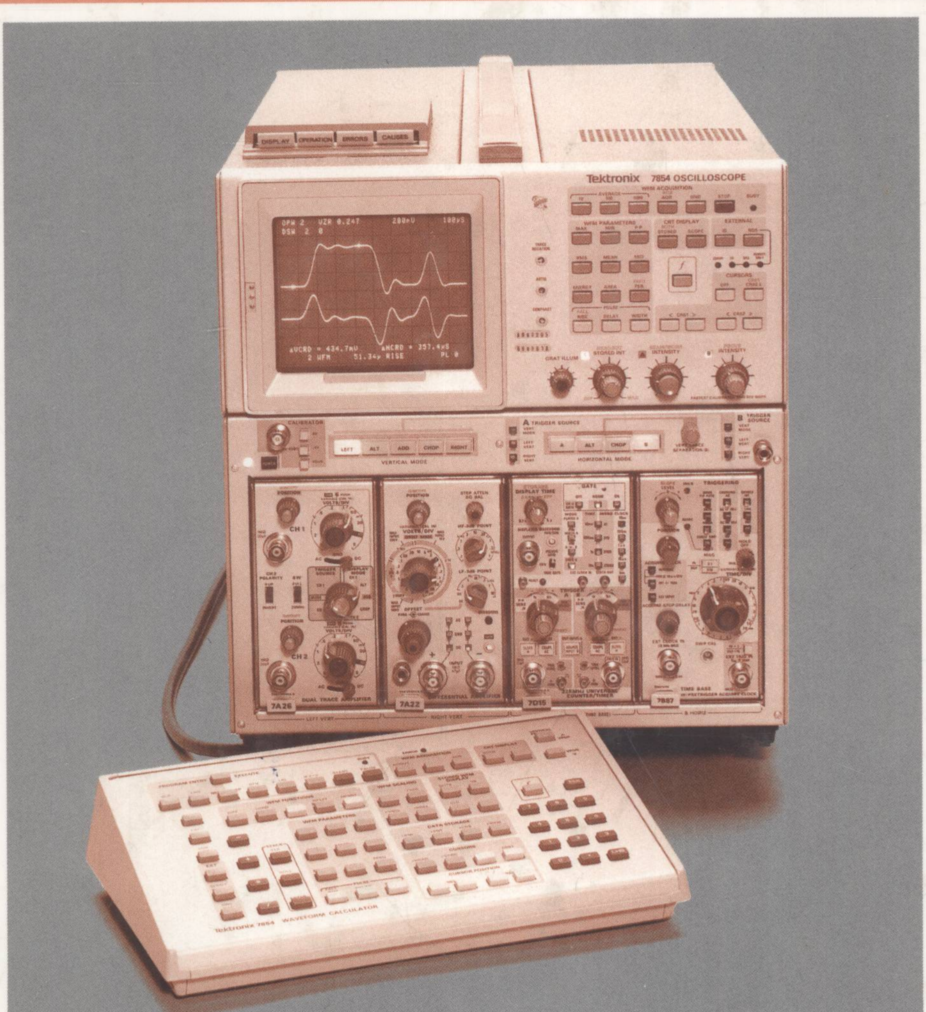
SENSORS AND CIRCUITS

Sensors, Transducers, and Supporting Circuits for Electronic Instrumentation, Measurement, and Control



JOSEPH J. CARR

Sensors and Circuits

SENSORS, TRANSDUCERS, and SUPPORTING CIRCUITS for ELECTRONIC INSTRUMENTATION, MEASUREMENT and CONTROL

Joseph J. Carr

PTR Prentice Hall, Englewood Cliffs, New Jersey 07632

Library of Congress Cataloging-in-Publication Data

Carr, Joseph J.

Sensors and circuits : sensors, transducers, and supporting circuits for electronic instrumentation, measurement, and control / Joseph Carr.

p. cm.

Includes bibliographical references and index

ISBN 0-13-805631-5

1. Transducers. 2. Detectors. 3. Biosensors. I. Title.

TK7872.T6C375 1993

681'.2—dc20 92-14958

CIP

Editorial Assistant: Diane Spina

Prepress and manufacturing buyer: Mary McCartney

Cover design: Wanda Lubelska

Copyeditor: Barbara Liguori

Proofreader: Kristen Cassereau, Carol A. Flynn, and Steven Fine

The publisher offers discounts on this book when ordered in bulk quantities. For more information, contact:

Corporate Sales Department

PTR Prentice Hall

113 Sylvan Avenue

Englewood Cliffs, NJ 07632.

