CHAPTER 2

Sensing and Sensor Fundamentals

Sensors utilize a wide spectrum of transducer and signal transformation approaches with corresponding variations in technical complexity. These range from relatively simple temperature measurement based on a bimetallic thermocouple, to the detection of specific bacteria species using sophisticated optical systems. Within the healthcare, wellness, and environmental domains, there are a variety of sensing approaches, including microelectromechanical systems (MEMS), optical, mechanical, electrochemical, semiconductor, and biosensing. As outlined in Chapter 1, the proliferation of sensor-based applications is growing across a range of sensing targets such as air, water, bacteria, movement, and physiology. As with any form of technology, sensors have both strengths and weaknesses. Operational performance may be a function of the transduction method, the deployment environment, or the system components. In this chapter, we review the common sensing mechanisms that are used in the application domains of interest within the scope of this book, along with their respective strengths and weaknesses. Finally, we describe the process of selecting and specifying sensors for an application.

What Is a Sensor and What Is Sensing?

There are no uniform descriptions of sensors or the process of sensing. In many cases, the definitions available are driven by application perspectives. Taking a general perspective, a sensor can be defined as:

> *A device that receives a stimulus and responds with an electrical signal.*

(Fraden, 2010)

Sensor definitions from a scientific or biomedical engineering perspective broaden the potential types of output signals to include, for example, an optical signal:

> *A device that responds to a physical input of interest with a recordable, functionally related output that is usually electrical or optical.*

(Jones, 2010)

Another common variation, which takes into account the observational element of the measurement, describes a sensor as follows:

> *A sensor generally refers to a device that converts a physical measure into a signal that is read by an observer or by an instrument.*

(Chen, et al., 2012)

Therefore, setting aside the various nuances of domain and application, a sensor simply measures something of interest and provides an output you can do something useful with.

The words sensor and transducer are both commonly used in the context of measurement systems, and often in an interchangeable manner. Transducer is used more in the United States while sensor has greater popularity in Europe (Sutherland, 2004). The blurring of the lines between the exact meaning of sensors and transducers leads to a degree of confusion.

ANSI (The American National Standards Institute) created a standard for Electrical Transducer Nomenclature and Terminology (ANSI, 1975), which defines a transducer as:

> *A device which provides a usable output in response to a specific measurand.*

An output is defined as an "electrical quantity," and a measurand is "A physical quantity, property, or condition which is measured".

The National Research Council (NRC, 1995) found, however, that the scientific literature had not generally adopted the ANSI definition (AALIANCE, 2010). Instead, descriptions of transducers focusing on the process of converting a physical quality into a measurable output, electrical or optical, for example, have emerged. One such definition is:

> *A converter of any one type of energy into another [as opposed to a sensor, which] converts any type of energy into electrical energy.*
>
> (Fraden, 2010)

An alternative description is:

> *A sensor differs from a transducer in that a sensor converts the received signal into electrical form only. A sensor collects information from the real world. A transducer only converts energy from one form to another.*
>
> (Khanna 2012)

However, it is difficult to find consensus on the distinction between sensors and transducers. This problem is exacerbated when the sensor becomes more sophisticated. For example, chemical sensors can be transducers that have been modified to become a sensor e.g. through the use of a sensitive coating covering the sample interface of the transducer. It is clear that strict definitions will always be contentious and driven in part by philosophical differences between engineers and scientists. These differences only hold academic interest when it comes to application development. So while there may be differences in the definitions of sensors and transducers, this has little impact on the ability to utilize sensors in applications. Within this book we use the simple and broad definition that a sensor measures something of interest using a variety of mechanisms, and a transducer converts the output of the sensing processing into a measurable signal. Sensor application developers simply focus on delivering a sensor system that can measure a quantity of interest with the required accuracy. A sensor system usually consists of sensors, measuring and processing circuits, and an output system (Wang, et al., 2011). The key hardware components of a sensor system are described in Chapter 3.

Introduction to the Key Sensing Modalities

Sensors can be used to measure or detect a vast variety of physical, chemical, and biological quantities, including proteins, bacteria, chemicals, gases, light intensity, motion, position, sound and many others, as shown in Figure 2-1. Sensor measurements are converted by a transducer into a signal that represents the quantity of interest to an observer or to the external world. In this section, we will review the most commonly used sensing techniques for our target domains.

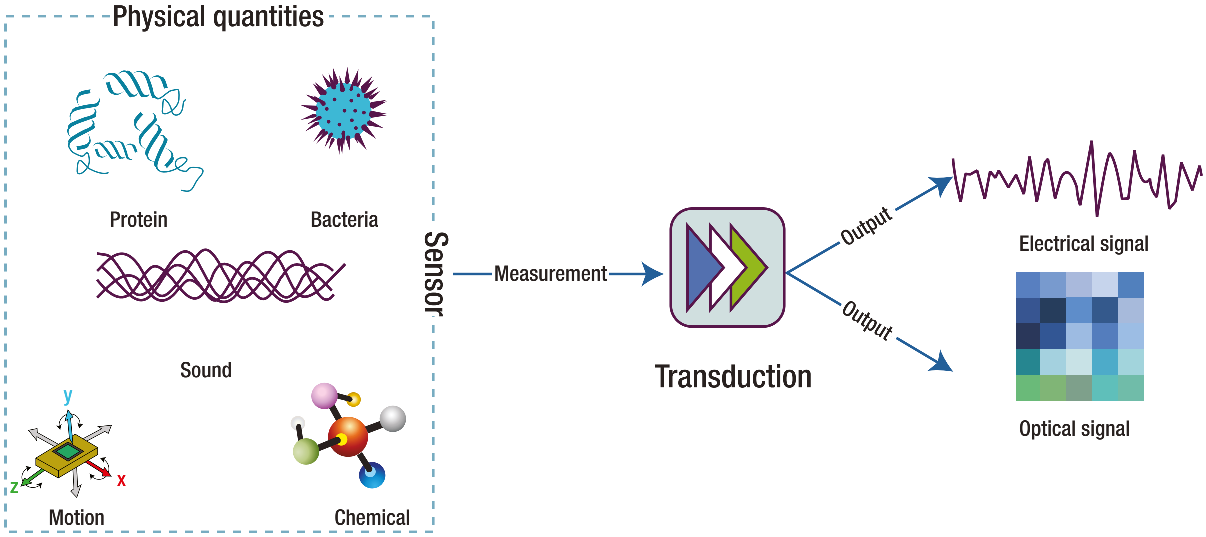

Figure 2-1. *The sensing process*

For any given quantity, there is usually more than one form of sensor that can be used to take a measurement. Each sensor type offers different levels of accuracy, sensitivity, specificity, or ability to operate in different environmental conditions. There are also cost considerations. More expensive sensors typically have more sophisticated features that generally offer better performance characteristics. Sensors can be used to measure quantities of interest in three ways:

- *Contact:* This approach requires physical contact with the quantity of interest. There are many classes to sense in this way—liquids, gases, objects such as the human body, and more. Deployment of such sensors obviously perturbs the state of the sample or subject to some degree. The type and the extent of this impact is application-specific. Let us look at the example of human body-related applications in more detail.

  Comfort and biocompatibility are important considerations for on-body contact sensing. For example, sensors can cause issues such as skin irritation when left in contact for extended periods of time. Fouling of the sensor may also be an issue, and methods to minimize these effects are critical for sensors that have to remain in place for long durations. Contact sensors may have restrictions on size and enclosure design. Contact sensing is commonly used in healthcare- and wellness-oriented applications, particularly where physiological measurements are required, such as in electrocardiography (ECG), electromyography (EMG), and electroencephalography (EEG). The response time of contact sensors is determined by the speed at which the quantity of interest is transported to the measurement site. For example, sensors such as ECGs that measure an electrical signal have a very fast response time. In comparison, the response time of galvanic skin response (GSR) is lower as it requires the transport of sweat to an electrode, a slower process. Contact surface effects, such as the quality of the electrical contact between an electrode and subject's skin, also play a role. Poor contact can result in signal noise and the introduction of signal artifacts.

On-body contact sensing can be further categorized in terms of the degree of "invasion" or impact. Invasive sensors are those, for example, introduced into human organs through small incisions or into blood vessels, perhaps for in vivo glucose sensing or blood pressure monitoring. Minimally invasive sensing includes patch-type devices on the skin that monitor interstitial fluids. Non-invasive sensors simply have contact with the body without effect, as with pulse oximetery.

- *Noncontact:* This form of sensing does not require direct contact with the quantity of interest. This approach has the advantage of minimum perturbation of the subject or sample. It is commonly used in ambient sensing applications—applications based on sensors that are ideally hidden from view and, for example, track daily activities and behaviors of individuals in their own homes. Such applications must have minimum impact on the environment or subject of interest in order to preserve state. Sensors that are used in non-contact modes, passive infrared (PIR) , for example, generally have fast response times.

- *Sample removal:* This approach involves an invasive collection of a representative sample by a human or automated sampling system. Sample removal commonly occurs in healthcare and environmental applications, to monitor E. coli in water or glucose levels in blood, for example. Such samples may be analyzed using either sensors or laboratory-based analytical instrumentation.

  With sensor-based approaches, small, hand-held, perhaps disposable sensors are commonly used, particularly where rapid measurements are required. The sensor is typically in close proximity to the sample collection site, as is the case with a blood glucose sensor. Such sensors are increasingly being integrated with computing capabilities to provide sophisticated features, such as data processing, presentation, storage, and remote connectivity.

  Analytical instrumentations, in contrast, generally have no size limitations and typically contain a variety of sophisticated features, such as autocalibration or inter-sample auto-cleaning and regeneration. Sample preparation is normally required before analysis. Some instruments include sample preparation as an integrated capability. Results for nonbiological samples are generally fast and very accurate. Biological analysis, such bacteria detection, is usually slower taking hours or days.

Mechanical Sensors

Mechanical sensors are based on the principle of measuring changes in a device or material as the result of an input that causes the mechanical deformation of that device or material (Fink, 2012). Inputs, such as such motion, velocity, acceleration, and displacement that result in mechanical deformation that can be measured. When this input is converted directly into an electrical output, the sensor is described as being electromechanical. Other possible output signals include magnetic, optical, and thermal (Patranabis, 2004).

The common mechanical and electromechanical sensing approaches as described by the IEEE Sensors Council are shown in Table 2-1.

Table 2-1. *Common Mechanical and Electromechanical Sensors*

Sensor	Type	Sensor	Type
Strain Gauge	Metallic Thin film Thick film Foil Bulk Resistance	Displacement	Resistive Capacitive Inductive
Pressure	Piezoelectric Strain gauge Potentiometric Inductive Capacitive	Force	Hydraulic load cell Pneumatic load cell Magneto-elastic Piezoelectric Plastic deformation
Accelerometer	Piezoelectric Piezoresistive Capacitive MEMS Quantum tunneling Hall effect	Acoustic Wave	Bulk Surface
Gyroscope	Vibrating structure Dynamically tuned MEMS London moment	Ultrasonic	Piezoelectric Magnetostrictive
Potentiometer	String Linear taper Linear slider Logarithmic Membrane	Flow	Gas Fluid Controller

Strain gauges are one of the most common mechanical sensors and come in many forms and types. They have been used for many years, and are the key sensing element in a variety of sensors types, including pressure sensors, load cells, torque sensors, and position sensors. Measurement is based on a change in resistance due to strain on a material or combination of materials. A common strain gauge implementation uses a grid-shaped sensing element, which comprises a thin metallic resistive foil (3 to 6 μm thick) bonded onto a thin plastic film backing (15 to 16 μm thick). The entire structure is encapsulated within a protective polyimide film. Strain gauges generally have nominal resistance values ranging from tens of ohms to thousands of ohms, with 120, 350, and 1,000Ω being the most common. An excitation voltage (typically 5V or 12V) is applied to the input leads of the gauge network and a voltage reading is taken from the output leads. The output readings in millivolts are measured by a measurement circuit normally in the form of a Wheatstone bridge, as shown in Figure 2-2 (Kyowa, 2013). As stress is applied to the strain gauge, a change in resistance unbalances the Wheatstone bridge. This results in a signal output, related to the magnitude of the applied stress. Both strain gauge elements and bridge resistors can usually be purchased in an encapsulated housing. This form of package is commonly called a load cell.

