SENSORS IN CONTROL SYSTEMS

David Zook
Dresden Associates, Golden Valley, MN, U.S.A

Ulrich Bonne
Honeywell Laboratories, Plymouth, MN, U.S.A

Tariq Samad
Honeywell Laboratories, Minneapolis, MN, U.S.A

Keywords: Transducer, semiconductor, power dissipation, signal processing, compensation, self-checking, biosensors, miniaturization, reliability, biology, sensing principles, manufacturing.

Contents

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.

An earlier version of this chapter appeared in *Automation, Complexity and Control: An Integrated View*, T. Samad and J. Weyrauch, eds., 2000. Portions © John Wiley & Sons Limited; reproduced with permission.

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.

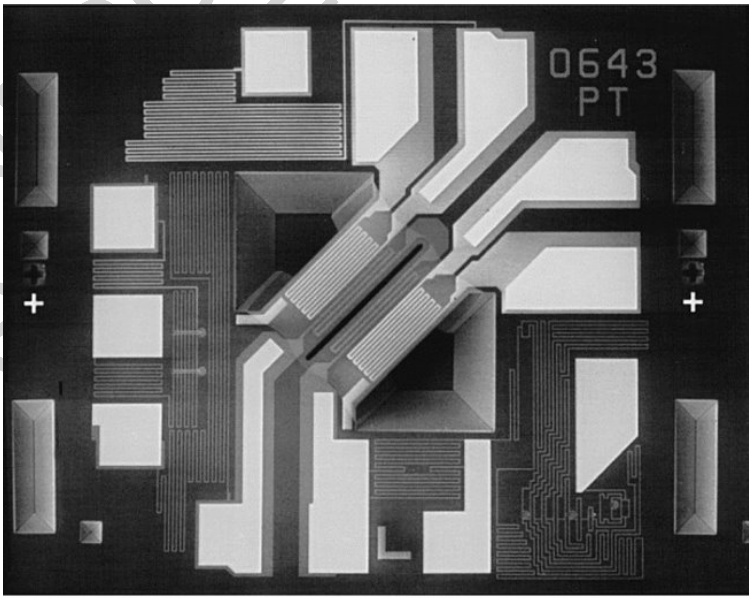

Figure 1: A micromachined mass flow sensor die (not packaged)

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.

Engineered sensors		Biological sensors	
Sensor	*Sensed quantity*	*Sensor*	*Sensed quantity*
Photodiode	Light intensity	Retina	Light intensity
Psychrometer	Humidity	Cochlea	Sound
Barometer	Pressure	Ear canal	Level, rotation
Thermometer	Temperature	Taste bud	Chemical composition
Phenolphthalein	pH	Skin	Temperature
Timer	Time	Skin and hair	Air flow
Odometer	Distance (inferred)	Olfactory cells	Gas composition

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.

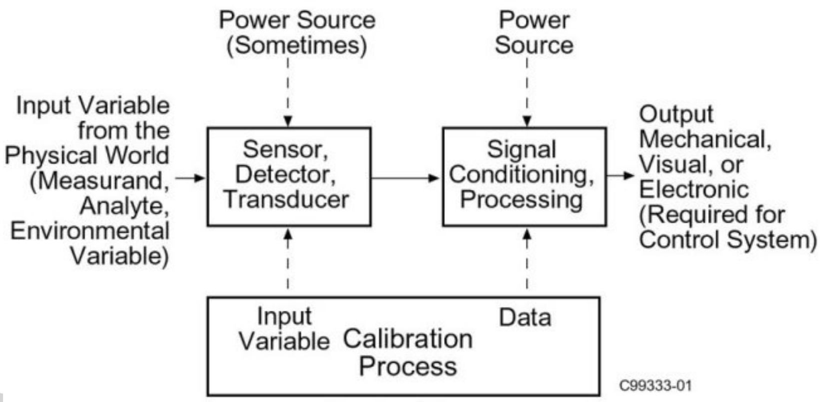

Figure 2: Sensor block diagram

Sensing Principle	Examples
Mechanical motion (including mechanical resonance)	Pendulum-clock, quartz clock, spring balance, odometer, piezoresistive pressure sensor, accelerometer, gyro
Thermal (incl. temperature differences)	Thermometer, thermocouple, thermistor, thermal conductivity detector, transistor built-in voltage, air flow sensors
Optical energy (photons)	Photodiode, CCD camera, Geiger-Mueller tube, color sensor, turbidity sensor,
Magnetic field	Compass, Hall-effect, magnetoresistance, inductive proximity sensor
Electric field	Electrostatic voltmeter, field-effect transistor

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.

