

INTERNATIONAL EDITION

Process Control Instrumentation Technology

Sixth Edition



Suranaree University of Technology



31051000606612

Curtis D. Johnson

CONTENTS

1	INTRODUCTION TO PROCESS CONTROL	1
	Instructional Objectives	1
1.1	Introduction	1
1.2	Control Systems	2
	1.2.1 Process-Control Principles 1.2.2 Servomechanisms	
	1.2.3 Discrete-State Control Systems	
1.3	Process-Control Block Diagram	5
	1.3.1 Identification of Elements 1.3.2 Block Diagram	
1.4	Control System Evaluation	9
	1.4.1 Stability 1.4.2 Steady-State Regulation 1.4.3 Transient Regulation	
	1.4.4 Evaluation Criteria	
1.5	Analog and Digital Processing	13
	1.5.1 Data Representation 1.5.2 ON/OFF Control 1.5.3 Analog Control	
	1.5.4 Digital Control 1.5.5 Programmable Logic Controllers	
1.6	Units, Standards, and Definitions	20
	1.6.1 Units 1.6.2 Analog Data Representation 1.6.3 Definitions	
	1.6.4 Process-Control Drawings	
1.7	Sensor Time Response	33
	1.7.1 First-Order Response 1.7.2 Second-Order Response	
1.8	Significance and Statistics	36
	1.8.1 Significant Figures 1.8.2 Statistics	
	Summary Problems	
2	ANALOG SIGNAL CONDITIONING	47
	Instructional Objectives	47
2.1	Introduction	47
2.2	Principles of Analog Signal Conditioning	48
	2.2.1 Signal-Level and Bias Changes 2.2.2 Linearization	
	2.2.3 Conversions 2.2.4 Filtering and Impedance Matching	
	2.2.5 Concept of Loading	
2.3	Passive Circuits	52
	2.3.1 Divider Circuits 2.3.2 Bridge Circuits 2.3.3 RC Filters	

2.4	Operational Amplifiers	77
2.4.1	Op Amp Characteristics 2.4.2 Op Amp Specifications	
2.5	Op Amp Circuits in Instrumentation	84
2.5.1	Voltage Follower 2.5.2 Inverting Amplifier 2.5.3 Noninverting Amplifier 2.5.4 Differential Instrumentation Amplifier	
2.5.5	Voltage-to-Current Converter 2.5.6 Current-to-Voltage Converter	
2.5.7	Integrator 2.5.8 Differentiator 2.5.9 Linearization	
2.6	Design Guidelines	97
	Summary Problems	

3 DIGITAL SIGNAL CONDITIONING

109

	Instructional Objectives	109
3.1	Introduction	109
3.2	Review of Digital Fundamentals	110
3.2.1	Digital Information 3.2.2 Fractional Binary Numbers 3.2.3 Boolean Algebra 3.2.4 Digital Electronics 3.2.5 Programmable Logic Controllers	
3.2.6	Computer Interface	
3.3	Converters	119
3.3.1	Comparators 3.3.2 Digital-to-Analog Converters (DACs)	
3.3.3	Analog-to-Digital Converters (ADCs) 3.3.4 Frequency-Based Converters	
3.4	Data-Acquisition Systems	150
3.4.1	DAS Hardware 3.4.2 DAS Software	
	Summary Problems	

4 THERMAL SENSORS

163

	Instructional Objectives	163
4.1	Introduction	163
4.2	Definition of Temperature	164
4.2.1	Thermal Energy 4.2.2 Temperature	
4.3	Metal Resistance Versus Temperature Devices	168
4.3.1	Metal Resistance Versus Temperature 4.3.2 Resistance Versus Temperature Approximations 4.3.3 Resistance-Temperature Detectors	
4.4	Thermistors	177
4.4.1	Semiconductor Resistance Versus Temperature	
4.4.2	Thermistor Characteristics	
4.5	Thermocouples	181
4.5.1	Thermoelectric Effects 4.5.2 Thermocouple Characteristics	
4.5.3	Thermocouple Sensors	

4.6	Other Thermal Sensors	193
4.6.1	Bimetal Strips	193
4.6.2	Gas Thermometers	193
4.6.3	Vapor-Pressure Thermometers	193
4.6.4	Liquid-Expansion Thermometers	193
4.6.5	Solid-State Temperature Sensors	193
4.7	Design Considerations	200
	Summary Problems	

5 MECHANICAL SENSORS 213

	Instructional Objectives	213
5.1	Introduction	213
5.2	Displacement, Location, or Position Sensors	214
5.2.1	Potentiometric	214
5.2.2	Capacitive and Inductive	214
5.2.3	Variable Reluctance	214
5.2.4	Level Sensors	214
5.3	Strain Sensors	222
5.3.1	Strain and Stress	222
5.3.2	Strain Gauge Principles	222
5.3.3	Metal Strain Gauges (SGs)	222
5.3.4	Semiconductor Strain Gauges (SGs)	222
5.3.5	Load Cells	222
5.4	Motion Sensors	236
5.4.1	Types of Motion	236
5.4.2	Accelerometer Principles	236
5.4.3	Types of Accelerometers	236
5.4.4	Applications	236
✓ 5.5	Pressure Sensors	248
5.5.1	Pressure Principles	248
5.5.2	Pressure Sensors ($p > 1$ atmosphere)	248
5.5.3	Pressure Sensors ($p < 1$ atmosphere)	248
✗ 5.6	Flow Sensors	257
5.6.1	Solid-Flow Measurement	257
5.6.2	Liquid Flow	257
	Summary Problems	

