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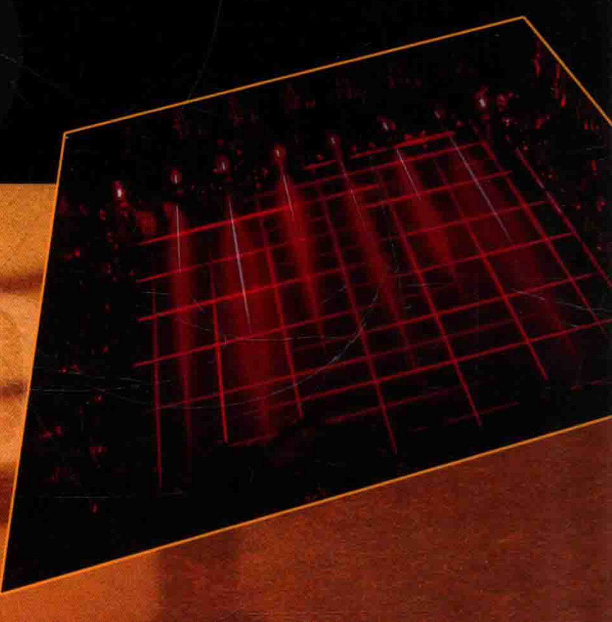
FUNDAMENTALS OF SENSORS FOR ENGINEERING AND SCIENCE

PATRICK F DUNN



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Length	1 m =	100 cm	1×10^{-3} km	39.37 in.	3.281 ft	6.214×10^{-4} mi	3.937×10^{4} mil
Area	1 m^2 =	1×10^{4} cm^2	10.76 ft^2	1550 $in.^2$	2.471×10^{-4} acre	1×10^{-4} ha	3.861×10^{-7} mi
Volume	1 m^3 =	1×10^{6} cm^3	1000 L	35.31 ft^3	6.102×10^{4} $in.^3$	264.17 US gallon	1056.7 liquid qt
Time	1 s =	1000 ms	1.667×10^{-2} min	2.778×10^{-4} h	1.157×10^{-5} d	3.169×10^{-8} y	3×10^{8} light m
Speed	1 m/s =	100 cm/s	3.281 ft/s	3.6 km/h	2.237 mi/h	1.944 nautical mi/h	
Mass	1 kg =	1000 g	6.852×10^{-2} slug	2.2046 lbm	1×10^{-3} metric ton	6.023×10^{26} amu	500 carat
Mass Density	1 kg/m^3 =	0.001 g/cm^3	1.940×10^{-3} slug/ft^3	6.242×10^{-2} lbm/ft^3	1.123×10^{-6} slug/$in.^3$	3.612×10^{-5} lbm/$in.^3$	
Weight, Force	1 N =	1×10^{5} dyne	0.2248 lbf	7.233 pdl			
Pressure	1 Pa =	10 dyne/cm^2	9.869×10^{-6} atm	4.015×10^{-3} in. H_2O	7.501×10^{-4} cm Hg	1.450×10^{-4} lbf/$in.^2$	2.089×10^{-2} lbf/ft^2
Energy, Work	1 J =	2.778×10^{-7} kW·h	9.481×10^{-4} Btu	1×10^{7} erg	0.7376 ft·lbf	3.725×10^{-7} hp·h	0.2389 cal
Power	1 W =	0.001 kW	3.413 Btu/h	0.7376 ft·lbf/s	1.341×10^{-3} hp	0.2389 cal/s	
Temperature	1 K =	$(5/9) \times {}^\circ F + 255.38$	$^\circ C + 273.15$	$(5/9) \times {}^\circ R$			
Plane Angle	1 rad =	57.30°	3438′	2.063×10^{5}″	0.1592 rev		

UNIT CONVERSIONS

Derived Unit	**Symbol**	**Base Units**
Force	N (newton)	$kg \cdot m \cdot s^{-2}$
Pressure	Pa (pascal)	$kg \cdot m^{-1} \cdot s^{-2}$
Energy, Work, Heat	J (joule)	$kg \cdot m^2 \cdot s^{-2}$
Power	W (watt)	$kg \cdot m^2 \cdot s^{-3}$
Electric Charge	C (coulomb)	$A \cdot s$
Electric Potential Difference	V (volt)	$kg \cdot m^2 \cdot s^{-3} \cdot A^{-1}$
Electric Resistance	Ω (ohm)	$kg \cdot m^2 \cdot s^{-3} \cdot A^{-2}$
Electric Conductance	S (siemens)	$kg^{-1} \cdot m^{-2} \cdot s^3 \cdot A^2$
Electric Capacitance	F (farad)	$kg^{-1} \cdot m^{-2} \cdot s^4 \cdot A^2$
Electric Inductance	H (henry)	$kg \cdot m^2 \cdot s^{-2} \cdot A^{-2}$
Magnetic Flux	Wb (weber)	$kg \cdot m^2 \cdot s^{-2} \cdot A$

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Cover

The two sensors featured on the cover are span temperature measurement chronology. The thermoscope marks its beginning. A modern temperature-field sensor symbolizes the present.