Phone: 201-592-2863

FAX: 201-592-2249

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-805631-5

Prentice-Hall International (UK) Limited, *London*

Prentice-Hall of Australia Pty. Limited, *Sydney*

Prentice-Hall Canada Inc., *Toronto*

Prentice-Hall Hispanoamericana, S.A., *Mexico*

Prentice-Hall of India Private Limited, *New Delhi*

Prentice-Hall of Japan, Inc., *Tokyo*

Simon & Schuster Asia Pte. Ltd., *Singapore*

Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

Preface

Sensors and transducers are the eyes and ears of modern measurement instrumentation and control systems. Many types of machines depend on sensors to provide input data about the environment. Sensors represent both one of the oldest segments of the electronic industry and one of the most modern. Never before have so many different high-quality sensors and transducers been available to designers. In an age when the computer and advanced analog circuitry are making measurement and control advanced arts, it is no surprise that a vast array of old and very modern sensors are needed to interface with the physical world. In short, a sensor is a machine's way to "see," "hear," and "touch" the environment.

The goal of this book is to provide a representative overview of sensors, how they work, how they are applied, and what basic electronic circuits are needed to support them. It is intended to be a practical book that will benefit a variety of professional users of sensors and the instruments they support. It is hoped that it will be useful for many years to come.

Acknowledgments

The author wishes to thank the following for their assistance: Dorothy Rosa, editor of *Sensors: The Journal of Machine Perception*; Charles E. McCullough, MSEE, CCE, Director of Biomedical Engineering at Greater Southeastern Community Hospital in Washington, D.C.; and Mr. John M. Brown of Burr-Brown Corporation. Thanks are also extended to Dr. Michael J. Shaffer, director of The Bioelectronics Laboratory, The George Washington University Medical Center and Professor in the Department of Anes-

Contents

Transducers, Sensors, and Signal Processing 1

This book is about electronic sensors, the artificial sense organs of instruments and machines. Widely used in both analog and digital instrumentation systems, sensors provide the interface between electronic circuits and the "real world" where things happen. The world of electronics would remain a curiosity for laboratory scientists—and a very few others—were it not for sensors.

A *sensor*, or *transducer* (the words are roughly equivalent for our purposes), is a device that converts energy derived from a physical phenomenon into an electrical current or voltage, for purposes of measurement, control, or information (as in scientific research).

ELECTRONIC INSTRUMENT SYSTEMS

Figure 1–1 shows a block diagram for a generic electronic instrument. Although this figure is merely an example, it could easily serve for a large class of actual analog and digital instruments presently on the market. The principal stages or functions of an electronic instrument are *input parameter* (*stimulus*); *sensor* or *transducer*; *input functions*; *amplification* and *signal processing*; *output functions*; and *display*, *recording*, or other means for presenting the data.

Physical stimulus. The physical stimulus that is sensed in an instrumentation system may be temperature, light, displacement, fluid or gas flow, electrical resistance, electrical potential, or any of a host of other physical parameters. The particular stimulus is not important in a discussion of generic

