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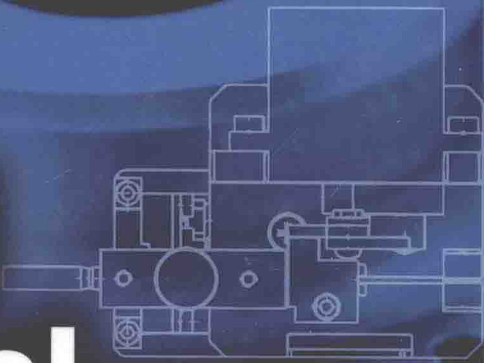

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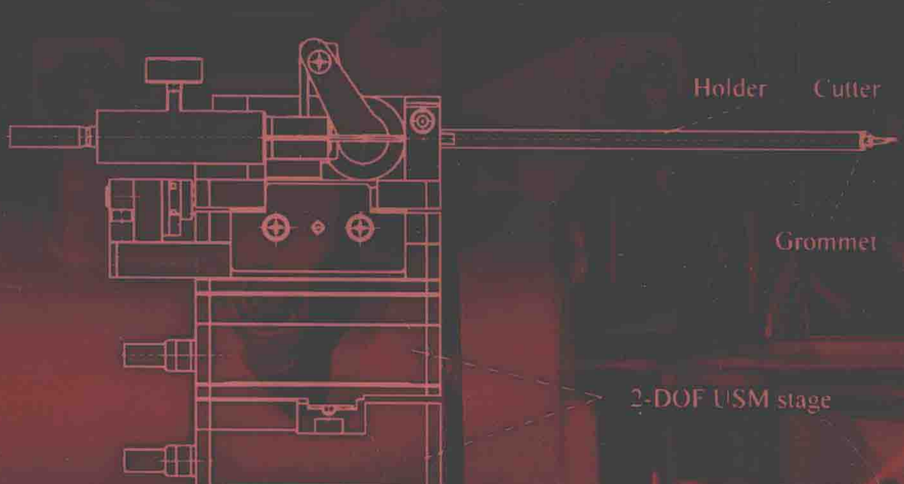

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Preface

Much fundamental research, technologies, and applications are now moving toward achieving high-precision positioning and higher specifications in production, thus achievable with the requirements of precision motion control up to the order of the submicrometer or nanometer level. This is driven by the emergence of current technologies, such as high-precision manufacturing processes, machines, biotechnology, and nanotechnology. From the early 1980s, semiconductor and biomedical industries demanded high-precision actuators to execute more precise positioning and manufacturing in their processes, and the move toward ever-higher precision has continued to now. Requirements pertaining to the precision of motion vary substantially. As such, high-precision actuators are now in high demand, and are expected to perform various types of movements, from rotation to translation, high torque capability, wide speed range, etc. The application areas of high-precision actuators are diverse in aerospace, microelectronics, biomedical engineering, and nanotechnology.

This book is a result of several years of work in the realization of precise actuators. The primary intent of this book is to report new technologies in the area of precision motion control, which can ultimately be applied in industry. It covers dynamical analysis of precise actuators and strategies of design for various control applications. The book consists of eight chapters treating different topics. The content is suitable for graduate students and engineers in precision engineering.

In what follows, the contents of the book are briefly reviewed.

Chapter 1 introduces the driving forces behind precise actuators, several typical types of the actuators, as well as their applications. Chapter 2 describes nonlinear dynamics of precise actuators and their mathematical forms, including hysteresis, creep, friction, and force ripples.

Chapter 3 presents control strategies for precise actuators based on the Preisach model as well as creep dynamics. The identification algorithm is first proposed to estimate Preisach model parameters, and then the inversion feedforward controller is designed for hysteresis compensation. This strategy is mainly for low frequency. For the case where precise actuators work at high bandwidth relative to the resonant frequencies, another identification and compensation strategy is designed. The proposed methods are illustrated by experimental results.

Chapter 4 develops relay feedback techniques for identifying nonlinearities such as friction and force ripples. By converting the closed-loop system into a multiple-relay feedback system, switching conditions of a stable limit cycle are obtained. Hence, friction and force ripples are identified by numerically solving a set of equations. Simulation and real-time experiments show the practical appeal of the proposed method.

Model predictive control (MPC) has become an attractive feedback strategy, especially for linear systems. MPC solves an online optimization to determine inputs, taking into account the current conditions of the plant, any disturbances affecting operation, and imposed safety and physical constraints. Over the last several decades, MPC technology has reached a mature stage. In Chapter 5, we present an MPC approach based on piecewise affine models that emulate the frictional effects in a precise actuator. Specially, an integral MPC design imposes robustness on a model–plant mismatch near zero speed. Implementation of the real-time control is handled by a gain scheduling table so that the complexity is comparable to the traditional feedforward proportional-integral-derivative (PID).

