

# Contents

Preface with Publisher's Acknowledgements xv

---

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Introduction	1
1.2	A Short Historical Note	3
1.3	Definitions	4
1.4	Classification of Sensors and Actuators	12
1.5	General Requirements for Interfacing	16
1.6	Units	18
1.6.1	<i>Base SI Units</i>	18
1.6.2	<i>Derived Units</i>	19
1.6.3	<i>Supplementary Units</i>	20
1.6.4	<i>Customary Units</i>	20
1.6.5	<i>Prefixes</i>	22
1.6.6	<i>Other Units and Measures</i>	22
	1.6.6.1 Units of Information	22
	1.6.6.2 The Decibel (dB) and Its Use	23
1.7	Problems	26
<hr/>		
<b>2</b>	<b>Performance Characteristics of Sensors and Actuators</b>	<b>31</b>
2.1	Introduction	31
2.2	Input and Output Characteristics	32
2.2.1	<i>Transfer Function</i>	32
2.2.2	<i>Impedance and Impedance Matching</i>	35
2.2.3	<i>Range, Span, Input and Output Full Scale, Resolution, and Dynamic Range</i>	39
2.2.4	<i>Accuracy, Errors, and Repeatability</i>	42
2.2.5	<i>Sensitivity and Sensitivity Analysis</i>	45
2.2.6	<i>Hysteresis, Nonlinearity, and Saturation</i>	52
2.2.7	<i>Frequency Response, Response Time, and Bandwidth</i>	56
2.2.8	<i>Calibration</i>	58
2.2.9	<i>Excitation</i>	59
2.2.10	<i>Deadband</i>	59
2.2.11	<i>Reliability</i>	59
2.3	Problems	61

---

**3 Temperature Sensors and Thermal Actuators 67**

- 3.1 Introduction 67
    - 3.1.1 *Units of Temperature, Thermal Conductivity, Heat, and Heat Capacity* 69
  - 3.2 Thermoresistive Sensors: Thermistors, Resistance Temperature Sensors, and Silicon Resistive Sensors 70
    - 3.2.1 *Resistance Temperature Detectors* 70
      - 3.2.1.1 Self-Heat of RTDs 78
      - 3.2.1.2 Response Time 80
    - 3.2.2 *Silicon Resistive Sensors* 81
    - 3.2.3 *Thermistors* 84
  - 3.3 Thermoelectric Sensors 88
    - 3.3.1 *Practical Considerations* 94
    - 3.3.2 *Semiconductor Thermocouples* 101
    - 3.3.3 *Thermopiles and Thermoelectric Generators* 102
  - 3.4 *p-n Junction Temperature Sensors* 104
  - 3.5 Other Temperature Sensors 109
    - 3.5.1 *Optical and Acoustical Sensors* 109
    - 3.5.2 *Thermomechanical Sensors and Actuators* 110
  - 3.6 Problems 118
- 

**4 Optical Sensors and Actuators 129**

- 4.1 Introduction 130
- 4.2 Optical Units 131
- 4.3 Materials 132
- 4.4 Effects of Optical Radiation 132
  - 4.4.1 *Thermal Effects* 132
  - 4.4.2 *Quantum Effects* 133
    - 4.4.2.1 The Photoelectric Effect 133
    - 4.4.2.2 Quantum Effects: The Photoconducting Effect 135
    - 4.4.2.3 Spectral Sensitivity 137
    - 4.4.2.4 Tunneling Effect 137
- 4.5 Quantum-Based Optical Sensors 138
  - 4.5.1 *Photoconducting Sensors* 138
  - 4.5.2 *Photodiodes* 142
  - 4.5.3 *Photovoltaic Diodes* 147
  - 4.5.4 *Phototransistors* 150
- 4.6 Photoelectric Sensors 153
  - 4.6.1 *The Photoelectric Sensor* 153
  - 4.6.2 *Photomultipliers* 154
- 4.7 Coupled Charge (CCD) Sensors and Detectors 156
- 4.8 Thermal-Based Optical Sensors 159
  - 4.8.1 *Passive IR Sensors* 160
    - 4.8.1.1 Thermopile PIR 160
    - 4.8.1.2 Pyroelectric Sensors 162
    - 4.8.1.3 Bolometers 165

