Precision Nanometrology

Sensors and Measuring Systems for Nanomanufacturing
Springer Series in Advanced Manufacturing
Series Editor
Professor D.T. Pham
Manufacturing Engineering Centre
Cardiff University
Queen’s Building
Newport Road
Cardiff CF24 3AA
UK

Other titles in this series

Assembly Line Design
B. Rekiek and A. Delchambre

Advances in Design
H.A. ElMaraghy and W.H. ElMaraghy (Eds.)

Effective Resource Management in Manufacturing Systems: Optimization Algorithms in Production Planning
M. Caramia and P. Dell’Olmo

Condition Monitoring and Control for Intelligent Manufacturing
L. Wang and R.X. Gao (Eds.)

Optimal Production Planning for PCB Assembly
W. Ho and P. Ji

Trends in Supply Chain Design and Management: Technologies and Methodologies
H. Jung, F.F. Chen and B. Jeong (Eds.)

Process Planning and Scheduling for Distributed Manufacturing
L. Wang and W. Shen (Eds.)

Collaborative Product Design and Manufacturing Methodologies and Applications
W.D. Li, S.K. Ong, A.Y.C. Nee and C. McMahon (Eds.)

Decision Making in the Manufacturing Environment
R. Venkata Rao

Reverse Engineering: An Industrial Perspective
V. Raja and K.J. Fernandes (Eds.)

Frontiers in Computing Technologies for Manufacturing Applications
Y. Shimizu, Z. Zhang and R. Batres

Automated Nanohandling by Microrobots
S. Fatikow

A Distributed Coordination Approach to Reconfigurable Process Control
N.N. Chokshi and D.C. McFarlane

ERP Systems and Organisational Change
B. Grabot, A. Mayère and I. Bazet (Eds.)

ANEMONA
V. Botti and A. Giret

Theory and Design of CNC Systems

Machining Dynamics
K. Cheng

Changeable and Reconfigurable Manufacturing Systems
H.A. ElMaraghy

Advanced Design and Manufacturing Based on STEP
X. Xu and A.Y.C. Nee (Eds.)

Artificial Intelligence Techniques for Networked Manufacturing Enterprises Management
L. Benyoucef, B. Grabet (Eds.)
To my family
“When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science.” – Lord Kelvin

The act of measuring, which is used for determining the size, amount or degree of a parameter by an instrument through comparison with a standard unit, or used indirectly by calculation based on theory, makes science and technology different from imagination. Measurement is also essential in industry, commerce and daily life. If we focus on the manufacturing industry, we can easily find that dimensional metrology plays an increasingly important role not only in the traditional field of manufacturing but also in the advanced field of nanomanufacturing, represented by ultra-precision machining and semiconductor fabrication.

Nanomanufacturing is a process of using precision machines that can generate precision tool motions to fabricate designed surface forms/dimensions with nanometric tolerances. Dimensional measurement of the workpiece and the machine is always an essential process for the purpose of quality control in all kinds of manufacturing. Because accuracy is the most important requirement for nanomanufacturing, the dimensional measurement is a much more crucial process for nanomanufacturing than other kinds of manufacturing. Figure 0.1 shows tolerances with respect to the dimensions of the workpieces and machines in nanomanufacturing. It can be seen that most of the workpieces and machines have sizes ranging from micrometers to meters while the corresponding tolerances range from 100 nm to 0.1 nm. In addition, more and more precision workpieces are required in a shorter amount of time in order to reduce manufacturing costs. Shapes of the precision workpieces are also becoming more and more complex. These factors are bringing greater challenges to the existing measuring technologies of precision metrology and nanometrology.

Precision metrology has a long history tracing back to the inventions of the micrometer (J. Watt 1772), gage block (C. Johansson, 1896), interferometer (A. Michelson 1881), etc. It established the foundation for the Industrial Revolution and contributed greatly to modernize industries based on
interchangeable manufacturing. The term “precision” best reflects the nature of precision metrology, which is often related to the ratio of resolution/accuracy to range. At present, precision metrology is still playing an important role in precision manufacturing, especially due to its ability to make a wide range of measurements. However, it is difficult for precision metrology to reach a measurement resolution/accuracy better than 100 nm (Figure 0.1), which is required by nanomanufacturing. On the other hand, nanometrology, represented by scanning probe microscopy, is a relatively new measuring technology having only been developed since the 1980s. It can reach a high measurement resolution, down to 0.1 nm. As shown in Figure 0.1, however, nanometrology also cannot satisfy the requirement of nanomanufacturing because the measurement range of nanometrology is typically limited to 1 μm (Working Group on Dimensional Metrology of the Consultative Committee for Length, 1998). In addition, most of the commercial SPM instruments are for qualitative imaging use but not precision enough for quantitative measurement.