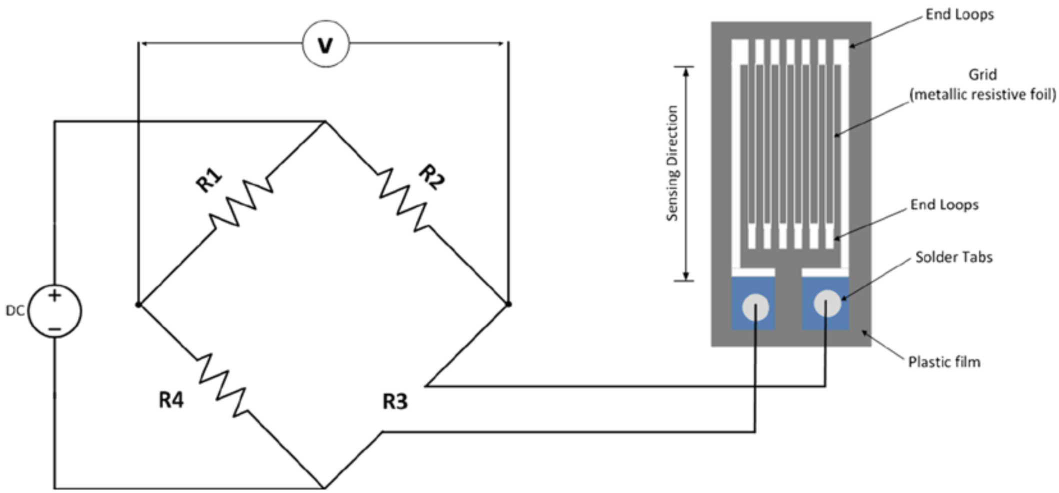

Figure 2-2. *Foil strain gauge attached to a wheatstone bridge*

Another common form of strain gauge is based on the piezoelectric (production of electricity when certain materials are subjected to mechanical stress) properties of some semiconductor materials, such as silicon or germanium. These were first used in the car industry during the 1970s, before being applied in other domains, including sports. This form of strain gauge is smaller, has higher unit resistance and sensitivity, and is lower in cost than grid-style strain gauges.

A key problem with strain measurements is that of thermal effects. Changes in temperature cause expansion or contraction of the sensing element, resulting in thermally induced strain. Temperature compensation is required to address the problem and this can be built into the Wheatstone bridge. Piezoelectric strain gauges have even greater sensitivity to temperature variation and greater drift characteristics, which must be compensated for during use by regular recalibration. Strain gauges are used in a variety of sporting and healthcare applications, including clinical dynamometers that measure grip strength (Kasukawa, et al., 2010, Bohannon, 2011).

MEMS Sensors

The name MEMS is often used to describe both a type of sensor and the manufacturing process that fabricates the sensor. MEMS are three-dimensional, miniaturized mechanical and electrical structures, typically ranging from 1 to 100 μm, that are manufactured using standard semiconductor manufacturing techniques. MEMS consist of mechanical microstructures, microsensors, microactuators, and microelectronics, all integrated onto the same silicon chip.

MEMS sensors are widely used in the car industry and, since the early 1990s, accelerometers have been used in airbag restraint systems, electronic stability programs (ESPs), and antilock braking systems (ABS). The recent availability of inexpensive, ultra-compact, low-power multi-axis MEMS sensors has led to rapid growth into customer electronics (CE) devices; MEMS can be found in smartphones, tablets, game console controllers, portable gaming devices, digital cameras, and camcorders. They have also found application in the healthcare domain in devices such as blood pressure monitors, pacemakers, ventilators, and respirators. While there are many forms of MEMS sensors, two of the most important and widely used forms are accelerometers and gyroscopes, which are produced by companies such as Analog Devices and Freescale Semiconductor.

Accelerometers

There are five modes of motion sensing: acceleration, vibration (periodic acceleration), shock (instantaneous acceleration), tilt (static acceleration), and rotation. All of these, except rotation, can be measured using accelerometers. It is unsurprising, therefore, that accelerometers have a wide range of applications, from triggering a hard disk protection system as a device is falling, to gesture recognition for gaming. MEMS accelerometers are typically either capacitive or piezoresistive. Capacitive accelerometers are composed of fixed plates attached to a substrate and moveable plates attached to the frame. Displacement of the frame, due to acceleration, changes the differential capacitance, which is measured by the on-board circuitry. Capacitive accelerometers offer high sensitivities and are utilized for low-amplitude, low-frequency devices. Piezoresistive accelerometers contain resistive material bonded to a cantilever beam that bends under the influence of acceleration. This bending causes deformation of the resistor, leading to a change in its resistance relative to the acceleration applied. Piezoresistive accelerometers tend to be more rugged and are used for accelerometers that achieve higher amplitudes and higher frequency response (Piezotronics[1], 2013, Piezotronics[2], 2013, Nanogloss, 2009).

Gyroscopes

MEMS gyroscopes measure the angular rate of rotation of one or more axes, as shown in Figure 2-3. Gyroscopes can measure intricate motions accurately in free space. They have no rotating parts that require bearings, and therefore lend themselves to miniaturization and batch fabrication using semiconductor manufacturing processes. Almost all MEMS gyroscopes use vibrating mechanical elements (proof-mass) to sense rotation based on the transfer of energy between two vibration modes of a structure caused by Coriolis acceleration. The most popular form of MEMS gyroscope is a tuning fork gyroscope, which contains a pair of masses that are driven to oscillate with equal amplitude but in opposite directions. When rotated, the Coriolis force creates an orthogonal vibration that can be sensed by a variety of mechanisms (Nasiri, 2013). Other forms of MEMS design include vibrating wheel, wine glass resonator (hemispherical resonator gyro), cylindrical vibratory, and piezoelectric. Major manufacturers of MEMS gyroscopes include Robert Bosch GmbH, InvenSense, STMicroelectronics, and Analog Devices. MEMS gyroscopes can be found in smartphones, fall detectors, and games consoles.

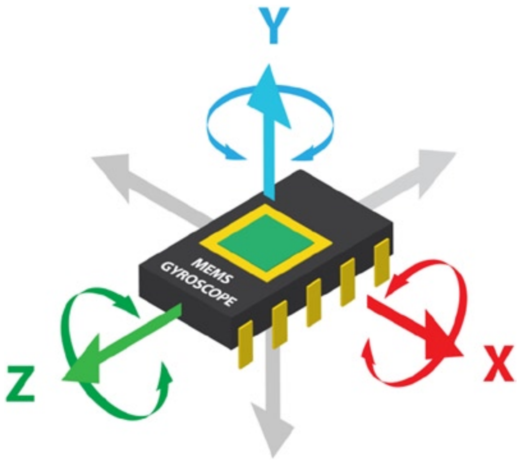

Figure 2-3. *3D Angular rotation measurements with a MEMS gyroscope*

Optical Sensors

Optical sensors work by detecting waves or photons of light, including light in the visible, infrared, and ultraviolet (UV) spectral regions. They operate by measuring a change in light intensity related to light emission or absorption by a quantity of interest. They can also measure phase changes occurring in light beams due to interaction or interference effects. Measuring the absence or interruption of a light source is another common approach. Sensors based on this principle are commonly used in automated doors and gates to ensure no obstacles are present in their opening path. They are widely used in industrial applications for measuring liquids and material levels in tanks or in factory production lines to detect the presence or absence of objects. Optical sensors are also used with stepper motors in applications that require position sensing and encoding, for example, in automated lighting systems in the entertainment industry (Cadena, 2013). Let us now look at the most common types of optical sensors.

Photodetectors

Photodetector sensors are based on the principle of photoconductivity, where the target material changes its conductivity in the presence or absence of light. Sensors are sensitive for a given spectral region (range of optical wavelengths) from ultra-violet to infrared. Examples include:

- Active pixel sensors, such as those found in smartphone cameras and web cams.
- Charged-coupled devices (CCD), such as those found in digital cameras.
- Light-dependent resistors (LDRs), such as those found in street lighting systems.
- Photodiodes, such as those used in room lighting-level control systems or in UV measurement systems.
- Phototransistors, such as those used in optoisolators for a variety of applications, including healthcare equipment, to provide electrical isolation between the patient and equipment.
- Photomultipliers such as those found in spectrophotometers detectors. Photomultipliers are also used in flow cytometers (a laser-based technology used for cell counting and sorting and biomarker detection) for blood analysis applications.

Infrared (IR)

IR sensors come in both active and passive forms, as shown in Figure 2-4. In the active form, the sensor employs an infrared light source, such as a light-emitting diode (LED) or laser diode, which projects a beam of light that is detected at a separate detector (photoelectric cells, photodiodes, or phototransistors). An object that passes through the beam disrupts the received signal at the detector. An alternative configuration is reflectance-based detection, where the source and detector are located in the same enclosure. Light from the IR source is reflected from an object as it moves into the sensor's field of detection. The amount of light received at the detector depends upon the reflectivity of the object surface. Infrared sensors can be used as counters, proximity sensors (as with automatic doors), or to identify the presence of people or other mobile objects under day or night conditions.

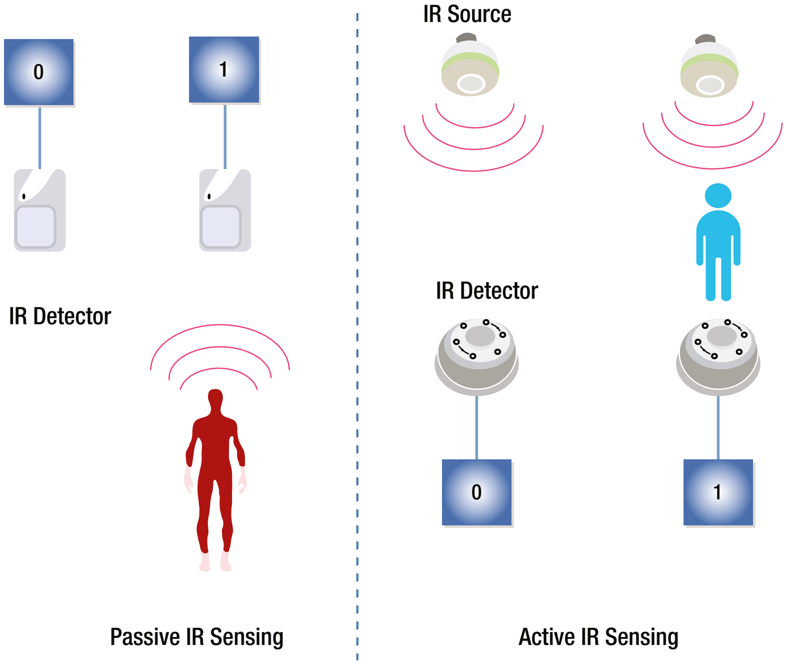

Figure 2-4. *Passive and active infrared sensing modes*

Unlike active sensors, passive sensors do not generate or radiate energy for the purposes of detection. They rely on detected heat from objects, such as human bodies in their detection field. They are commonly used in security lighting around homes and in home security systems to detect intruders (Fried, 2012). They can also be used for ambient sensing applications, an example of which is presented in Chapter 8.