The two-bulb "Dutch" thermoscope is depicted on the top left of the cover. This is just one variation of the thermoscope, which was invented in Europe around the turn of the 16th century. Who is its inventor is debatable. The thermoscope was invented about 40 years before the first sealed thermometer and more than 100 years before Gabriel Fahrenheit developed his temperature scale. The thermoscope indicated changes of temperature but did not measure them. Its sensor was the liquid within the thermoscope, which usually was water.

The grid of red laser beams shown on the bottom right of the cover is produced by an arrangement of fiber optics used for gas temperature imaging. The arrangement has been developed by Professor Scott Sanders's research group at the University of Wisconsin—Madison. For the photo shown, a visible laser source was coupled into each of the 30 delivery fibers, and the measurement plane was visualized using fog. In actual operation, a specially designed infrared laser source is coupled into the fibers. Water vapor in the measurement plane absorbs some of this infrared radiation, and, by analyzing the absorption, gas temperatures are determined. Tomographic reconstruction is used to generate planar gas temperature images from the 30-beam absorption data. The apparatus can provide movies of gas temperature with a frame rate of 50 kHz (20 ms/frame) and accommodates gas temperatures up to 2500 K.

Preface

This text describes the fundamental aspects of sensors that currently are used by both engineers and scientists throughout the world. Its material is presented in a contemporary style to enable the user to make informed decisions when choosing a sensor. Forty-five different man-made sensors are considered. In addition, the sensors of the human body are reviewed. Finally, several biomimetic sensors that mimic their human counterparts are presented. Their examples exemplify the current trend toward making sensors smaller, more precise, and more robust.

Besides serving as a text on sensor fundamentals, this text is a companion to the second edition of **Measurement and Data Analysis for Engineering and Science**. This new text greatly expands the coverage of sensors presented in the second edition's Chapter 3 (Measurement Systems). This project grew out of requests by instructors to increase coverage of modern sensors and their basic principles.

This text follows a unique approach. It discusses the role of a sensor, its characteristics, and the various ways in which it is classified. Contemporary sensors are organized and described with respect to their basic physical principles. A new feature is coverage of human sensors, which are the ultimate goal of many biomimetic sensor designers. Several recent biomimetic sensors are described to illustrate recent progress in biomimetic sensor design.

This text's web site (www.nd.edu/~pdunn/www.text/sensors.html) should be consulted for up-to-date information, as well as that for the second edition of **Measurement and Data Analysis for Engineering and Science** (www.nd.edu/~pdunn/www.text/measurements.html). Instructors who adopt either text for their course can receive a CD containing the particular problem solutions manual by contacting their Taylor & Francis / CRC Press representative.

Many people contributed to the two editions of **Measurement and Data Analysis for Engineering and Science** and, thus, to this new text. They are acknowledged in those editions. Two individuals that have contributed notably to both texts deserve special mention. They are Jonathan Plant, the editor of both editions of my measurements text, who suggested writing this new text, and my wife, Carol, who has supported me all along the way.

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Patrick F. Dunn, Ph.D., P.E., is a professor of aerospace and mechanical engineering at the University of Notre Dame, where he has been a faculty member since 1985. Prior to 1985, he was a mechanical engineer at Argonne National Laboratory from 1976 to 1985 and a postdoctoral fellow at Duke University from 1974 to 1976. He earned his B.S., M.S., and Ph.D. degrees in engineering from Purdue University (1970, 1971, and 1974). He is the author of more than 160 scientific journal and refereed symposia publications and a licensed professional engineer in Indiana and Illinois. He is a Fellow of the American Society of Mechanical Engineers and an Associate Fellow of the American Institute of Aeronautics and Astronautics. He is the recipient of departmental, college, and university teaching awards.

Professor Dunn's scientific expertise is in fluid mechanics and microparticle behavior in flows. He is an experimentalist with more than 40 years of experience. He is the author of the textbook **Measurement and Data Analysis for Engineering and Science** (first edition by McGraw-Hill, 2005; second edition by Taylor & Francis / CRC Press, 2010) and **Uncertainty Analysis for Forensic Science** with R.M. Brach (first and second editions by Lawyers & Judges Publishing Company, 2004 and 2009).

