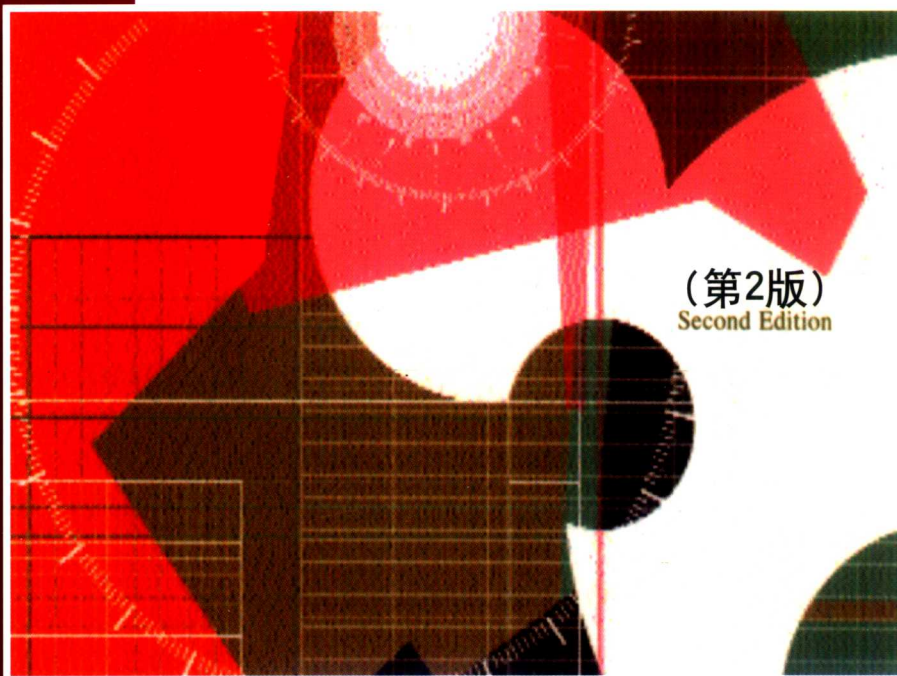


Introduction to Mechatronics
and Measurement Systems

机电一体化与 测量系统基础教程



(第2版)
Second Edition

David G. Alciatore Michael B. Histanal

清华大学出版社



影印版

Introduction to Mechatronics
and Measurement Systems (Second Edition)

机电一体化与 测量系统基础教程 (第2版)

David G. Alciatore Michael R. Hiestand

江苏工业学院图书馆
藏书章

清华大学出版社
北 京

David G. Alciatore, Michael B. Hstand

Introduction to Mechatronics and Measurement Systems, Second Edition

EISBN: 0-07-119557-2(ISE)

Copyright © 2003 by The McGraw-Hill Companies, Inc.

Original language published by The McGraw-Hill Companies, Inc. All Rights reserved. No part of this publication may be reproduced or distributed by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

Authorized English language edition jointly published by McGraw-Hill Education (Asia) Co. and Tsinghua University Press. This edition is authorized for sale only to the educational and training institutions, and within the territory of the People's Republic of China (excluding Hong Kong, Macao SAR and Taiwan). Unauthorized export of this edition is a violation of the Copyright Act. Violation of this Law is subject to Civil and Criminal Penalties.

本书英文影印版由清华大学出版社和美国麦格劳-希尔教育出版(亚洲)公司合作出版。此版本仅限在中华人民共和国境内(不包括中国香港、澳门特别行政区及中国台湾地区)针对教育及培训机构之销售。未经许可之出口,视为违反著作权法,将受法律之制裁。

未经出版者预先书面许可,不得以任何方式复制或抄袭本书的任何部分。

北京市版权局著作权合同登记号 图字: 01-2003-8334

版权所有, 翻印必究。举报电话: 010-62782989 13901104297 13801310933

本书封面贴有 McGraw-Hill 公司防伪标签, 无标签者不得销售。

图书在版编目(CIP)数据

机电一体化和测量系统基础教程 = Introduction to Mechatronics and Measurement Systems: 英文: 第2版 / 阿尔恰托雷 (Alciatore, D. G.), 希斯坦德 (Hstand, M. B.) 著. —影印本. —北京: 清华大学出版社, 2004.9
ISBN 7-302-09058-0

I. 机… II. ①阿… ②希… III. ①机电一体化—高等学校—教材—英文 ②测量系统—高等学校—教材—英文 IV. ①TH-39 ②P2

中国版本图书馆 CIP 数据核字 (2004) 第 070987 号

出版者: 清华大学出版社

地址: 北京清华大学学研大厦

<http://www.tup.com.cn>

邮编: 100084

社总机: (010) 6277 0175

客户服务: (010) 6277 6969

责任编辑: 王一玲

印刷者: 北京市清华园胶印厂

装订者: 三河市化甲屯小学装订二厂

发行者: 新华书店总店北京发行所

开本: 185×230 印张: 31

版次: 2004年9月第1版 2004年9月第1次印刷

书号: ISBN 7-302-09058-0/TH·128

印数: 1~3000

定价: 45.00 元

本书如存在文字不清、漏印以及缺页、倒页、脱页等印装质量问题, 请与清华大学出版社出版部联系调换。联系电话: (010) 62770175-3103 或 (010) 62795704