Infrared sensors generally have low power requirements, relatively high immunity to noise, and do not require complex signal processing circuitry. They do, however, have a number of key disadvantages, including the need to be in line-of-sight of the object of interest, a relatively short detection range, and being subject to interference from environmental sources such as sunlight, fog, rain, and dust (EngineersGarage, 2012).

Fiber Optic

This form of optical sensor uses an optical glass fiber as the sensing element. Multimode fibers with large core diameters (>10 μm) are used for sensor applications. Optical fibers can be coated with materials that respond to changes in strain, temperature, or humidity. The most commonly used fiber-optic sensor types include:

- *Strain sensing:* Mechanical strain in the fiber changes the geometric properties of the fiber, which changes the refraction of the light passing through it. These changes can be correlated to the applied strain.
- *Temperature sensing:* Strain in the fiber is caused by thermal expansion or contraction of the fiber. A strain measurement can be correlated directly with changes in temperature.
- *Pressure sensing:* Fiber-optic pressure sensors can be of two types—intensity and interferometric. In intensity-sensing fiber-optic sensors, the magnitude of light intensity reflected from a thin diaphragm changes with applied pressure (Udd, 2011). Interferometric pressure sensors work on the principle that pressure changes introduce perturbations into the sensor, which generate path-length changes in a fiber. This in turn causes the light/dark bands

of an interference pattern to shift. By measuring the shift of the wavelength spectrum, the pressure applied on it can be quantitatively obtained (Lee, et al., 2012).

- *Humidity sensing:* A broad range of principles have been applied to optical fiber-based humidity sensors, including (i) luminescent systems with fluorescent dyes that are humidity-sensitive (ii) refractive index changes due to absorption in a hygroscopic (moisture absorbing) fiber coating such as polyimide; and (iii) reflective thin film-coated fibers made from tin dioxide (SiO_2) and titanium dioxide (TiO_2), which change the refractive index, resulting in a shift in resonance frequency (Morendo-Bondi, et al., 2004).

Interferometers

An interferometer is a device used to measure changes in a propagating light beam, such as path length or wavelength along the path of propagation. Generally, the sensor uses a light source such as a laser LED and two single fibers. The light is split and coupled into both of the fibers. The quantity being measured modulates the phase of the optical signal, which can be detected by comparison with a reference optical signal. There are four types of interferometric configuration: Fabry-Perot, Mach-Zehnder, Michelson, and Sagnac. This form of sensor is commonly used for measuring physical quantities, such as temperature, velocity, vibration, pressure, and displacement (Baldini, et al., 2002).

Because optical sensors use light either directly or indirectly for measurements, they have a number of advantages over other forms of sensing. However, these advantages are application-specific, as are the associated disadvantages. Table 2-2 presents the general advantages and disadvantages of optical sensors.

Table 2-2. *Advantages and Disadvantages of Optical Sensors*

Advantages	Disadvantages
High sensitivity	Susceptible to interference from environmental effects
Chemically inert	Can be costly
Small and lightweight	Susceptible to physical damage
Suitable for remote sensing	
Immunity to electromagnetic interference	
Wide dynamic range	
Capable of monitoring a wide range of chemical and physical parameters	
Reliable operation	

Semiconductor Sensors

Semiconductor sensors have grown in popularity due to their low cost, reliability, low power consumption, long operational lifespan, and small form factor. They can be found in a wide range applications including:

- Gas monitoring
  - Pollution monitoring, for example CO, NO_2, SO_2, and O_3 (Nihal, et al., 2008, Wetchakun, et al., 2011)
  - Breath analyzers, for breath-alcohol content (BAC) measurements (Knott, 2010)
  - Domestic gas monitoring, such as propane(Gómez-Pozos, et al., 2013)

- Temperature, as in integrated electronic equipment (Fraden, 2010)
- Magnetism, for example, magnetometers for six degrees of freedom applications (Coey, 2010, Sze, et al., 2007)
- Optical sensing, such as in charge-coupled device detectors in cameras (EUROPE.COM, 2013)

Gas Sensors

Semiconductor sensors are commonly used to detect hydrogen, oxygen (O_2), alcohol, and harmful gases, such as carbon monoxide (CO). Domestic CO detectors are one of the most popular applications of gas-monitoring semiconductors. A typical gas sensor has a sensing layer and a sensor base, and is housed in a porous enclosure. The sensing layer is composed of a porous, thick-film metal oxide semiconductor (MOS) layer, such as SnO_2 or tungsten trioxide (WO_3). This is deposited onto a micro-sensor layer containing electrodes that measure the resistance of the sensing layer and a heater that heats the sensing layer to 200°C to 400°C. When the metal oxide is heated to a high temperature in air, oxygen is absorbed on the crystal surface with a negative charge, and donor electrons in the crystal surface are transferred to the absorbed oxygen, leaving positive charges in a space-charge layer. This creates a potential barrier against electron flow. In the presence of reducing gases, such as CO or (Hydrogen) H_2, catalytic reduction at the pre-absorbed oxygen layer decreases the resistance of the sensor. Oxidizing gases, such as nitrogen dioxide (NO_2) and ozone (O_3), have the opposite effect, resulting in an increase in resistance. The magnitude of resistance change can be correlated to the concentration of the gas species. The magnitude of the change depends on the microstructure and composition/doping of the base material; on the morphology and geometrical characteristics of the sensing layer and substrate; as well as on the temperature at which the sensing takes place (AppliedSensor, 2008). These parameters can be altered to tune the sensitivity toward different gases or classes of gases.

Despite many advantages, including low cost, relatively low maintenance, and long operational lifespan, semiconductor gas sensors can lack specificity in mixed gas environments. Thus, gases that are not of interest contribute to the overall signal response, resulting in an inaccurate elevated reading or false positives. To increase the selectivity of the gas sensors, chemical filters can be placed before the sensing material to remove the interfering components in the sample. These filters can be either passive or active, depending on whether a physical (passive) or chemical (active) mechanism is used. Filters can also be classified according to their location in the sensor, that is, internal (directly on the sensing element) or external (in a separate block). External filters such as charcoal are commonly used in commercial gas sensors.

Temperature Sensors

Semiconductor temperature sensors are based on the change of voltage across a p-n junction, which exhibits strong thermal dependence. The simplest form of temperature sensor is a silicon diode where the forward bias across the diode has a temperature coefficient of approximately 2.0–2.3mV/°C. Measurements are made by holding the bias current constant and measuring voltage changes. For accurate readings, the sensor needs to be calibrated (two-point calibration is sufficient due to good linearity) as significant inter-device variations can occur in the ±30 °C range. For more accurate measurements, diode-connected bipolar transistors are used. Again, a constant current is applied through the base-emitter junction, generating a voltage that is a linear function of the temperature. An offset may be applied to convert the signal from absolute temperature to Celsius or Fahrenheit. Typically, operating ranges are –55°C to +150°C. Semiconductor temperature sensors are often categorized by their output signal type, which can be analog (voltage and current), logic, or digital (Gyorki, 2009). The key advantages of this sensor type are ease of integration into a circuit, general ruggedness, and low cost. Their primary disadvantages are limitations of accuracy and stability, often poor thermal chip design, and slow response time (CAPGO, 2010)(Fraden, 2010).

Magnetic Sensors

Semiconductor magnetic sensors detect changes or disturbances in magnetic fields and convert these changes into a measureable electrical signal. They can produce information on properties, such as directional movement, position, rotation, angle, or electrical currents in machines or devices. They are used in medical devices such as ventilators to control the extent of movement; in enclosures for consumer electronic devices to detect opening and shutting of a device; and in renewable-energy scenarios, such as solar installations. For example, in domestic solar installations, magnetic sensors are used in power invertors that convert the electricity generated by the solar panels into usable electrical current for the home. They can also be used to monitor the charge level of batteries used in conjunction with solar panels for energy storage (Racz, 2011). The most common semiconductor magnetic integrated circuits apply the Hall effect (discovered by Edwin Hall in 1879) or magnetoresistive principles (ansiotropic, giant, or tunnel magnetoresistivity).

Hall-effect sensors comprise a thin layer of p-type (or n-type) semiconductor material that carries a continuous current. When the device is placed within a magnetic field, the measured voltage difference across the semiconductor depends on the intensity of the magnetic field applied perpendicular to the direction of the current flow. Charge carriers (electrons) moving through the magnetic field are subjected to Lorentz force (the force experienced by a charged particle as it moves through an electromagnetic field) at right angles to the direction of motion and the direction of the field. A voltage called the Hall voltage is generated in response to Lorentz force on the electrons. This voltage is directly proportional to the strength of the magnetic field passing through the semiconductor material. Semiconductor materials that have high electron mobility, such as indium (In), indium antimonide (InSb), indium arsenide (InAs), or gallium arsenide (GaAs) are commonly used in Hall-effect sensors (Eren, 2001). The output voltage is often relatively small—no more than a couple of microvolts—which requires amplification and signal conditioning to improve sensitivity and compensate for hysteresis (the difference in output between the rising and falling output values for a given input). In commercial sensors, sensing, signal amplification, voltage regulation, and signal conditioning are contained in a single package.

Hall-effect sensors demonstrate good environmental immunity to problems such as dust, vibration, and moisture. However, they can be affected by other sources of magnetic flux that are in close proximity, such as those generated by electrical wires. They are robust, having no mechanical contacts for sensing. They are, however, effective only over a limited distance and do not work at distances great than 10cm unless the magnetic field strength is very high.

Optical Sensors

There are a variety of optical semiconductor sensors, the most common of which is the photodiode, a type of photodetector that converts light into either current or voltage. Photodiodes normally have a window or optical fiber connection to allow light to reach a p-n or a PIN junction (an intrinsic semiconductor region between p-type and n-type semiconductor regions). Photodiodes often use a PIN junction rather than a p-n junction to increase the speed of response. When a photon of sufficient energy strikes the depletion region of the diode, it may hit an atom with sufficient energy to release an electron, thereby creating a free electron (and a positively charged electron hole). Free electrons and holes in the depletion region, or one diffusion length away, are pulled away in an applied electrical field. The holes move toward the anode, and electrons move toward the cathode, resulting in a photocurrent. This photocurrent is the sum of both the dark current (without light) and the light current, so the dark current must be minimized to enhance the sensitivity of the device. Photodiodes are used in a variety of applications, including pulse oximeters, blood particle analyzers, nuclear radiation detectors, and smoke detectors.