Contents

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Sensor Fundamentals

CONTENTS

1.1 Chapter Overview

Sensors are at the beginning of every measurement system, whether it is a liquid in a thermometer responding to a change in temperature or a rod in our retina sensing a single photon of light. This chapter discusses the role of a sensor in a measurement system. Classifications of sensors are presented along with their characteristics. Additional considerations also are offered, including how sensor scaling affects its design, the instrument uncertainties of sensors, and sensor calibration.

1.2 Role in a Measurement System

A measurement system comprises the equipment used to sense an experiment's environment, to modify what is sensed into a recordable form, and to record its values. Formally, the elements of a measurement system include the sensor, the transducer, the signal conditioner, and the signal processor. These elements, acting in concert, sense the physical variable, provide a response in the form of a signal, condition the signal, process the signal, and store its value.

A measurement system's main purpose is to produce an accurate numerical value of the measurand. Ideally, the recorded value should be the exact value of the physical variable sensed by the measurement system. In practice, the perfect measurement system does not exist, nor is it needed. A result only

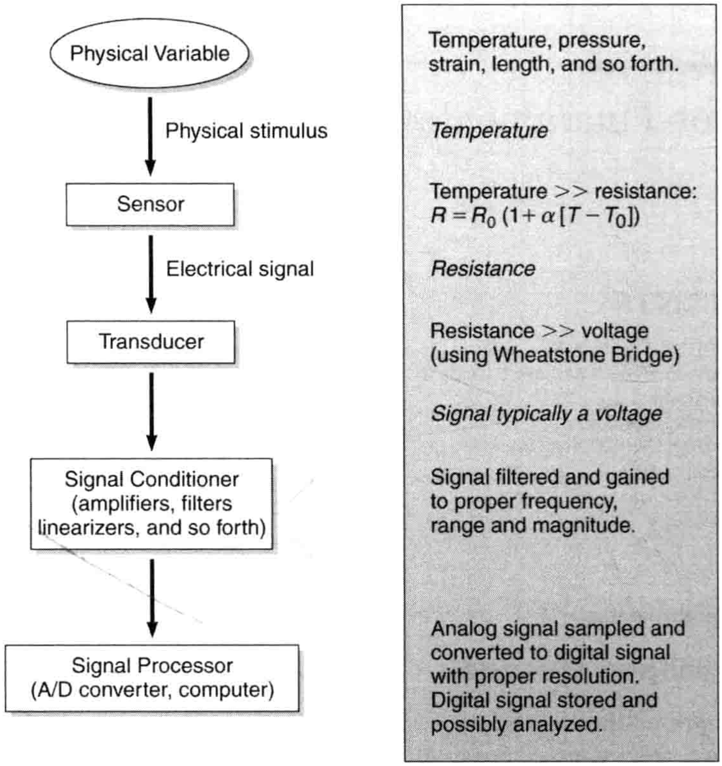

FIGURE 1.1
The general measurement system configuration.

needs to have a certain accuracy that is achieved using the most simple equipment and measurement strategy. This can be accomplished provided there is a good understanding of the system's response characteristics.

To accomplish the task of measurement, the system must perform several functions in a series. These are illustrated schematically in Figure 1.1. First, the physical variable must be sensed by the system. The variable's stimulus determines a specific state of the sensor's properties. Any detectable physical property of the sensor can serve as the sensor's **signal**. When this signal changes rapidly in time, it is referred to as an **impulse**. So, by definition, the **sensor** is a device that senses a physical stimulus and converts it into a signal. This signal usually is electrical, mechanical, or optical.

For example, as depicted by the words in italics in Figure 1.1, the temperature of a gas (the physical stimulus) results in an electrical resistance (the signal) of a resistance temperature device (RTD), a temperature sensor that is located in the gas. This is because the resistance of the RTD sensor (typically a fine platinum wire) is proportional to the change in temperature from a reference temperature. Thus, by measuring the RTD's resistance, the local temperature can be determined. In some situations, however, the signal may not be amenable to direct measurement. This requires that the signal be changed into a more appropriate form, which, in almost all circumstances, is electrical. Most of the sensors in our bodies have electrical outputs.