This book describes a new field of dimensional metrology called precision nanometrology for nanomanufacturing. Precision nanometrology is referred to as the science of dimensional measurement with nanometric accuracy over a broad measurement range from micrometers to meters. It is innovated through improving the measurement accuracy of precision metrology and expanding the measurement range of nanometrology (Figure 0.1). State-of-the-art sensors and measuring systems of precision nanometrology developed by the author’s research group at Tohoku University are presented. This book especially focuses on the
measurement of surface forms of precision workpieces and stage motions of precision machines, which are important items for nanomanufacturing.

The first half of the book (Chapters 1–4) describes optical sensors used for the measurement of angle and displacement, which are fundamental quantities for precision nanometrology. Technologies for improvement of the sensor sensitivity and bandwidth, reduction of the sensor size as well as development of new multi-axis sensing methods are presented. The methods addressed in this book for detection of the multi-axis positions and angles at a single measuring point are effective for reduction of Abbe errors in various measuring systems.

The second half (Chapters 5–10) presents a number of scanning-type measuring systems for precision nanometrology of surface forms and stage motions. Scanning-type measuring systems have the following advantages: simple structure, flexibility to the size and shape of the specimen, as well as the robustness to the measurement environment. The measuring time can be shortened by increasing the scanning speed. In conventional systems, however, there are still critical issues concerning precision nanometrology that need to be addressed, including reduction of scanning errors, automatic alignment of measuring positions, fast scanning mechanisms, etc. Error separation algorithms and systems for measurement of straightness and roundness, which are the most fundamental geometries treated in nanomanufacturing, are addressed in Chapters 5 and 6. Chapter 7 describes the measurement of micro-aspherics, which requires development in both the scanning mechanism and probing technology. In Chapters 8 and 9, novel systems based on scanning probe microscopy are described for precision nanometrology of micro- and nanostructures in response to new and important challenges from nanomanufacturing. Chapter 10 shows scanning image-sensor systems, which can carry out fast and accurate measurements of micro-dimensions of long structures.

This book is a comprehensive summary of an important part of the research work the author has been involved in over the past ten years. I would like to thank my colleagues and many students in the Nano-Metrology & Control Lab for their marvelous contributions to the technologies addressed in this book. Additionally, a number of students were involved in the preparation of the manuscript. I would also like to acknowledge Mr. Simon Rees, Editorial Assistant at Springer, for helping me to start the writing process and Ms. Claire Protherough, Senior Editorial Assistant, Ms. Katherine Guenthner, Copy Editor, Ms. Sorina Moosdorf, Production Editor, for their dedicated efforts that have made this book possible.

Finally, I wish to express my thanks and dedicate this book to my wife Hong Shen and my daughter Youyang. My wife, a doctor and professor in computer science, has carefully read through and checked the book. This book would never have been completed without their patience, encouragement and assistance. This book is also dedicated to my father who passed away when I was starting my first research project as a graduate student twenty years ago, and to my mother and my parents-in-law for their warm and continuous support.

Sendai, Japan
January 2010

Wei Gao
Contents

1 Angle Sensor for Measurement of Surface Slope and Tilt Motion ............ 1
  1.1 Introduction ........................................................................................................ 1
  1.2 Angle Sensor with Quadrant Photodiode ......................................................... 2
  1.3 Angle Sensor with Photodiode Array ............................................................... 15
  1.4 Angle Sensor with Single-cell Photodiode ..................................................... 28
  1.5 Summary ............................................................................................................ 31
  1.6 References .......................................................................................................... 33

2 Laser Autocollimator for Measurement of Multi-axis Tilt Motion .......... 35
  2.1 Introduction .......................................................................................................... 35
  2.2 Two-axis Laser Autocollimator ......................................................................... 36
  2.3 One-lens Laser Micro-autocollimator ............................................................... 53
  2.4 Three-axis Laser Autocollimator ....................................................................... 56
  2.5 Summary ............................................................................................................. 67
  2.6 References .......................................................................................................... 67