Chapter 6 presents the concepts of air bearing stages with the corresponding control method. A linear air bearing stage is first considered. Since it is a floating object, eddy current braking is introduced into the system. A nonlinear control with proportional-integral (PI) control is designed for dealing with nonlinear terms. Subsequently, a multi-DOF (degrees of freedom) spherical air bearing stage is presented. An adaptive noise filter and a controller for angular positioning are proposed to achieve high performance. Finally, experimental results are given to show the effectiveness of the proposed control algorithm.

Chapter 7 presents a set of schemes suitable for fault detection and accommodation control of mechanical systems. The basic idea of designing a fault detection scheme is to use the information provided by a model-based nonlinear observer to find failure occurrences. The fault detection decision is carried out by comparing the observer outputs with their signatures. After a fault is detected, the controller is reconfigured by incorporating neural networks that are used to capture the nonlinear characteristics of unknown faults. The designed schemes can achieve the automated fault detection and accommodation control using a dead-zone operator.

Chapter 8 is intended to provide readers with a bridge between the design methods of the previous chapters and their applications. With this purpose in mind, the chapter emphasizes the key issues involved and how to implement the precision motion control tasks in a practical system. These issues are demonstrated by three case studies. The first case study describes a robust adaptive control method for positioning piezoelectric actuators (ultrasonic motor) to achieve highly precise motion. Real-time experimental results are provided to verify the effectiveness of the proposed scheme when applied to high-precision motion trajectory tracking, such as intracytoplasmic sperm injection (ICSI). The second case study is focused on a motion control for a two-dimensional stage that is used to treat a common disease called otitis media with effusion (OME), involving a surgeon inserting a grommet in the eardrum to bypass the Eustachian tube to drain fluid when medication fails. The third application is a vision-based real-time temperature monitoring system, where an object recognition and tracking algorithm will be applied to guide a temperature sensor to monitor the temperature of the working tool while it is carrying out operations.

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Tan Kok Kiong
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Huang Sunan earned his PhD degree from Shanghai Jiao Tong University, Shanghai, China, in 1994. Currently, he is a research fellow in the Singapore Institute of Neurotechnology, National University of Singapore. His research interests include error compensation of high-precision machines, adaptive control, neural network control, and rehabilitation robot control.

Contents

1

Introduction

In a wide range of industries, many applications require much higher precision over a high bandwidth and speed than traditional actuators can deliver. This increase in demand for higher-precision motion control has led to many new innovations, including high-speed Maglev transportation systems, robotics machines, micromanipulation systems, semiconductors, and the use of piezoelectric materials to create motion. Precise actuators are the motion enablers of the motion control system. They utilize a physical interaction to convert an electrical energy into mechanical motion to achieve high speed and high accuracy resolution. Developments of such precise actuators and their control technologies will have an impact on a wide range of industries, from medical technology to precision tooling machines and 3D printing. The purpose of this chapter is to discuss the drivers of precise actuators, main types of precise actuators, challenges in their control, and precision applications.

1.1 Growing Interest in Precise Actuators

In recent years, electronic control and machine control have become more efficient as new microprocessors, digital signal processors (DSPs), and other electronics chips are providing the control platform with tremendous computing and processing power. Advances in actuators, such as direct drive motors, piezo motors, coil motors, air bearing motors, linear motors, and brushless motors are reducing traditional issues such as backlash, hysteresis, friction, and parasitic system dynamics. The technical field of precision actuators has expanded significantly over the past 30 years to include design method, error compensation, control, actuator, sensor, fault failure, software platform, and design methodology.

Frequently used actuators in the domain of precision and ultraprecision are piezoelectric actuator (PA) and linear motors. For example, PAs have been applied to products such as a piezoelectric buzzer, a printer head, and ultrasonic motors. In precision engineering applications, PAs have been increasingly employed, such as in modern micro- and nanofabrication, dynamic imaging with scanning probe microscopes (SPMs), and advanced spacecrafts with sensitive optical instruments. With the development of ultra-accurate applications, more stringent requirements are presented [1], which lay out the scope of current techniques.

- High bandwidth: In SPMs, the PAs are required to track at very high rates, which may exceed the resonant frequencies of PAs. Currently, most PAs operate at frequencies less than 10% of the resonant frequencies.
- High accuracy: In addition to high-bandwidth requirements, high accuracy is another requirement for PAs. Moreover, both high bandwidth and high accuracy are current requirements in which the precision tracking is required at rates possibly beyond the resonant frequencies.
- Feedforward control: Feedback control is validated at normal working frequency, but it is limited at frequencies higher than the resonant frequencies due to the measurement noise at high frequencies. The model-based inversion feedforward compensation, which relies on the model identification, is a useful technology to increase the tracking rates and enhance the trajectory tracking accuracy at high frequencies, because the feedforward controller is effective for avoiding the measurement noise that is more serious at high frequencies.