**4.9 Active Far Infrared (AFIR) Sensors 166****4.10 Optical Actuators 167****4.11 Problems 168**

---

**5 Electric and Magnetic Sensors and Actuators 177**

- 5.1 Introduction 177
  - 5.2 Units 179
  - 5.3 The Electric Field: Capacitive Sensors and Actuators 180
    - 5.3.1 *Capacitive Position, Proximity, and Displacement Sensors* 183
    - 5.3.2 *Capacitive Fluid Level Sensors* 187
    - 5.3.3 *Capacitive Actuators* 189
  - 5.4 Magnetic Fields: Sensors and Actuators 194
    - 5.4.1 *Inductive Sensors* 199
      - 5.4.1.1 Inductive Proximity Sensors 201
      - 5.4.1.2 Eddy Current Proximity Sensors 205
      - 5.4.1.3 Position and Displacement Sensing: Variable Inductance Sensors 208
    - 5.4.2 *Hall Effect Sensors* 211
  - 5.5 Magnetohydrodynamic (MHD) Sensors and Actuators 218
    - 5.5.1 *MHD Generator or Sensor* 219
    - 5.5.2 *MHD Pump or Actuator* 219
  - 5.6 Magnetoresistance and Magnetoresistive Sensors 222
  - 5.7 Magnetostrictive Sensors and Actuators 224
    - 5.7.1 *Magnetostrictive Actuators* 227
  - 5.8 Magnetometers 230
    - 5.8.1 *Coil Magnetometer* 230
    - 5.8.2 *The Fluxgate Magnetometer* 232
    - 5.8.3 *The SQUID* 235
  - 5.9 Magnetic Actuators 236
    - 5.9.1 *Voice Coil Actuators* 237
    - 5.9.2 *Motors as Actuators* 240
      - 5.9.2.1 Operation Principles 241
      - 5.9.2.2 Brushless, Electronically Commutated DC Motors (BLDC Motors) 245
      - 5.9.2.3 AC Motors 247
      - 5.9.2.4 Stepper Motors 248
      - 5.9.2.5 Linear Motors 254
    - 5.9.3 *Magnetic Solenoid Actuators and Magnetic Valves* 256
  - 5.10 Voltage and Current Sensors 259
    - 5.10.1 *Voltage Sensing* 260
    - 5.10.2 *Current Sensing* 263
  - 5.11 Problems 267
- 