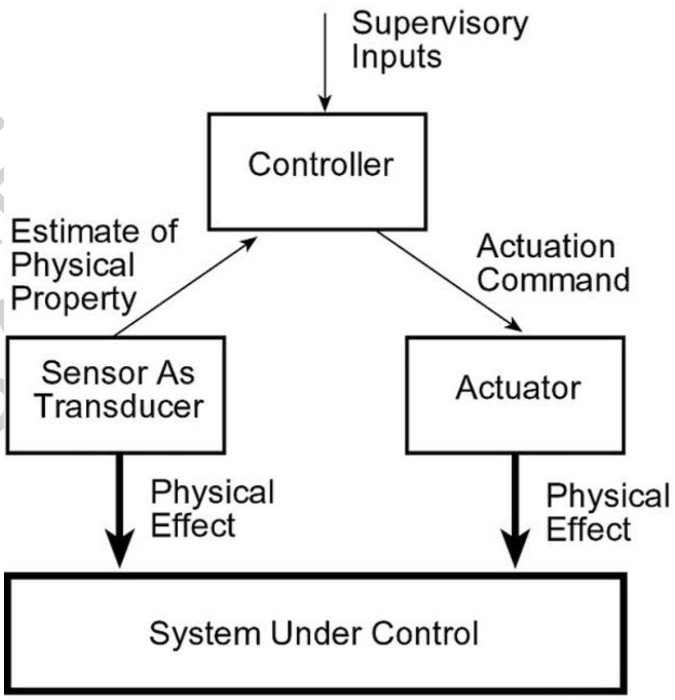

Figure 3: Example of a simple control system

-
-
-

Bibliography

Allen, P. (1984) Sensors in silicon. *High Technology*, September, 43–50. [Description of an integrated pressure sensor which incorporates both sensing and data processing on one integrated circuit chip.]

Ayres, R.U. (1994) *Information, Entropy, and Progress – a New Evolutionary Paradigm*. American Institute of Physics, Woodbury, NY. [This book presents an information-theoretic perspective on evolution.]

Barron, A.R. (1993) Universal approximation bounds for superposition of a sigmoid function. *IEEE Transactions on Information Theory*, 39(3), 930–945. [This article identifies the inherent advantage in predictive accuracy of statistical models with adjustable basis functions—such as feedforward neural networks—compared to standard multiple linear regression.]

Bonne, U. (1990) Flowmeter fluid composition correction. U.S. Patent No. 4,961,348. [An approach to resolving the problem of changes in output due to changes in fluid composition, in a mass flow sensor based on any type of thermal anemometry.]

Bonne, U. (1992) Fully compensated flow microsensor for electronic gas metering. *Proceedings of the International Gas Research Conference*, III, 859, Orlando, FL. [A fluid-property-based approach for compensating for composition, temperature, and pressure sensitivities for thermal flow sensors.]

Bonne, U and Kubisiak, D. (2001) "Actuation-Based Microsensors," *J. Smart Materials & Structures*, vol. 10, p. 1185. [A fluid motion-based approach for compensating for composition, temperature, and pressure sensitivities for any type of flow sensors. See Fig. 6]

Bonne, U, Detry, J., Higashi, R.E., Rezacheck, T. and Swanson, S. (2002) New gas composition and trace contaminant sensors. *Proceedings of the GTI Gas Technology Conference*, Orlando, Forida, 30 Sep. - 2 Oct.. [Describes application of phased heater array structure for enhanced detection (PHASED) sensor technology with application to gas composition as well as other actuation-based sensors.]

Bonne, U. (1996) Sensing fuel properties with thermal microsensors. *Proc. SPIE Conference on Smart Electronics and MEMS*, paper no. 2722-24, San Diego, CA. [Description of a particular temperature-compensated flow sensor including the nonlinear function used for the compensation.]

Desvergne, J.P. and Czarnik, A.W. (eds.) (1997) *Chemosensors of Ion and Molecule Recognition*. Kluwer Academic Publishers, Dordrecht, The Netherlands. [This edited volume contains contributions that include a description of fluorescent chemosensor techniques for single-molecule detection and the use of chemical sensors based on conjugated polymers.]