The 2009 global market for piezoelectric-operated actuators and motors was estimated to be 6.6 billion, and the market is estimated to reach 12.3 billion by 2014, showing an average annual growth rate of 13.2% per year [2]. Due to the demand from the consumer electronics market beyond computers, hard disk drive (HDD) demand has been experiencing continual growth over the past decade. It was reported in 2007 that 516.2 million hard disk drives were sold [3]. Meanwhile, the linear motor is gaining attention in precision manufacturing. The main driver of linear motor technology is the ever-increasing performance demand in incremental positioning applications [4]. Unlike rotary machines, linear motors require no indirect coupling mechanisms as in gear boxes, chains, and screws coupling. This greatly reduces the effects of contact-type nonlinearities and disturbances, such as backlash and frictional forces. In addition to precise actuator design, the control of precision systems also has a wide range of applications in high-speed and high-accuracy automation. The growth of nanotechnology and nanoscale manufacturing has further raised the positioning requirements for machine and controller design. The performance of such systems depends on the application of advanced feedback control due to the large-scale system of controlled variables and the uncertainties that might affect the system significantly.

1.2 Types of Precise Actuators

In this book, we will focus mainly on two common types of actuation technology used to achieve linear motion: piezoelectric actuator and linear motor.

1.2.1 Piezoelectric Actuator

The piezoelectric actuator (PA) has become an increasingly popular candidate as a precise actuator in industry, due to its ability to achieve high precision and its versatility to be implemented in various applications. More specifically, the PA can provide very precise positioning (of the order of nanometer) and produce forces from low force (a few grams) to high force (up to a few thousand Newtons). This is because PAs have the following appealing properties:

- High bandwidth (at rates of kHz)
- Small displacement (typically several microns)
- High accuracy (typically subnanometer accuracy)
- High force
- Friction-free (flexible joints are commonly used to avoid generating the friction)
- Minimal static energy consumption
- Small size

The increasingly widespread industrial applications of the PA in various optical fiber alignments, mask alignment, and medical micromanipulation surgical robots are self-evident testimonies of the effectiveness of the PA in these application domains. To obtain maximum performance from PAs, various types have been designed.

1.2.1.1 Stack Actuator

The most popular design for PAs is a stack of ceramic layers separated by thin metallic electrodes, called stack actuator (see Figure 1.1). The stack actuator changes its dimension or size when an electric field with a power supply is applied to it. Such change is very small and produces linear motion. This implies that the stack actuator can achieve high-precision displacements (typically 20 nm). The actuator can also produce different forces according to supply voltage. Commercial products for such stack actuators are available from Physik Instrumente, Kinetic Ceramics, and NEC, which can provide precise positioning in microns or at the nanometer level.

1.2.1.2 Piezoelectric Shear Actuator

Piezoelectric shear actuators are also very common, as shown in Figure 1.2. Compared with linear PAs, shear actuators are adapted for small transverse

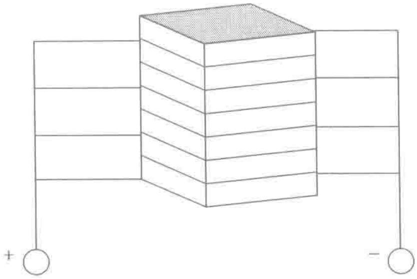

FIGURE 1.1
Piezoelectric stack actuator.

displacements where space is a constraint. They offer very fast response times. The main advantage of the shear actuators is their suitability for a bipolar operational source, whereby the mid-position corresponds to a drive voltage of 0 V. It should be noticed that in a shear actuator, the electric field is applied perpendicular to the polarization direction, which is different from the other types of actuators.

1.2.1.3 Piezoelectric Bending Actuator

In addition to the stack and shear actuators, piezoelectric bending actuators (these actuators are often referred to as benders, piezoelectric cantilevers, or piezoelectric bimorphs) are another important PA. The working principle is that the application of an electric field across the two-layer element produces curvature when one layer expands while the other layer contracts. Typical movement for this kind of actuator is on the micrometer level (from hundreds to thousands of microns), while the bender force generated is small (from tens to hundreds of grams). Figures 1.3 and 1.4 show two common bending configurations that are often used in various applications. The first configuration, as shown in Figure 1.3, is called serial bender and has two piezoelectric layers with two electrodes and an antiparallel polarization connected to each other. The second configuration, as shown in Figure 1.4, is

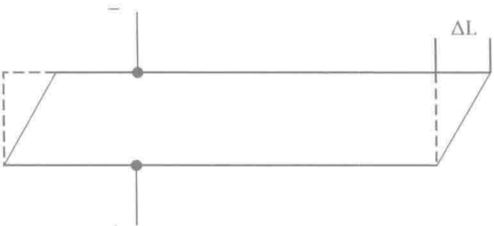

FIGURE 1.2
Piezoelectric shear actuator.