Another form of photodetector is the phototransistor, which is essentially a bipolar transistor with a transparent window, like the photodiode, that allows light to hit the base-collector junction. The intensity of the light shining on the phototransistor's base terminal determines how much current can pass into its collector terminal and out through its emitter terminal. Higher light intensity results in more current and, inversely, less light results in less current. Phototransistors have the advantage of being more sensitive than photodiodes. However, they have a slower response time. Applications for phototransistors include detecting ambient light, monitoring intravenous (IV) infusion rates, and atmospheric monitoring. For IV applications, the phototransistor is used as a drip sensor that attaches to the IV bag drip chamber. It counts the number of drips per unit time, which is feedback to an infusion pump controller to ensure that the set point flow rate is maintained (Times, 2004). In atmospheric monitoring applications, phototransistors with sensitivity in the IR spectral region are used for Lidar sensing, a laser-based technique that can be used for monitoring and profiling atmospheric species and constituents such as water vapor, carbon dioxide (CO_2), CO, methane (CH_4) and ethane (C_2H_6). Phototransistors are used in detectors that convert the collected returned optical signal into an electrical signal. Differences in the return optical signal are due to absorption by the gas of interest (Refaat, et al., 2007).

A third type of photodetector is the light-dependent resistor (LDR), the conductivity of which changes in proportion to the intensity of light. When light strikes the LDR, photons are absorbed, resulting in excitation of electrons from the valence band into the conduction band of the semiconductor material. As a consequence, the electrical resistance of the device decreases. The cells exhibit very high resistance (1–10 MΩ) when in the dark, decreasing to a few hundred ohms when fully illuminated. LDRs can be constructed from various materials, including lead sulfide (PbS), lead selenide (PbSe), indium antimonide (InSb), cadmium sulfide (CdS), and cadmium selenide (CdSe). The semiconductor material utilized determines the wavelengths of greatest sensitivity, ranging from the visible (390–700 nm) to the infrared region (>700 nm). Applications for LDRs include lighting control, camera shutter control, and commercial light meters.

Ion-Sensitive Field-Effect Transistors (ISFETs)

ISFETs are used for measuring ion concentrations in solution, such as H^+ in pH measurements. In devices with ISFETs, the sample solution is in direct contact with the FET gate-electrode material, and this determines the gate voltage, which in turn controls the source-to-drain current through the transistor. Hence, changes in the source-to-drain current occur as the sample ion concentration varies. To convey a degree of selectivity to this effect, the transistor gate surface in the ISFET is typically covered by an ion-sensitive membrane, for example, one sensitive to hydrogen ions for pH measurements. SiO_2 films can be used for pH measurements, but materials such as silicon nitride (Si_3N_4), alumina (Al_2O_3), zirconium oxide (ZrO_2), and tantalum oxide (Ta_2O_5) are normally employed as they have better properties in relation to pH response, hysteresis, and drift. The key advantages of ISFETs are their small size, which allows them to be used with small volumes; low cost; good stability; and ability to work in wide temperature ranges. Their key disadvantages are long-term drift, hysteresis, and relatively short life span. Additionally, the availability of miniature reference electrodes remains an issue. While conventional silver chloride (AgCl) or mercury(II) chloride ($HgCl_2$) reference electrodes can be used, they are unsuitable for many biological and in vivo analyses that require miniaturization. The development of suitable reference electrodes, such as solid state electrodes for ISFETs, remains an area of active research (Adami, et al., 2014)(Guth, et al., 2009). ISFET sensing approaches that do not require a reference electrode have also been reported in the literature (Kokot, 2011).

Electrochemical Sensors

An electrochemical sensor is composed of a sensing or working electrode, a reference electrode, and, in many cases, a counter electrode. These electrodes are typically placed in contact with either a liquid or a solid electrolyte. In the low-temperature range (<140° C), electrochemical sensors are used to monitor pH, conductivity, dissolved ions, and dissolved gases. For measurements at high temperatures (>500° C), such as the measurement of exhaust gases and molten metals, solid electrolyte sensors are used (Guth, et al., 2009). Electrochemical sensors work on the principle of measuring an electrical parameter of the sample of interest. They can be categorized based on the measurement approach employed.

Electrochemical sensors present a number of advantages, including low power consumption, high sensitivity, good accuracy, and resistance to surface-poisoning effects. However, their sensitivity, selectivity, and stability are highly influenced by environmental conditions, particularly temperature. Environmental conditions also have a strong influence on operational lifespan; for example, a sensor's useful life will be significantly reduced in hot and dry environments. Cross-sensitivity to other gases can be problem for gas sensors. Oversaturation of the sensor to the species of interest can also reduce the sensor's lifespan. The key electrochemical sensor types follow.

Potentiometric Sensors

This type of sensor measures differences in potential (voltage) between the working electrode and a reference electrode. The working electrode's potential depends on the concentration (more exactly, the ion activity) of the species of interest (Banica, 2012). For example, in a pH sensor, the electric potential, created between the working electrode and the reference electrode, is a function of the pH value of the solution being measured. Other applications of potentiometric sensors include ion-selective electrodes for both inorganic (for example, monitoring of metal ion contamination in environmental samples or profiling of blood electrolytes) and organic ions (for example, aromatic aldehyde or ibuprofen in human serum samples).

Amperometric Sensors

This form of electrochemical sensor measures changes in current. The potential of the working electrode is maintained at a fixed value (relative to a reference electrode) and the current is measured on a time basis. Electron transfer (current) is determined by redox (reduction-oxidation) reactions at the electrode surface that are driven by the applied potential (Wang, et al., 1995). The working electrode is designed so the measured current is directly proportional to the concentration of a redox active species of interest in the sample solution. Typical applications include oxygen-sensing (${}_{P}O_2$ and ${}_{P}CO_2$ patient monitoring), fire detection (for example, CO from smoldering fires), and toxic gas detection (such as chlorine (Cl)).

Coulometric

Coulometric sensors measure the quantity of electricity in coulombs as a result of an electrochemical reaction. This is achieved by holding a working electrode at a constant potential and measuring the current that flows through an attached circuit. The analyte of interest is fully oxidized or reduced at the electrode. As the analyte is consumed, the current being measured decreases towards zero. The rate of reaction is dependent on the rate that the analyte is transferred to the working electrode. Some oxygen sensors utilize a variation of this configuration where both a cathode and an anode are used with a DC voltage maintained between them. Oxygen atoms from the sample diffuse to the cathode through a porous membrane where they are reduced. The oxygen ions, O^{2-}, are attracted though a solid electrolyte that is heated to 400°C. The oxygen ions are then converted back to molecular oxygen at the anode electrode.

Coulometric sensors also find application in detecting glucose. The enzyme used in the sensor, glucose oxidase, is specific for glucose, so all of the charge measured by the sensor corresponds to the complete concentration of glucose in the sample—provided the enzymatic reaction completes. A great advantage of this under-utilized method is that in principle, no calibration is required; you just count the electrons and convert this into the number of glucose molecules. Removing the need for calibration greatly simplifies the complexity of the device for on-body sensing, or for implantable sensors (Andoralov, et al., 2013).

Coulometric sensors have a number of advantages over amperometric sensors, including higher sensitivity, greater selectivity, and better stability. Another key advantage of this sensor is that, if used correctly, it can offer absolute quantitation. If the cell volume of the sensor is known and the species of interest is fully electrolyzed, the corresponding charge is an absolute measure of quantity and concentration (Carroll, et al., 2011).

Conductometric Sensors

This form of sensor operates on the principle that electrical conductivity can change in the presence or absence of some chemical species. Two configurations are commonly used. The first arrangement consists of two elements—a sensitive conducting layer and contact electrodes. DC voltage is applied to the sensor and the resistance is measured. This configuration is typically used for chemiresistors in gas-sensing applications. The conducting layer can either be a porous thick film (2–300 μm), which allows the gas to diffuse through it, resulting in good sensitivity, or a thin film (5–500 nm), on which the source material is sputtered (a process where atoms are ejected from a target or source material and deposited onto a substrate) or deposited using chemical vapor deposition onto a substrate layer, mainly oxide semiconductors (Janta, 2009). In the second configuration, an electrode (often glass) with a chemically interactive layer on the top is placed in an electrolytic solution to which the analyte of interest is added. A counter electrode is used to complete the circuit. This form of configuration is often used for biosensors. Conductometric sensors are generally inexpensive, making them popular.

Biosensors

Biosensors use biochemical mechanisms to identify an analyte of interest in chemical, environmental (air, soil, and water), and biological samples (blood, saliva, and urine). The sensor uses an immobilized biological material, which could be an enzyme, antibody, nucleic acid, or hormone, in a self-contained device (see Figure 2-5). The biological material being used in the biosensor device is immobilized in a manner that maintains its bioactivity. Methods utilized include membrane (for example, electroactive polymers) entrapment, physical bonding, and noncovalent or covalent binding. The immobilization process results in contact being made between the immobilized biological material and the transducer. When an analyte comes into contact with the immobilized biological material, the transducer produces a measurable output, such as a current, change in mass, or a change in color. Indirect methods can also be utilized, in which a biochemical reaction occurs between the analyte and sensor material, resulting in a product. During the reaction, measurable quantities such as heat, gas (for example, oxygen), electrons, or hydrogen ions are produced, and can be measured.

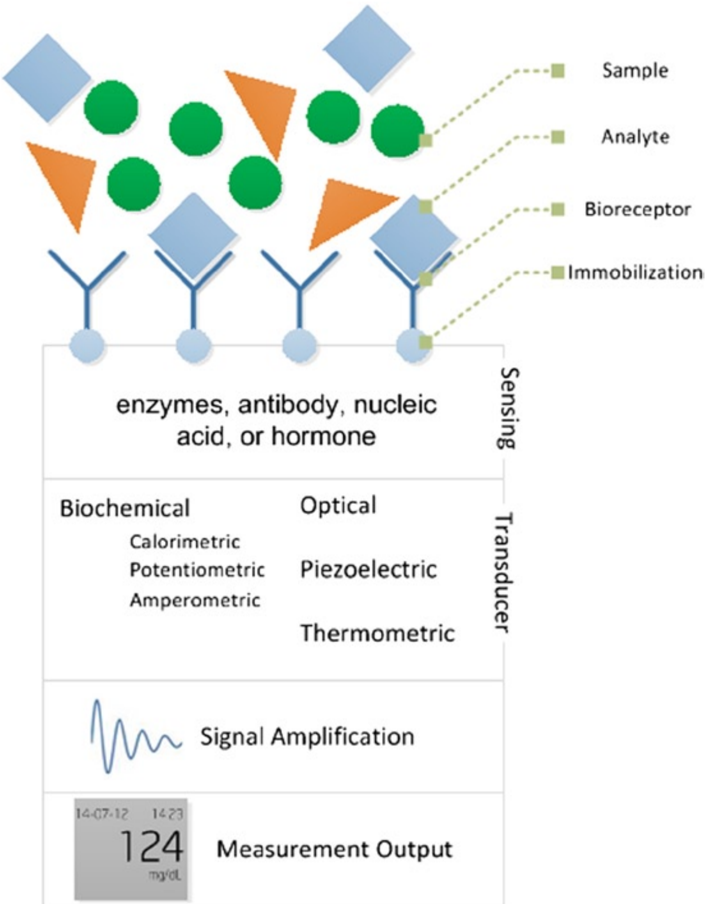

Figure 2-5. *The biosensing process*

The use of biosensors has increased steadily since Yellow Springs Instruments produced the first commercially successful glucose biosensor in 1975 (Setford, et al., 2005). Biosensors are now available over the counter for a large variety of consumer applications, including cholesterol measurement, fertility monitoring, ovulation status, bacterial infection or exposure (such as Heliobacter pylori), allergies, and STD detection. A report by Global Industry Analysts (GIA) estimates that the biosensors market will be worth approximately USD 16.5 billion by 2017 (PRWeb, 2012). Biosensors have also found niches in domains outside of healthcare. The key biosensor application domains are summarized in Table 2-3.

