# SENSORS AND SIGNAL CONDITIONING

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# PREFACE

Many electronics applications present in our everyday life would not be possible without sensors. Without their ability to measure or control physical quantities, many electronic devices would remain as simple laboratory curiosities.

Sensors are required for automation in process and manufacturing industries, including robotics, in experimental engineering, in nonmanufacturing areas such as streetlight control and environmental control (air, noise, water quality), in cars and household machines, in agriculture and medicine, and so on. Even data-processing equipment, so common in offices, includes several sensors in order for it to work properly. Think, for example, about position control for read heads in magnetic storage disks. In the future the availability of new sensors based on semiconductors (silicon in particular), fiber optics, and new materials like polymers and elastomers will result in an increased importance for sensors as their applications will cover new areas.

This unquestionable importance for sensors contrasts with the rather limited bibliography on them, particularly from the electronic engineering point of view. This book hopes to contribute to filling this gap. We describe the principle of operation of the most common sensors and discuss their advantages and disadvantages. But we feel that for the electronic engineer facing problems related to the design of measuring systems, that is not enough. Therefore we also analyze the electronic signal-conditioning circuits required by these sensors. This way we cover all areas going from the physical quantity to the analog-to-digital converter that is the usual input device for microprocessors in measurement and control applications.

The selection of the sensor influences the sensitivity, accuracy, and stability of measuring instruments. Thus one of our goals has been to describe a broad range of sensors and give the actual specifications for several commercial sensors, which have been compiled in tables elsewhere in the book. We have not considered those devices whose applications are only for research purposes rather than for practical use. We give several worked-out circuit design examples and include problems at the end of each chapter. An appendix at the end of the book gives annotated solutions to the problems. In addition we give the most important specifications for several common electronic components, as it is indispensable in any design work to use this kind of information. At the beginning of each chapter there is a short introduction.

We have grouped the sensors according to an electronic criterion, namely, depending on whether they are variable resistors, inductors, or capacitors, or whether they are voltage, charge, or current generators. In other groups there are digital sensors and those based on different principles (semiconductor junctions, fiber optic, ultrasound, etc.). This classification criterion eases the study of the associated circuits. We do not ignore, however, the fact that the real problem is not usually to find a possible application, for example, for a given variable resistor, but to measure flow, pressure, or temperature. For this reason we have included a section on sensors for the most common quantities. Also we give application examples for each of the sensors described. A bibliography section is included at the end of the book where we evaluate several books that describe measurement methods for a large number of physical quantities. We hope that our approach will stimulate the search for and development of new solutions, and thus overcome the need for buying (expensive) subsystems even for the most elementary measurement problems.

The mathematical tools used in this book depend on the nature of the problem being analyzed, but they should be well known by third-year engineering students. We have omitted lengthy mathematical derivations without endangering the clarity of the explanation. For ease of reference, figures for examples and problems are preceded by an E or a P, respectively. In figures, line crossings are not a connection, unless indicated by a black dot.

From its organization and contents, this book is intended for electronic engineering students at different levels. But it may also be of interest to practicing engineers because of the systematic classification of sensors as electronic devices. They may also find interesting some of the original solutions proposed for common sensor signal-conditioning problems and the generalization of some solutions proposed by IC manufacturers in their applications notes. We hope that they will all find useful the dates of the discovery of different physical laws, at least to prevent them from thinking that all has come after the transistor (1947), the operational amplifier (1963), or the microprocessor (1971). Some sensors existed long before all of them. It is the work of electronic engineers to apply all the capabilities of integrated circuits in order that the information provided by sensors results in more economical, reliable, and efficient systems for the benefit of the humans, who certainly have limited perception but who have no equal in intelligence and creativity.

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# 1

# INTRODUCTION TO MEASUREMENT SYSTEMS

## 1.1 GENERAL CONCEPTS AND TERMINOLOGY

### 1.1.1 Measurement Systems

A system is a combination of two or more elements, subsystems, and parts necessary to carry out one or more functions. The function of a measurement system is the objective and empirical assignment of a number to a property or quality of an object or event in order to describe it. That is, the result of a measurement must be independent of the observer (objective) and based on experimental (empirical) findings. There must be a correspondence between numerical quantities and the described properties.

