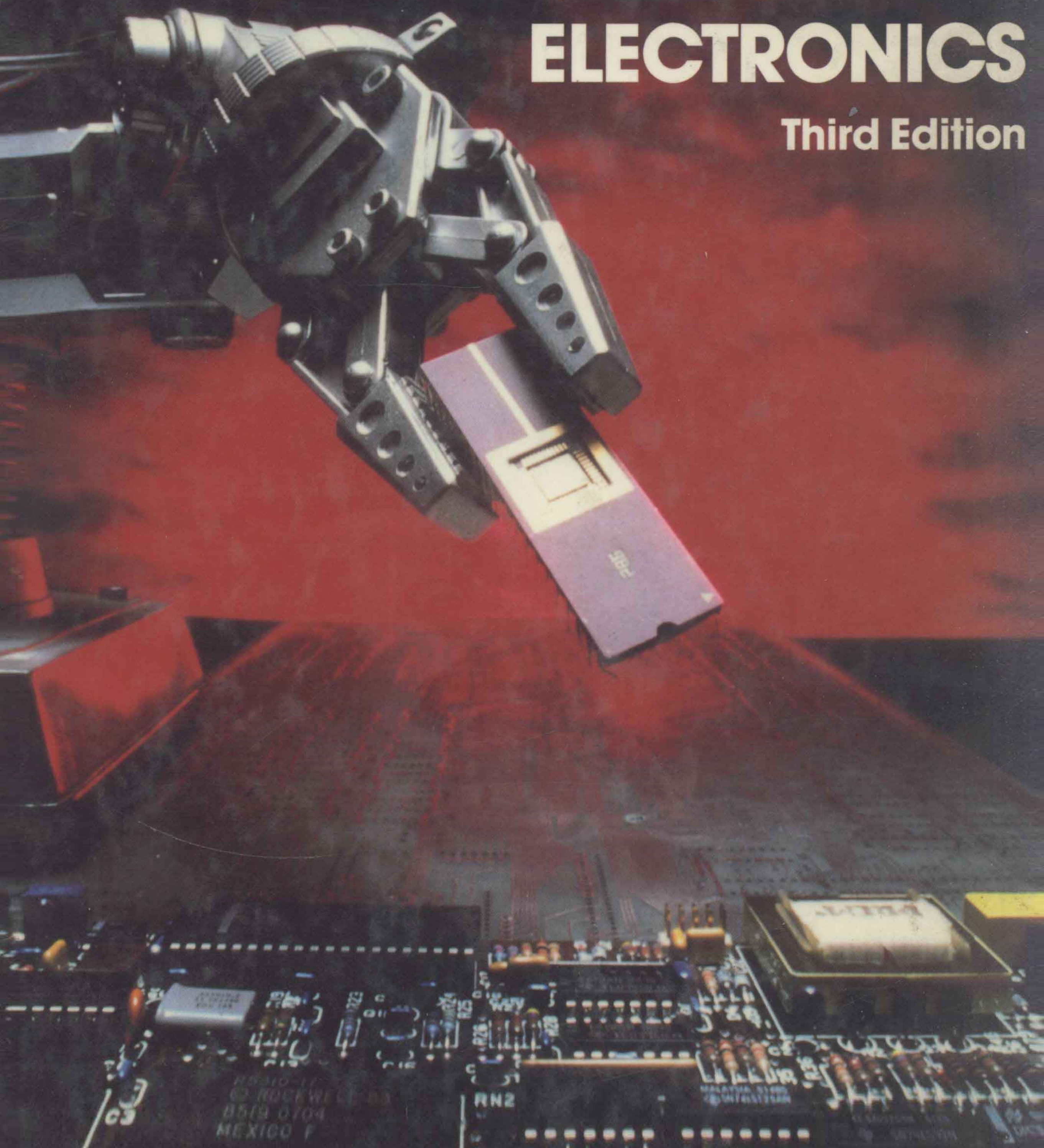
James T. Humphries

Leslie P. Sheets

INDUSTRIAL ELECTRONICS

Third Edition



THIRD EDITION

INDUSTRIAL ELECTRONICS

James T. Humphries
Santa Fe Community College

Leslie P. Sheets
College of Technical Careers
Southern Illinois University at Carbondale