3 Surface Encoder for Measurement of In-plane Motion ....................... 69
  3.1 Introduction .......................................................................................................... 69
  3.2 Surface Encoder for MDOF In-plane Motion .................................................. 70
    3.2.1 Multi-probe-type MDOF Surface Encoder .................................................. 70
    3.2.2 Scanning Laser Beam-type MDOF Surface Encoder ............................... 83
  3.3 Fabrication of Two-axis Sinusoidal Grid for Surface Encoder ................ 90
    3.3.1 Fabrication System .................................................................................. 90
    3.3.2 Analysis and Compensation of Fabrication Error ................................. 91
  3.4 Application of Surface Encoder in Surface Motor-driven Planar Stage .... 99
    3.4.1 Stage System ......................................................................................... 99
    3.4.2 Stage Performance ................................................................................. 104
  3.5 Summary ............................................................................................................. 107
  3.6 References .......................................................................................................... 107
4 Grating Encoder for Measurement of In-plane and Out-of-plane Motion .............................................................. 109
  4.1 Introduction ................................................................................................................................. 109
  4.2 Two-degree-of-freedom Linear Grating Encoder ................................................................. 110
  4.3 Three-axis Grating Encoder with Sinusoidal Grid ............................................................ 129
  4.4 Three-axis Grating Encoder with Rectangular XY-grid .................................................. 136
  4.5 Summary .................................................................................................................................. 140
  4.6 References .............................................................................................................................. 140

5 Scanning Multi-probe System for Measurement of Roundness ................................................. 143
  5.1 Introduction ................................................................................................................................ 143
  5.2 Three-slope Sensor Method .................................................................................................... 144
  5.3 Mixed Method ........................................................................................................................... 157
  5.4 Summary .................................................................................................................................. 169
  5.5 References .............................................................................................................................. 173

6 Scanning Error Separation System for Measurement of Straightness ............................................ 175
  6.1 Introduction ................................................................................................................................ 175
  6.2 Three-displacement Sensor Method with Self Zero-adjustment .......................................... 175
    6.2.1 Three-displacement Sensor Method and Zero-adjustment Error ................................... 175
    6.2.2 Three-displacement Sensor Method with Self Zero-adjustment .................................. 180
  6.3 Error Separation Method for Machine Tool Slide ................................................................... 195
    6.3.1 Slide Straightness Error of Precision Machine Tool .................................................... 195
    6.3.2 Error Separation Method for Slide Straightness Measurement .................................. 195
  6.4 Summary .................................................................................................................................. 208
  6.5 References .............................................................................................................................. 210

7 Scanning Micro-stylus System for Measurement of Micro-aspherics .............................................. 211
  7.1 Introduction ................................................................................................................................ 211
  7.2 Compensation of Scanning Error Motion ................................................................................. 212
  7.3 Micro-stylus Probe .................................................................................................................... 225
    7.3.1 Micro-ball Glass Tube Stylus ............................................................................................. 225
    7.3.2 Tapping-type Micro-stylus .................................................................................................. 233
  7.4 Small-size Measuring Instrument for Micro-aspherics .......................................................... 237
  7.5 Summary .................................................................................................................................. 242
  7.6 References .............................................................................................................................. 242

8 Large Area Scanning Probe Microscope for Micro-textured Surfaces ............................................ 245
  8.1 Introduction ................................................................................................................................ 245
  8.2 Capacitive Sensor-compensated Scanning Probe Microscope ............................................ 246
  8.3 Linear Encoder-compensated Scanning Probe Microscope .................................................. 258
  8.4 Spiral Scanning Probe Microscope ......................................................................................... 266
  8.5 Summary .................................................................................................................................. 279
  8.6 References .............................................................................................................................. 281
9 Automatic Alignment Scanning Probe Microscope System
for Measurement of 3D Nanostructures ..................................................... 283
  9.1 Introduction............................................................................................ 283
  9.2 Optical Probe for Automatic Alignment................................................ 285
      9.2.1 Alignment Principle.................................................................. 285
      9.2.2 Alignment Procedure.............................................................. 288
  9.3 Instrumentation of the Automatic Alignment AFM............................... 299
      9.3.1 Instrument Design .................................................................. 299
      9.3.2 Instrument Performance .......................................................... 305
  9.4 Summary................................................................................................ 317
  9.5 References.............................................................................................. 318

10 Scanning Image-sensor System for Measurement
of Micro-dimensions ..................................................................................... 321
  10.1 Introduction............................................................................................ 321
  10.2 Micro-width Measurement by Scanning Area-image Sensor .......... 322
      10.2.1 Micro-width of Long Tool Slit ............................................... 322
      10.2.2 Evaluation of Slit Width ......................................................... 323
      10.2.3 Scanning Area-image Sensor.................................................. 327
      10.2.4 Slit Width Measurement in Production Line ......................... 331
  10.3 Micro-radius Measurement by Scanning Line-image Sensor .......... 335
      10.3.1 Micro-radius of Long Tool Edge ........................................... 335
      10.3.2 Evaluation of Edge Radius ..................................................... 336
      10.3.3 Edge Radius Measurement in Production Line .................... 341
  10.4 Summary................................................................................................ 350
  10.5 References.............................................................................................. 351