Introduction to Mechatronics and Measurement Systems, Second Edition

影 印 版 序

Mechatronics (机电一体化或机械电子学) 是机械学科与信息学科结合的一门交叉学科。相应的名词还有机械电子工程, 它不仅包括机械和电子技术, 而且与控制技术和计算机技术结合。不少学校设立了机械电子工程课程和专业, 拓宽了原来的机类或电类专业。国内外有专门的机械电子学学术会议, 会议文章涉及机电 (机光电、机电液等) 技术一体化、微机电系统集成等内容。这些反映了技术发展和对人才需求的一种趋势, 是现代工程技术综合发展的一个重要特征。

本书是一本美国的大学教材, 作者在前言中说明本书用于: (1) 现代仪器和测量课程; (2) 电子和机械工程的一门跨学科课程, 可以替代传统的电路和仪器课程; (3) 独立的机械电子学课程; (4) 机械电子学系列中的初期课程。它的内容包括: 机电一体化和测量系统的名词术语、电路基础和电路分析、半导体电子学、机械电子和测量系统的响应、模拟信号处理和运算放大器、数字器件和集成电路、微控制器编程和接口、数据采集和计算机测量系统、传感器、执行器、机械电子系统的控制体系结构。本书未涉及控制理论。

本书的特点是: (1) 注重对基本概念和基本知识的阐述, 理论联系实际, 并附有参考书目, 便于阅读; (2) 每章有联系实际的课堂讨论题目, 每节有大量的例题, 习题和思考题, 有利于学生深入思考, 学习分析和解决问题。培养这些能力十分重要, 本书在这方面的努力是值得提倡的。(3) 本书综合选择了电路、电子、计算机接口和测试技术的相关内容, 这是一种方案。由于机械电子工程专业、机或电类专业设置的课程数量增加, 必然要优化教学课程设置和减少课程学时。但根据不同专业的要求, 对本课程的内容会有不同考虑的, 在宽与深、各模块与体系结构的关系会有不同的选择。

本书的内容结构和我国高校的课程体系虽然有些差别, 但仍是一本很好的参考书和英文教材。本书可作为机、电、仪等相关专业的学生、教师和工程技术人员的参考教材或参考书。

周兆英 教授
清华大学精密仪器与机械学系
2004 年 4 月 28 日

APPROACH

The formal boundaries of traditional engineering disciplines have become fuzzy following the advent of integrated circuits and computers. Nowhere is this more evident than in mechanical and electrical engineering, where products today include an assembly of interdependent electrical and mechanical components. The field of mechatronics has broadened the scope of the traditional field of electromechanics. *Mechatronics* is defined as the field of study involving the analysis, design, synthesis, and selection of systems that combine electronic and mechanical components with modern controls and microprocessors.

This book is designed to serve as a text for (1) a modern instrumentation and measurements course, (2) a hybrid electrical and mechanical engineering course replacing traditional circuits and instrumentation courses, (3) a stand-alone mechatronics course, or (4) the first course in a mechatronics sequence. The second option, the hybrid course, provides an opportunity to reduce the number of credit hours in a typical mechanical engineering curriculum. Options 3 and 4 could involve the development of new interdisciplinary courses.

Currently, many curricula do not include a mechatronics course but include some of the elements in other, more traditional courses. The purpose of a course in mechatronics is to provide a focused interdisciplinary experience for undergraduates that encompasses important elements from traditional courses as well as contemporary developments in electronics and computer control. These elements include measurement theory, electronic circuits, computer interfacing, sensors, actuators, and the design, analysis, and synthesis of mechatronic systems. This interdisciplinary approach is valuable to students because virtually every newly designed engineering product is a mechatronic system.

CONTENT

Chapter 1 introduces mechatronic and measurement system terminology. Chapter 2 provides a review of basic electrical relations, circuit elements, and circuit analysis. Chapter 3 deals with semiconductor electronics. Chapter 4 presents approaches to analyzing and characterizing the response of mechatronic and measurement systems. Chapter 5 covers the basics of analog signal processing and the design and analysis of operational amplifier circuits. Chapter 6 presents the basics of digital devices and the use of integrated circuits. Chapter 7 provides an introduction to microcontroller programming and interfacing, and specifically covers the PIC microcontroller and PicBasic Pro programming. Chapter 8 deals with data acquisition and how to couple computers to measurement systems. Chapter 9 provides an overview of the many

sensors common in mechatronic systems. Chapter 10 introduces a number of devices used for actuating mechatronic systems. Finally, Chapter 11 provides an overview of mechatronic system control architectures and presents some case studies. The appendices review the fundamentals of unit systems, statistics, error analysis, and mechanics of materials to support and supplement measurement systems topics in the book. One mechatronics topic this book does not cover is control theory. This topic is important and should be included in a curriculum that emphasizes mechatronics, but we decided it would be impractical to adequately cover the topic in this book.

