Chapter 2
Sensors

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2.1 Introduction

A sensor is an electronic device used to detect or measure a physical quantity and convert it into an electronic signal. In other words, sensors are devices that translate aspects of physical reality into representations understandable and processable by computers.

In a wireless sensor network, sensors play an important part, as sensing is one of its central roles. Technology behind sensors, however, is not of major interest when considering sensor networks, with the emphasis being more on communication, network management, and data manipulation. Most sensors used in WSN systems have been developed independently of WSN technology, and these two fields continue to develop somewhat independently. Nevertheless, any in-depth discussion of wireless sensor networks, especially when aimed toward providing the reader with a holistic picture of current capabilities and limitations of wireless sensor networks, must include sensors.

In this chapter, first we will look at some important issues regarding sensors and introduce some of the terminology used later in the chapter. Then we move on to examine basic types of sensors, categorized by the function they perform. Characteristics of currently available sensors are given, along with a brief overview of their operating principals. The goal is not to go into a detailed analysis of sensor technology, but to give the reader a basic notion of how a certain sensor operates, under which conditions, and with which limitations. This insight should prove handy when designing a new WSN application. For a more detailed study of sensors and sensing technologies, readers are referred to [1].

Finally, as this book puts much emphasis on utilization of WSN technology in personal and public health, we examine some of the more complex sensing devices used within this field.

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L. Gavrilovska et al. (eds.), *Application and Multidisciplinary Aspects of Wireless Sensor Networks*, Computer Communications and Networks,
DOI 10.1007/978-1-84996-510-1_2,

2.2 Sensor Characteristics

In this chapter we introduce some of the important characters of sensors. Understanding of these is important when choosing the right sensors for your application.

2.2.1 Transfer Function

Transfer function is a mathematical representation of the relation between the input and output of a system. In terms of sensors it represents the relationship between the physical signal on the input, and the electrical output signal.

2.2.2 Hysteresis

A sensor should be capable of following changes in the input parameter, regardless of what direction the parameter changes in (whether there is an increase or a decrease in value). Some sensors do not return the same value for both directions of change. Hysteresis is the measure of this property.

2.2.3 Linearity

Linearity of a sensor shows how much the measured curve deviates from the ideal transfer function. There are several ways to interpret and represent linearity, the most commonly used being:

- End point linearity
- Best-fit straight line (BFSL)
- Least squares BFSL linearity

On the Input against Output graph a straight line is drawn from the zero point to the full-scale output point. The point on the actual measured curve that deviates most from this line is used to define the linearity of the sensor. This is usually quoted as a percentage of the full-scale output of the sensor.

2.2.3.1 Best-Fit Straight Line (BFSL)

BFSL linearity is a measure of the most accurate overall results that can be obtained for a given sensor. Instead of using a line that connects the full-scale point to the end point, a different line is chosen so that the maximal deviation of the actual measured curve is minimal. Note that this is simply a means of interpretation of the results and relies entirely on the system, including the measuring equipment, being set up to take advantage of this technique.

2.2.3.2 Least Squares BFSL Linearity

The method of least squares assumes that the best-fit curve of a given type is the curve that has the minimal sum of the deviations squared (least square error) from a given set of data.

When defining least squares BFSL linearity, the slope of the best-fit line is defined using the measured results in a number of calibration points with the equation:

$$\frac{\Sigma(\text{actual sensor output at each data point}) * (\text{actual sensor output at each data point})}{\Sigma(\text{actual sensor output at each data point})^2}$$

Having mathematically determined the slope of the best-fit straight line it is then possible to determine the maximum deviation of any point from this line.

2.2.4 Sensitivity

Sensitivity of a sensor is the ratio between a small change of the input and the resulting change in the output signal. Mathematically speaking, it is defined as the slope of the output characteristic curve. Sensitivity error is a departure from the ideal slope of the characteristic curve.

2.2.5 Accuracy

Accuracy represents the largest expected error between the ideal output signal and the actual output signal. Sometimes it is presented as a percentage of the maximum output signal.

2.2.6 Dynamic Range

Dynamic range (or Span) is the range of the input signal that can be accurately converted into the electrical output. Outside of the dynamic range sensor produces either a predefined value, or, more commonly, undefined and inconsistent.

2.2.7 Noise

All sensors produce noise in addition to output signal. For applications that require high precision, sensing amount of noise introduced by a sensor can be of at most importance.

2.2.8 Resolution

The resolution of a sensor is the minimum fluctuation of the input signal that can be detected.

2.2.9 Bandwidth

After any change in the input parameter, a certain amount of time is required before the resulting change in the output parameter can be detected and measured. This time is called response time. Some sensors also many sensors have decay times, which would represent the time after a step change in physical signal for the sensor output to decay to its original value. Values reciprocal to the response time and the decay time are called lower and upper cutoff frequencies. The bandwidth of a sensor is the frequency range between these two frequencies. A sensor with high bandwidth can change its output to follow fast (high-frequency) variations in the input. For measures that change slowly, such as the temperature of a large liquid tank, bandwidth may not be important. For other applications such as scanning shape or vibration sensors, bandwidth may be the most important figure of merit.

2.3 Classifications

There are two basic ways to categorize sensors. The first is based on the principal by which they function, and the second is based on the function the sensor performs. Most sensors act like passive devices (i.e., capacitors or resistors). These sensors require external circuitry for biasing and amplification of the output signal.

Resistive sensors are devices whose resistance changes with the value of input signal being measured. These sensors can be used in a simple voltage-divider configuration (Fig. 2.1). For more precise measurements a variety of configurations can be used (e.g., the Whetstone bridge circuit).