One objective of a measurement can be process monitoring: for example, ambient temperature measurement, gas and water volume measurement, and clinical monitoring. Another objective can be process control: for example, for temperature or level control in a tank. Another objective could be to assist experimental engineering: for example, to study temperature distribution inside an irregularly shaped object, or to determine force distribution on a dummy driver in a car crash. Because of the nature of the desired information and its quantity, CAD (computer-aided design) does not yield complete data for these experiments. Thus measurements in prototypes are also necessary to verify the results of computer simulations.

Figure 1.1 shows the data flow of a measurement and control system. In general, in addition to the acquisition of information carried out by a sensor or a transducer, a measurement requires the processing of that information and the presentation of the result in order to make it perceptible to human

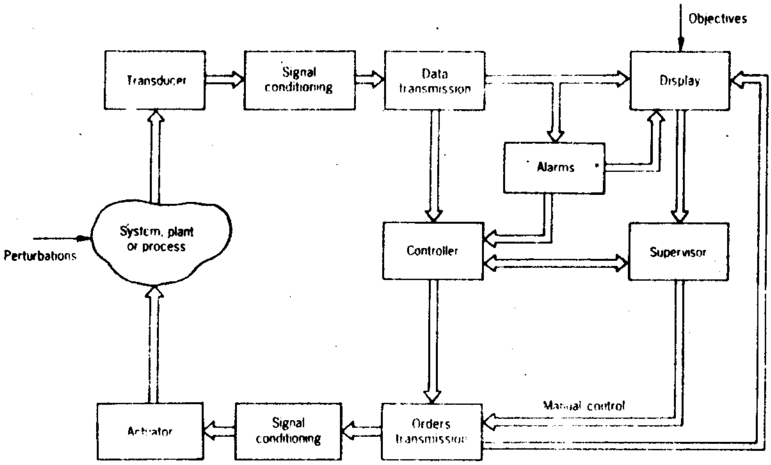


**FIGURE 1.1** General structure of a measurement and control system.

senses. Any of these functions can be local or remote, but remote functions require information transmission.

### 1.1.2 Transducers, Sensors, and Actuators

A transducer is a device that converts a signal from one physical form to a corresponding signal having a different physical form. Therefore it is an energy converter. This means that the input signal always has energy or power. But in measurement systems one of the two components of the measured signal, which is multiplied to yield power, is usually so small that it is negligible, and thus only the remaining component is measured.

When measuring a force, for example, we assume that the displacement in the transducer is insignificant. That is, that there is no "loading" effect. Otherwise, it might happen that the measured force is unable to deliver the needed energy to allow the movement. But there is always a certain power taken by the transducer, so we must ensure that the measured system is not perturbed by the measuring action.

Since there are six different kinds of signals—mechanical, thermal, magnetic, electric, optical, and chemical—any device converting signals of one kind to signals of a different kind is considered to be a transducer. The output signals can be of any useful physical form. In practice, however, only devices offering an electric output are called transducers. This is because electric signals are used in most measurement systems. Some of the advantages of electronic measurement systems are the following:

1. Electrical transducers can be designed for any nonelectric quantity, by selecting an appropriate material. Any variation in a nonelectric parameter yields a variation in an electric parameter because of the electronic structure of matter.
2. Energy is not drained from the process being measured because the transducer output signals can be amplified. With electronic amplifiers it is easy to obtain power gains exceeding $10^{10}$ in a single stage.
3. A large number of diverse integrated circuits are available for electric signal conditioning or modification. There are even transducers that incorporate these conditioners in a single package.
4. Many options exist for information display or recording by electronic means. These options permit us to handle not only numerical data but also text, graphics, and diagrams.
5. Signal transmission is more versatile for electric signals. Mechanical, hydraulic, or pneumatic signals may be more suitable in some circumstances, such as in environments where ionizing radiation or explosive atmospheres are present, but electric signals have replaced most nonelectric signals. In fact in processing industries (chemicals, petroleum, gas, food, textile, paper, etc.) where automation was introduced some time ago, pneumatic systems are frequently found alongside more recent electric systems. However, in manufacturing industries (machinery, automotive, computing, and communication equipment, etc.) where automation is more recent and there are several discontinuous processes, we usually find only electronic systems used.