LEARNING TOOLS

Class discussion items are included throughout the book to serve as thought-provoking exercises for the students and instructor-led cooperative learning activities in the classroom. They can also be used as out-of-class homework assignments to supplement the questions and exercises at the end of each chapter. Analysis and design examples are also provided throughout the book to improve a student's ability to apply the material. To enhance student learning, carefully designed laboratory exercises coordinated with the lectures should accompany a course using this text. The combination of class discussion items, design examples, and laboratory exercises exposes a student to a real-world practical approach and provides a useful framework for future design work.

SUPPLEMENTS

More information, including a recommended course outline, a typical laboratory syllabus, MathCAD files for examples from the book, Class Discussion Item hints, links to mechatronics resources, and other supplemental material, is available on the author's Internet site at

www.engr.colostate.edu/~dga/mechatronics.html

These resources, and a complete, password-protected Instructor's Guide containing solutions to all end-of-chapter problems, are also available at the McGraw-Hill Book Website at:

www.mhhe.com/engcs/mech/alciatore/

ACKNOWLEDGMENTS

To ensure the accuracy of this text, it has been class-tested at Colorado State University and the University of Wyoming. We'd like to thank all of the students at both institutions who provided us valuable feedback throughout this process. In addition, we'd like to thank our many reviewers for their valuable input. The second edition manuscript was reviewed by the following people in the field of mechatronics:

Burford Furman *San Jose State University*

Jan Paul Huisson *University of Waterloo*

Y. C. Lee *University of Colorado*

E. I. Meletis *Louisiana State University*
Donald G. Morin *Rose-Hulman Institute of Technology*
Satish Nair *University of Missouri–Columbia*
Yuen-Cjen Yong *California Polytechnic State University*
David Walrath *University of Wyoming*

We would again like to acknowledge the reviewers of the first edition of the book for their valuable contributions:

J. Edward Carryer *Stanford University*
Melvin R. Corley *Louisiana Tech University*
Louis Everett *Texas A&M University*
Jawarharlal Mariappan *Kettering University*
Donald G. Morin *Rose-Hulman Institute of Technology*
Ramendra P. Roy *Arizona State University*
Ahmad Smaili *Tennessee Technological University*
Gregory P. Starr *University of New Mexico*
Charles Ume *Georgia Institute of Technology*
David E. Walrath *University of Wyoming*

CONTENTS

Chapter 1

Introduction to Mechatronics and Measurement Systems 1

- 1.1 Mechatronics 1
- 1.2 Measurement Systems 4

Chapter 2

Electric Circuits and Components 6

- 2.1 Introduction 7
- 2.2 Basic Electrical Elements 9
 - 2.2.1 Resistor 10
 - 2.2.2 Capacitor 13
 - 2.2.3 Inductor 14
- 2.3 Kirchhoff's Laws 16
 - 2.3.1 Series Resistance Circuit 18
 - 2.3.2 Parallel Resistance Circuit 20
- 2.4 Voltage and Current Sources and Meters 23
- 2.5 Thevenin and Norton Equivalent Circuits 29
- 2.6 Alternating Current Circuit Analysis 30
- 2.7 Power in Electrical Circuits 36
- 2.8 Transformer 38
- 2.9 Impedance Matching 39

- 2.10 Grounding and Electrical Interference 41

- 2.10.1 Electrical Safety 44

Chapter 3

Semiconductor Electronics 53

- 3.1 Introduction 54
- 3.2 Semiconductor Physics as the Basis for Understanding Electronic Devices 54
- 3.3 Junction Diode 56
 - 3.3.1 Zener Diode 60
 - 3.3.2 Voltage Regulators 65
 - 3.3.3 Optoelectronic Diodes 66
 - 3.3.4 Analysis of Diode Circuits 67
- 3.4 Bipolar Junction Transistor 70
 - 3.4.1 Bipolar Transistor Physics 70
 - 3.4.2 Common Emitter Transistor Circuit 72
 - 3.4.3 Bipolar Transistor Switch 74
 - 3.4.4 Bipolar Transistor Packages 77
 - 3.4.5 Darlington Transistor 77
 - 3.4.6 Phototransistor and Opto-Isolator 78
- 3.5 Field Effect Transistors 80
 - 3.5.1 Behavior of Field-Effect Transistors 81
 - 3.5.2 Symbols Representing Field Effect Transistors 83
 - 3.5.3 Applications of MOSFETs 84

Chapter 4

System Response 96

- 4.1 System Response 97
- 4.2 Amplitude Linearity 98
- 4.3 Fourier Series Representation of Signals 99
- 4.4 Bandwidth and Frequency Response 102