The device that changes (transduces) the signal into the desired quantity (be it electrical, mechanical, optical, or another form) is the **transducer**. In the most general sense, a transducer transforms energy from one form to another. Usually, the transducer's output is an electrical signal, such as a voltage or current. For the RTD example, this would be accomplished by having the RTD's sensor serve as one resistor in an electrical circuit (a Wheatstone bridge) that yields an output voltage proportional to the sensor's resistance. Often, either the word *sensor* or the word *transducer* is used to describe the combination of the actual sensor and transducer. A transducer also can change an input into an output providing motion. In this case, the transducer is called an **actuator**. Sometimes, the term *transducer* is considered to encompass both sensors and actuators [1]. So, it is important to clarify what someone specifically means when referring to a transducer.

The sensor/transducer system in a house thermostat basically consists of a metallic coil (the sensor) with a small glass capsule (the transducer) fixed to its top end. Inside the capsule is a small amount of mercury and two electrical contacts (one at the bottom and one at the top). When the thermostat's set temperature equals the desired room temperature, the mercury is at the bottom of the capsule such that no connection is made via the electrically conducting mercury and the two contacts. The furnace and its blower are off. As the room temperature decreases, the metallic coil contracts, thereby tilting the capsule and causing the mercury to close the connection between the two contacts. The capsule transduces the length change in the coil into a digital (on/off) signal.

Another type of sensor/transducer system is in a landline telephone mouthpiece. This consists of a diaphragm with coils housed inside a small magnet. There is one system for the mouthpiece and one for the earpiece. The diaphragm is the sensor. Its coils within the magnet's field are the transducer. Talking into the mouthpiece generates pressure waves, causing the diaphragm with its coils to move within the magnetic field. This induces a current in the coil, which is transmitted (after modification) to another telephone. When the current arrives at the earpiece, it flows through the coils of the earpiece's diaphragm inside the magnetic field and causes the diaphragm to move. This sets up pressure waves that strike a person's eardrum as sound. Newer phones use piezo-sensors/transducers that generate an electric current from applied pressure waves and, alternatively, pressure waves from an applied electric current. Today, most signals are digitally encoded for transmission either in optical pulses through fibers or in electromagnetic waves to and from satellites. Even with this new technology, the sensor still is a surface that moves, and the transducer still converts this movement into an electrical current.

Often after the signal has been transduced, its magnitude still may be too small or may contain unwanted electrical noise. In this case, the signal must be conditioned before it can be processed and recorded. In the signal conditioning stage, an amplifier may be used to increase the signal's amplitude, or a filter may be used to remove the electrical noise or some unwanted frequency content in the signal. The **signal conditioner**, in essence, puts the signal in its final form to be processed and recorded.

In most situations, the conditioner's output signal is analog (continuous in time), and the **signal processor** output is digital (discrete in time). So, in the signal processing stage, the signal must be converted from analog to digital. This is accomplished by adding an analog-to-digital (A/D) converter, which usually is contained within the computer that is used to record and store data. That computer also can be used to analyze the resulting data or to pass this information to another computer.

A standard glass-bulb thermometer contains all the elements of a measurement system. The sensor is actually the liquid within the bulb. As the temperature changes, the liquid volume changes, either expanding with an increase in temperature or contracting with a decrease in temperature. The transducer is the bulb of the thermometer. A change in the volume of the liquid inside the bulb leads to a mechanical displacement of the liquid because of the bulb's fixed volume. The stem of the thermometer is a signal conditioner that physically amplifies the liquid's displacement, and the scale on the stem is a signal processor that provides a recordable output.

1.3 Domains

There are a variety of ways by which a sensor can be categorized. Often, a sensor is located within the environment of interest. This type of sensor, which usually is mechanical or electrical, is considered an **invasive**, or *in situ*, sensor. Ideally, invasive sensors should not disturb the environment, which could alter the process under investigation. A sensor also can be located outside the environment. For example, an optical pyrometer senses temperature remotely. This is a **noninvasive** sensor.

Almost all of the signals between the sensor and the detectable output are electrical, mechanical, or optical. Electrical-based sensors and transducers can be **active** or **passive**. Active elements require an external power supply to produce a voltage or current output. The electrical elements of active electrical sensors are resistors, capacitors, or inductors. Passive elements require no external power supply. Their elements typically are either electromagnetic or thermoelectric. Mechanically based sensors and transducers usually use a secondary sensing element that provides an electrical output. Often the sensor and transducer are combined physically into one device.

Sensors in the human body convert a stimulus input into an electrical output. These sensors include those for vision, taste, smell, hearing, equilibrium, touch, temperature, nociception, and proprioception. Because energy is required to restore the potential difference to its potential that existed prior to stimulus application, these sensors would be characterized best as active electrical sensors.