A transducer is a device that takes energy from the system that it measures to give an output signal that can be transduced to an electric signal and that corresponds to the measured quantity.

Sensor and transducer are sometimes used as synonymous terms. However, *sensor* suggests a broader meaning that includes the extension of our capacity to acquire information about physical quantities not perceived by human senses because of their subliminal nature or minuteness. *Transducer* suggests only that input and output quantities are not the same. The word *modifier* has been proposed for instances where input and output quantities are the same; but it has not been widely accepted.

The distinction between input-transducer (physical signal/electric signal) and output-transducer (electric signal/display or actuation) is seldom used today. The trend, particularly in robotics is toward using *sensor* to refer to the input transducer while *actuator* refers to the output transducer. Sensors are intended to acquire information. Actuators are designed for power conversion.

In this book we use *sensor* to refer to input transducers. Output transducers or actuators are beyond the scope of this work. Sometimes, particularly when mechanical quantities are being measured, an element called a *primary* *sensor* is introduced to convert the measured variable into a measuring signal. Then a sensor would convert that signal into an electric signal. For example, one would use a diaphragm as the primary sensor to measure a pressure difference but measure deformation using a strain gage which serves as the sensor (see Section 1.7.2 and Section 2.2). In this book we will designate as sensor the whole device, including the package and leads.

### 1.1.3 Signal Conditioning and Display

In a broad sense signal-conditioning units, adapters, or amplifiers are measuring system elements that start with an electric sensor output signal and then yield a signal suitable for display or recording, or that better meets the requirements of a subsequent standard equipment or device. They normally consist of electronic circuits performing any of the following functions: amplification, filtering, impedance matching, modulation, and demodulation.

In the usual case one of the stages of the measuring system is digital and the sensor output is analog. Then an analog-to-digital converter (ADC) is used. The ADC devices have low input impedance, and they require that the signal applied to their input be dc or slowly varying and that their amplitudes not exceed specified margins, usually less than $\pm 10$ V. Therefore, sensor output signals, which may have an amplitude in the millivolt range must be signal conditioned before they can be applied to the ADC.

The display of measured results can be in an analog (optical, acoustic, or tactile) or in a digital (optical) form. The recording can be magnetic, electronic, or on paper, but the information to be recorded should always be in electrical form.

### 1.1.4 Interfaces, Data Domains, and Conversion

In measurement systems the functions of signal transduction, conditioning, processing, and display are not always divided into physically distinct elements. Furthermore the border between signal conditioning and processing may be indistinct. But generally there is a need for some signal processing of the sensor output signal before its end use. Some authors use the term *interface* to refer to signal-modifying elements that change signals, even from one data domain to another, such as an ADC. These always operate in the electrical domain.

A *data domain* is the name of a quantity used to represent or transmit information. The concept of data domains and conversion between domains is very useful to describe sensors and electronic circuits associated with them [1]. Figure 1.2 shows some possible domains, most of which are electrical.

In the *analog domain* the information is carried by signal amplitude (i.e., charge, voltage, current, or power). In the *time domain* the information is