Table 2-3. *Key Biosensor Application Domains*

Domain	Application
Healthcare	Chronic disease management, such as glucose monitoring in diabetes Diagnosis and screening for home pregnancy testing; stomach ulcers: Helicobacter pylori Biochemistry, for example, cholesterol testing Bacterial infection testing Acute disease evaluation, as for cancers, such as prostate
Biotechnology/fermentation	Wine fermentation Citric acid Brewing Enzyme production Biopharmaceutical production
Food quality	Chemical contaminant detection, such as contamination with antibiotics Toxin detection Pathogen detection Hormone detection, as in milk
Personal safety/law enforcement/ employment	Alcohol testing Drug testing
Environmental monitoring	Pollution, such as testing for fecal coliforms in water Agriculture Pesticides in water such as organophosphates Heavy metals Hormones
Security	Chemical and warfare agent detection

Transducers for Biosensors

The transduction process in a biosensor involves converting the biological activity that the sensor has measured via a bioreceptor into a quantifiable signal, such as current, an optical signal, or a change in measurable mass. The most commonly utilized transducer mechanisms are electrochemical, optical, piezoelectric, and thermometric.

- There are three common electrochemical sensing approaches used in biosensors (Pohanka and Skládal, 2008).
    - Conductometric and impedimetric biosensors measure changes in conductivity (the inverse of resistivity) during enzymatic redox reactions (Yoon, 2013).
    - Potentiometric biosensors measure potential changes due to biochemical reactions using ISE and ISFETs (Lee, et al., 2009).

    - Amperometric biosensors function by measuring the current produced by a biochemical redox reaction, such as glucose oxidization by glucose dehydrogenase (Corcuera, et al., 2003)
    - Coulometric biosensors measure the current generated during an enzymatic reaction in coulombs. Biomedical applications include glucose measurements in blood samples (Wang, 2008)(Peng, et al., 2013).
- In optical biosensors, an immobilized biological component on an optical fiber interacts with its target analyte, forming a complex that has distinct and measurable optical properties. Alternatively, in immunoassays, the biological component (such as an antibody) is immobilized in an assay tray. When the sample is added, a measureable, visible change in color or luminescence occurs. Measurement approaches include photometric and colorimetric detection.
    - Piezoelectric biosensors are based on a change in mass or elastic properties that results in a change to the resonant frequency of a piezoelectric crystalline structure (for example, in quartz, cadmium sulfide, lithium niobate ($LiNbO_3$), or gallium nitride (GaN)). There are two common implementations of piezoelectric biosensors: bulk acoustic wave (BAW) and surface acoustic wave (SAW) devices. An acoustic wave is applied to an oscillating electric field to create a mechanical wave, which propagates either through the surface (SAW) or substrate (BAW), before conversion back to an electric field for measurement. In a biosensor configuration, the resonant frequency is a function of the biosensing membranes attached to a crystal resonator, such as immobilized monoclonal antibodies. As the analyte of interest binds with the antibodies, a change in mass occurs that changes the resonant frequency. BAW implementations are generally favored over SAW for biosensor applications since the shear horizontal wave generated during the detection process radiates limited energy in liquid samples, impacting the signal-to-noise ratio (Durmus, et al., 2008).
    - Thermometric and calorimetric biosensors are based on the measurement of heat effects. Many enzyme-catalyzed reactions are exothermic in nature, resulting in heat generation that can be used for measuring the rate of reaction and hence the analyte concentration. The heat generated can be measured by a transducer such as a thermistor.

Key Characteristics of Biosensors

Biosensors have a unique set of characteristics, due to the use of bioreceptors that differentiate them from other sensing approaches. Biosensors can offer superior sensitivity and specificity over other sensor types. However, they can lack robustness due to sensitivity to the operating environment. The key characteristics that affect biosensors in most applications are:

- Because biosensors rely on biological components, they can have stability or time-dependent degradation of performance; that is, the enzymes or antibodies can lose activity over time. Storage conditions and the method of manufacture can significantly influence operational lifespan.
- Biosensors are normally for single use only. They are generally suitable for point-of-care applications, but they are currently not suitable for long-term monitoring where continuous measurements are required, such as the monitoring of bacteria in water.
- Biosensors often have a limited operational range, in terms of factors such as temperature, pH, or humidity, in which they will operate reliably.

- Sample preparation, such as the preparation of biological samples before presentation to the sensor, is often necessary and this can increase the complexity of the sensor system as well as the sample turnaround time.
- Sensor fouling can be a significant issue, particularly with biological samples, as in the case of protein deposits. These issues can be addressed in part through the use micro- and nanofluidic systems, such as micro-dialysis, to prepare the sample before presentation to the sensor.
- Some compounds can interfere with the sensor readings, particularly biochemical transducers, as in the case of paracetamol interference in glucose measurements.
- Generally, biosensors exhibit very high sensitivity and specificity.

Application Domains

As outlined in the previous section, researchers and commercial solution providers have at their disposal many different sensing options. As a result, more than one sensor type is usually available to measure a quantity of interest. Each sensing option presents its own unique set of advantages and disadvantages. These must be weighed in the context of the use case or application being implemented to determine which sensing technology should be selected. Depending on the specific application, this can involve a complex mixture of competing variables that need to be thought through. Factors such as the sensor type, hardware options, form of enclosure, and the application protocol should be carefully considered. Let us now look briefly at the key challenges and requirements for our application domains.

Environmental Monitoring

Increased urbanization, intensive agricultural methods, industrialization, demands for power, and climate change have significantly impacted our ability to maintain a clean environment. Contaminants and pollutants from a large variety of sources can affect our air, water, soil, and ambient environment. These range from chemical pollutants, biological blooms, heavy metals, gases, and bacterial pathogens, to ambient noise sources (Ho, et al., 2005).

Protection of human health and ecosystems is of the highest priority, requiring rapid, sensitive, robust, and scalable sensor solutions that are capable of detecting pollutants, often at very low concentrations and on a widespread basis. While many solutions are already available for environmental monitoring, there are on-going pressures to develop new sensor technologies that are even more accurate and more sensitive, in order to drive effective, scalable solutions. This will enable improvements in real-time decision-making, sensing-granularity, and compliance-monitoring.

Many analyses especially for bacterial contamination still require in-situ sampling with laboratory-based analysis of samples. Strict protocols must be adhered to in the sampling process, particularly for regulated monitoring; otherwise the integrity of the samples and results can be compromised. Sensors, which operate in situ, can address these issues but bring their own set of challenges; particularly relating to sensor fouling, sensitivity stability, accuracy, and environmental influences. Growth in the use of sensors for these applications is currently inhibited by significant technological barriers that must be overcome. Progress towards sustainable performance, comparable to a laboratory, must also be demonstrated and maintained in sensor networks distributed over a wide geographical area.

Air

Air pollutants come in many forms, including: sulfur dioxide (SO_2), CO, NO_2, and volatile organic compounds, such as benzene (C_6H_6). The sources of these pollutants include vehicle emissions, electric power plants, farming, and industrial manufacturing. Air pollution remains an issue both in the developed and developing world. Fossil fuel power generation facilities are a major source of air pollution and demand for solutions is likely to grow, given the public outcry and government policy changes with respect to nuclear power plants in countries such as Germany and Japan following the Fukushima nuclear power plant explosions in 2011 (Inajima, et al., 2012). The burning of fossil fuels generates particulate matter, sulfur dioxides, nitrogen oxides, and mercury (Hg), which can impact human health. In parallel, increased urbanization and personal car ownership, resulting in concentrated vehicular emissions in large cities, such as Mexico City and Rio de Janeiro, can also have a negative impact on human health (Schwela, 2000). In China, more than 13 million cars were sold in 2012 alone. This rapid proliferation of cars has resulted in serious air pollution problems, like $PM_{2.5}$ (fine particulate matter with a diameter of 2.5 micrometers or less), in cities such as Beijing (Watt, 2013). For the first time, the Chinese government has publically admitted the link between extensive environmental pollution and cancer in China (Wee, et al., 2013).

In many parts of the world, air quality specifications and monitoring regimes are now controlled on a regulatory basis (for example, with the Clean Air Act in the US) by national bodies such as the Environmental Protection Agency (EPA) in the United States. Limits are in place for various gases, hydrocarbons, metals and particulate matter in air to safeguard public health. Concentrations of the various pollutants and contaminants are monitored on a continuous basis to ensure compliance with the regulations. These regulations are discussed in more detail in Chapter 6.

Many different combinations of sensors may come with an air-monitoring station. Air sensing can range from monitoring a single gas species, using a single sensor, to monitoring multiple gases, particulate matter, hydrocarbons, and metals sensing, as defined by regulatory requirements for air quality. Regulatory monitoring utilizes expensive analytical instrumentation, including spectroscopy analysis, as in the case of sulfur dioxide monitoring by UV fluorescence, and O_3 absorption of UV light at 254nm (EPA, 2012). As a result, only a small number of high functionality, high cost monitoring stations are deployed in any given geographical area. This low-density deployment results in less than satisfactory resolution of the data; particularly in highly urbanized areas where local effects due to specific emission sources, traffic patterns, or the types of buildings can affect local air quality. With the availability of low-cost sensors, there is growing interest, particularly in the research community, in using high-density sensor deployments to provide high-granularity air quality sensing. A detailed description of such applications is presented in Chapter 11. A variety of sensor technologies are being utilized for air quality and ambient environmental applications, including:

- Semiconductor sensors are used to monitor atmospheric gases (CO, CO_2, O_3, ammonia (NH_3), CH_4, NO_2), as well as ambient temperature, humidity and atmospheric pressure (Fine, et al., 2010, Kumar, et al., 2013).
- Optical and optical fiber sensors are used for ambient monitoring of humidity and temperature, as well as for monitoring atmospheric gases (SO_2, NO_2, O_2 H_2, CH_4, NH_3) (Diamond, et al., 2013, Zhang, et al., 2010, Borisov, et al., 2011)
- Electrochemical sensors are used for atmospheric gases monitoring (O_3, CO, H_2S, H_2, NO, NO_2, SO_2) (Mead, et al., 2013, Bales, et al., 2012, Kumar, et al., 2011, Korotcenkov, et al., 2009)

Water

The increasing need for clean water, driven by global demand for drinking water and industrial water requirements, has created a critical requirement for monitoring water quality. Similar to air quality, strict regulations are set out by national bodies (such as the EPA) and geopolitical bodies (such as the EU) that apply to public water systems. These are legally enforceable and drive the need for reliable sensor technologies that can monitor different water quality parameters with the required sensitivity. Sensor technologies need to provide real-time or near real-time readings in order to ensure that any anomalous changes in water quality will have the minimum impact on human health or manufacturing operations. The absence of such monitoring can led to incidents like the one experienced by Perrier. Benzene, a known carcinogen, was found in the company's bottled water, resulting in a recall of their entire inventory from store shelves throughout the United States (James, 1990). Numerous parameters can be monitored in a water-quality regime. The specific mix of parameters depends on the application area, whether it be drinking water, an industrial application (such as beverage manufacturing), or monitoring industrial discharges or storm drains. There are normally three major categories of interest: physical (turbidity, temperature, conductivity,) chemical (pH, dissolved oxygen, metals concentration, nitrates, organics), and biological (biological oxygen demand, bacterial content).