Index .................................................................................................................... 353
Angle Sensor for Measurement of Surface Slope and Tilt Motion

1.1 Introduction

Angle is one of the most fundamental quantities for precision nanometrology. Angle sensors based on the principle of autocollimation, which are conventionally called autocollimators, can accurately measure small tilt angles of a light-reflecting flat surface [1]. Autocollimators have a long history of being used in metrology laboratories for calibration of angle standards, such as polygons, rotary index tables and angle gage blocks. They are also traditionally used in machine shops for surface profile measurements of straightedges, machine tool guideways, precision surface plates, as well as for measurement of tilt error motions of translational stages [2].

In a conventional photoelectric autocollimator, the light rays from a filament lamp are collimated to a parallel light beam with a large beam size, on the order of 30 to 50 mm in diameter [3]. The beam is then projected onto a flat target mirror mounted on the specimen surface. The deviation of the reflected beam with respect to the axis of the incident beam is detected by the autocollimation unit, which is composed of an objective lens and a light position detector placed at the focal plane of the objective lens. Autocollimators using CCD image sensors with image processing can achieve a resolution of up to 0.01 arcsec through employing an objective lens with a long focal length, typically on the order of 300 to 400 mm [3–6]. The large dynamic range of the CCD image sensor also makes the autocollimator have a dynamic range of 60 to 80 dB. However, the requirement of a large target mirror makes it difficult to measure soft specimens such as diamond turned optical surfaces, or thin specimens such as silicon wafers because the target mirror may damage the specimen. The large diameter of the light beam from the filament lamp also limits the lateral resolution for detecting the local slope of a surface. The low bandwidth and large dimension are other disadvantages of conventional autocollimators for the measurement of dynamic tilt error motions of a stage.
This chapter presents angle sensors using different types of photodiodes instead of CCD image sensors for improving the measurement speed and reduction of the sensor size.

1.2 Angle Sensor with Quadrant Photodiode

An angle sensor is a sensor typically for detecting the tilt angle of a surface. Such a sensor with a thin light beam, typically called a surface slope sensor, can also detect surface local slopes. The simplest way to construct an angle sensor is to utilize the method of optical lever. As shown in Figure 1.1, a light beam is projected onto the target surface. The optical spot of the reflected beam on a position photodetector with a distance $L$ from the target will move in the $W$- and $V$-directions if the sample tilts about the $X$- and $Y$-axes. The two-dimensional components of the tilt angle $\theta_X$ and $\theta_Y$ can be calculated from the moving distances $\Delta w$ and $\Delta v$ of the spot on the photodetector as follows:

$$\theta_X = \frac{\Delta w}{2L}, \quad (1.1)$$

$$\theta_Y = \frac{\Delta v}{2L}. \quad (1.2)$$

![Figure 1.1. Detection of tilt angle by the optical level method](image)
This method is simple but errors arise when distance $L$ changes. This problem can be solved by the technique of autocollimation [7]. As shown in Figure 1.2, an objective lens is placed between the sample and the photodetector. If the photodetector is placed at the focal position of the lens, the relationship between the tilt and the readout of the photodetector becomes:

$$\theta_X = \frac{\Delta w}{2f}$$, \hspace{1cm} (1.3)

$$\theta_Y = \frac{\Delta v}{2f}$$, \hspace{1cm} (1.4)

where $f$ is the focal length of the objective lens. As can be seen in Equations 1.3 and 1.4, the distance between the sample surface and the autocollimation unit composed of the objective lens and the position detector does not affect the angle detection.

In the case of form measurements of precision surfaces and motion measurements of precision stages, the angle of interest is very small and the sensitivity of the angle sensor is required to be very high. The sensitivity of the angle sensor based on autocollimation can be improved by choosing an objective lens with a long focal length. However, this will influence the compactness of the angle sensor. Here, we discuss how to improve the sensitivity of the angle sensor by choosing proper photodetectors without increasing the focal length of the lens.