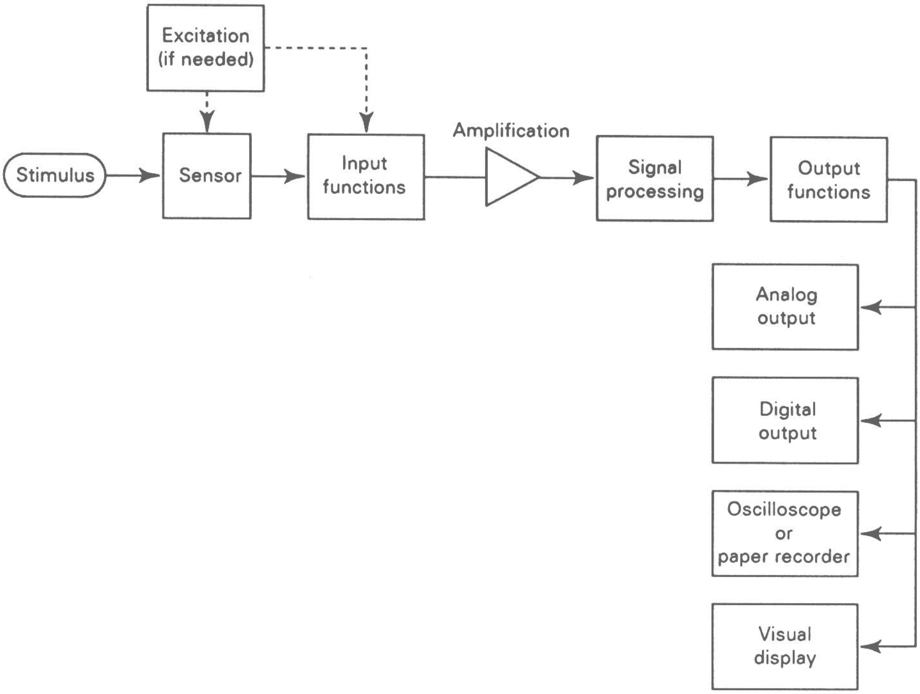


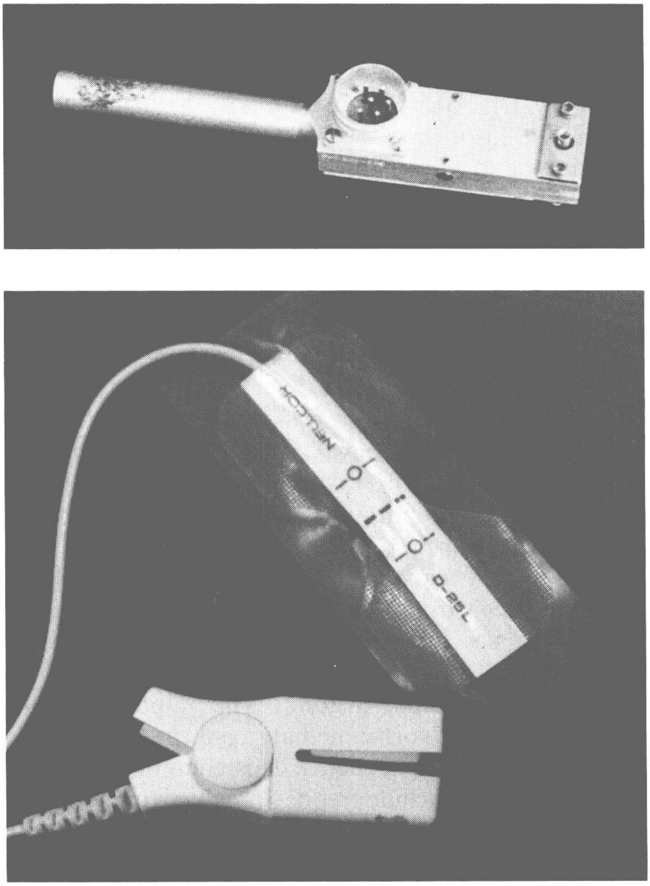
Figure 1–1 A typical sensor-based instrumentation system.

parameters. The particular stimulus is not important in a discussion of generic instruments but becomes important when specific applications are being discussed. Various chapters discuss the applicable sensors for specific forms of physical parameters or stimuli.

Sensors and transducers. The *sensor* or *transducer* is a device that is capable of responding to the applied stimulus and producing an electrical output signal that corresponds to the value of the applied stimulus.

Examples of typical sensors are shown in Fig. 1–2. The device shown in Fig. 1–2(a) is a Grass FT-3 force-displacement sensor. It consists of a Wheatstone bridge strain gage to measure minute forces (in units of gram·force) or minute deflections from the rest position. The devices in Fig. 1–2(b) are photoplethysmograph (PPG) blood oxygen monitors. These sensors are used to measure the blood O_2 level without physically invading the body. They utilize a property of blood, namely, the *isosbestic point*, the wavelength (color) at which the absorptivity of oxygenated and deoxygenated blood is the same (a wavelength of about 800 nm), as the transducible reference point.