- 4.5 Phase Linearity 108
- 4.6 Distortion of Signals 109
- 4.7 Dynamic Characteristics of Systems 110
- 4.8 Zero-Order System 111
- 4.9 First-Order System 112
 - 4.9.1 *Experimental Testing of a First-Order System* 114
- 4.10 Second-Order System 115
 - 4.10.1 *Step Response of a Second-Order System* 119
 - 4.10.2 *Frequency Response of a System* 121
- 4.11 System Modeling and Analogies 130

Chapter 5

Analog Signal Processing Using Operational Amplifiers 141

- 5.1 Introduction 142
- 5.2 Amplifiers 142
- 5.3 Operational Amplifiers 144
- 5.4 Ideal Model for the Operational Amplifier 144
- 5.5 Inverting Amplifier 147
- 5.6 Noninverting Amplifier 150
- 5.7 Summer 152
- 5.8 Difference Amplifier 152
- 5.9 Instrumentation Amplifier 155
- 5.10 Integrator 157
- 5.11 Differentiator 158
- 5.12 Sample and Hold Circuit 159
- 5.13 Comparator 160
- 5.14 The Real Op Amp 161
 - 5.14.1 *Important Parameters from Op Amp Data Sheets* 163

Chapter 6

Digital Circuits 178

- 6.1 Introduction 179
- 6.2 Digital Representations 180
- 6.3 Combinational Logic and Logic Classes 183
- 6.4 Timing Diagrams 186

- 6.5 Boolean Algebra 187
- 6.6 Design of Logic Networks 189
 - 6.6.1 *Define the Problem in Words* 189
 - 6.6.2 *Write Quasi-Logic Statements* 190
 - 6.6.3 *Write the Boolean Expression* 190
 - 6.6.4 *AND Realization* 191
 - 6.6.5 *Draw the Circuit Diagram* 191

- 6.7 Finding a Boolean Expression Given a Truth Table 192

- 6.8 Sequential Logic 194

- 6.9 Flip-Flops 195
 - 6.9.1 *Triggering of Flip-Flops* 196
 - 6.9.2 *Asynchronous Inputs* 198
 - 6.9.3 *D Flip-Flop* 199
 - 6.9.4 *JK Flip-Flop* 200

- 6.10 Applications of Flip-Flops 203
 - 6.10.1 *Switch Debouncing* 203
 - 6.10.2 *Data Register* 204
 - 6.10.3 *Binary Counter and Frequency Divider* 205
 - 6.10.4 *Serial and Parallel Interfaces* 205

- 6.11 TTL and CMOS Integrated Circuits 207
 - 6.11.1 *Using Manufacturer IC Data Sheets* 209
 - 6.11.2 *Digital IC Output Configurations* 213
 - 6.11.3 *Interfacing TTL and CMOS Devices* 215

- 6.12 Special Purpose Digital Integrated Circuits 217
 - 6.12.1 *Decade Counter* 217
 - 6.12.2 *Schmitt Trigger* 220
 - 6.12.3 *555 Timer* 220

- 6.13 Integrated Circuit System Design 224
 - 6.13.1 *IEEE Standard Digital Symbols* 227

Chapter 7

Microcontroller Programming and Interfacing 238

- 7.1 Microprocessors and Microcomputers 239
- 7.2 Microcontrollers 242
- 7.3 The PIC16F84 Microcontroller 244
- 7.4 Programming a PIC 248

7.5 PicBasic Pro	254
7.5.1 <i>PicBasic Pro Programming Fundamentals</i>	254
7.5.2 <i>PicBasic Pro Programming Examples</i>	262
7.6 Using Interrupts	274
7.7 Interfacing Common PIC Peripherals	277
7.7.1 <i>Numeric Keypad</i>	278
7.7.2 <i>LCD Display</i>	280
7.8 Interfacing to the PIC	282
7.8.1 <i>Digital Input to the PIC</i>	284
7.8.2 <i>Digital Output from the PIC</i>	287
7.9 Method to Design a Microcontroller-Based System	287

Chapter 8

Data Acquisition 297

8.1 Introduction	298
8.2 Quantizing Theory	302
8.3 Analog-to-Digital Conversion	303
8.3.1 <i>Introduction</i>	303
8.3.2 <i>Analog-to-Digital Converters</i>	307
8.4 Digital-to-Analog (D/A) Conversion	310

Chapter 9

Sensors 315

9.1 Introduction	316
9.2 Position and Speed Measurement	316
9.2.1 <i>Proximity Sensors and Switches</i>	317
9.2.2 <i>Potentiometer</i>	318
9.2.3 <i>Linear Variable Differential Transformer</i>	319
9.2.4 <i>Digital Optical Encoder</i>	322
9.3 Stress and Strain Measurement	330
9.3.1 <i>Electrical Resistance Strain Gage</i>	330
9.3.2 <i>Measuring Resistance Changes with a Wheatstone Bridge</i>	335
9.3.3 <i>Measuring Different States of Stress with Strain Gages</i>	339
9.3.4 <i>Force Measurement with Load Cells</i>	345

