Displacement Measurement. *Optics Express* 2019 (Under review)
- [A3] Fu. S, Cheng. F, and Tjahjowidodo. T. Surface texture evaluation on mirror finish surface using patterned area illumination method. *Metals* 2019 (Manuscript in preparation for submission)

Conference Proceedings

- [A4] Fu. S, Cheng. F, Tjahjowidodo. T, Liu. M. Image Grating: A Novel Technology for Position Measurement, *Proc. SPIE, International Conference on Optical and Photonics Engineering, 2019*
- [A5] Fu. S, Cheng. F, and Tjahjowidodo. T. Surface texture evaluation on mirror finish surface using patterned area illumination method, *Lecture Notes in Mechanical Engineering, International Conference of Advanced Surface Enhancement, 2019*
- [A6] Fu. S, Cheng. F, and David B. Comparison study of the surface measurement and characterisation of metal additive manufactured parts, *Proceedings of the 16th International Conference on Metrology and Properties of Engineering Surfaces, 2017*

- [A7] Fu. S, Cheng. F, and David B. Surface roughness study on mirror finish surface products using patterned area illumination method, *Proceedings of the 17th International Conference of the European Society for Precision Engineering and Nanotechnology*, 2017
- [A8] Cheng. F, Fu. S, Leong Y. S. Research on optical measurement for additive manufacturing surfaces, *Proc. SPIE, International Conference on Optical and Photonics Engineering*, 2016

Patents

- [A9] Cheng F and Fu. S. Apparatus and Method for Assessing Surface Roughness, Singapore PCT Patent 050018, Jan 11, 2019

Reference

- [1] Nakasuji T, Kodera S, Hara S, Matsunaga H, Ikawa N and Shimada S 1990 Diamond Turning of Brittle Materials for Optical Components *CIRP Ann. - Manuf. Technol.* **39** 89–92
- [2] Hattori T, Okamoto A and Kuniyasu H 2005 Challenges of Finer Particle Detection on Bulk-Silicon and SOI Wafers *Solid State Phenom.* **103–104** 121–8
- [3] Ponsonnet L, Comte V, Othmane A, Lagneau C, Charbonnier M, Lissac M and Jaffrezic N 2002 Effect of surface topography and chemistry on adhesion, orientation and growth of fibroblasts on nickel–titanium substrates *Mater. Sci. Eng. C* **21** 157–65
- [4] Pérez C J L 2002 Analysis of the surface roughness and dimensional accuracy capability of fused deposition modelling processes *Int. J. Prod. Res.* **40** 2865–81
- [5] Miranda-Medina M L, Somkuti P, Bianchi D, Cihak-Bayr U, Bader D, Jech M and Vernes A 2015 Characterisation of orange peel on highly polished steel surfaces *Surf. Eng.* **31** 519–25
- [6] Scheer B W 1997 Development of a smooth-surface microroughness standard *Proc. SPIE* **3141** 78–87
- [7] Turner B N and Gold S a. 2015 A review of melt extrusion additive manufacturing processes: II. Materials, dimensional accuracy, and surface roughness *Rapid Prototyp. J.* **21** 250–261
- [8] Leach R, Evans C, He L, Davies A, Duparré A, Henning A, Jones C W and O'Connor D 2015 Open questions in surface topography measurement: a roadmap *Surf. Topogr. Metrol. Prop.* **3** 013001
- [9] Gao W 1997 Development of an optical probe for profile measurement of mirror surfaces *Opt. Eng.* **36** 3360–6

- [10] Whitehouse D 2009 A new look at surface metrology *Wear* **266** 560–5
- [11] Fuh Y-K, Fan J R, Huang C Y and Jang S C 2013 In-process surface roughness measurement of bulk metallic glass using an adaptive optics system for aberration correction *Measurement* **46** 4200–5
- [12] Davim J P 2010 *Surface integrity in machining* ed J P Davim (London: Springer London)
- [13] Vorburger T V, Dagata J A, Wilkening G and Iizuka K Characterization of Surface Topography *Beam Effects, Surface Topography, and Depth Profiling in Surface Analysis* vol 597 (Boston: Kluwer Academic Publishers) pp 275–354
- [14] Spagnolo G S, Cozzella L and Leccese F 2014 Viability of an optoelectronic system for real time roughness measurement *Measurement* **58** 537–43
- [15] Vorburger T V., Rhee H G, Renegar T B, Song J F and Zheng A 2007 Comparison of optical and stylus methods for measurement of surface texture *Int. J. Adv. Manuf. Technol.* **33** 110–8
- [16] Smith G T 2002 *Industrial Metrology* (London: Springer London)
- [17] British Standards Institution 2010 *BS 1134 Assessment of surface texture – Guidance and general information*
- [18] Whitehouse D 2004 *Surfaces and Their Measurement* (London: Butterworth-Heinemann)
- [19] British Standards Institution 1998 *BS EN ISO 4288 Profile method: Rules and procedures for the assessment of surface texture*
- [20] British Standards Institution 2002 *BS EN ISO 1302 Indication of surface texture in technical product documentation*
- [21] Leach R 2013 *Characterisation of Areal Surface Texture* (Berlin: Springer-Verlag)