DELMAR PUBLISHERS INC®

For information, address Delmar Publishers Inc.
2 Computer Drive West, Box 15-015
Albany, NY 12212

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America
Published simultaneously in Canada
by Nelson Canada
A Division of International Thomson Limited

ISBN 0-8273-3828-7

Production: *Technical Texts, Inc.*
Interior and Cover Design: *Sylvia Dovner*
Typesetting: *Publication Services, Inc.*
Cover Printing: *Phoenix Color*
Printing and Binding: *Vail-Ballou*
Cover Photo: ©*Don Carroll/The Image Bank*. Used with permission.

ACKNOWLEDGMENTS

Chapter 1: Figure 1.27, National Semiconductor Corporation; Figures 1.49 and 1.53, RCA Solid State Division.
Chapter 2: Figure 2.16, Reprinted with permission of National Semiconductor Corporation. National holds no responsibility for any circuitry described. National reserves the right at any time to change without notice said circuitry.
Chapter 3: Figures 3.1A and 3.4, Reliance Electric Company; Figure 3.5, reprinted from EDN, 1978 © Cahners Publishing Company; Table 3.6, reprinted from EDN, 1978 © Cahners Publishing Company.
Chapter 4: Figure 4.6, Bodine Electric Company, Chicago, IL 60618; Figures 4.12, 4.15, and 4.19, Pacific Scientific; Figure 4.21, Pittman, a division of Penn Engineering & Manufacturing Corp.; Figures 4.23, 4.26, 4.27, 4.28, 4.29, 4.30, 4.31, 4.32, 4.33, 4.34, 4.35, 4.36, 4.37, and 4.38, Western Division IMC Magnetics Corporation; portions of the section on brushless DC motors are drawn from Chapter 6 of *DC Motors, Speed Controls, and Servo Systems,* 6th edition, 1982 Electro-Craft Corporation, Hopkins, MN; portions of the section on stepper motors are drawn from the *TORMAX® Steppers and Control Manual*, Western Division IMC Magnetics Corporation, Maywood, CA.
Chapter 5: Figure 5.1, Reliance Electric Company; Figure 5.1, G.M. Ferree, STC Photography; Figures 5.7 and 5.11, Bob White, STC Photography.
Chapter 6: Figures 6.2, 6.3, 6.4, and 6.5, Micro Switch, a Honeywell Division; Figure 6.6, Allen-Bradley Company; Figures 6.8 and 6.11, Micro Switch, a Honeywell division; Figure 6.13, Chilton Company, a division of ABC, Inc; Figure 6.14, Ledex, Inc.; Figure 6.19, Square D Company; Figures 6.21 and 6.22, reprinted from *Machine Design*, May 19, 1983, copyright 1983, by Penton/IPC, Inc., Cleveland,
(*continued on page 638*)