A number of sensor technologies are being used commercially or are currently being evaluated to measure water quality parameters, including:

- Electrochemical (pH (ISFET), ammonium, conductivity)
    - Amperometric (chlorine, biochemical oxygen demand (BOD), dissolved oxygen, nitrates)
    - Colorimetric (organics, pesticides such as methyl parathion, Cl)
- MEMS (dissolved oxygen, NH_3)
- Optical (dissolved oxygen, turbidity, calcium (Ca), metal ions)
- Natural biosensors (bacteria, toxins)

The use of species-specific reagents is also popular for many water-analysis applications. While reagent-based approaches are not conventional sensors, they are used to sense or monitor many key water-quality parameters, such as the presence of nitrates. The reagent reacts with the analyte of interest in the water sample, resulting in a measurable color change using optical detection methods (Czugala, et al., 2013, Cogan, et al., 2013). In addition to water-quality monitoring, sensors (such as MEMS pressure sensors) are also being used to monitor the water distribution infrastructure, in order to improve the control and manageability of the system. Concepts such as smart water grids and predictive models are starting to emerge in the applied research domain. Sensors deployed in the water distribution infrastructure will assist in the identification of leaks through pressure drops, thus enabling rerouting of flow and minimizing water loss. Another area of interest in the research domain is predictive model-based water quality monitoring. This approach is based on fusing data from water quality, environmental sensors, and metrological sensors to predict potential changes in future water quality.

Sound (Noise Pollution)

As our society becomes more urbanized and we live in closer proximity to each other, noise and noise pollution becomes more problematic. Noise can have significant implications for the quality of life, ranging from being a nuisance to having a substantial physiological or psychological impact. Noise pollution can be described as unwanted sound that affects our daily lives and activities. Noise pollution can be transient or continuous. Common sources include cars, rail, and air transport, industry, neighbors, and recreational noise. Noise pollution monitoring is becoming increasingly regulated. The European Directive 2002/49/EC now requires member states to provide accurate mappings of noise levels in urban areas of more than 250,000 inhabitants on a regular basis, and to make this data easily available to the public (Santini, et al., 2008).

Spanish company Libelium, for example, offers noise-pollution sensing as part of its Smart Cities wireless sensor platform. More recently, with the rapid adoption of smartphones, citizen-led monitoring of noise levels in urban environments has gained popularity. Smartphone apps use the phone’s built-in microphone (MEMS) to collect noise-level data points, which are tagged with location information from the phone’s GPS coordinates and uploaded to the Web over 3G or Wi-Fi. Citizens can then use the data to create noise maps to influence city planners to make changes that improves quality of life within the city (Maisonneuve, et al., 2009).

Soil

A number of handheld instruments to measure the characteristics and quality of soil are in commonly use. Among the most popular are field-portable X-ray fluorescence (FP-XRF) instruments to measure metal contamination. A key advantage of the technique is that it requires almost no sample preparation, such as acid digestion. However, the technique is limited to bulk concentration analysis in which high concentrations of an element are likely to be present in a sample (Radu, et al., 2013). Other commonly used instruments include temperature and moisture meters and penetrometer for the measurement of soil strength. While the performance of these instruments is normally very accurate, they suffer from the limitation of being able to provide only a single measurement in time. For applications such as horticulture that require more frequent data points, sensors are now available to address that need.

When using sensors to monitor or analyze soil, we are normally interested in the soil's physical, chemical, and biological content. This type of data has a broad range of application, including agricultural, contamination, and geophysical monitoring. Key measurements include water content (capacitance, neutron moisture gauge, time-domain transmission (TDT), and time-domain reflectometry (TDR), temperature, pH, organic matter content (optical reflectance), and nitrogen levels.

Soil contaminants can be classified as microbiological (such as fecal coliforms), radioactive (such as tritium), inorganic (such as chromium (Cr)), synthetic organic (such as organophosphate pesticides), and volatile organic compounds (such as benzene). Sensors can serve two roles in soil contamination applications: the detection of the contaminants using species-specific sensors, and monitoring the physical characteristics of the soil during clean-up operations, including moisture content (ground water contamination) and soil temperature (soil temperatures play an important role when using fungal treatment of soil to remove contamination).

Geophysical monitoring of soil employs many of the same physical sensor readings that are used in agricultural applications. This type of monitoring is applied to dikes and dams to determine structural integrity. Motion sensors (MEMS accelerometers) and GPS sensors are also commonly used. Other typical applications include monitoring areas subject to landside threats, monitoring buildings that may have subsidence issues, landfill leachate monitoring, and biogas monitoring.

Healthcare

Sensor applications in the healthcare domain range from physiological monitoring, such as heart rate, to screening applications, such as blood biochemistry, to falls risk estimation. Sensors and applications utilized in the healthcare domain are typically developed by companies implementing a specific medical use case requiring approval and registration with an appropriate regulatory body, such as the US FDA. In the home and community, telehealth, telemonitoring, and mHealth (or mobile health) sensor applications enable remote monitoring and management of patients with chronic diseases, including diabetes, chronic obstructive pulmonary disease (COPD), and congestive heart failure (CHF). Sensor use in hospitals and primary healthcare facilities focuses more on medical screening and diagnostics applications, such as point-of-care blood chemistry testing, electrolyte-level measurement, and analyzing blood gas concentrations. There is also a growing market for over-the-counter diagnostic sensors that perform cholesterol monitoring, pregnancy testing, food allergy testing, and DNA testing. While often not strictly diagnostic in terms of accuracy, in many cases these over-the-counter sensors can deliver indicative results, which can assist decision-making prior to seeking formal clinical intervention and care.

Key to the proliferation of sensors in healthcare has been the development of low-cost microsystem sensor technologies coupled, in some cases, with low-cost, low-power microcontrollers (MCUs) and radios. These devices have enabled the development of small form-factor, reliable, robust, accurate, low-power sensor solutions. Some key application areas of sensors in clinical healthcare are:

- *Screening and Diagnostics:* Biochemical and optical sensors are used for point-of-care monitoring and diagnostics applications, including blood and tissue analysis (Yang, et al., 2013, Girardin, et al., 2009). Biosensors can be used to identify bacterial infection, drugs, hormones, and proteins levels in biological samples (Swensen, et al., 2009)(McLachlan, et al., 2011, Wang, et al., 2011).
- *Motion and Kinematics:* Body-worn wireless sensors, such as accelerometer and gyroscopes, can be used to identify balance and falls risk issues and to monitor the impact of clinical interventions. Kinematic sensors can be used in the assessment of prosthetic limb replacements (Arami, et al., 2013). They are also used in stroke rehabilitation to monitor the performance of targeted physical exercises (Uzor, et al., 2013) (Shyamal, et al., 2012). Sensors have also be been printed onto fabrics for motion-detection applications (Wei, et al., 2013) (Metcalf, et al., 2009).

- *Physiological:* Sensors in this category are used to measure key physiological indicators of health, such as ECG/EKG and blood pressure (Mass, et al., 2010) (Brown, et al., 2010). IR sensors can be found in noncontact thermometers (Buono, et al., 2007).
- *Musculoskeletal:* Body-worn sensors, such as an EMG, are used to assess muscular issues and tissue damage (Spulber, et al., 2012); (Reaston, et al., 2011) Sensors integrated directly into fabrics for rehabilitation applications have also been reported in the literature (Shyamal, et al., 2012)
- *Imaging:* Low cost CCD and ultrasound sensors are used for medical imaging (Jing, et al., 2012, Ng, et al., 2011). Smart pills can be used for intestinal imaging (McCaffrey, et al., 2008).

Wellness

Wellness is generally described as maintaining a healthy balance between the mind, body, and soul in order to create an overall feeling of well-being in an individual. The National Wellness Institute definition is (Institute, 2013):

> *Wellness is multi-dimensional and holistic, encompassing lifestyle, mental and spiritual well-being, and the environment.*

The use of sensors in the wellness domain encompasses a broad range of applications, from monitoring activity levels during recreational sporting activities, to sleep quality, to personal safety in the home.

Monitoring Recreational Activity

As people have become more aware of their health, there is a growing market for off-the-shelf sensors that had been found previously only in clinical applications. Such sensors are now used by consumers to track progress in wellness programs, such as those for obesity prevention, that encompass fitness and increased activity levels. Devices such as body-worn heart-rate and blood-pressure monitors, integrated activity monitors, and pulse oximeters are increasingly being used in this emerging domain. These sensors are supplemented by standard activity monitoring sensors, such as body-worn pedometers, which are coupled with software applications to provide analysis of activities and to encourage goal-directed behavior. There are a variety of commercial solutions that provide hybrid software/hardware solutions, including the Nike+ Fuelband, which features three accelerometers, user-defined goal setting, and visualization of daily activities.

Companies such as Freescale are already offering silicon building blocks for multisensor activity and wellness monitoring solutions (Freescale, 2012). Their use will increase as the cost of these sensors falls and as they are integrated into lifestyle elements of consumer electronic devices, particularly smartphones. The Nike+ iPhone application is a good example of a sensor/CE application (Apple, 2012). The ease of building new consumer applications will also increase as new standards emerge, driven by bodies such as the Continua Health Alliance (Alliance, 2010) and the ever-growing electronics hobbyist community.

Personal Safety

Another key element of wellness is personal safety, particularly in the home. The use of smoke detectors and CO sensors is long established. Semiconductor or electrochemical sensors are commonly used in residential CO sensors. Electrochemical instant detection and response (IDR) sensors are frequently used by emergency personnel, such as fire fighters, to determine almost immediately if a building contains dangerous levels of CO. Smoke detectors are generally based on one of two sensor types: ionization detectors or photoelectric detectors. Both types are effective, but differ in their response characteristics. Ionization detectors demonstrate a faster response to fires with flames, while photoelectric detectors respond faster to fires that generate more smoke (such as a smoldering fire from an electrical fault or initial furniture fire). Ionization detectors have the disadvantage of giving false alarms due to their sensitivity to small smoke particles, which result from normal cooking. In modern homes, smoke detectors (ionization and photoelectric) are normally AC powered with batteries as a backup power source (Helmenstine, 2013), thus eliminating issues with batteries dying.

Activity and Location Detection

As the average lifespan of the global population increases due to better healthcare, nutrition, and lifestyles, there is an increasing focus on allowing older adults to remain in their homes as long as possible. Sensor-based applications can enable this by providing in-home location and presence monitoring. Location data, usually measured using PIR sensors, can be combined with machine-learning algorithms and data from other sources, such as temperature and humidity, to determine the wellness of an individual and to trigger intervention if required. In situations where a resident has mild cognitive impairment, the perimeter of the house could be monitored using sensors (for example, magnetic contact sensors) on exit doors to determine if the individual leaves the home—and alert family members if required. Ambient sensing can be further augmented with body-worn sensors (MEMS accelerometers and gyroscopes) to detect problems such as falls.

The availability of GPS trackers and other sensors, such as accelerometers in smartphones, has enabled new personal location-tracking capabilities. This category of sensing can be used for recreational purposes, to provide real-time pace, location, elevation, and direction information to a jogger; as well as for personal safety applications, where the GPS trackers can be used by parents to determine the location of a child or a cognitively impaired older adult. There are limitations, however, particularly in determining the type or intensity of the monitored activity, such as walking on flat ground versus walking up steps.