- [22] British Standards Institution 1998 *BS EN ISO 4287 Profile method — Terms, definitions and surface texture parameters*
- [23] Gadelmawla E S, Koura M M, Maksoud T M A, Elewa I M and Soliman H H 2002 Roughness parameters *J. Mater. Process. Technol.* **123** 133–45
- [24] Al-Kindi G a. and Shirinzadeh B 2009 Feasibility assessment of vision-based surface roughness parameters acquisition for different types of machined specimens *Image Vis. Comput.* **27** 444–58
- [25] Butler D L 2014 *Surface Topography Part One: An Introduction to design, operation, and applications* (Singapore)
- [26] Leach R, Leigh Brown X J, Blunt R and Mike Conroy D M 2008 *Guide for the Measurement of Smooth Surface Topography using Coherence Scanning Interferometry* (London: National Physical Laboratory)
- [27] Dong W, Sullivan P and Stout K 1994 Comprehensive study of parameters for characterising three-dimensional surface topography: III: Parameters for characterising amplitude and some functional *Wear* **178** 29–43
- [28] Dong W P, Sullivan P J and Stout K J 1994 Comprehensive study of parameters for characterising three-dimensional surface topography: IV: Parameters for characterising spatial and hybrid properties *Wear* **178** 45–60
- [29] Blunt L and Jiang X 2003 *Advanced techniques for assessment surface topography: Development of a basis for 3D surface texture standards “surfstand”* (London: Kogan Page Science)
- [30] British Standards Institution 2012 *BS EN ISO 25178-2 Terms, definitions and surface texture parameters*
- [31] Petzing J, Coupland J and Leach R 2010 *The Measurement of Rough Surface Topography using Coherence Scanning Interferometry* (London: National

Physical Laboratory)

- [32] British Standards Institution 1998 *BS EN ISO 3274 Profile method — Nominal characteristics of contact (stylus) instruments*
- [33] Durakbasa M N, Osanna P H and Demircioglu P 2011 The factors affecting surface roughness measurements of the machined flat and spherical surface structures – The geometry and the precision of the surface *Measurement* **44** 1986–99
- [34] Jiang B X, Scott P J J, Whitehouse D J J, Blunt L, Jiang X, Scott P J J, Whitehouse D J J and Blunt L 2007 Paradigm shifts in surface metrology. Part I. Historical philosophy *Proc. R. Soc. London, Ser. A (Mathematical, Phys. Eng. Sci.* **463** 2049–70
- [35] Leach R K 2010 *Fundamental Principles of Engineering Nanometrology* (Elsevier)
- [36] Paddock S W 1998 *Confocal Microscopy* vol 122 (New Jersey: Humana Press)
- [37] Sandoz P, Tribillon G, Gharbi T and Devillers R 1996 Roughness measurement by confocal microscopy for brightness characterization and surface waviness visibility evaluation *Wear* **201** 186–92
- [38] Giusca C L and Leach R K 2012 *Calibration of the metrological characteristics of Imaging Confocal Microscopes (ICMs)* (London: National Physical Laboratory)
- [39] Richard L 2011 *Optical Measurement of Surface Topography*
- [40] British Standards Institution 2013 *BS EN ISO 25178-604-2013 coherence scanning interferometry*
- [41] Kaplonek W and Lukianowicz C 2012 Coherence Correlation Interferometry in Surface Topography Measurements *Recent Interferometry Applications in*

- [42] Viotti M R, Albertazzi A, Fantin A V. and Pont A D 2008 Comparison between a white-light interferometer and a tactile formtester for the measurement of long inner cylindrical surfaces *Opt. Lasers Eng.* **46** 396–403
- [43] Lehmann P, Tereschenko S and Xie W 2016 Fundamental aspects of resolution and precision in vertical scanning white-light interferometry *Surf. Topogr. Metrol. Prop.* **4** 024004
- [44] Chkhalo N I, Churin S A, Pestov A E, Salashchenko N N, Vainer Y A and Zorina M V. 2014 Roughness measurement and ion-beam polishing of super-smooth optical surfaces of fused quartz and optical ceramics *Opt. Express* **22** 20094
- [45] Yoshizawa T 2009 *Handbook of Optical Metrology: Principles and Applications* (CRC Press)
- [46] Shahabi H H and Ratnam M M 2010 Noncontact roughness measurement of turned parts using machine vision *Int. J. Adv. Manuf. Technol.* **46** 275–84
- [47] Hocken R J, Chakraborty N and Brown C 2005 Optical Metrology of Surfaces *CIRP Ann. - Manuf. Technol.* **54** 169–83
- [48] Persson U 1992 Real time measurement of surface roughness on ground surfaces using speckle-contrast technique *Opt. Lasers Eng.* **17** 61–7
- [49] Kruse D, Patzelt S, Dollinger C, Tausendfreund A and Goch G 2011 Laser Optical Characterization of Smooth Surfaces with Respect to Roughness and Defects in the Micrometer Range *Procedia Eng.* **19** 235–40
- [50] Everton S K, Hirsch M, Stravroulakis P, Leach R K and Clare A T 2016 Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing *Mater. Des.* **95** 431–45
- [51] Syam W P, Leach R, Rybalcenko K, Gaio A and Crabtree J 2018 In-process

measurement of the surface quality for a novel finishing process for polymer additive manufacturing *Procedia CIRP* **75** 0–6