Quantity Symbols and SI Units

Quantity	Symbol	SI Unit	Symbol	Derivation
acceleration	a	m s^{-2}	—	velocity/time
acceleration due to gravity	g	m s^{-2}	—	velocity/time
amount of substance	n	mole	mol	mole fraction (n) used
amplification factor	μ	*a ratio*	—	—
angle	$\theta_1, \varphi_1, \alpha_1$	—	—	—
angle of incidence	i	degree or radian	°	—
angle of refraction	r	degree or radian	°	—
angle, Bragg	θ	number	—	—
angle, critical	c	degree or radian	°	—
anode slope resistance	R_A	ohm	Ω	$\Delta V_a / \Delta I_a$
area	A	metres squared	m^2	$l \times b$
atomic number	Z	a number	—	number of protons
Avogadro constant	L, N_A	number	—	—
breadth	b	metre	m	fundamental unit
capacitance	C	farad	F	charge/p.d.
charge, electric	Q	coulomb	C	current × time
charge on electron	e	coulomb	C	$1{\cdot}6 \times 10^{-19}$ C
conductance	G	ohm^{-1}	Ω^{-1}	reciprocal of resistance
current, electric	I	ampere	A	fundamental unit
decay constant	λ	*a ratio*	—	—
density	ρ	kg m^{-3}	—	m/V
distance along path	s	metre	m	fundamental unit
efficiency	η	*a ratio*	—	work output/work input
electrochemical equiv.	z	g C^{-1}	—	mass/charge
electromotive force	E	volt	V	energy/charge
electron	e	—	—	—
energy	E	joule	J	N m
energy, kinetic	E_k	joule	J	N m. $E_k = 1/2mv^2$
energy, potential	E_p	joule	J	N m. $E_p = mgh$
Faraday constant	F	coulomb mol^{-1}	C mol^{-1}	96,500 C mol^{-1}
field strength, electric	E	V m^{-1}	—	potential gradient: p.d./dist.
field-strength magnetic	H	ampere-turns	—	current × no. of turns
flux, magnetic	Φ	weber	Wb	e.m.f/rate of change of flux
flux density	B	tesla	T	flux/area
focal length	f	metre	m	—
force	F	newton	N	kg m s^{-2}
free energy	ΔG	joule	J	—
frequency	f	hertz	Hz	oscillations/time
gas constant	r	joule	J	energy
half-life,radioactivity	$t_{1/2}$	second	s	fundamental unit
heat capacity	C	J K^{-1}	—	quantity of heat/temp. rise
heat of reaction	ΔH	joule	J	heat energy
heat capacity, specific	c	J K^{-1} kg^{-1}	—	heat capacity/mass
heat, quantity of	q	joule	J	energy
height	h	metre	m	fundamental unit
image distance	v	metre	m	fundamental unit
inductance, mutual	M	henry	H	induced e.m.f./rate of change of current
inductance, self	L	henry	H	—
intensity of radiation	I	*a number*	—	—
latent heat	L	joule	J	quantity of heat
latent heat, specific	l	J kg^{-1}	—	quantity of heat
latent heat, molar	L_m	joule mol^{-1}	J	quantity of heat

Quantity	Symbol	SI Unit	Symbol	Derivation
length	l	metre	m	fundamental unit
magnetizing force	H	ampere-turns	—	—
magnetic moment	m	Wb m	—	torque in unit magnetic field
magnification, linear	m	*a ratio*	—	—
mass	m	kilogramme	kg	fundamental unit
mass number	A	*a number*	—	number of neutrons + protons
molar volume	V_m	(dm^3)	—	volume of 1 mole
molar solution	M	*a ratio*	—	moles/dm^3
moment of force	—	N m	—	force × perp. distance
neutron number	N	*a number*	—	number of neutrons
number	n	—	—	—
number of molecules	N	—	—	—
number turns on coil	n	*a number*	—	—
number order spectrum	p	*a number*	—	—
object distance	u	metre	m	fundamental unit
peak current	I_o	ampere	A	see current
peak e.m.f.	E_o	volt	V	see e.m.f.
period	T	second	s	fundamental unit
permeability	μ	H m^{-1}	—	henry/metre
permeability, vacuum	μ_o	H m^{-1}	—	—
permeability, relative	μ_r	*a ratio*	—	$\mu = \frac{\mu}{\mu_o}$
permittivity	ε	F m^{-1}	—	farad/metre
permittivity, vacuum	ε_o	F m^{-1}	—	farad/metre
permittivity, relative	ε_r	*a ratio*	—	$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$
potential, electric	V	volt	V	energy/charge
potential difference	V	volt	V	energy/charge
power	P	watt	W	J s^{-1}
pressure	p	pascal	Pa	N m^{-2}: force/area
radius	r	metre	m	fundamental unit
reactance	X	ohm	Ω	E_o/I_o
refractive index	n	*a ratio*	—	—
resistance	R	ohm	Ω	p.d./current
resistivity, electrical	ρ	ohm-metre	—	resistance × length
relative density	d	*a ratio*	—	ρ_{sub}/ρ_{water}
r.m.s. current	$I_{r.m.s}$	ampere	A	see current
r.m.s. voltage	$V_{r.m.s}$	volt	V	see e.m.f.
slit separation	s	metre	m	fundamental unit
tension	T	newton	N	see force
temperature, Celsius	θ	degree C	°C	from kelvin
temp. interval	θ	degree	° or K	—
temp. absolute	T	kelvin	K	fundamental unit
thickness	d	metre	m	fundamental unit
time	t	second	s	fundamental unit
torque	T	Nm	—	see moment
turns ratio	T	*a ratio*	—	n_{sec}/n_{prim}
(unit of electricity)	—	kW h	—	kilowatt × hour
velocity	u, υ	ms^{-1}	—	distance/time
velocity, angular	ω	$second^{-1}$	s^{-1}	angle/time
velocity, e.m.waves	c	m s^{-1}	—	—
velocity of sound	υ	m s^{-1}	—	—
volume	V	metre cubed	m^3	l × b × h
wavelength	λ	metre	m	fundamental unit
work	w	joule	J	force x distance (Nm)
weight	W	newton	N	kg m s^{-2}or mg