6 OPTICAL SENSORS 273

	Instructional Objectives	273
6.1	Introduction	273
6.2	Fundamentals of EM Radiation	274
6.2.1	Nature of EM Radiation	274
6.2.2	Characteristics of Light	274
6.2.3	Photometry	274
✓ 6.3	Photodetectors	284
6.3.1	Photodetector Characteristics	284
6.3.2	Photoconductive Detectors	284
6.3.3	Photovoltaic Detectors	284
6.3.4	Photodiode Detectors	284
6.3.5	Photoemissive Detectors	284
6.4	Pyrometry	300
6.4.1	Thermal Radiation	300
6.4.2	Broadband Pyrometers	300
6.4.3	Narrowband Pyrometers	300

viii | CONTENTS

6.5	Optical Sources	305
6.5.1	Conventional Light Sources 6.5.2	Laser Principles
6.6	Applications	311
6.6.1	Label Inspection 6.6.2	Turbidity 6.6.3 Ranging
Summary Problems		

7 FINAL CONTROL 321

Instructional Objectives		321
7.1	Introduction	321
7.2	Final Control Operation	322
7.2.1	Signal Conversions 7.2.2	Actuators 7.2.3 Control Element
7.3	Signal Conversions	324
7.3.1	Analog Electrical Signals 7.3.2	Digital Electrical Signals
7.3.3	Pneumatic Signals	
7.4	Industrial Electronics	331
7.4.1	Silicon-Controlled Rectifier (SCR) 7.4.2	TRIAC
7.5	Actuators	341
7.5.1	Electrical Actuators 7.5.2	Pneumatic Actuators
7.5.3	Hydraulic Actuators	
7.6	Control Elements	352
7.6.1	Mechanical 7.6.2	Electrical 7.6.3 Fluid Valves
Summary Problems		

8 DISCRETE-STATE PROCESS CONTROL 369

Instructional Objectives		369
8.1	Introduction	369
8.2	Definition of Discrete-State Process Control	370
8.3	Characteristics of the System	371
8.3.1	Discrete-State Variables 8.3.2	Process Specifications
8.3.3	Event Sequence Description	
8.4	Relay Controllers and Ladder Diagrams	385
8.4.1	Background 8.4.2	Ladder Diagram Elements
8.4.3	Ladder Diagram Examples	
8.5	Programmable Logic Controllers (PLCs)	395
8.5.1	Relay Sequencers 8.5.2	Programmable Logic Controller Design
8.5.3	PLC Operation 8.5.4	Programming 8.5.5 Advanced Features
Summary Problems		

9 CONTROLLER PRINCIPLES 411

Instructional Objectives	411
9.1 Introduction	411
9.2 Process Characteristics	412
9.2.1 Process Equation 9.2.2 Process Load 9.2.3 Process Lag	
9.2.4 Self-Regulation	
9.3 Control System Parameters	414
9.3.1 Error 9.3.2 Variable Range 9.3.3 Control Parameter Range	
9.3.4 Control Lag 9.3.5 Dead Time 9.3.6 Cycling	
9.3.7 Controller Modes	
9.4 Discontinuous Controller Modes	420
9.4.1 Two-Position Mode 9.4.2 Multiposition Mode	
9.4.3 Floating-Control Mode	
9.5 Continuous Controller Modes	429
9.5.1 Proportional Control Mode 9.5.2 Integral Control Mode	
9.5.3 Derivative Control Mode	
9.6 Composite Control Modes	438
9.6.1 Proportional-Integral Control (PI) 9.6.2 Proportional-Derivative	
Control Mode (PD) 9.6.3 Three-Mode Controller (PID)	
9.6.4 Special Terminology	
Summary Problems	

10 ANALOG CONTROLLERS 453

Instructional Objectives	453
10.1 Introduction	453
10.2 General Features	454
10.3 Electronic Controllers	455
10.3.1 Error Detector 10.3.2 Single Mode	
10.3.3 Composite Controller Modes	
10.4 Pneumatic Controllers	477
10.4.1 General Features 10.4.2 Mode Implementation	
10.5 Design Considerations	482
Summary Problems	

11 DIGITAL CONTROLLERS 491

Instructional Objectives	491
11.1 Introduction	491

x | CONTENTS

11.2	Digital Electronics Methods	492
	11.2.1 Simple Alarms 11.2.2 Two-Position Control	
	11.2.3 Multivariable Alarms	
11.3	Computers in Process Control	497
	11.3.1 Programmable Logic Controllers 11.3.2 Data Logging	
	11.3.3 Supervisory Control 11.3.4 Computer-Based Controller	
11.4	Characteristics of Digital Data	510
	11.4.1 Digitized Value 11.4.2 Sampled Data Systems	
11.5	Controller Software	515
	11.5.1 Software Format 11.5.2 Input Data Operations	
	11.5.3 Controller Modes	
11.6	Computer Controller Examples	531
	Summary Problems	

12 CONTROL-LOOP CHARACTERISTICS

541

	Instructional Objectives	541
12.1	Introduction	541
12.2	Control System Configurations	542
	12.2.1 Single Variable 12.2.2 Cascade Control	
12.3	Multivariable Control Systems	547
	12.3.1 Analog Control 12.3.2 Supervisory and Direct Digital Control	
12.4	Control System Quality	549
	12.4.1 Definition of Quality 12.4.2 Measure of Quality	
12.5	Stability	557
	12.5.1 Transfer Function Frequency Dependence 12.5.2 Stability Criteria	
12.6	Process Loop Tuning	562
	12.6.1 Open-Loop Transient Response Method 12.6.2 Ziegler-Nichols	
	Method 12.6.3 Frequency Response Methods	
	Summary Problems	

APPENDICES

581

REFERENCES

619

GLOSSARY

621

SOLUTIONS TO THE ODD-NUMBERED PROBLEMS

625

INDEX

673