- [52] Li Z and Liu J 2010 The in-process and real-time roughness measuring system design for free-form surface *Proc. - 2010 Int. Conf. Comput. Inf. Sci. ICCIS 2010* 824–6
- [53] Fang F Z, Zhang X D, Weckenmann a., Zhang G X and Evans C 2013 Manufacturing and measurement of freeform optics *CIRP Ann. - Manuf. Technol.* **62** 823–46
- [54] Vacharanukul K and Mekid S 2005 In-process dimensional inspection sensors *Measurement* **38** 204–18
- [55] Tay C ., Wang S ., Quan C and Shang H . 2003 In situ surface roughness measurement using a laser scattering method *Opt. Commun.* **218** 1–10
- [56] Wong P L and Li K Y 1999 In-process roughness measurement on moving surfaces *Opt. Laser Technol.* **31** 543–8
- [57] Quinsat Y and Tournier C 2012 In situ non-contact measurements of surface roughness *Precis. Eng.* **36** 97–103
- [58] Minoni U and Cavalli F 2008 Surface quality control device for on-line applications *Measurement* **41** 774–82
- [59] Jiang X, Lin D, Blunt L, Zhang W and Zhang L 2006 Investigation of some critical aspects of on-line surface measurement by a wavelength-division-multiplexing technique *Meas. Sci. Technol.* **17** 483–7
- [60] Lin D, Jiang X, Xie F, Zhang W, Zhang L and Bennion I 2004 High stability multiplexed fiber interferometer and its application on absolute displacement measurement and on-line surface metrology *Opt. Express* **12** 5729
- [61] Tian G Y and Lu R-S 2006 Hybrid vision system for online measurement of

- surface roughness *J. Opt. Soc. Am. A* **23** 3072
- [62] Fuh Y K, Hsu K C and Fan J R 2012 Rapid in-process measurement of surface roughness using adaptive optics *Opt. Lett.* **37** 848
- [63] ASTM 2014 *A480/A480M 14b: Standard Specification for General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip*
- [64] Bogue R 2009 Finishing robots: a review of technologies and applications ed J Norberto Pires *Ind. Robot An Int. J.* **36** 6–12
- [65] Brinksmeier E, Riemer O, Gessenharter A and Autschbach L 2004 Polishing of Structured Molds *CIRP Ann. - Manuf. Technol.* **53** 247–50
- [66] Kanda T, Mitsuhashi M, Ueda T, Toyohara A and Yamamoto K 1995 New mirror-finish surface-grinding technology for the fabrication of optical device endfaces *International Conference on Optical Fabrication and Testing* vol 2576, ed T Kasai pp 84–91
- [67] Ando M, Negishi M, Takimoto M, Deguchi A and Nakamura N 1995 Super-smooth polishing on aspherical surfaces *Nanotechnology* **6** 111–20
- [68] Sreejith P S, Udupa G, Noor Y B M and Ngoi B K A 2001 Recent Advances in Machining of Silicon Wafers for Semiconductor Applications *Int. J. Adv. Manuf. Technol.* **17** 157–62
- [69] Tay C ., Wang S ., Quan C, Ng B . and Chan K . 2004 Surface roughness investigation of semi-conductor wafers *Opt. Laser Technol.* **36** 535–9
- [70] Evans C J, Paul E, Dornfeld D, Lucca D A, Byrne G, Tricard M, Klocke F, Dambon O and Mullany B A 2003 Material Removal Mechanisms in Lapping and Polishing *CIRP Ann. - Manuf. Technol.* **52** 611–33
- [71] Tournier C, Iabassene C, Guiot A, Quinsat Y and Of G 2012 Grinding of medical