Industrial Electronics

To our wives, Marg and Joyce

She is far more precious than jewels – Proverbs 31:10

Preface

Anyone involved in industrial electronics knows that industry is changing rapidly. This statement is reflected in the third edition of *Industrial Electronics*. Since an industrial electronics course tries to prepare students for entry into the workplace, our text should reflect those changes that are occurring in industry. In this third edition, we have made every effort to bring this text up-to-date to reflect what industry is demanding of our graduates and what instructors are teaching in their courses.

The goal of *Industrial Electronics* in the third edition is the same as in the first and second editions. It is to provide the student with an understanding of the basic components and systems used in industrial electronics. The book is intended for use in electronics programs offered in two- or four-year colleges.

The text avoids design questions. Instead the text focuses on the underlying concepts and the operation of electronic devices, circuits, and systems. We feel that if concepts are understood, designing circuits, in most cases, is not a problem. We definitely do not subscribe to the notion that the best way to understand electronic circuits is to design them.

The text is comprehensive. Experience has shown that a course in industrial electronics requires the coverage of a large number of topics. But how can these topics be covered in one course? One solution is to use several textbooks for the course. Another is to supplement one text extensively with instructor-prepared materials. A third approach is to modify the course and teach only those topics covered in the textbook. However, we feel that all of these alternatives are unacceptable. Thus, we have purposely written a comprehensive text that includes most of the required topics.

Alternatively, we have also written the book so that its presentation is as flexible as possible, so that certain topics can be easily omitted. Although we cover most of the topics in the book in a one-semester course, some of the topics can be treated in other courses. Thus, the material in this book could easily be expanded to two semesters or two quarters, depending on the depth of treatment for each topic.

We require all our electronics students at the College of Technical Careers at Southern Illinois University, Carbondale, to take an industrial electronics course. We feel that every graduate of a two-year or four-year electronics program should have a basic understanding of both digital and analog circuitry. Many of our graduates report that their preparation in analog circuits and systems has been invaluable. They typically find themselves acting as liaisons between analog applications and people who have a predominantly digital background.

The text is not overly mathematical. We expect students to have a mathematics background no higher than algebra and trigonometry, and we have avoided any higher level of mathematics in our presentation. We realize, however, that mathematics is a concise way of representing concepts. Thus, we have included it where we feel that an adequate grasp of the concept demands a mathematical treatment.

We also expect students to have some background in basic digital gates and logic gained from an introductory course in digital electronics earlier in their electronics education. It may also be helpful, but not essential, for the student to have completed a technical physics course.

Users of the second edition of *Industrial Electronics* will notice some differences in the text. All the chapters present in the second edition have been retained in this third edition. Most chapters have been expanded to include more in-depth coverage of the devices and circuits covered. For example, the coverage of AC motors has been significantly expanded in Chapter 5 to include concepts such as power factor and power factor controllers, and Chapter 4 has been expanded to include permanent magnet DC motors. We have also made an effort to discuss many of the circuits used in the accompanying laboratory manual in the appropriate chapters.