Sensor Characteristics

Sensors provide an output signal in response to a physical, chemical, or biological measurand and typically require an electrical input to operate; therefore, they tend to be characterized in sensor specifications (commonly called "specs") or datasheets in much the same way as electronic devices. To truly understand sensors, and how sensors that measure the same measurand can differ, it is necessary to understand sensor performance characteristics. Unfortunately, there is no standard definition for many of these characteristics and different parts of the sensor community have different names for these characteristics, depending on the sensing domain. This confusion is compounded by manufacturers publishing an abundance of performance characteristics, that make it even more difficult for potential users to identify the ones relevant to their applications, and how they should be applied. The following section will describe these characteristics, using their most common names, and will reference alternative names where relevant.

Sensor characteristics can be categorized as systematic, statistical, or dynamic. Bently defines systematic characteristics as "those which can be exactly quantified by mathematical or graphical means;" statistical characteristics as "those which cannot be exactly quantified;" and dynamic characteristics as "the ways in which an element responds to sudden input changes" (Bently, 1995).

Range

Range is a static characteristic and, as the name implies, it describes both the minimum and maximum values of the input or output. The term range is commonly used in the following ways in datasheets:

- Full-scale range describes the maximum and minimum values of a measured property. Full-scale input is often called *span*. Full-scale output (FSO) is the algebraic difference between the output signals measured at maximum input stimulus and the minimum input stimulus. Span (or dynamic range) describes the maximum and minimum input values that can be applied to a sensor without causing an unacceptable level of inaccuracy.

- Operating voltage range describes the minimum and maximum input voltages that can be used to operate a sensor. Applying an input voltage outside of this range may permanently damage the sensor.

Transfer Function

Sensor characteristics describe the relationship between the measurand and the electrical output signal. This relationship can be represented as a table of values, a graph, or a mathematical formula. Expensive sensors that are individually calibrated may even provide a certified calibration curve. If this relationship is time-invariant, it is called the sensor transfer function. A mathematical formula describing the transfer function is typically expressed as follows:

$$S = F(x)$$

Where x is the measurand and S is the electrical signal produced by the sensor. It is rare to find a transfer function that can be completely described by a single formula, so functional approximations of the actual transfer function are used.

Linear Transfer Functions

The simplest transfer function is a linear transfer function, with the following form:

$$S = A + Bx$$

where A is the sensor offset and B is the sensor slope. The sensor offset is the output value of the sensor when no measurand is applied. The slope of a linear transfer function is equal to the sensor's sensitivity, which is described later. In practice, very few sensors are truly linear, but they are considered to have linear characteristics if the plot of measurand versus the output values is approximately a straight line across the specified operating range. An ideal straight line, that is a linear approximation of the transfer function, is most commonly drawn using one of the following methods (see Figure 2-6):

- *End-point method:* The ideal straight line is drawn between the upper- and lower-range values of the sensor. This method is generally less accurate than the best-fit method.
- *Best-fit method:* Also called independent linearity, the ideal straight line can be positioned in any manner that minimizes the deviations between it and the device's actual transfer function. This method is most commonly used by sensor manufacturers to describe their sensor performance as it provides the best fit or smallest deviation from the actual data. The least-squares method is the most common method to determine best fit. This statistical method samples a number of different points to calculate the best fit.

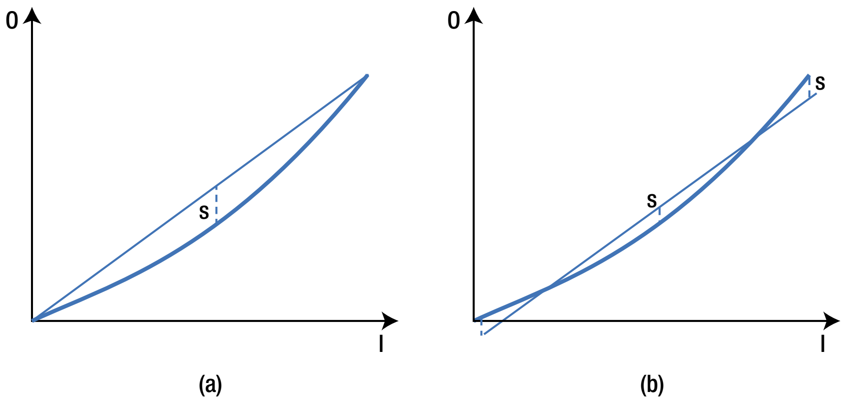

Figure 2-6. *An ideal straight line drawn using the (a) end-point and (b) best-fit methods. Nonlinearity is indicated by the dotted line(s) between the actual data and the ideal straight line*

Linearization

There are a number of advantages to linear transfer functions. First, it is simple to calculate the measurand value from the electrical output of a sensor and to predict the electrical output based on the measurand value. Second, the sensor offset and sensor slope characteristics are easily read from the transfer function. Third, non-ideal characteristics, such as nonlinearity and hysteresis, can be defined relative to a linear transfer function. A non-linear sensor output can be "linearized" using hardware or software to leverage the advantages of linear sensors (van der Horn, et al., 1998). The traditional hardware-based linearization method often requires manual calibration and precision resistors to achieve the desired accuracy. Modern smart sensors employ less complex and less costly digital techniques to create a linear output. These techniques perform digital linearization and calibration by leveraging the smart sensor's integrated microcontroller and memory to store the factory calibration results for each individual sensor. The microcontroller can correct the sensor output by searching for the compensation value or the actual linearized output in a look-up table. If memory is limited, calibration coefficients, rather than a full-look up table, are used to construct a linearized output.

Non-Linear Transfer Functions

Some transfer functions do not approximate well to linear transfer functions. However, they can be approximated using other mathematical functions (Fraden, 2010), including:

Logarithmic functions: $S = A + B.\ln(x)$

Exponential functions: $S = A.e^{k.x}$

Power functions: $S = A + B.x^k$

where x is the measurand, S is the electrical signal produced by the sensor, A and B are parameters, and k is the power factor. A polynomial function can be used when none of the functions previously described can be applied to describe the sensor transfer function. Second- and third-order polynomials can be described using the following transfer functions:

Second-Order Polynomial functions: $S = A.x^2 + B.x + C$

Third-Order Polynomial functions: $S = A.x^3 + B.x^2 + C.x + D$

A third-order polynomial will provide a better fit to the sensor transfer function than a second-order polynomial. However, a second-order polynomial may provide a sufficiently accurate fit when applied to a relatively narrow range of input stimuli.

Linearity and Nonlinearity

Nonlinearity, which is often called linearity in datasheets, is the difference between the actual line and ideal straight line. As nonlinearity may vary along the input-output plot, a single value, called maximum nonlinearity, is used to describe this characteristic in datasheets. Maximum nonlinearity is typically expressed as a percentage of span. Nonlinearity can often be affected by environmental changes, such as temperature, vibration, acoustic noise level, and humidity. It is important to be aware of the environmental conditions under which nonlinearity is defined in the datasheet, particularly if they differ from the application operating environment.

Sensitivity

Sensitivity is the change in input required to generate a unit change in output. If the sensor response is linear, sensitivity will be constant over the range of the sensor and is equal to the slope of the straight-line plot (as shown in Figure 2-7). An ideal sensor will have significant and constant sensitivity. If the sensor response is non-linear, sensitivity will vary over the sensor range and can be found by calculating the derivative of S with respect to x (dS/Dx).

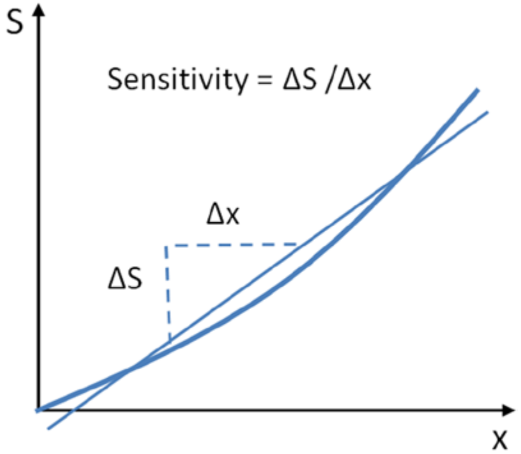

Figure 2-7. *Sensor sensitivity*

Common sensitivity-related issues include dead-bands and saturation. The dead-band is a specific range of input signals in which the sensor is unresponsive or insensitive. In that range, the output may remain near a certain value (generally zero) over the entire dead-band zone. Dead-band is usually expressed as a percentage of span. The saturation point is the input value at which no more changes in output can occur.

Environmental Effects

Sensor outputs can be affected by external environmental inputs as well as the measurand itself. These inputs can change the behavior of the sensor, thus affecting the range, sensitivity, resolution, and offset of the sensor. Datasheets specify these characteristics under controlled conditions (such as fixed temperature and humidity, fixed input voltage, and so on). If a sensor is to be operated outside these conditions, it is highly recommended to recalibrate the sensor under the conditions in which it will be used.

Modifying Inputs

Modifying inputs changes the linear sensitivity of a sensor. The voltage supplied to the sensor, V_s, is a common example of a modifying input as it can modify the output range of the sensor, which in turn modifies the resolution and sensitivity.

Interfering Inputs

Interfering inputs change the straight-line intercept of a sensor. Temperature is a common example of an interfering input, as it changes the zero-bias of the sensor. An example of a temperature effect on sensor output is shown in Figure 2-8.

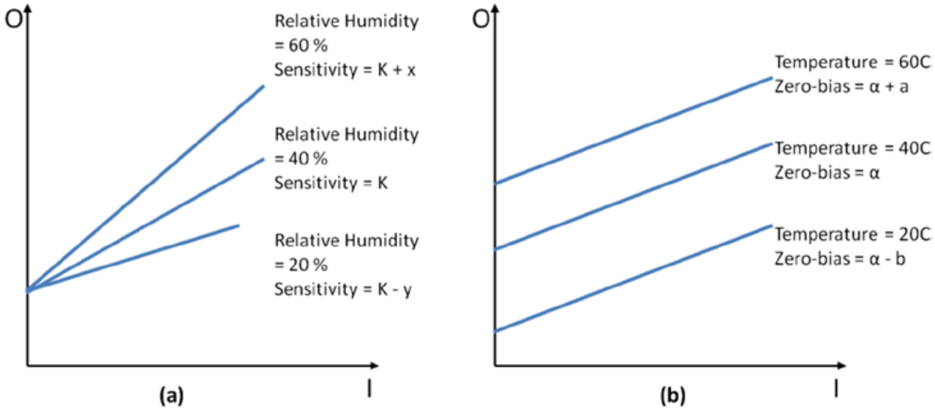

Figure 2-8. *(a) Effect of a modifying input (relative humidity) on the sensor's sensitivity, K; (b) Effect of an interfering input (temperature) on the sensor*

Hysteresis

The output of a sensor may be different for a given input, depending on whether the input is increasing or decreasing. This phenomenon is known as *hysteresis* and can be described as the difference in output between the rising and falling output values for a given input as illustrated in Figure 2-9. Like nonlinearity, hysteresis varies along the input-output plot; thus maximum hysteresis is used to describe the characteristic. This value is usually expressed as a percentage of the sensor span. Hysteresis commonly occurs when a sensing technique relies on the stressing of a particular material (as with strain gauges). Elastic and magnetic circuits may never return to their original start position after repeated use. This can lead to an unknown offset over time and can therefore affect the transfer function for that device.