**6 Mechanical Sensors and Actuators 281**

- 6.1 Introduction 281
- 6.2 Some Definitions and Units 282

<b>6.3</b>	<b>Force Sensors</b>	<b>283</b>
6.3.1	<i>Strain Gauges</i>	283
6.3.2	<i>Semiconductor Strain Gauges</i>	285
6.3.2.1	Application	288
6.3.2.2	Errors	288
6.3.3	<i>Other Strain Gauges</i>	292
6.3.4	<i>Force and Tactile Sensors</i>	292
<b>6.4</b>	<b>Accelerometers</b>	<b>297</b>
6.4.1	<i>Capacitive Accelerometers</i>	298
6.4.2	<i>Strain Gauge Accelerometers</i>	300
6.4.3	<i>Magnetic Accelerometers</i>	301
6.4.4	<i>Other Accelerometers</i>	302
<b>6.5</b>	<b>Pressure Sensors</b>	<b>305</b>
6.5.1	<i>Mechanical Pressure Sensors</i>	305
6.5.2	<i>Piezoresistive Pressure Sensors</i>	310
6.5.3	<i>Capacitive Pressure Sensors</i>	314
6.5.4	<i>Magnetic Pressure Sensors</i>	314
<b>6.6</b>	<b>Velocity Sensing</b>	<b>315</b>
<b>6.7</b>	<b>Inertial Sensors: Gyroscopes</b>	<b>319</b>
6.7.1	<i>Mechanical or Rotor Gyroscopes</i>	320
6.7.2	<i>Optical Gyroscopes</i>	321
<b>6.8</b>	<b>Problems</b>	<b>324</b>
<hr/>		
<b>7</b>	<b>Acoustic Sensors and Actuators</b>	<b>335</b>
7.1	Introduction	335
7.2	Units and Definitions	337
7.3	Elastic Waves and Their Properties	340
7.3.1	<i>Longitudinal Waves</i>	341
7.3.2	<i>Shear Waves</i>	349
7.3.3	<i>Surface Waves</i>	349
7.3.4	<i>Lamb Waves</i>	350
7.4	Microphones	350
7.4.1	<i>The Carbon Microphone</i>	350
7.4.2	<i>The Magnetic Microphone</i>	352
7.4.3	<i>The Ribbon Microphone</i>	354
7.4.4	<i>Capacitive Microphones</i>	354
7.5	The Piezoelectric Effect	357
7.5.1	<i>Electrostriction</i>	361
7.5.2	<i>Piezoelectric Sensors</i>	361
7.6	Acoustic Actuators	363
7.6.1	<i>Loudspeakers</i>	363
7.6.2	<i>Headphones and Buzzers</i>	369
7.6.2.1	The Magnetic Buzzer	369
7.6.2.2	The Piezoelectric Headphone and Piezoelectric Buzzer	371
7.7	Ultrasonic Sensors and Actuators: Transducers	373
7.7.1	<i>Pulse-Echo Operation</i>	377
7.7.2	<i>Magnetostrictive Transducers</i>	380

<b>7.8</b>	<b>Piezoelectric Actuators</b>	<b>381</b>
<b>7.9</b>	<b>Piezoelectric Resonators and SAW Devices</b>	<b>385</b>
<b>7.10</b>	<b>Problems</b>	<b>390</b>
<hr/>		
<b>8</b>	<b>Chemical Sensor and Actuators</b>	<b>403</b>
8.1	Introduction	404
8.2	Chemical Units	405
8.3	Electrochemical Sensors	406
8.3.1	<i>Metal Oxide Sensors</i>	406
8.3.2	<i>Solid Electrolyte Sensors</i>	409
8.3.3	<i>The Metal Oxide Semiconductor (MOS) Chemical Sensor</i>	413
8.4	Potentiometric Sensors	413
8.4.1	<i>Glass Membrane Sensors</i>	414
8.4.2	<i>Soluble Inorganic Salt Membrane Sensors</i>	417
8.4.3	<i>Polymer-Immobilized Ionophore Membranes</i>	418
8.4.4	<i>Gel-Immobilized Enzyme Membranes</i>	419
8.4.5	<i>The Ion-Sensitive Field-Effect Transistor (ISFET)</i>	420
8.5	Thermochemical Sensors	421
8.5.1	<i>Thermistor-Based Chemical Sensors</i>	421
8.5.2	<i>Catalytic Sensors</i>	422
8.5.3	<i>Thermal Conductivity Sensor</i>	425
8.6	Optical Chemical Sensors	425
8.7	Mass Sensors	429
8.7.1	<i>Mass Humidity and Gas Sensors</i>	431
8.7.2	<i>SAW Mass Sensors</i>	431
8.8	Humidity and Moisture Sensors	432
8.8.1	<i>Capacitive Moisture Sensors</i>	433
8.8.2	<i>Resistive Humidity Sensor</i>	435
8.8.3	<i>Thermal Conduction Moisture Sensors</i>	436
8.8.4	<i>Optical Humidity Sensor</i>	437
8.9	Chemical Actuation	439
8.9.1	<i>The Catalytic Converter</i>	439
8.9.2	<i>The Airbag</i>	441
8.9.3	<i>Electroplating</i>	442
8.9.4	<i>Cathodic Protection</i>	444
8.10	Problems	445
<hr/>		
<b>9</b>	<b>Radiation Sensors and Actuators</b>	<b>457</b>
9.1	Introduction	457
9.2	Units of Radiation	459
9.3	Radiation Sensors	460
9.3.1	<i>Ionization Sensors (Detectors)</i>	461
9.3.1.1	Ionization Chambers	461
9.3.1.2	Proportional Chamber	463
9.3.1.3	Geiger-Muller Counters	463