Sensors can be categorized into **domains**, according to the type of physical variables that they sense [1], [2]. These domains and the sensed variables include

- chemical: chemical concentration, composition, and reaction rate;
- electrical: current, voltage, resistance, capacitance, inductance, and charge;
- magnetic: magnetic field intensity, flux density, and magnetization;
- mechanical: displacement or strain, level, position, velocity, acceleration, force, torque, pressure, and flow rate;
- radiant: electromagnetic wave intensity, wavelength, polarization, and phase; and
- thermal: temperature, heat, and heat flux.

Sensors also can be organized with respect to the physical basis of how they sense. These are

- electric,
- piezoresistive,
- fluid mechanic,
- optic,
- photoelastic,
- thermoelectric, and
- electrochemical.

This is the manner by which the sensors described in Chapter 2 are presented.

1.4 Characteristics

The characteristics of a sensor can include those related to the sensor's input and output, which are the sensor's

- operational bandwidth,
- magnitude and frequency response over that bandwidth,
- sensitivity,
- accuracy,
- resolution,
- response time,
- recovery time, and
- output type.

All of these, except for the last, relate to how well the sensor responds to a stimulus. These response characteristics are described in further detail in Chapter 4 of [3].

Further, there are characteristics that describe the sensor as a component of a measurement system. These are sensor

- selectivity;
- voltage or current supply requirements;
- physical dimensions, weight, and materials;
- environmental operating conditions (pressure, temperature, relative humidity, air purity, and radiation);
- additional signal conditioning requirements;
- operational complexity; and
- cost.

Different sensors from which to choose can be assigned level of priorities or weights for each of these characteristics. Statistical methods, such as the design of experiments or factorial design (see Chapter 6 in [3]), then can be used to determine the sensor that is best. Ultimately, the final choice of sensor may involve either some or all of the aforementioned characteristics.

The following example illustrates how the design of a sensor can be a process that often involves reconsideration of the design constraints before arriving at the final design.

Example Problem 1.1

Statement: A design engineer intends to scale down a pressure sensor to fit inside an ultra-miniature robotic device. The pressure sensor consists of a circular diaphragm that is instrumented with a strain gage. The diaphragm is deflected by a pressure difference that is sensed by the gage and transduced by a Wheatstone bridge. The diaphragm of the full-scale device has a 1 cm radius, is 1 mm thick, and is made of stainless steel. The designer plans to make the miniature diaphragm out of silicon. The miniature diaphragm is to have a 600 μm radius, operate over the same pressure difference range, and have the same deflection. The diaphragm deflection, δ, at its center is

$$\delta = \frac{3(1-\nu^2)r^4\Delta p}{16Eh},$$

in which ν is Poisson's ratio, E is Young's modulus, r is the diaphragm radius, h is the diaphragm thickness, and Δp is the pressure difference. Determine the required diaphragm thickness to meet these criteria and comment on the feasibility of the new design.

Solution: Assuming that Δp remains the same, the new thickness is

$$h_n = h_o\left[\frac{(1-\nu_n^2)r_n^4 E_o}{(1-\nu_o^2)r_o^4 E_n}\right].$$

The properties for stainless steel are $\nu_o = 0.29$ and $E_o = 203$ GPa. Those for silicon are $\nu_n = 0.25$ and $E_n = 190$ GPa. Substitution of these and the aforementioned values into the expression yields $h_n = 1.41 \times 10^{-8}$ m = 14 nm. This thickness is too small to be practical. An increase in h_n by a factor of 10 will increase the Δp range likewise. Recall that this design required a similar deflection. A new design would be feasible if the required deflection for the same transducer output could be reduced by a factor of 1000, such as by the use of a piezoresistor on the surface of the diaphragm. This would increase h_n to 14 μm, which is reasonable using current micro-fabrication techniques. Almost all designs are based upon many factors, which usually require compromises to be made.

1.5 Scaling Considerations

Sensors have evolved considerably since the beginning of scientific instruments. Marked changes have occurred in the past 300 years. The temperature sensor serves as a good example. Daniel Gabriel Fahrenheit (1686–1736) produced the first mercury-in-glass thermometer in 1714 with a calibrated scale based upon the freezing point of a certain ice/salt mixture, the freezing point of water, and body temperature. This device was accurate to within several degrees and was approximately the length scale of 10 cm. In 1821, Thomas Johann Seebeck (1770–1831) found that by joining two dissimilar metals at both ends to form a circuit, with each of the two junctions held at a different temperature, a magnetic field was present around the circuit. This eventually led to the development of the thermocouple. Until very recently,