9.4 Temperature Measurement	347
9.4.1 <i>Liquid-in-Glass Thermometer</i>	348
9.4.2 <i>Bimetallic Strip</i>	348
9.4.3 <i>Electrical Resistance Thermometer</i>	349
9.4.4 <i>Thermocouple</i>	349
9.5 Vibration and Acceleration Measurement	357
9.5.1 <i>Piezoelectric Accelerometer</i>	362
9.6 Pressure and Flow Measurement	366
9.7 Semiconductor Sensors and Microelectromechanical Devices	366

Chapter 10

Actuators 372

10.1 Introduction	373
10.2 Electromagnetic Principles	373
10.3 Solenoids and Relays	374
10.4 Electric Motors	376
10.5 DC Motors	383
10.5.1 <i>DC Motor Electrical Equations</i>	386
10.5.2 <i>Permanent Magnet DC Motor Dynamic Equations</i>	386
10.5.3 <i>Electronic Control of a Permanent Magnet DC Motor</i>	389
10.6 Stepper Motors	393
10.6.1 <i>Stepper Motor Drive Circuits</i>	397
10.7 Selecting a Motor	400
10.8 Hydraulics	404
10.8.1 <i>Hydraulic Valves</i>	406
10.8.2 <i>Hydraulic Actuators</i>	410
10.9 Pneumatics	411

Chapter 11

Mechatronic Systems—Control Architectures and Case Studies 416

11.1 Introduction	417
11.2 Control Architectures	417
11.2.1 <i>Analog Circuits</i>	417
11.2.2 <i>Digital Circuits</i>	418

11.2.3 Programmable Logic Controller	418
11.2.4 Microcontroller	418
11.2.5 Single-Board Computer	418
11.2.6 Personal Computer	419
11.3 Case Study 1—Mechatronic Design of a Coin Counter	419
11.4 Case Study 2—Mechatronic Design of a Robotic Walking Machine	429
11.5 List of Various Mechatronic Systems	435
 <u>Appendix A</u>	
Measurement Fundamentals	437
A.1 Systems of Units	437
A.1.1 Three Classes of SI Units	439
A.1.2 Conversion Factors	441
A.2 Significant Figures	442
A.3 Statistics	444
A.4 Error Analysis	447
A.4.1 Rules for Estimating Errors	448
 <u>Appendix B</u>	
Physical Principles	451
 <u>Appendix C</u>	
Mechanics of Materials	456
C.1 Stress and Strain Relations	456
 Index	461

- 1.1 Mechatronic system components 3
- 1.2 Elements of a measurement system 4

- 2.1 Electrical circuits 8
- 2.2 Electric circuit terminology 8
- 2.3 Basic electrical elements 9
- 2.4 Voltage-current relation for an ideal resistor 10
- 2.5 Wire resistance 10
- 2.6 Resistor packaging 11
- 2.7 Wire-lead resistor color bands 12
- 2.8 Potentiometer schematic symbols 13
- 2.9 Parallel plate capacitor 14
- 2.10 Inductor flux linkage 15
- 2.11 Kirchhoff's voltage law 16
- 2.12 Kirchhoff's current law 18
- 2.13 Series resistance circuit 18
- 2.14 Parallel resistance circuit 20
- 2.15 Real voltage source with output impedance 24
- 2.16 Example of a commercially available power supply 24
- 2.17 Real current source with output impedance 25
- 2.18 Real ammeter with input impedance 25
- 2.19 Real voltmeter with input impedance 25
- 2.20 Examples of commercially available digital multimeters 26
- 2.21 Example of a commercially available oscilloscope 26
- 2.22 Example illustrating Thevenin's theorem 29
- 2.23 Thevenin equivalent circuit 30
- 2.24 Norton equivalent circuit 30
- 2.25 Sinusoidal waveform 31
- 2.26 Phasor representation of a sinusoidal signal 33
- 2.27 Power in a circuit element 36
- 2.28 Transformer 38
- 2.29 Signal termination 39
- 2.30 Impedance matching—string analogy 40
- 2.31 Impedance matching 40
- 2.32 Common ground 42
- 2.33 Inductive coupling 43
- 2.34 Three-prong AC power plug 44

- 3.1 Valence and conduction bands of materials 55
- 3.2 pn junction characteristics 56
- 3.3 Silicon diode 57
- 3.4 Diode check valve analogy 57
- 3.5 Ideal, approximate, and real diode curves 58
- 3.6 Zener diode symbol and current-voltage relationship 61
- 3.7 Zener diode voltage regulator 61
- 3.8 Zener diode voltage regulator circuit 63
- 3.9 15 V regulated DC supply 65
- 3.10 1.2 to 37 V adjustable regulator 66
- 3.11 Light-emitting diode (LED) 67
- 3.12 Photodiode light detector circuit 67
- 3.13 npn bipolar junction transistor 71
- 3.14 pnp bipolar junction transistor 71
- 3.15 Common emitter circuit 73
- 3.16 Common emitter characteristics for a transistor 73
- 3.17 Transistor switch circuit 75
- 3.18 Models for transistor switch states 75
- 3.19 Bipolar transistor packages 77
- 3.20 Darlington pair 77