![Figure 1.2. Detection of tilt angle by the autocollimation method with a PSD](image-url)
The linear lateral effect position-sensing device (PSD) is widely used to detect the position of a light spot [8, 9]. PSDs provide continuous position information and have the advantage of good linearity. Position detection is also not affected by the intensity distribution of the light spot. Let the sensitive length of a two-dimensional (2D) PSD be $L_P$ in both $X$- and $Y$-directions. The two-dimensional positions $\Delta v$ and $\Delta w$ can be obtained from the two-dimensional output $v_{PSD\_out}$ and $w_{PSD\_out}$ of the PSD, which are calculated from the photoelectric currents $I_{v1}$, $I_{v2}$, $I_{w1}$, and $I_{w2}$ in Figure 1.2 through the following equations:

$$v_{PSD\_out} = \frac{(I_{v1} - I_{v2})}{(I_{v1} + I_{v2})} \times 100\% = \frac{2}{L_P} \Delta v = \frac{4f}{L_P} \theta_Y , \quad (1.5)$$

$$w_{PSD\_out} = \frac{(I_{w1} - I_{w2})}{(I_{w1} + I_{w2})} \times 100\% = \frac{2}{L_P} \Delta w = \frac{4f}{L_P} \theta_X . \quad (1.6)$$

It can be seen that the sensitivities of a 2D PSD, which are defined as $v_{PSD\_out}/\Delta v$ (or $x_{PSD\_out}/\theta_Y$) and $w_{PSD\_out}/\Delta w$ (or $y_{PSD\_out}/\theta_X$), respectively, are mainly determined by the sensitive length, and are not adjustable. Since the sensitivities are inversely proportional to the sensitive length, a PSD with a short sensitive length is preferred for obtaining high sensitivity. In Equations 1.5 and 1.6, when an objective lens with a focal length of 40 mm is used, a 0.01 arc-second angle $\theta_X$ (or $\theta_Y$) only corresponds to a position change $\Delta w$ (or $\Delta v$) of approximately 4 nm. Assume that the required resolution of the angle sensor is 0.01 arcsec and the dynamic range (measurement range/resolution) is 10,000. The preferred sensitive length of the PSD, which corresponds to the measurement range of the angle sensor, is calculated to be approximately 40 $\mu$m. However, commercially available PSDs typically have sensitive lengths of several millimeters, which generate unnecessarily large measurement ranges of angle. Considering the fact that the practical signal to noise ratios (dynamic ranges) of the current/voltage conversion amplifiers used to pick up the photoelectric currents do not easily exceed 10,000, it is difficult to achieve the required resolution of angle detection, which is determined by the measurement range and the dynamic range. Another parameter to determine the resolution of a PSD is the noise current. The noise current level of a 2D PSD is several times larger than that of a one-dimensional (1D) PSD. From this point of view, it is more feasible to use 1D PSDs instead of 2D PSDs. However, two 1D PSDs, with sensitive directions aligned perpendicularly, are necessary for detecting any 2D angle information. This results in a more complicated structure. Misalignment of the sensitive axes of each PSD will also increase the measurement uncertainty. Moreover, just as with a 2D PSD, the resolution of a 1D PSD will not be high enough, where the resolution is basically dominated by the sensitive length and the dynamic range.

Another possible photodetector is the quadrant photodiode (QPD) [10, 11]. As shown in Figure 1.3, a QPD is placed at or slightly apart from the focal point of the objective lens so that a light spot with a width of $D_S$ is generated on the QPD.
For simplicity, assume the shape of the light spot is rectangular and the intensity distribution of the light spot is uniform. The two-dimensional position of the light spot can be calculated by:

\[ v_{\text{QPD - out}} = \frac{(I_1 + I_3) - (I_2 + I_4)}{(I_1 + I_2 + I_3 + I_4)} \times 100\% = \frac{2}{D_s} \Delta v = \frac{4}{D_s} f \theta_Y, \]  
\[ w_{\text{QPD - out}} = \frac{(I_1 + I_2) - (I_3 + I_4)}{(I_1 + I_2 + I_3 + I_4)} \times 100\% = \frac{2}{D_s} \Delta w = \frac{4}{D_p} f \theta_X, \]

where \( I_1, I_2, I_3, I_4 \) are the photoelectric currents from the QPD cells.

It can be seen that the sensitivity of the QPD for position and/or angle detection is inversely proportional to the width of the light spot on the sensitive window of the QPD. The width of the light spot is a function of the location of the QPD relative to the focal position of the objective lens along the optical axis of the autocollimation unit. A proper measurement range/sensitivity of position and/or angle detection can thus be obtained through adjusting the location of the QPD.