SENSORS IN CONTROL SYSTEMS

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*Summary*

Sensors and analyzers are a control system’s window to the world. A sensor is defined as a device that converts a physical stimulus into a readable output, and the definition is illustrated with several examples of engineered and biological sensors. The design of sensors is driven by desired improvements on one or more of surprisingly many
performance features and attributes: signal-to-noise ratio, reliability, safety and intrinsic safety, accuracy, response time, dynamic range, cost, power consumption, size, electromagnetic interference immunity, etc. Recent trends and developments in sensor technology include the increasing use of signal processing for compensation, typically used for reducing cross-sensitivity to secondary variables; multivariable inferential sensing, which allows sensing solutions to be developed for parameters that are infeasible to directly measure online; and self-checking and self-compensating sensors that enhance reliability and reduce maintenance costs.

The chapter also discusses biological sensors with specific reference to olfaction and chemical sensing; in these modalities, our best artificial sensors are no match for biology. In conclusion, visions for improved safety and efficiency through sensor-enabled automation in automobiles, commercial aircraft, health care, asset management, and other areas are outlined.


1. Introduction

Control is more than information processing; it implies direct interaction with the physical world. Control systems include sensors and actuators, the critical pieces needed to ensure that our automation systems can help us manage our activities and environments in desired ways. By extracting information from the physical world, sensors provide inputs to control and automation systems.

We may label our times the Information Age, but it would be a mistake to believe that advances in automation and control are solely a matter of more complex software, Web-enabled applications, and other developments in information technology. In particular, progress in control depends critically on advances in our capabilities for measuring and determining relevant aspects of the state of physical systems.

Technologists tasked with automation and control of systems of ever-increasing levels of complexity, whether as designers, operators, or managers, or in other capacities, thus need to be familiar with sensor technology. The increasing sophistication of sensors and sensing systems, the considerations driving this sophistication, new sensors and uses of sensors in control systems, the increasing reliability of sensors, and the like are topics whose relevance today is not limited to sensor application specialists.

Our objective in this chapter is to discuss sensors from these points of view. Our focus is on the role of sensors in control systems and the trends and outstanding needs therein. Since excellent reviews of recent sensor developments and current applications already exist, we give some selected examples of new sensor developments, without any claims at comprehensiveness. Rather, our goal is to point out the benefits of increased sensor sophistication as well as key approaches and areas where more understanding is needed.
In the following sections, we first offer a definition of a sensor along with several examples. Next, we outline the application of sensors in simple control systems and discuss some of the important attributes of sensors, followed by reviews of recent developments in sensor systems, including sensor compensation and inferential sensing. We then focus on the sensing capabilities of biological systems and lessons we can hope to draw from them. We conclude by presenting some visions for how control and automation can help realize a safer, more productive, and more prosperous future and the role that sensors will need to play.

2. Sensor Fundamentals and Classifications

We can define ‘sensor’ as a device that converts a physical stimulus or input into a readable output, which today would preferably be electronic, but which can also be communicated via other means, such as visual and acoustic. As perhaps the simplest example, consider the sensor on a keyboard switch actuator – which provides a signal when the associated key is pressed. The keyboard switch sensor has several desirable features. It is inexpensive, it has a high signal-to-noise ratio (its on/off impedance ratio), it is compact, and it has low power consumption. Its reliability and ability to operate over a wide range of environmental conditions are also exemplary.

Unlike most sensors, a keyboard switch sensor lacks an analog input range, and its output is binary. Temperature, pressure, and flow sensors are more typical examples. In these cases, the output is not a binary quantity but a value that is sensitive to a range of those physical conditions. Figure 1 shows an example of a state-of-the-art sensor, in this case, a mass flow sensor. As evidenced by this example, many advanced sensors today are microscopic, microstructure devices that leverage the economies of scale and the fabrication technologies of semiconductor manufacturing.

![Figure 1: A micromachined mass flow sensor die (not packaged)](image_url)
A semiconductor sensor that provides a wealth of information is the silicon photodiode. A CCD array of such devices typically generates on the order of $10^9$ bits/second. Yet another example of a near-ideal sensor, it is a very simple device, easily fabricated into arrays with modern solid-state technology, with a very wide dynamic range (the ratio of the maximum to the minimum detectable photon intensity). One characteristic that is almost uniquely ideal is its stability. It has essentially no baseline drift and excellent scale factor stability.