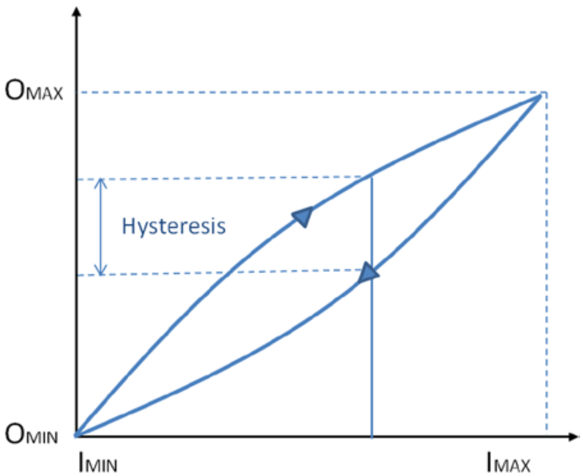

Figure 2-9. *Hysteresis curve, illustrating the different responses of a sensor to an increasing input and a decreasing input*

Resolution

Resolution, also called discrimination, is the smallest increment of the measurand that causes a detectable change in output. The resolution of modern sensors varies considerably, so is important to understand the resolution required for an application before selecting a sensor. If the sensor resolution is too low for the application, subtle changes in the measurand may not be detected. However, a sensor whose resolution is too high for the application is needlessly expensive. Threshold is the name used to describe resolution if the increment is measured from zero, although it is more commonly described as the minimum measurand required to trigger a measurable change in output from zero.

Accuracy

Accuracy refers to a sensor's ability to provide an output close to the true value of the measurand. Specifically, it describes the maximum expected error between the actual and ideal output signals. Accuracy is often described relative to the sensor span. For example, a thermometer might be guaranteed to be accurate to within five percent of the span. As accuracy is relative to the true value of the measurand, it can be quantified as a percentage relative error using the following equation:

$$Percentage\ Relative\ Error = \frac{(Measured\,Value - True\,Value)}{(True\,Value)} \times 100$$

Precision

Precision is sometimes confused with accuracy. Figure 2-10 illustrates the key differences between the two. Precision describes the ability of an output to be constantly reproduced. It is therefore possible to have a very accurate sensor that is imprecise (a thermometer that reports temperatures between 62–64° F for an input of 63° F), or a very precise sensor that is inaccurate (a thermometer that always reports a temperature of 70° F for an input of 63° F). As precision relates to the reproducibility of a measure, it can be quantified as percentage standard deviation using the following equation:

$$Percentage\,Standard\ Deviation = \frac{(Standard\ Deviation)}{(Mean)} \times 100$$

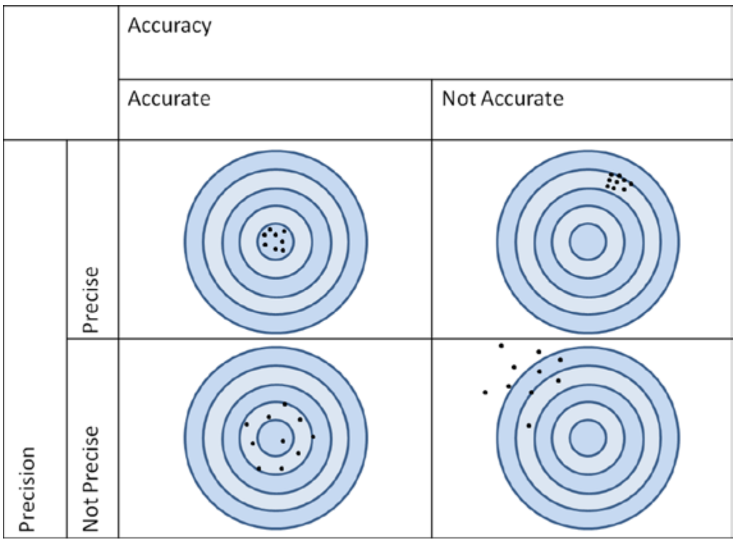

***Figure 2-10.** The difference between accuracy and precision, illustrated using a dartboard analogy*

Error

Error is the difference between the measured value and true value, where true value is a reference to an absolute or agreed standard. There are two forms of error: systematic error and random error.

Systematic Errors

Systematic errors are reproducible inaccuracies that can be corrected with compensation methods, such as feedback, filtering, and calibration (Wilson, 2004). These errors result from a variety of factors including:

- Interfering inputs, which introduce error by changing the zero-bias of the sensor.
- Modifying inputs (such as humidity) introduce error by modifying the relationship between the input and the output signal.
- Changes in chemical structure or mechanical stresses, due to aging or long-term exposure to elements (such as UV light), can result in the gain and the zero-bias of the sensor to drift. This gradual deterioration of the sensor and associated components can result in outputs changing from their original calibrated state. This source of error can be compensated for through frequent recalibration.
- Interference, also called loading error, can occur when the sensor itself changes the measurand it is measuring. A simple example of this is a flow-rate sensor that may disrupt the flow, resulting in an erroneous reading. In chemical sensors, interference relates to a process by which other species in the sample compete with the target (primary) species of interest.
- Signal attenuation, and sometimes signal loss, can occur when the signal moves through a medium.
- Humans can inadvertently introduce a number of errors into a system, including parallax errors, due to incorrect positioning; zero error, due to incorrectly calibrated instruments; and resolution error, where the resolution of the reference device is too broad. Human errors are commonly called "operator errors".

Random Errors (Noise)

Random error (also called noise) is a signal component that carries no information. The quality of a signal is expressed quantitatively as the signal-to-noise ratio (SNR), which is the ratio of the true signal amplitude to the standard deviation of the noise. A high SNR represents high signal quality. Noise can be measured by recording the signal in the absence of the measurand, or by recording a known measurand several times, then subtracting the known true signal from the measured signal. SNR is inversely proportional to the relative standard deviation of the signal amplitude used to measure precision. Therefore, a noisy signal is also an imprecise signal.

In analytical chemistry, the limit of detection (LOD) and limit of quantification (LOQ) have a particular relevance to noise. The LOD is the lowest quantity of a substance that can be distinguished from the absence of that substance (noise). The LOQ is the limit at which the difference between the substance and absence of that substance can be quantified. LOD is quantified as three times the standard deviation of noise and LOQ is defined as 10 times the standard deviation of noise. True random errors (white noise) follow a Gaussian distribution. Sources of randomness include:

- Noise in the measurand itself (such as the height of a rough surface)
- Environmental noise (such as background noise picked up by a microphone)
- Transmission noise

Error Bands

Error bands combine several sensor characteristics (including nonlinearity, hysteresis, and resolution) into a single measure and guarantee that the output will be within a ±h of the ideal straight line. The value "h" is typically a percentage, such as ±5 percent; or a value, such as ± 0.5°C. Figure 2-11 illustrates the concept of error bands around an ideal straight line sensor output. They are advantageous to users as they reduce the number of characteristics that need to be considered when designing an application and are advantageous to manufacturers as they eliminate individual testing and calibrating of each separate characteristic of a sensor.

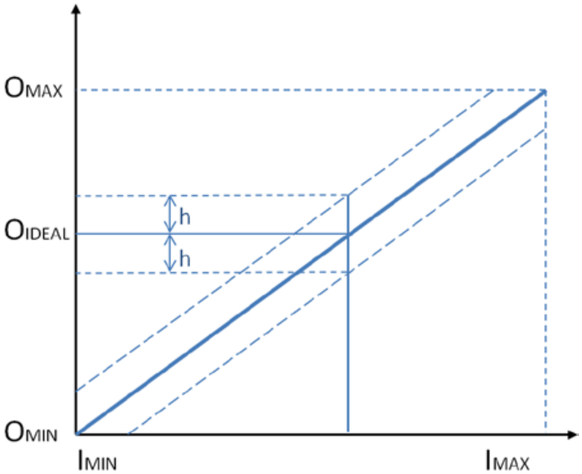

Figure 2-11. *Error bands around an ideal straight line*

Statistical Characteristics

Statistical characteristics are characteristics that can't be exactly described by formulas or graphical means. These characteristics describe a summary of numerous measurements taken with a single or multiple sensors. The most commonly used statistical characteristics in sensor datasheets are repeatability and tolerance.

Repeatability

Repeatability is the ability of a sensor to produce the same output when the same input is applied to it. Lack of repeatability generally occurs due to random fluctuations in environmental inputs or operator error.

Tolerance

Tolerance describes the variations in the reported output among a batch of similar elements due to small random manufacturing variations. If a manufacturer reports a tolerance of ±5 percent, it can't sell any sensors that fall outside of this range.

Dynamic Characteristics

Dynamic characteristics are time-dependent characteristics of a sensor. Sensor dynamics are less important in applications that have sensor inputs that are constant over long periods of time. Dynamic characteristics can be classified as zero-order, first-order, and second-order systems. The most common dynamic characteristics found in datasheets are response time and dynamic linearity.

Response Time

Sensors do not change their output immediately following a change in the input. The period of time taken for the sensor to change its output from its previous state to a value within a tolerance band of the new correct value is called response time (see Figure 2-12). The tolerance band is defined based on the sensor type, sensor application, or the preferences of the sensor designer. It can be defined as a value, such as 90 percent of the new correct value. Response time is commonly defined using time constants in first-order systems (Fraden, 2010). A time constant is the time required by a sensor to reach 63.2 percent of a step change in output under a specified set of conditions. A time constant can be easily estimated by fitting a single exponential curve to the response curve.

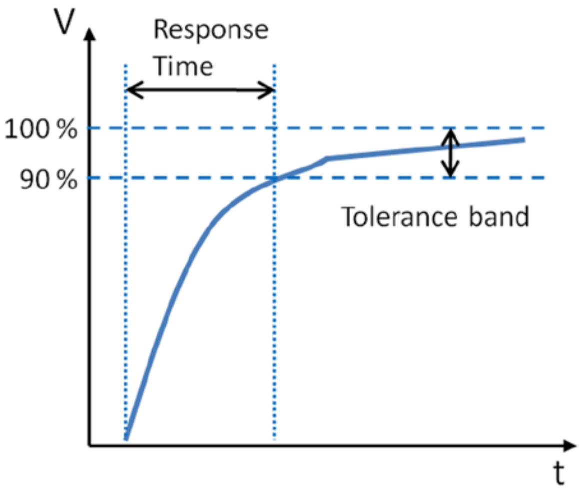

Figure 2-12. *Response time for a sensor based on a tolerance band set to 90–100 percent*

Dynamic Linearity

The dynamic linearity of a sensor is a measure of its ability to follow rapid changes in the input parameter. Amplitude distortion characteristics, phase distortion characteristics, and response time are important in determining dynamic linearity.

Summary

The terms sensor and transducer are commonly used interchangeably, and both devices are encapsulated in sensor systems for a given application. As described in this chapter, a great variety of sensing techniques are available for measuring physical, chemical, and biological quantities of interest. We have briefly outlined the various techniques—mechanical, optical, semiconductor, and biosensing—and have highlighted their respective advantages and disadvantages. We introduced our key sensing domains and described how the various sensor technologies can be utilized within these domains to address problems associated with increased urbanization, global ageing, pollution, and climate change. The role of regulation in driving sensor applications for monitoring air and environmental compliance was also outlined. Finally, sensor characteristics were defined to simplify the process of reading datasheets and comparing performance characteristics of different sensors.

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