Fanger P.O. (1970) *Thermal Comfort*. McGraw-Hill Book Co., New York. [A comprehensive discussion of thermal comfort, including the Predictive Mean Vote (PMV) formula.]

Frank, R. (1996) *Understanding Smart Sensors*. Artech House, Boston, MA. [Reviews the principles behind and developments in the embedding of "intelligence" in sensor systems. Also presents a classification of different sensor types.]

Honeywell Inc. (1998) Shutter-check flame detectors, models C7012E, C7012D, C7024E, C7024F, C7061A, C7076A and C7076D. *Tradeline Catalog*, Publ. No. 70-6910, Honeywell Home and Building Control, Golden Valley, MN, 753–763. ["Fail-safe" systems with optomechanical sensors for flame detection.]

ISO 7730 (1994) *Moderate Thermal Environments – Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort* (2nd ed.). International Standards Organization, Geneva, ref. no. ISO 7730:1994(E). [Adoption of Predicted Mean Vote as an international standard for thermal comfort of human occupants.]

Kroot, P. (1996) A new oxygen sensor for cleaner, more efficient combustion. *Scientific Honeyweller*, 15, 29–33. [A sophisticated self-checking oxygen sensor.]

Liu, C.H., Barzilai, A.M., Reynolds, J.K., Partridge, A., Kenny, T.W., Grade, J.D. and Rockstad, H.K. (1998) Characterization of a high-sensitivity micromachined tunneling accelerometer with micro-g resolution, *Journal of Microelectromechanical Systems*, 7, 235. [A force-rebalanced accelerometer used to eliminate the effects of zero drift and nonlinearity in a sensor.]

Margulis, L. and Sagan, D. (1997) *Microcosmos*. University of California Press. [A view of evolution that emphasizes the interconnectedness of all life on our planet, drawing on insights from microbiology.]

Medtronic (1997) Medtronic rapid technological growth. http://www.medtronic.com/corporate/ early.htm. [A brief history of Medtronic, Inc., a company specializing in biomedical devices. Modern devices may be based on sensing of properties such as blood sugar and body motion.]

Middelhoek, S. and Audet, S.A. (1989) *Silicon Sensors*. Academic Press, London. [An excellent review of modern silicon-based sensor technology. A classification scheme for sensors is also detailed.]

Nagle, H.T., Schiffman, S.S. and Gutierrez-Osuna, R. (1998) The how and why of electronic noses. *IEEE Spectrum*, 35, 9, 22–31. [This article reviews different technological approaches to the development of artificial nose sensors and describes several companies who are developing products and solutions in this area.]

Pierce, J.R. (1980) *An Introduction to Information Theory – Symbols, Signals and Noise*. (2nd rev ed.). Dover Publications, Inc., New York. [An accessible treatment of information theory.]

Shannon, C. (1948) A mathematical theory of communication. *Bell System Technical Journal*, 27, 379–423, 623–656. [The seminal papers that established information theory. Shannon's contributions included relating energy and information content.]

Soloman, S. (1994) *Sensors and Control Systems in Manufacturing*. McGraw-Hill, New York. [A review of sensors for manufacturing applications along with their integration into automation and control systems.]

Suga, N. (1990) Cortical computational maps for auditory imaging. *Neural Networks*, 3, 3–21. [The processing in the bat cortex of returned sonar signals.]

Swager, T.M. (1997) New approaches to sensory materials: molecular recognition in conjugated polymers, in Chemosensors of Ion and Molecule Recognition (eds. J.P. Desvergne and A.W. Czarnik). Kluwer Academic Publishers, Dordrecht, The Netherlands. [New chemosensors for TNT with parts-per-billion sensitivity.]

Travis, J. (1999) Making sense of scents: scientists begin to decipher the alphabet of odors. *Science News*, 155, 236–238. [An article that highlights advances in our understanding of olfaction.]

Van der Ziel, A. (1976) *Noise in Measurements*. John Wiley & Sons, Inc., Chichester, U.K. [Discusses sources of and types of noise in measurement and instrumentation systems.]

Wolffenbuttel, R.F. (ed.) (1996) *Silicon Sensors and Circuits*. Chapman and Hall, London. [An edited volume with contributions describing a variety of silicon-based sensor technology.]

Yamatake (1999) Integrated environmental comfort control. http://www.yamatake.co.jp/innovat/ iecc.htm. [Products and technology from one manufacturer in the area of comfort control for indoor environments, based on the PMV standard.]

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 Sweatt 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. Sweatt 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.