- implants in cobalt-chromium alloy *1st International Conference on Design and PROCesses for MEDical Devices* (Brescia) pp 95–8
- [72] Kunzler T P, Drobek T, Schuler M and Spencer N D 2007 Systematic study of osteoblast and fibroblast response to roughness by means of surface-morphology gradients *Biomaterials* **28** 2175–82
 - [73] Jianfeng Luo and Dornfeld D A 2001 Material removal mechanism in chemical mechanical polishing: theory and modeling *IEEE Trans. Semicond. Manuf.* **14** 112–33
 - [74] Zantye P B, Kumar A and Sikder A K 2004 Chemical mechanical planarization for microelectronics applications *Mater. Sci. Eng. R Reports* **45** 89–220
 - [75] Komanduri R, Lucca D A and Tani Y 1997 Technological Advances in Fine Abrasive Processes *CIRP Ann. - Manuf. Technol.* **46** 545–96
 - [76] Golini D, Kordonski W I, Dumas P and Hogan S J 1999 Magnetorheological finishing (MRF) in commercial precision optics manufacturing *Optical Manufacturing and Testing III* pp 80–91
 - [77] Pollicove H M, Fess E M and Schoen J M 2003 Deterministic manufacturing processes for precision optical surfaces *Window and Dome Technologies VIII* ed R W Tustison p 90
 - [78] Zhong Z W 2008 Recent Advances in Polishing of Advanced Materials *Mater. Manuf. Process.* **23** 449–56
 - [79] Kanaoka M, Takino H, Nomura K, Mori Y, Mimura H and Yamauchi K 2007 Removal properties of low-thermal-expansion materials with rotating-sphere elastic emission machining *Sci. Technol. Adv. Mater.* **8** 170–2
 - [80] Han X and Gan Y X 2011 Analysis the complex interaction among flexible nanoparticles and materials surface in the mechanical polishing process *Appl.*

- [81] British Standards Institution 1983 *BS 1449-2 Steel plate, sheet and strip. Specification for stainless and heat-resisting steel plate, sheet and strip*
- [82] Golkar E, Prabuwno A and Patel A 2012 Real-Time Curvature Defect Detection on Outer Surfaces Using Best-Fit Polynomial Interpolation *Sensors* **12** 14774–91
- [83] Wu L Q and Chao Y 2011 Study on Optimal Methodology of RMS Roughness in Super Smooth Surfaces by CCI *Adv. Mater. Res.* **308–310** 1050–3
- [84] Yang S M and Jiang X Q 2008 The Roughness Measurement and Assessment of the Super-Smooth Surface of Hard Disks *Key Eng. Mater.* **364–366** 1174–9
- [85] Biegen J F and Smythe R A 1989 High Resolution Phase Measuring Laser Interferometric Microscope For Engineering Surface Metrology *Surface Measurement and Characterization* ed J M Bennett p 35
- [86] Chang M and Lin P P 1996 Noncontact Sphericity Measurement by Means of Phase Shift Interferometry *J. Manuf. Sci. Eng.* **118** 394
- [87] Fuh Y K and Wang C H 2013 Adaptive Optics Integrated Surface Roughness Measurement of Sputtered PT Film on Silicon Substrate *Microw. Opt. Technol. Lett.* **55** 2055–9
- [88] Persson U 2006 Surface roughness measurement on machined surfaces using angular speckle correlation *J. Mater. Process. Technol.* **180** 233–8
- [89] Dhanasekar B, Mohan N K, Bhaduri B and Ramamoorthy B 2008 Evaluation of surface roughness based on monochromatic speckle correlation using image processing *Precis. Eng.* **32** 196–206
- [90] Sugino T and Yamane Y 2015 Gloss Evaluation of Hairline-Finished Metal Surface Using Patterned Area Illumination Method: Reproduction of Gloss

Evaluation by Ray Tracing *Key Eng. Mater.* **656–657** 468–72

- [91] Sugino T, Tashiro Y and Yamane Y 2017 Gloss Evaluation of Hairline-Finished Metal Surface Using Patterned Area Illumination Method: Relationship between Gloss Evaluation and Surface Roughness for the Estimation of Surface Roughness *Key Eng. Mater.* **749** 251–6
- [92] Klocke F, Dambon O and Behrens B 2011 Analysis of defect mechanisms in polishing of tool steels *Prod. Eng.* **5** 475–83
- [93] Zhang X, Krewet C and Kuhlenkötter B 2006 Automatic classification of defects on the product surface in grinding and polishing *Int. J. Mach. Tools Manuf.* **46** 59–69
- [94] Rosati G, Boschetti G, Biondi a. and Rossi a. 2009 Real-time defect detection on highly reflective curved surfaces *Opt. Lasers Eng.* **47** 379–84
- [95] Bobby R A, Sonakar P S, Singaperumal M and Ramamoorthy B 2010 Identification of defects on highly reflective ring components and analysis using machine vision *Int. J. Adv. Manuf. Technol.* **52** 217–33
- [96] Tsai D M and Hsieh C Y 2003 Automated surface inspection for statistical textures *Image Vis. Comput.* **21** 307–323
- [97] Tsai D-M and Lai S-C 2008 Defect detection in periodically patterned surfaces using independent component analysis *Pattern Recognit.* **41** 2812–32
- [98] Kim K and Kim E Y 2010 Film line scratch detection using texture and shape information *Pattern Recognit. Lett.* **31** 250–8
- [99] Kim E Y, Kim K and Kim B 2013 Genetic algorithm-based reconstruction of old films corrupted by scratches and blotches *Pattern Recognit. Lett.* **34** 226–37
- [100] Frazier W E 2014 Metal Additive Manufacturing: A Review *J. Mater. Eng. Perform.* **23** 1917–28