The reasons for these ideal characteristics lie in the physics of the device. It is basically an energy converter – changing light energy (photons) into electrical energy (electrons in higher energy states that can generate current or voltage). When there are no incoming photons, there is no photocurrent – hence the baseline cannot drift. The quantum efficiency is close to unity (meaning one electron per photon) – hence the scale factor (photocurrent divided by light intensity) is constant and stable over many orders of magnitude. A well-designed photodiode is linear over eight orders of magnitude in intensity and provides a primary standard for light intensity measurement within defined wavelength limits. It is not surprising that photodiodes are at the heart of CCD cameras and are ubiquitous in video information systems.

Still other types of sensors operate on chemical principles and may consist of single molecules. For example, a phenolphthalein molecule (the dye in litmus paper) signals a change in hydrogen ion concentration (i.e., pH value) by changing its color. Similarly, a biosensor may be based on a molecule that interacts with a biological analyte to produce a signal we can pick up with our senses.

The generic block diagram for a sensor shown in Figure 2 highlights the role of a sensor as an interface between a control system and the physical world. The detector or transducer converts a physical or chemical phenomenon into (typically) an electrical signal. The signal processor performs one or more of various mathematical operations on the sensed value, such as amplification, rectification, demodulation, digitizing, or filtering. The measured and processed value is communicated to other subsystems (e.g., via a compatible electrical signal) or to a human (e.g., via a display). The sophistication of these functions and of the calibration process varies widely.

The term smart sensor implies that some degree of signal conditioning is included in the same package as the sensor. On the more sophisticated end of the spectrum, the ‘sensor’ unit can include devices or systems with elaborate signal processing, displays, and diagnostic or self-calibration features. Such devices are often referred to as ‘instruments’, ‘analyzers’, or ‘transmitters’ (this last term is common in the process industries), usage that emphasizes that the transducer is but one part of a sensing system in the context of large-scale automation. In this chapter, we will not, however, be making hard distinctions between sensor categories.

There are many ways to list or classify kinds of sensors. Classifications can be found in the literature based on the form of energy being transduced and on whether the transduction mechanism is self-generating (like a thermocouple or a piezoelectric material) or a modulating mechanism (like a thermistor or a piezoresistor). Table 1 shows some sensor examples based on a simple classification criterion: human-made...
versus biological. Either type may be used in an automation system – human operators can be considered part of the system.

<table>
<thead>
<tr>
<th>Engineered sensors</th>
<th>Biological sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensor</strong></td>
<td><strong>Sensed quantity</strong></td>
</tr>
<tr>
<td>Photodiode</td>
<td>Light intensity</td>
</tr>
<tr>
<td>Psychrometer</td>
<td>Humidity</td>
</tr>
<tr>
<td>Barometer</td>
<td>Pressure</td>
</tr>
<tr>
<td>Thermometer</td>
<td>Temperature</td>
</tr>
<tr>
<td>Phenolphthalein</td>
<td>pH</td>
</tr>
<tr>
<td>Timer</td>
<td>Time</td>
</tr>
<tr>
<td>Odometer</td>
<td>Distance (inferred)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Sensor</strong></th>
<th><strong>Sensed quantity</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Retina</td>
<td>Light intensity</td>
</tr>
<tr>
<td>Cochlea</td>
<td>Sound</td>
</tr>
<tr>
<td>Ear canal</td>
<td>Level, rotation</td>
</tr>
<tr>
<td>Taste bud</td>
<td>Chemical composition</td>
</tr>
<tr>
<td>Skin</td>
<td>Temperature</td>
</tr>
<tr>
<td>Skin and hair</td>
<td>Air flow</td>
</tr>
<tr>
<td>Olfactory cells</td>
<td>Gas composition</td>
</tr>
</tbody>
</table>

Table 1: Examples of engineered and biological sensors

A classification focusing on the physical effects that sensors can respond to is the basis of Table 2. One may argue about the classification of some examples, in view of their principle of operation being based on mixed effects. For example, the Hall effect depends on an electric current as well as a magnetic field.

![Sensor block diagram](image)

**Figure 2**: Sensor block diagram

<table>
<thead>
<tr>
<th><strong>Sensing Principle</strong></th>
<th><strong>Examples</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical motion</td>
<td>Pendulum-clock, quartz clock, spring balance, odometer, piezoresistive pressure sensor, accelerometer, gyro</td>
</tr>
<tr>
<td>Thermal (incl. temp.</td>
<td>Thermometer, thermocouple, thermistor, thermal conductivity detector, transistor built-in voltage, air flow sensors</td>
</tr>
<tr>
<td>Optical energy</td>
<td>Photodiode, CCD camera, Geiger-Mueller tube, color sensor, turbidity sensor,</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>Compass, Hall-effect, magnetoresistance, inductive proximity sensor,</td>
</tr>
<tr>
<td>Electric field</td>
<td>Electrostatic voltmeter, field-effect transistor</td>
</tr>
</tbody>
</table>

Table 2: Classification of sensors based on their sensing principle, with examples
3. Sensors in Control Systems

The role of a sensor in a simple automation system is depicted in Figure 3. The detection and measurement of some physical effect provides information to the control system regarding a related property of the system under control, which we are interested in regulating to within some 'set point' range.