- 3.21 Opto-isolator 78
- 3.22 n-channel enhancement-mode MOSFET 81
- 3.23 Enhancement-mode MOSFET n-channel formation 81
- 3.24 n-channel enhancement-mode MOSFET characteristic curves 82
- 3.25 p-channel enhancement-mode MOSFET 82
- 3.26 Field effect transistor schematic symbols 83
- 3.27 MOSFET power switch circuit 84
- 3.28 MOSFET analog switch circuit 85

- 4.1 Measurement system input-output 97
- 4.2 Amplitude linearity and nonlinearity 98
- 4.3 Square wave 100
- 4.4 Harmonic decomposition of a square wave 101
- 4.5 Spectrum of a square wave 102
- 4.6 Frequency response and bandwidth 103
- 4.7 Effect of measurement system bandwidth on signal spectrum 105
- 4.8 Relationship between phase and time displacement 108
- 4.9 Amplitude distortion of a square wave 110
- 4.10 Phase distortion of a square wave 110
- 4.11 Displacement potentiometer 112
- 4.12 First-order response 114
- 4.13 Experimental determination of τ 115
- 4.14 Second-order mechanical system and free-body diagram 116
- 4.15 Strip chart recorder as an example of a second-order system 117
- 4.16 Transient response of second-order systems 119
- 4.17 Second-order step responses 120
- 4.18 Features of an underdamped step response 120
- 4.19 Second-order system amplitude response 123
- 4.20 Second-order phase response 124
- 4.21 Example of system analogies 131
- 4.22 Mechanical system analogy example 133
- 4.23 Beginning the analog schematic 134
- 4.24 Electrical system analogy example 134

- 5.1 Amplifier model 143
- 5.2 Op amp terminology and schematic representation 144
- 5.3 Op amp feedback 145
- 5.4 Op amp equivalent circuit 145
- 5.5 741 op amp pin-out 146
- 5.6 741 internal design 147
- 5.7 Inverting amplifier 148
- 5.8 Equivalent circuit for inverting amplifier 148
- 5.9 Illustration of inversion 149
- 5.10 Noninverting amplifier 150
- 5.11 Equivalent circuit for noninverting amplifier 150
- 5.12 Buffer or follower 151
- 5.13 Summer circuit 152
- 5.14 Difference amplifier circuit 152
- 5.15 Difference amplifier with V_2 shorted 153
- 5.16 Difference amplifier with V_1 shorted 154
- 5.17 Instrumentation amplifier 155
- 5.18 Ideal integrator 157
- 5.19 Improved integrator 158
- 5.20 Differentiator 159
- 5.21 Sample and hold circuit 160
- 5.22 Comparator 160
- 5.23 Comparator open collector output 161
- 5.24 Effect of slew rate on a square wave 162
- 5.25 Typical op amp open- and closed-loop response 163
- 5.26 Example op amp data sheet 165
- 5.27 TL071 FET input op amp 167

- 6.1 Analog and digital signals 179
- 6.2 AND gate timing diagram 186
- 6.3 OR gate timing diagram 186