- [101] Sames W J, List F A, Pannala S, Dehoff R R and Babu S S 2016 The metallurgy and processing science of metal additive manufacturing *Int. Mater. Rev.* **61** 315–60
- [102] Shen Z-H, Duan Y-X, Ren X-D and Ni X-W 2010 Surface Roughness of Laser-Shock-Peened Aluminum Alloys and Its Effect on the Dispersion of Surface Acoustic Waves *Jpn. J. Appl. Phys.* **49** 042701
- [103] Stavroulakis P I and Leach R K 2016 Invited Review Article: Review of post-process optical form metrology for industrial-grade metal additive manufactured parts *Rev. Sci. Instrum.* **87** 041101
- [104] Yap C Y, Chua C K, Dong Z L, Liu Z H, Zhang D Q, Loh L E and Sing S L 2015 Review of selective laser melting: Materials and applications *Appl. Phys. Rev.* **2** 041101
- [105] Townsend A, Senin N, Blunt L, Leach R K, Taylor J S, Team M M and Livermore L 2016 Surface Texture Metrology for Metal Additive Manufacturing : a Review *Precis. Eng.* **In Press** 34–47
- [106] Cheng F, Fu S W and Leong Y S 2017 Research on optical measurement for additive manufacturing surfaces *Proc. SPIE 10250, International Conference on Optical and Photonics Engineering (icOPEN 2016)* ed A K Asundi, X Huang and Y Xie p 102501F
- [107] Triantaphyllou A, Giusca C L, Macaulay G D, Roerig F, Hoebel M, Leach R K, Tomita B, Milne K A, MacAualy G D, Leach R K and Milne K A 2015 Surface texture measurement for additive manufacture *Surf. Topogr. Metrol. Prop.* **3** 024002
- [108] Herzog D, Seyda V, Wycisk E and Emmelmann C 2016 Additive manufacturing of metals *Acta Mater.* **117** 371–92

- [109] Jamshidinia M and Kovacevic R 2015 The influence of heat accumulation on the surface roughness in powder-bed additive manufacturing *Surf. Topogr. Metrol. Prop.* **3** 014003
- [110] Launhardt M, Wörz A, Loderer A, Laumer T, Drummer D, Hausotte T and Schmidt M 2016 Detecting surface roughness on SLS parts with various measuring techniques *Polym. Test.* **53** 217–26
- [111] Jiang X Q, Blunt L and Stout K J 2000 Comparison Study of Areal Functional Parameters for Rough Surfaces *ASPE Annu. Meet.* 2000
- [112] Calignano F, Manfredi D, Ambrosio E P, Iuliano L and Fino P 2013 Influence of process parameters on surface roughness of aluminum parts produced by DMLS *Int. J. Adv. Manuf. Technol.* **67** 2743–51
- [113] Grimm T, Wiora G and Witt G 2015 Characterization of typical surface effects in additive manufacturing with confocal microscopy *Surf. Topogr. Metrol. Prop.* **3** 014001
- [114] Jiang X, Scott P and Whitehouse D 2007 Freeform Surface Characterisation - A Fresh Strategy *CIRP Ann. - Manuf. Technol.* **56** 553–6
- [115] Guo W, Zhao L and Chen I-M 2014 Reference-free beam-sampling system for freeform surface measurements *Appl. Opt.* **53** H20
- [116] Charlton P and Blunt L 2008 Surface and form metrology of polished “freeform” biological surfaces *Wear* **264** 394–9
- [117] Davis G E, Roblee J W and Hedges A R 2009 Comparison of freeform manufacturing techniques in the production of monolithic lens arrays ed J H Burge, O W Föhnle and R Williamson p 742605
- [118] Taniguchi N 1983 Current Status in, and Future Trends of, Ultraprecision Machining and Ultrafine Materials Processing *CIRP Ann.* **32** 573–82

- [119] AMETEK Ultra Precision Technologies 2012 Form Talysurf PGI 400 / 800 / 1200 Ultra precision surface form and finish measurement system *Catalogue*
- [120] Fan K-C 1997 A non-contact automatic measurement for free-form surface profiles *Comput. Integr. Manuf. Syst.* **10** 277–85
- [121] Bradley C 2000 Automated Surface Roughness Measurement *Int. J. Adv. Manuf. Technol.* **16** 668–74
- [122] Panasonic UA3P 3D Profilometer
- [123] Chang M and Lin P P 1999 On-line free form surface measurement via a fuzzy-logic controlled scanning probe *Int. J. Mach. Tools Manuf.* **39** 537–52
- [124] Xue S, Chen S, Fan Z and Zhai D 2018 Adaptive wavefront interferometry for unknown free-form surfaces *Opt. Express* **26** 21910
- [125] Fan K-C, Wang N, Wang Z-W and Zhang H 2014 Development of a roundness measuring system for microspheres *Meas. Sci. Technol.* **25** 064009
- [126] Wang H-Y, Fan K-C, Ye J-K and Lin C-H 2014 A Long-Stroke Nanopositioning Control System of the Coplanar Stage *IEEE/ASME Trans. Mechatronics* **19** 348–56
- [127] Schwenke H, Neuschaefer-Rube U, Pfeifer T and Kunzmann H 2002 Optical Methods for Dimensional Metrology in Production Engineering *CIRP Ann. - Manuf. Technol.* **51** 685–99
- [128] Cheng F and Fan K-C 2011 Linear diffraction grating interferometer with high alignment tolerance and high accuracy *Appl. Opt.* **50** 4550
- [129] Gao W, Kim S W, Bosse H, Haitjema H, Chen Y L, Lu X D, Knapp W, Weckenmann A, Estler W T and Kunzmann H 2015 Measurement technologies for precision positioning *CIRP Ann.* **64** 773–96
- [130] Zhang L and Kümme R 2004 Investigation of a homodyne and a heterodyne laser