More learning aids have been built into the presentation. We have included questions at the end of every chapter that give immediate feedback on student understanding. Users of the second edition will notice that the numbers of problems at the end of chapters, in most cases, have been doubled. Bibliographies are included at the end of the book for each chapter. These references may be used as supplemental reading or study assignments for topics that are to be covered in depth. Data sheets have also been included at the back of the book for reference. They present detailed information about some of the IC chips used in the text. We hope that students will use this information to gain greater understanding of the IC chips and circuits we have used as examples. These same IC chips can also be used in student design projects, and the data sheets should help.

A book of laboratory experiments is available as an accompaniment to the third edition. We have tried to include experiments in the lab manual that will reinforce the concepts taught in the text material. Every effort has been made to use inexpensive, generic components and circuits for experiments. In many cases, equipment already on hand can be adapted for use in these experiments. The laboratory manual is available as a separate publication and is keyed to reading assignments in the text. An ancillary instructor's guide is available without charge from the publisher for the convenience of instructors who adopt this book for classroom use. The instructor's guide will include the solutions to problems at the end of the chapters, as well as solutions to the laboratory experiments.

Publishing a textbook is the result of a coordinated effort that involves many people. We would like to express our thanks to the following individuals: A. R. Beets (Iowa Central Community College), Leonard Bundra (Lincoln Technical Institute), Edward F. Herman (Corning Community College), and Erik Liimatta (Anne Arundel Community College) for their helpful reviews of the third edition manuscript; Betty O'Bryant of Technical Texts, Inc., and Nancy Gregory of PWS-KENT Publishing Company for their patience and kindness; our copy editor, Carol Beal, for her thorough editing of our manuscript; our colleagues at Santa Fe Community College and at Southern Illinois University; and, finally, our wives and children.

James T. Humphries
Leslie P. Sheets

Introduction

Industrial electronics can be defined as the control of industrial machinery and processes through the use of electronic circuits and systems. Each of the topics in this text has been carefully chosen to help you, the future technician, survive in such an environment. We feel that knowledge gained by studying these topics will make you better prepared for entry-level employment as an electronics technician.

Although many topics have been included in this text, there are many additional topics you will need to know to function successfully in industry. As a starting point we assume that your previous electronics courses have given you a firm grounding in alternating and direct current theory, the functions of electrical and electronic components, and mathematics through algebra and trigonometry.

The topics in this text are built around a very general process control system, since we believe the electronics technician should be a generalist. Furthermore, it is not possible to cover in one text all the circuits and systems you are likely to encounter in industry. The range of industrial applications is simply too broad. Therefore, we have concentrated on some basic circuit and component concepts with appropriate examples. Once you have mastered the basic circuit and component functions, you will be ready to put these parts together into a functional system. That is, your knowledge of the functions of subparts and subsystems will help you understand how the overall system functions.

An example of a very basic process control system is illustrated in Figure I.1. Each block in the diagram represents a division of the elements within a process control system. Note that it is sometimes difficult to separate physically one block or topic from another in a real system. And, of course, not all blocks will be used in every control system; however, all are likely to be encountered in industry.

Each block in Figure I.1 contains the associated chapter in which that topic is discussed. The chapters by themselves may seem disconnected from one another, but they obviously are related when you consider the complete system.

The process in Figure I.2 is a hypothetical example. It shows a conveyor belt and a motor driver that must keep a constant speed on the belt regardless of the load. This example is related to the system of Figure I.1 in the following manner: The process in Figure I.1 is the transportation of the load from one point to another at a constant speed. As the load on the belt changes, some type of speed sensor is used to detect changes in speed and convert this change into an electric output. If the controlling system is some distance from the belt, telemetering can be used to transport the information from the sensor to the controller.

Before the controller can operate on this sensor output, it may require conditioning of some type to get the electric signal in the correct range or form. The controller can then make a decision, on the basis of the results of the incoming data, as to whether the belt should have more or less power than it had previously or the same power. This decision is then telemetered back to the belt drive circuitry, which will apply the appropriate amount of power, depending on the results of the controller's decision. The final control element, the motor, will then be provided with the appropriate power necessary to keep the belt operating at a constant speed. This simple process illustrates the concept of process control and the basis for the inclusion of the topics in this text.