- 6.4** AND realization schematic of the security system 191
- 6.5** Clock pulse edges 194
- 6.6** RS flip-flop 195
- 6.7** RS flip-flop internal design and timing 196
- 6.8** Edge-triggered RS flip-flops 197
- 6.9** Positive edge-triggered RS flip-flop timing diagram 198
- 6.10** Latch 198
- 6.11** Latch timing diagram 199
- 6.12** Preset and clear flip-flop functions 199
- 6.13** Positive edge-triggered D flip-flop 200
- 6.14** Negative edge-triggered JK flip-flop 200
- 6.15** Positive edge-triggered T flip-flop 201
- 6.16** Switch bounce 203
- 6.17** Switch debouncer circuit 204
- 6.18** 4-bit data register 204
- 6.19** 4-bit binary counter 205
- 6.20** Serial-to-parallel converter 206
- 6.21** Parallel-to-serial converter 206
- 6.22** TTL and CMOS input and output levels 207
- 6.23** TTL and CMOS output circuits 208
- 6.24** NAND gate internal design 210
- 6.25** QUAD NAND gate IC pin-out 210
- 6.26** DM74LS00 NAND gate IC data sheet 211
- 6.27** CMOS 4011B NAND gate internal design 212
- 6.28** CMOS 4011B NAND gate IC data sheet 213
- 6.29** Open collector output with pull-up resistor 214
- 6.30** Interfacing TTL to digital devices 215
- 6.31** Interfacing CMOS to digital devices 216
- 6.32** Decade counter timing 217
- 6.33** Cascaded decade counters 218
- 6.34** Seven-segment LED display 218
- 6.35** 7447 internal design 219
- 6.36** 7447 output circuit 219
- 6.37** Input and output of a Schmitt trigger 220
- 6.38** Block diagram of the 555 IC 221
- 6.39** 555 pin-out 221
- 6.40** Monostable multivibrator (one-shot) 222
- 6.41** One-shot timing 222
- 6.42** Astable pulse generator 223
- 6.43** IEEE standard symbols for digital ICs 228
- 7.1** Microcomputer architecture 240
- 7.2** Components of a typical full-featured microcontroller 243
- 7.3** PIC16F84 block diagram 245
- 7.4** PIC16F84 pin-out and required external components 246
- 7.5** Reset switch circuit 247
- 7.6** Circuit schematic for the flash.bas example 255
- 7.7** Interrupt example schematic 276
- 7.8** Numeric keypad 278
- 7.9** Numeric keypad schematic and PIC interface 278
- 7.10** LCD PIC interface 281
- 7.11** Block diagram for pins RA0 through RA3 283
- 7.12** Block diagram for pin RA4 283
- 7.13** Block diagram for pins RB4 through RB7 284
- 7.14** Block diagram for pins RB0 through RB3 285
- 7.15** Interface circuits for input devices 285
- 7.16** Interface circuits for output devices 286
- 7.17** Software flowchart building blocks 288
- 8.1** Analog signal and sampled equivalent 298
- 8.2** Aliasing 299
- 8.3** Analog-to-digital conversion 302
- 8.4** Components used in A/D conversion 304
- 8.5** Example data acquisition and control card 305
- 8.6** Example data acquisition and control card architecture 305
- 8.7** A/D conversion aperture time 306

- 8.8 Successive approximation A/D converter 307
- 8.9 4-bit successive approximation A/D conversion 308
- 8.10 A/D flash converter 309
- 8.11 4-bit resistor ladder D/A converter 310
- 8.12 4-bit resistor ladder D/A with digital input 0001 311
- 8.13 Computer control hardware 312
- 9.1 Various configurations for photoemitter-detector pairs 317
- 9.2 Example of a photoemitter-detector pair in a single housing 317
- 9.3 Switches 318
- 9.4 Potentiometer 319
- 9.5 Linear variable differential transformer 319
- 9.6 LVDT linear range 320
- 9.7 LVDT demodulation 320
- 9.8 LVDT output filter 321
- 9.9 Commercial LVDT 322
- 9.10 Components of an optical encoder 323
- 9.11 4-bit gray code absolute encoder disk track patterns 324
- 9.12 4-bit natural binary absolute encoder disk track patterns 325
- 9.13 Gray-code-to-binary-code conversion 326
- 9.14 Incremental encoder disk track patterns 327
- 9.15 Quadrature direction sensing and resolution enhancement 328
- 9.16 1X quadrature decoder circuit 329
- 9.17 Metal foil strain gage construction 331
- 9.18 Strain gage application 332
- 9.19 Rectangular conductor 333
- 9.20 Static balanced bridge circuit 335
- 9.21 Dynamic unbalanced bridge circuit 336
- 9.22 Leadwire effects in 1/4 bridge circuits 338
- 9.23 Temperature compensation with a dummy gage in half bridge 339
- 9.24 Bar under uniaxial stress 339
- 9.25 Biaxial stress in a long, thin-walled pressure vessel 340
- 9.26 General state of planar stress on the surface of a component 342
- 9.27 Assortment of different strain gage and rosette configurations 342
- 9.28 Most common strain gage rosette configurations 342
- 9.29 Rectangular strain gage rosette 343
- 9.30 Various three-gage commercial rosettes 343
- 9.31 Typical axial load cells 345
- 9.32 Bimetallic strip 348
- 9.33 Thermoelectric junction 349
- 9.34 Thermocouple circuit 350
- 9.35 Law of leadwire temperatures 350
- 9.36 Law of intermediate leadwire metals 351
- 9.37 Law of intermediate junction metals 351
- 9.38 Law of intermediate temperatures 352
- 9.39 Law of intermediate metals 352
- 9.40 Standard thermocouple configuration 353
- 9.41 Attaching leadwires of selected metal 353
- 9.42 Thermopile 354
- 9.43 Thermocouple types and characteristics 356
- 9.44 Accelerometer displacement references and free-body diagram 357
- 9.45 Ideal accelerometer amplitude response 360
- 9.46 Ideal accelerometer phase response 360
- 9.47 Vibrometer amplitude response 362
- 9.48 Piezoelectric accelerometer construction 362
- 9.49 Equivalent circuit for piezoelectric crystal 364
- 9.50 Thevenin equivalent of piezoelectric crystal 364
- 9.51 Piezoelectric accelerometer frequency response 365
- 9.52 Surface acoustic wave transponder device 367
- 10.1 Right-hand rule for magnetic force 374
- 10.2 Solenoids 375
- 10.3 Voice coil 375