interferometer for dynamic force measurement p 608

- [131] Kunzmann H, Pfeifer T and Flügge J 1993 Scales vs. Laser Interferometers Performance and Comparison of Two Measuring Systems *CIRP Ann.* **42** 753–67
- [132] HEIDENHAIN 2012 Linear Encoders For Numerically Controlled Machine Tools *Catalogue*
- [133] HEIDENHAIN 2011 NEW LC 200 – Absolute Linear Encoder for Machine Tools with Long Axes
- [134] HEIDENHAIN 2016 Exposed Linear Encoders *Catalogue*
- [135] Chen Z, Pu H, Liu X, Peng D and Yu Z 2015 A Time-Grating Sensor for Displacement Measurement With Long Range and Nanometer Accuracy *IEEE Trans. Instrum. Meas.* **64** 3105–15
- [136] Wang xianquan, Wu Min, Zhu Ge and Yang Jishen 2009 New time-grating displacement sensor and harmonic wave error-correction 2009 *International Conference on Information and Automation* (IEEE) pp 1452–7
- [137] Zhou P 2001 Subpixel displacement and deformation gradient measurement using digital image/speckle correlation (DISC) *Opt. Eng.* **40** 1613
- [138] Pan B, Qian K, Xie H and Asundi A 2009 Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review *Meas. Sci. Technol.* **20** 062001
- [139] Luo M 2006 Displacement/strain measurements using an optical microscope and digital image correlation *Opt. Eng.* **45** 033605
- [140] Zhou Y, Pan B and Chen Y Q 2012 Large deformation measurement using digital image correlation: a fully automated approach *Appl. Opt.* **51** 7674
- [141] Yoshimizu N, Lal A and Pollock C R 2010 Nanometrology optical ruler imaging system using diffraction from a quasiperiodic structure *Opt. Express* **18** 20827

- [142] Pan B, Yu L and Wu D 2014 High-accuracy 2D digital image correlation measurements using low-cost imaging lenses: implementation of a generalized compensation method *Meas. Sci. Technol.* **25** 025001
- [143] DALSA T 2018 Line Scan Primer
- [144] NOVUS LIGHT TECHNOLOGIES TODAY 2017 Line-Scan vs. Area-Scan: What is right for machine vision applications?
- [145] Wang C L, Zhao C X and Yang J Y 2011 Local Upsampling Fourier Transform for High Accuracy Image Rotation Estimation *Adv. Mater. Res.* **268–270** 1488–93
- [146] Szeliski R 2006 Image Alignment and Stitching: A Tutorial *Found. Trends® Comput. Graph. Vis.* **2** 1–104
- [147] Zitová B and Flusser J 2003 Image registration methods: a survey *Image Vis. Comput.* **21** 977–1000
- [148] Debella-Gilo M and Käab A 2011 Sub-pixel precision image matching for measuring surface displacements on mass movements using normalized cross-correlation *Remote Sens. Environ.* **115** 130–42
- [149] Moravec H P 1990 The Stanford Cart and the CMU Rover *Autonomous Robot Vehicles* (New York, NY: Springer New York) pp 407–19
- [150] Govindu V, Shekhar C and Chellappa R Using geometric properties for correspondence-less image alignment *Proceedings. Fourteenth International Conference on Pattern Recognition (Cat. No.98EX170)* vol 1 (IEEE Comput. Soc) pp 37–41
- [151] Zoghلامي I, Faugeras O and Deriche R Using geometric corners to build a 2D mosaic from a set of images *Proceedings of IEEE Computer Society Conference on Computer Vision and Pattern Recognition* (IEEE Comput. Soc) pp 420–5