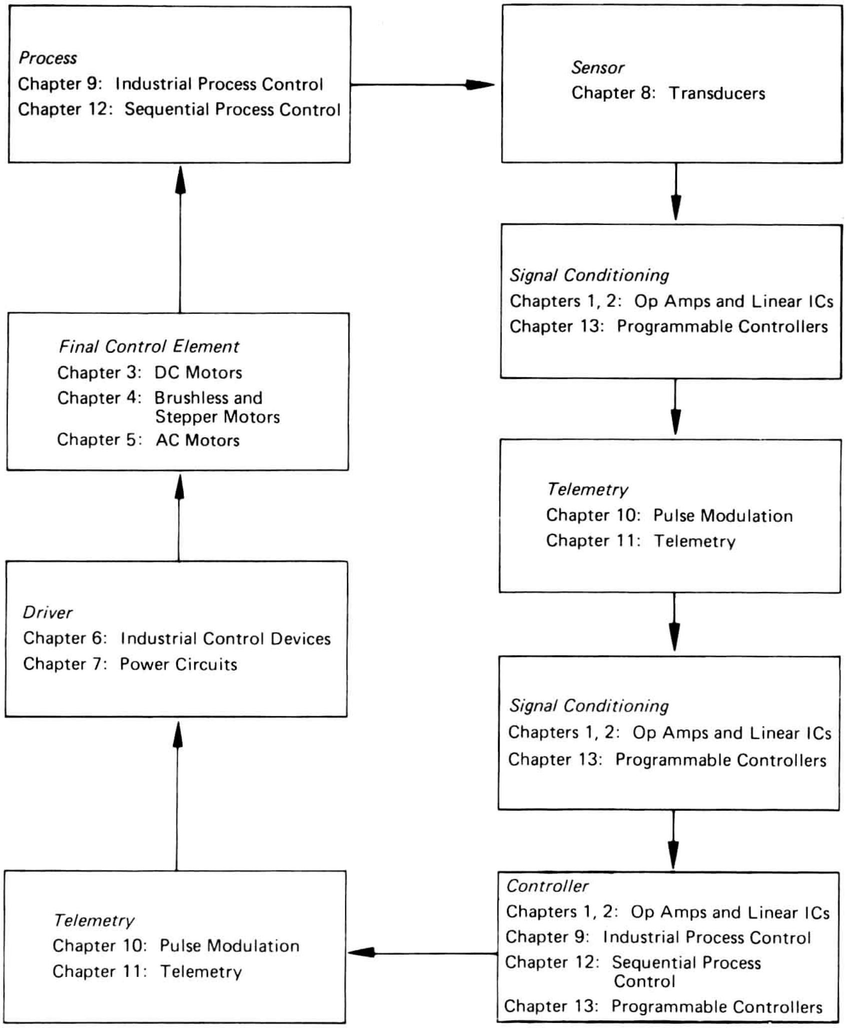


Figure I.1 General Process Control System

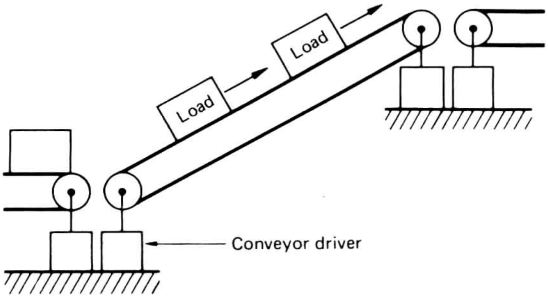


Figure I.2 Conveyor Belt System Used to Illustrate a Simple Process and Its Control

Contents

1: Operational Amplifiers for Industrial Applications 1

2: Linear Integrated Circuits for Industrial Applications 47

3: Wound-Field DC Motors and Generators 94

4: Brushless and Stepper DC Motors 140

7: Power Control Circuits 275

8: Transducers 323

9: Industrial Process Control 399

10: Pulse Modulation 445

11: Industrial Telemetry and Data Communication 481

12: Sequential Process Control 517