- 10.4** Classification of electric motors 376
- 10.5** Motor construction and terminology 377
- 10.6** Examples of commercial motors 378
- 10.7** Electric motor field-current interaction 379
- 10.8** Electric motor six-winding commutator 380
- 10.9** Electric motor field-field interaction 381
- 10.10** Motor torque-speed curve 383
- 10.11** DC permanent magnet motor schematic and torque-speed curve 384
- 10.12** DC shunt motor schematic and torque-speed curve 384
- 10.13** DC series motor schematic and torque-speed curve 384
- 10.14** DC compound motor schematic and torque-speed curve 385
- 10.15** Motor armature equivalent circuit 386
- 10.16** Permanent magnet DC motor characteristics 388
- 10.17** Pulse width modulation of a DC motor 389
- 10.18** PWM velocity feedback control 390
- 10.19** PWM voltage and motor current 391
- 10.20** Stepper motor step sequence 394
- 10.21** Dynamic response of a single step 395
- 10.22** Stepper motor torque-speed curves 395
- 10.23** Standard unipolar stepper motor field coil schematic 396
- 10.24** Example of a unipolar stepper motor 396
- 10.25** Typical stepper motor rotor and stator configuration 398
- 10.26** Actual stepper motor rotor 398
- 10.27** Unipolar stepper motor full-step drive circuit 398
- 10.28** Timing diagram for full-step unipolar stepper motor drive circuit 399
- 10.29** Typical stepper motor performance curves 400
- 10.30** Typical servomotor performance curves 401
- 10.31** Motor operating speed 403
- 10.32** Hydraulic system components 404
- 10.33** Gear pump 405
- 10.34** Vane pump 405
- 10.35** Swash plate piston pump 406
- 10.36** Pressure regulator 407
- 10.37** 4/3 valve schematic 407
- 10.38** Double-acting hydraulic cylinder 407
- 10.39** Check and poppet valves 408
- 10.40** Spool valve 409
- 10.41** Pilot-operated spool valve 410
- 10.42** Single-acting and double-acting cylinders 410
- 10.43** Example mechanisms driven by a hydraulic cylinder 411
- 10.44** Pneumatic system components 412
- 11.1** Example of coin counter presentation mechanisms 420
- 11.2** Sensor array and chute design 422
- 11.3** TTL outputs corresponding to different coins 423
- 11.4** Counter design 1 424
- 11.5** Counter design 2 426
- 11.6** Student-designed walking machines from Colorado State University 430
- 11.7** Aluminum frame and telescoping pneumatic legs 432
- 11.8** Flowchart for forward motion routine 433
- 11.9** Pneumatic system 434
- 11.10** Computer ports and I/O board 434
- A.1** Histogram of experimental data 445
- A.2** Distributions of data 445
- A.3** Accuracy and precision 448
- C.1** Axial and transverse deformation of a cylindrical bar 457
- C.2** General state of planar stress and principal stresses 458
- C.3** Mohr's circle of plane stresses 459

TABLES

- 2.1 Resistivities of common conductors 11
- 2.2 Resistor color band codes 12
- 4.1 Second-order system modeling analogies 130
- 6.1 Decimal to binary conversion 181
- 6.2 Hexadecimal symbols and equivalents 182
- 6.3 Combinational logic operations 184
- 6.4 Truth table for the RS flip-flop 195
- 6.5 Positive edge-triggered RS flip-flop truth table 197
- 6.6 Latch truth table 198
- 6.7 Positive edge-triggered D flip-flop truth table 200
- 6.8 Truth for a negative edge-triggered JK flip-flop 201
- 6.9 Positive edge-triggered T flip-flop truth table 202
- 6.10 7490 decade counter BCD coding 217
- 6.11 7447 BCD to seven-segment decoder 218
- 7.1 PIC16F84 pin name descriptions 247
- 7.2 PIC16F84 instruction set 249
- 7.3 Selected PicBasic Pro math operators and functions 257
- 7.4 PicBasic Pro logical comparison operators 259
- 7.5 PicBasic Pro statement summary 260
- 7.6 Liquid crystal display pin descriptions 282
- 8.1 2-bit flash converter output 309
- 9.1 4-bit gray and natural binary codes 326
- 9.2 Thermocouple data 355
- 10.1 Unipolar full-step phase sequence 397
- 10.2 Unipolar half-step phase sequence 397
- 10.3 Comparison of pump characteristics 406
- A.1 SI base units 439
- A.2 Examples of SI-derived units expressed in terms of base units 439
- A.3 SI-derived units with special names (supplemental units) 440
- A.4 Unit prefixes 440
- A.5 Useful English to SI conversion factors 441
- A.6 Set of experimental data 445