9.3.2	<i>Scintillation Sensors</i>	465
9.3.3	<i>Semiconductor Radiation Detectors</i>	466
9.3.3.1	Bulk Semiconductor Radiation Sensor	467
9.3.3.2	Semiconducting Junction Radiation Sensors	470
<b>9.4</b>	<b>Microwave Radiation</b>	<b>474</b>
9.4.1	<i>Microwave Sensors</i>	476
9.4.1.1	Radar	476
9.4.1.2	Reflection and Transmission Sensors	479
9.4.1.3	Resonant Microwave Sensors	482
9.4.1.4	Propagation Effects and Sensing	487
<b>9.5</b>	<b>Antennas as Sensors and Actuators</b>	<b>487</b>
9.5.1	<i>General Relations</i>	487
9.5.2	<i>Antennas as Sensing Elements</i>	489
9.5.3	<i>Antennas as Actuators</i>	494
<b>9.6</b>	<b>Problems</b>	<b>495</b>

---

<b>10</b>	<b>MEMS and Smart Sensors</b>	<b>507</b>
<b>10.1</b>	<b>Introduction</b>	<b>508</b>
<b>10.2</b>	<b>Production of MEMS</b>	<b>509</b>
<b>10.3</b>	<b>MEMS Sensors and Actuators</b>	<b>514</b>
10.3.1	<i>MEMS Sensors</i>	515
10.3.1.1	Pressure Sensors	515
10.3.1.2	Mass Air Flow Sensors	515
10.3.1.3	Inertial Sensors	517
10.3.1.4	Angular Rate Sensors	519
10.3.2	<i>MEMS Actuators</i>	523
10.3.2.1	Thermal and Piezoelectric Actuation	524
10.3.2.2	Electrostatic Actuation	526
10.3.3	<i>Some Applications</i>	529
10.3.3.1	Optical Switches	529
10.3.3.2	Mirrors and Mirror Arrays	529
10.3.3.3	Pumps	530
10.3.3.4	Valves	531
10.3.3.5	Others	533
<b>10.4</b>	<b>Smart Sensors and Actuators</b>	<b>533</b>
10.4.1	<i>Wireless Sensors and Actuators and Issues Associated with Their Use</i>	538
10.4.1.1	The ISM and SRD Bands	538
10.4.1.2	The Wireless Link and Data Handling	540
10.4.1.3	Transmitters, Receivers, and Transceivers	542
10.4.2	<i>Modulation and Demodulation</i>	542
10.4.2.1	Amplitude Modulation	543
10.4.2.2	Frequency Modulation	544
10.4.2.3	Phase Modulation	545
10.4.2.4	Amplitude Shift Keying	547
10.4.2.5	Frequency Shift Keying	548
10.4.2.6	Phase Shift Keying	548

10.4.3	<i>Demodulation</i>	549
10.4.3.1	Amplitude Demodulation	549
10.4.3.2	Frequency and Phase Demodulation	549
10.4.4	<i>Encoding and Decoding</i>	550
10.4.4.1	Unipolar and Bipolar Encoding	550
10.4.4.2	Biphase Encoding	550
10.4.4.3	Manchester Code	551
<b>10.5</b>	<b>Sensor Networks</b>	<b>552</b>
<b>10.6</b>	<b>Problems</b>	<b>556</b>