The controller outputs a command to an actuator (a valve, for example) to correct for measured deviations from the set point, and the control loop is thereby closed.

Because of the simplicity of the control system example of Figure 3, it represents a fair number of practical control systems. In especially simple systems, a distinct controller may not be immediately evident. For example, the ‘Honeywell Round’ thermostat contains a bimetal strip as an analog sensing mechanism that responds to temperature, and the switch attached to it serves as the actuator.

This integration of sensor and actuator turns a furnace or other space conditioning device on or off, depending on whether the room temperature is within the set-point differential.

In general, however, the trend is to incorporate more, not less, information processing with the sensor. The increasing complexity of sensors is in part a consequence of this trend. In many cases, the information processing is being incorporated within the sensor device, blurring the distinction between transducer and processor, and between sensor and instrument.

![Figure 3: Example of a simple control system](image-url)
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Biographical Sketches

David Zook is currently Chief Technology Officer with Dresden Associates, a small consulting firm in the Minneapolis–St. Paul metropolitan area (U.S.A.). He received his Ph.D. in Solid State Physics from the University of Wisconsin–Madison in 1962. He spent 38 years with Honeywell developing
mechanical, optical and chemical sensors and systems for commercial and military applications and recently retired from Honeywell Laboratories as a Principal Research Fellow. He has authored over 20 patents and 60 refereed papers and twice won the Sweat Award (Honeywell’s highest technical achievement award). He has experience with working over a wide range of technology areas, including electronic and photonic device physics, optical system design, plasma-surface interactions and micro-electro-mechanical systems (MEMS). His most recent work involved MEMS-based fiber optic pressure sensors that are self-resonant such that unmodulated light incident on them is reflected as modulated light with the modulation frequency dependent on pressure. He has also been involved with sensors and actuators for chemical and biological sensing.

Ulrich Bonne is a Senior Research Fellow at Honeywell Laboratories in Plymouth, Minnesota, U.S.A. He received a B.S. degree in Physics at the University of Freiburg i. Br., Germany, in 1957; and his M.S. (Physics, 1960) and Ph.D. (Chemical Physics, 1964) degrees from the University of Göttingen, where he was a Research Associate in the Physical Chemistry Department at the University until joining Honeywell Laboratories in 1965. His current R&D interests and activities include micro sensors and actuators for monitoring air quality and water quality for DoD, DoE, EPA, aerospace, process industry, combustion engines, and appliance applications; non-intrusive approaches for sensing and controlling micro-flows; low-cost sensing of fuel oxygen demand; and sensor self-calibration and actuation-based sensors. His earlier work was in the areas of flame ionization, PZT transformers, liquid crystal displays, and IR/visible/UV spectroscopy in low-pressure flat flames. Dr. Bonne is the author or co-author of some 130 technical publications and 60 U.S. patents. He is the recipient of several technical Honeywell awards: an H.W. Sweat Award (1971) for development of combustion instrumentation; a Honeywell “Pioneer” Award (1990) for electronic gas meter development; Product Development Team Awards for a Gasoline Vapor Sensor (1997) and a Breath Flow Sensor (2001); and a Minnesota Society of Professional Engineers “One of the Seven Wonders of Engineering” Team Award for the development of an advanced heat pump control in 1979.

Tariq Samad is a Corporate Fellow with Honeywell Automation and Control Solutions in Minneapolis, U.S.A. He has been with various R&D organizations in Honeywell for 17 years, and he has been involved in a number of projects that have explored applications of intelligent systems and intelligent control technologies to domains such as autonomous aircraft, building and facility management, power system security, and process monitoring and control. He was the editor-in-chief of IEEE Control Systems Magazine. He is the author or coauthor of about 100 publications and holds 11 U.S. patents. His recent publications include the edited volumes Automation, Control, and Complexity: An Integrated View (Wiley), Perspectives in Control: Technologies, Applications, New Directions (IEEE Press), and Software-Enabled Control: Information Technology for Dynamical Systems (Wiley, in press). Dr. Samad received his B.S. in Engineering and Applied Science from Yale University and his M.S. and Ph.D. in Electrical and Computer Engineering from Carnegie Mellon University. He is the recipient of an IEEE Third Millennium Medal and corecipient of an “Excellence” award for Control Systems Magazine from the Society for Technical Communications, New York Metro Chapter.