- [152] Douini Y, Riffi J, Mahraz A M and Tairi H 2017 An image registration algorithm based on phase correlation and the classical Lucas–Kanade technique *Signal, Image Video Process.* **11** 1321–8
- [153] Alba A, Aguilar-Ponce R M, Vigueras-Gómez J F and Arce-Santana E 2013 Phase Correlation Based Image Alignment with Subpixel Accuracy *Micai 2012* pp 171–82
- [154] Foroosh H, Zerubia J B and Berthod M 2002 Extension of phase correlation to subpixel registration *IEEE Trans. Image Process.* **11** 188–200
- [155] Takita K, Aoki T, Sasaki Y, Higuchi T and Kobayashi K 2003 High-Accuracy Subpixel Image Registration Based on Phase-Only Correlation *IEICE Trans. Fundam. Electron. Commun. Comput. Sci.* **E86-A** 1925–34
- [156] Li Chen and Kim-Hui Yap 2008 An Effective Technique for Subpixel Image Registration Under Noisy Conditions *IEEE Trans. Syst. Man, Cybern. - Part A Syst. Humans* **38** 881–7
- [157] Lu H, Huang C, Wang C, Wang X, Fu H and Chen Z 2014 Fast and noninterpolating method for subpixel displacement analysis of digital speckle images using phase shifts of spatial frequency spectra *Appl. Opt.* **53** 2806
- [158] Bing P, Hui-min X, Bo-qin X and Fu-long D 2006 Performance of sub-pixel registration algorithms in digital image correlation *Meas. Sci. Technol.* **17** 1615–21
- [159] Riha L, Fischer J, Smid R and Docekal A 2007 New interpolation methods for image-based sub-pixel displacement measurement based on correlation 2007 *IEEE Instrumentation & Measurement Technology Conference IMTC 2007* (IEEE) pp 1–5
- [160] Thevenaz P, Ruttimann U E and Unser M 1998 A pyramid approach to subpixel

- registration based on intensity *IEEE Trans. Image Process.* **7** 27–41
- [161] Fienup J R 1997 Invariant error metrics for image reconstruction *Appl. Opt.* **36** 8352
- [162] Guizar-Sicairos M, Thurman S T and Fienup J R 2007 Efficient Image Registration Algorithms for Computation of Invariant Error Metrics *Adaptive Optics: Analysis and Methods/Computational Optical Sensing and Imaging/Information Photonics/Signal Recovery and Synthesis Topical Meetings on CD-ROM* (Washington, D.C.: OSA) p SMC3
- [163] Wang C, Jing X and Zhao C 2012 Local Upsampling Fourier Transform for accurate 2D/3D image registration *Comput. Electr. Eng.* **38** 1346–57
- [164] Foroosh H and Balci M 2004 Sub-pixel registration and estimation of local shifts directly in the fourier domain *2004 International Conference on Image Processing, 2004. ICIP '04.* vol 3 (IEEE) pp 1915–8
- [165] Balci M and Foroosh H 2006 Subpixel estimation of shifts directly in the Fourier domain *IEEE Trans. Image Process.* **15** 1965–72
- [166] Guizar-Sicairos M, Thurman S T and Fienup J R 2008 Efficient subpixel image registration algorithms *Opt. Lett.* **33** 156
- [167] Almonacid-Caballer J, Pardo-Pascual J E and Ruiz L A 2017 Evaluating fourier cross-correlation sub-pixel registration in Landsat images *Remote Sens.* **9**
- [168] Wang C, Cheng Y and Zhao C 2009 Robust Subpixel Registration for Image Mosaicing *2009 Chinese Conference on Pattern Recognition* (IEEE) pp 1–5
- [169] Sugino T, Satozono Y and Yamane Y 2009 Gloss Evaluation Method for Metal Surface with Hairline Using Patterned Area Illumination *Key Eng. Mater.* **407–408** 723–6
- [170] Pelli D G and Bex P 2013 Measuring contrast sensitivity *Vision Res.* **90** 10–4

- [171] Cowan W B and MacIntyre B 1992 A practical approach to calculating luminance contrast on a CRT *ACM Trans. Graph.* **11** 336–47
- [172] Kukkonen H, Rovamo J, Tiippana K and Näsänen R 1993 Michelson contrast, RMS contrast and energy of various spatial stimuli at threshold *Vision Res.* **33** 1431–6
- [173] Russ J C . 2011 Acquiring Images *The Image Processing Handbook, Sixth Edition* (CRC Press) pp 1–84
- [174] Brinkmann M, Hayden J, Letz M, Reichel S, Click C, Mannstadt W, Schreder B, Wolff S, Ritter S, Davis M J, Bauer T E, Ren H, Fan Y-H, Menke Y, Wu S-T, Bonrad K, Krätzig E, Buse K and Paquin R A 2012 Optical Materials and Their Properties *Springer Handbook of Lasers and Optics* (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 253–399
- [175] Thorlabs I 2018 Motorized 2" (50 mm) Linear Translation Stages
- [176] ZOLIX INSTRUMENTS 2013 Motorized Linear Stages
- [177] Physik Instrumente (PI) GmbH & Co. KG 2018 Linear Stages with Motor/Screw - Drives
- [178] Wyawahare M V, Patil P M and Abhyankar H K 2009 Image Registration Techniques: An overview *Int. J. Signal Process. Image Process. Pattern Recognit.* **2** 11–28
- [179] Yousef A, Li J and Karim M 2015 High-speed image registration algorithm with subpixel accuracy *IEEE Signal Process. Lett.* **22** 1796–800
- [180] Li X 2017 High-Accuracy Subpixel Image Registration With Large Displacements *IEEE Trans. Geosci. Remote Sens.* **55** 6265–76
- [181] Stone H S, Orchard M T, Ee-Chien Chang and Martucci S A 2001 A fast direct Fourier-based algorithm for subpixel registration of images *IEEE Trans. Geosci.*