---

<b>11</b>	<b>Interfacing Methods and Circuits</b>	<b>567</b>
<b>11.1</b>	<b>Introduction</b>	<b>567</b>
<b>11.2</b>	<b>Amplifiers</b>	<b>570</b>
11.2.1	<i>The Operational Amplifier</i>	570
11.2.1.1	Differential Voltage Gain	571
11.2.1.2	Common-Mode Voltage Gain	571
11.2.1.3	Bandwidth	571
11.2.1.4	Slew Rate	572
11.2.1.5	Input Impedance	573
11.2.1.6	Output Impedance	573
11.2.1.7	Temperature Drift and Noise	573
11.2.1.8	Power Requirements	573
11.2.2	<i>Inverting and Noninverting Amplifiers</i>	573
11.2.2.1	The Inverting Amplifier	574
11.2.2.2	The Noninverting Amplifier	575
11.2.3	<i>The Voltage Follower</i>	577
11.2.4	<i>The Instrumentation Amplifier</i>	577
11.2.5	<i>The Charge Amplifier</i>	578
11.2.6	<i>The Integrator and the Differentiator</i>	580
11.2.7	<i>The Current Amplifier</i>	581
11.2.8	<i>The Comparator</i>	582
<b>11.3</b>	<b>Power Amplifiers</b>	<b>584</b>
11.3.1	<i>Linear Power Amplifiers</i>	584
11.3.2	<i>PWM and PWM Amplifiers</i>	586
<b>11.4</b>	<b>Digital Circuits</b>	<b>588</b>
<b>11.5</b>	<b>A/D and D/A Converters</b>	<b>595</b>
11.5.1	<i>A/D Conversion</i>	595
11.5.1.1	Threshold Digitization	595
11.5.1.2	Threshold Voltage-to-Frequency Conversion	596
11.5.1.3	True A/D Converters	598
11.5.1.4	Dual-Slope A/D Converter	598
11.5.1.5	Successive Approximation A/D	600
11.5.2	<i>D/A Conversion</i>	602
11.5.2.1	Resistive Ladder Network D/A Conversion	602
11.5.2.2	PWM D/A Conversion	605
11.5.2.3	Frequency to Voltage (F/V) D/A Conversion	605

<b>11.6</b>	Bridge Circuits	606
11.6.1	Sensitivity	607
11.6.2	Bridge Output	611
<b>11.7</b>	Data Transmission	614
11.7.1	Four-Wire Transmission	614
11.7.2	Two-Wire Transmission for Passive Sensors	615
11.7.3	Two-Wire Transmission for Active Sensors	615
11.7.4	Digital Data Transmission Protocols and Buses	618
<b>11.8</b>	Excitation Methods and Circuits	618
11.8.1	Linear Power Supplies	619
11.8.2	Switching Power Supplies	621
11.8.3	Current Sources	624
11.8.4	Voltage References	625
11.8.5	Oscillators	626
11.8.5.1	Crystal Oscillators	627
11.8.5.2	LC and RC Oscillators	629
<b>11.9</b>	Noise and Interference	635
11.9.1	Inherent Noise	635
11.9.2	Interference	636
<b>11.10</b>	Problems	639

---

<b>12</b>	Interfacing to Microprocessors	653
<b>12.1</b>	Introduction	654
<b>12.2</b>	The Microprocessor as a General Purpose Controller	654
12.2.1	Architecture	655
12.2.2	Addressing	656
12.2.3	Execution and Speed	656
12.2.4	Instruction Set	657
12.2.5	Input and Output	659
12.2.6	Clock and Timers	662
12.2.7	Registers	664
12.2.8	Memory	664
12.2.9	Power	666
12.2.10	Other Peripherals and Functionalities	669
12.2.11	Programs and Programmability	670
<b>12.3</b>	General Requirements for Interfacing Sensors and Actuators	670
12.3.1	Signal Level	671
12.3.2	Impedance	672
12.3.3	Response and Frequency	676
12.3.4	Input Signal Conditioning	677
12.3.4.1	Offset	677
12.3.4.2	Scaling	681
12.3.4.3	Isolation	683
12.3.4.4	Loading	684
12.3.5	Output Signals	684

<b>12.4</b>	Errors	687
12.4.1	Resolution Errors	687
12.4.2	Computation Errors	690
12.4.3	Sampling and Quantization Errors	697
12.4.4	Conversion Errors	698
<b>12.5</b>	Problems	699

  

<b>Answers to Problems</b>	<b>711</b>
<b>Appendix A</b>	<b>725</b>
<b>Appendix B</b>	<b>729</b>
<b>Appendix C</b>	<b>743</b>
<b>Index</b>	<b>753</b>