There is often some ambiguity in the use of the words *sensor* and *transducer*, and in many cases they are properly used interchangeably. A transducer is a device that converts energy from one form to another (e.g., pressure



(a)

(b)

Figure 1–2 (a) Force-displacement sensor; (b) Pulse oximeter sensors used to noninvasively measure blood oxygen level.

to an electrical potential), whereas a sensor may or may not make some sort of conversion, at least in an obvious way (e.g., a biomedical electrode). Thus, an electrode used in medical electrocardiograph (ECG) recording is a sensor but not a transducer, but a pressure transducer is both a sensor and a transducer. A loudspeaker transduces an electrical audio frequency signal into a mechanical acoustical vibration. It is an *output transducer* and not a sensor at all.*

Some physical parameter or stimulus (e.g., temperature, flow, pressure, or displacement) affects the output state of a sensor; the sensor is a device

*For those who know more than is necessary for this discussion, it is recognized that certain loudspeakers, notably those of the *dynamic PMMC* design, can also serve as microphones—so they are both sensors and output devices.

that produces an output signal that is proportional to the applied parameter. Thus, the output of the sensor will be either a voltage or current that represents the parameter being measured (e.g., a temperature sensor that outputs a voltage V of 10 mV/K). More often than not, the magnitude of the voltage or current from the sensor represents the magnitude of the parameter at the instant of measurement. Over time, this voltage or current represents the time-history of the parameter.

The most desirable sensors have an output signal characteristic that is linear with respect to the stimulus parameter. However, there are also many useful transducers that are either quasi-linear (i.e., linear over only a portion of their total range) or even nonlinear. Such transducers are often used over a limited range, or they must be artificially linearized.

Input functions. The purpose of the input circuit is to receive the signal from the transducer and convert it into whatever form (usually a voltage) that is required by the circuits to follow. In this section of the instrument, interfacing becomes very important. The input functions usually include amplification, but they can also include an ac or dc excitation voltage (especially in the case of Wheatstone bridge sensors), dc level shifting, or isolation of the input circuit from the remainder of the instrument (common in medical instruments because of patient safety considerations).

Signal processing/amplification. The output signal from most sensors is not usually suitable for immediate display. Rather, some form of signal conditioning is usually needed. This conditioning may be only amplification, but it may also include frequency-selective filtering; mathematical operations such as differentiation, integration, "logging" or "antilogging"; or simple dc level translation. In other cases the signal processing uses the analog circuit, in effect, as a fixed-program, dedicated analog computer to solve for a mathematical expression. Some of these functions are most reasonably assigned to analog circuits, whereas others are most reasonably assigned to either digital circuits or computer software. In each case the designer must decide the proper choice for the problem at hand.

Output functions. The output of the instrument must often be processed in some manner before it can be displayed. The output functions may include power amplification (as in the case of a control system motor driver), digitization for input to a computer, or voltage scaling for ease of reading by a human operator.

Output and display. Finally, for an instrument to be useful there must be a display, data storage, or a control function. Various forms of output and display function are available, depending on the need. An analog output may be necessary, especially if the signal must be passed to some other instrument for further processing or application. Alternatively, the signal may be digitized (or, indeed, originally generated as a digital signal) and applied to some form of digital display. A y-time or x-y oscillographic display can be interfaced with either a strip-chart recorder or a cathode ray oscilloscope. Various forms of visual (sometimes called alphanumeric) display devices are used, especially when the output information is in the form of a numerical value (e.g., 100 torr of pressure).

The visual display or recording device may be a dc meter movement (Fig. 1–3), an oscilloscope (Fig. 1–4), a strip-chart recorder (Fig. 1–5), a digital printer (Fig. 1–6), a video terminal, or even a simple GO–NO GO lamp. In some systems the signal has to be digitized before it can be stored as data in a digital computer system. In still other systems the output signal is simply stored in a mass storage device for later use.

DIRECT, INDIRECT, AND INFERENTIAL MEASUREMENTS

One way to categorize instrumentation systems is according to how a measurement is derived. It is reasonable to speak of three different categories: direct measurements, indirect measurements, and inferential measurements (although some authorities generally lump together the latter two categories).