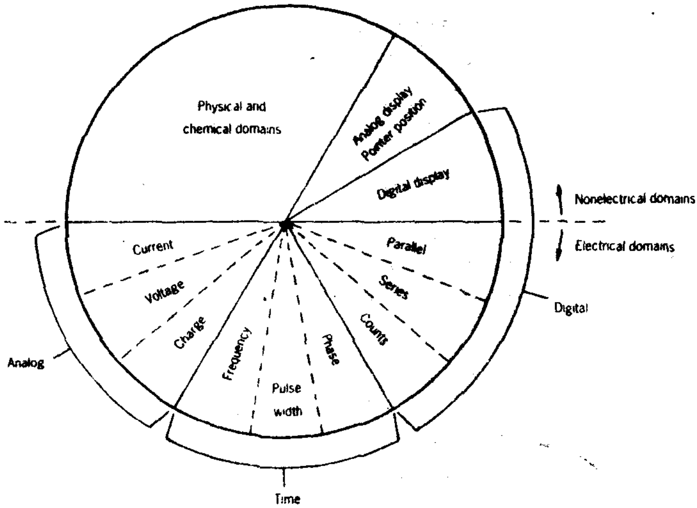


**FIGURE 1.2** Data domains [1]. (From H. V. Malmstadt, C. G. Enke, and S. R. Crouch, *Electronics and Instrumentation for Scientists*, © 1981. Reprinted by permission of Benjamin/Cummings, Menlo Park, CA.)

not carried by amplitude but by time relations (period or frequency, pulse width, or phase). *In the digital domain signals have only two values.* The information can be carried by the number of pulses or by a coded serial or parallel word.

The analog domain is the most prone to electric interference (see Section 1.3.1). In the time domain the coded variable cannot be measured, that is, converted to the numerical domain in a continuous way. Rather, a cycle or pulse duration must elapse. In the digital domain numbers are easily displayed.

The structure of a measurement system can be described then in terms of domain conversions and changes, depending on the direct or indirect nature of the measurement method.

A physical measurement is said to be direct when quantitative information about a physical object or action is obtained by direct comparison with a reference quantity. This comparison is sometimes simply mechanical, such as in a weighing scale.

In indirect physical measurements the quantity of interest is calculated by applying an equation that describes the law relating other quantities measured with a device, usually an electric one. For example, one measures the mechanical power transmitted by a shaft by multiplying the measured torque and speed of rotation.

## 1.2 SENSOR CLASSIFICATION

A great number of sensors are available for different physical quantities. In order to study them, it is advisable first to classify sensors according to some criterion. In addition to the criteria mentioned here, several additional criteria are given in [10].

In considering the need for a power supply, sensors are classified as modulating or self-generating. In modulating (or active) sensors most of the output signal power comes from an auxiliary power source. The input only controls the output. Conversely, in self-generating (or passive) sensors output power comes from the input.

Modulating sensors usually require more wires than self-generating ones because power is supplied by wires different from the signal wires. Moreover the presence of an auxiliary power source can increase the danger of explosion in explosive atmospheres. Modulating sensors have the advantage that their overall sensitivity can be controlled by the power supply voltage. Some authors use the terms *active* for self-generating and *passive* for modulating. To avoid confusion, we will not use these terms.

In considering output signals, we classify sensors as analog or digital. In analog sensors the output changes in a continuous way at a macroscopic level. The information is usually obtained from the amplitude, although sensors with output in the time domain are usually considered as analog. Sensors whose output is in the form of a variable frequency are called *quasi-digital* because it is very easy to obtain a digital output from them.

The output of digital sensors takes the form of discrete steps or states. Digital sensors do not require an ADC, and their output is easier to transmit than that of analog sensors. Digital output is also more repeatable and reliable, and often more accurate. But regrettably many physical quantities cannot be measured by digital sensors.

In considering the operating mode, sensors are classified in terms of their function in a deflection or a null mode. In *deflection* sensors the measured quantity produces a physical effect that generates in some part of the instrument a similar but opposing effect that is related to some useful variable. For example, a dynamometer to measure force is a sensor where the force to be measured deflects a spring to the point where the force it exerts, which is proportional to its deformation, balances the applied force.

*Null*-type sensors attempt to prevent deflection from the null point by applying a known effect that opposes that produced by the quantity being measured. There is an imbalance detector and some means to restore balance. In a weighing scale, for example, the placement of a load on a pan produces an imbalance indicated by a pointer. The user has to place one or more calibrated weights on the other pan until a balance is reached, which can be ascertained from the pointer's position.

Null measurements are usually more accurate because the opposing known effect can be calibrated against a high-precision standard or a refer