- [182] Soummer R, Pueyo L, Sivaramakrishnan A and Vanderbei R J 2007 Fast computation of Lyot-style coronagraph propagation *Opt. Express* **15** 15935
- [183] Brown D 1966 Decentering Distortion of Lenses *Photom. Eng.* **32** 444–62
- [184] Brown D C 1971 Close-range camera calibration *Photogramm. Eng.* **37** 855–66
- [185] Weng J, Cohen P and Herniou M 1992 Camera calibration with distortion models and accuracy evaluation *IEEE Trans. Pattern Anal. Mach. Intell.* **14** 965–80
- [186] Visscher M and Struik K G 1994 Optical profilometry and its application to mechanically inaccessible surfaces Part I: Principles of focus error detection *Precis. Eng.* **16** 192–8
- [187] Ruprecht A K, Pruss C, Tiziani H J, Osten W, Lucke P, Last A, Mohr J and Lehmann P 2005 Confocal micro-optical distance sensor: principle and design *Optical Measurement Systems for Industrial Inspection IV* ed W Osten, C Gorecki and E L Novak p 128
- [188] Jordan H-J, Wegner M and Tiziani H 1998 Highly accurate non-contact characterization of engineering surfaces using confocal microscopy *Meas. Sci. Technol.* **9** 1142–51
- [189] Chen L-C 2012 Full-field chromatic confocal surface profilometry employing digital micromirror device correspondence for minimizing lateral cross talks *Opt. Eng.* **51** 081507
- [190] Artigas R 2011 Imaging Confocal Microscopy *Optical Measurement of Surface Topography* (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 237–86
- [191] Thanh V, Chizhik S A, Xuan T, Trong N and Chikunov V V 2012 Tuning Fork Scanning Probe Microscopes - Applications for the Nano-Analysis of the Material Surface and Local Physico-Mechanical Properties *Scanning Probe*

- [192] Qiu Z R, Qin J, Zhang H W and Zhang G X 2006 Structure Design of A Laser Confocal Probe For Measuring the Micro-Sphere *J. Phys. Conf. Ser.* **48** 641–6
- [193] British Standards Institution 2012 *BS EN ISO 16610-21 Linear profile filters: Gaussian filters*
- [194] British Standards Institution 2015 *BS EN ISO 16610-20 Linear profile filters: Basic concepts*
- [195] Zygo Corporation 2002 *MetroPro Reference Guide*
- [196] Carl Zeiss AG 2010 *StitchArt Guide for ZEN 2010*
- [197] Wyant J C and Schmit J 1998 Large field of view, high spatial resolution, surface measurements *Int. J. Mach. Tools Manuf.* **38** 691–8
- [198] Kume T, Enami K, Higashi Y and Ueno K 2006 Evaluation of Error Propagation in Profilometry using Stitching *International Workshop on Accelerator Alignment* vol TH002 pp 1–8
- [199] Chen S, Li S, Dai Y, Ding L and Zeng S 2008 Experimental study on subaperture testing with iterative stitching algorithm *Opt. Express* **16** 4760
- [200] Xue J, Huang L, Gao B, Kaznatcheev K and Idir M 2017 One-dimensional stitching interferometry assisted by a triple-beam interferometer *Opt. Express* **25** 9393
- [201] Mauch F and Osten W 2014 Model-based approach for planning and evaluation of confocal measurements of rough surfaces *Meas. Sci. Technol.* **25** 105002
- [202] British Standards Institution 2001 *BS EN ISO 5436-1-2001 Surface texture. Profile method calibration. Measurement standards*
- [203] Haitjema H and Morel M 2000 The concept of a virtual roughness tester *Proceedings X. International Colloquium on Surfaces* ed M Dietzch and H

Trumpold (Aachen: Shaker Verlag) pp 239 – 244

- [204] Haitjema H, van Dorp B W, Morel M and Schellekens P H J 2001 Uncertainty estimation by the concept of virtual instruments *Proc. SPIE 4401, Recent Developments in Traceable Dimensional Measurements* vol 4401, ed J E Decker and N Brown (Munich) p 147
- [205] Dai G, Jung L, Koenders L and Krüger-Sehm R 2005 Calibration of stylus profilometers using standards calibrated by metrological SFMs *J. Phys. Conf. Ser.* **13** 236–9
- [206] Sheppard C J R, Gan X, Gu M and Roy M 2006 Signal-to-Noise Ratio in Confocal Microscopes *Handbook Of Biological Confocal Microscopy* (Boston, MA: Springer US) pp 442–52