The *direct measurement* is, as the term implies, a measurement that is made of the parameter itself without the need for interpretation, calculation, or any form of interpolation. The force-displacement sensor in the preceding discussion is an instrument that directly measures the applied force. Another example of an instrument that performs the direct type of measurement is a pressure gauge

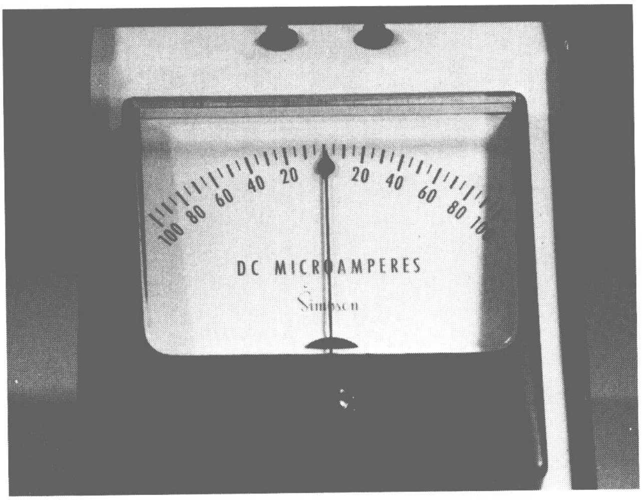


Figure 1–3 Zero-center analog meter.

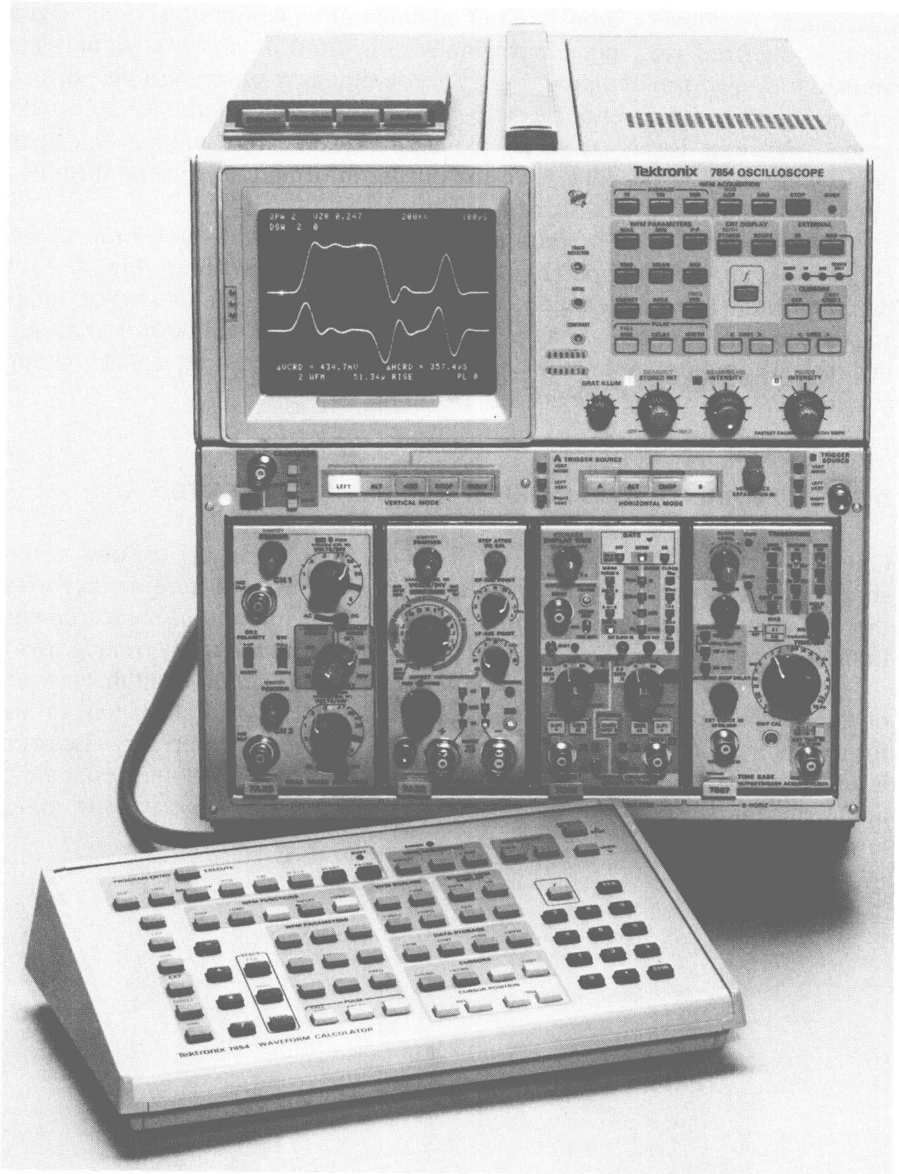


Figure 1–4 Modern oscilloscope uses plug-in modules to enhance versatility.