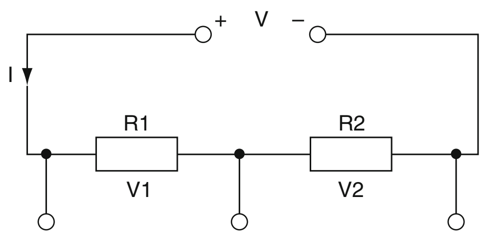

Fig. 2.1 Voltage divider. Legend: R1 – Resistive sensor, R2 – Reference resistor, V1 – Voltage on the resistive sensor, V2 – Voltage on the reference resistor, V – reference voltage

Capacitive sensors produce a change in capacitance proportionate to the value of the measured input signal. Detection of this change is done quite similarly as with the resistive sensors, only in this case the impedance of the capacitor is observed, which means that an AC bias must be provided. Inductance-based sensors can be observed in much the same way.

As opposed to these sensors some sensors produce their own bias voltage, and can directly be connected to an AD converter or an amplifier, if amplification is required.

Perhaps the more logical way to classify sensors is with regard to the physical property they measure. The most common categories include [2]:

- Mechanical
- Thermal
- Electrical
- Magnetic
- Radiant
- Chemical and biochemical

2.4 Mechanical Sensors

Mechanical sensors detect mechanical properties and actions. These include (among other things) pressure, velocity, vibration sensors, and accelerometers.

2.4.1 Pressure Sensors

Pressure is one of the most important physical properties and, thus, pressure micro-sensors were the first micro-sensors developed and used by the industry. A wide variety of applications calls for a wide variety of pressure sensors, but most belong in one of three major categories.

Piezorezistive pressure sensors have a piezoresistor integrated in a membrane. Pressure is applied to the membrane, causing it to deform. This in turn, causes a change in resistance, proportionate to the applied force.

In capacitive pressure sensors (whether membrane or comb-based) pressure is applied on the sensor surface, causing a membrane to deflect and the capacitance to change. These sensors generally have greater sensitivity and linearity, while exhibiting very little or no hysteresis. However, these sensors also have higher production costs when compared to piezoresistive pressure sensors.

2.4.2 Optical Pressure Sensors

Optical pressure sensors operate on the principal of the Mach–Zehnder interferometer. Laser light is brought into the sensor via an optical fiber. This light is split into two beams. One of the two beams crosses through one of the beams, which is deformed by the pressure. This deformation changes the light's properties. The two beams are combined and brought to a photodiode. Different propagation speeds create a phase shift between these beams which is detected at the diode.

2.4.3 Position and Motion Sensors

Position sensors play an important role in a wide variety of applications. Numerous ways of detecting position are available, ranging from simple contact sensors to more complex contact-free ones. Position measurement can either be relative (displacement sensors) or absolute, linear or angular.

All types of position sensors have their own advantages and drawbacks; thus, it is important to choose the right type of the sensor for the given application.

2.4.4 Resistive Position Sensors

Resistive position sensors are better known as potentiometers. In various forms, these sensors have found applications from volume adjustment knobs and sliders on radios to industrial machine slide sensing. A potentiometer is simply a resistor whose resistance changes based on the position of a movable part.

2.4.5 Limit Switches

Limit switches are the simplest of position sensors. They are electromechanical contact devices. A limit switch consists of a number of switches. When the monitored object comes into contact with one of the switches, this switch is activated.

2.4.6 Magnetic Position Sensors

Magnetic Position Sensors are noncontact position sensors that are magnetic-fields-generated or affected by target objects.

The magnetic field is a vector quantity that has both magnitude and direction. Scalar magnetometers measure only the total magnitude. Others measure the magnitude of the component of magnetization along their sensitive axis (unidirectional sensors). Vector magnetic sensors have two or three bidirectional sensors.

2.4.7 Hall Effect Sensors

A Hall Effect sensor is a transducer that varies its output voltage in response to changes in magnetic field.

In its simplest form, the sensor operates as an analogue transducer, directly returning a voltage. They contain a Hall element constructed from a thin sheet of conductive material with output connections perpendicular to the direction of current flow. With a known magnetic field, its distance from the Hall plate can be determined. Using groups of sensors, the relative position of the magnet can be deduced.

Electricity carried through a conductor will produce a magnetic field that varies with current, and a Hall sensor can be used to measure the current without interrupting the circuit. Typically, the sensor is integrated with a wound core or permanent magnet that surrounds the conductor to be measured.

2.4.8 Magnetoresistive Sensors

Magnetoresistance is the property of a material to change the value of its electrical resistance when an external magnetic field is applied to it.

MR sensors measure both linear and angular position and displacement in the Earth's magnetic field (below 1 gauss). They are an excellent solution for locating objects in motion. By affixing a magnet or sensor element to an angular or linear moving object with its complementary sensor or magnet stationary, the relative direction of the resulting magnetic field can be quantified electronically.

2.4.9 Ultrasonic Position Sensors

Ultrasonic sensors work on a principle similar to radar or sonar which evaluates attributes of a target by interpreting the echoes from radio or sound waves, respectively. Ultrasonic sensors generate high-frequency sound waves and evaluate the echo which is received back by the sensor. Sensors calculate the time interval between sending the signal and receiving the echo to determine the distance to an object.

2.4.10 Accelerometers

Accelerometers are sensors that measure acceleration they are subjected to. Most are based on resistive or capcitative and piezoelectric methods.

2.4.11 Resistive and Capacitive Accelerometers

With these micro-sensors an elastic cantilever with an attached mass is usually used. When the sensor is subjected to acceleration, a force proportionate to this acceleration deforms the cantilever. With piezoresistive sensors a piezoresistor is integrated into the cantilever, whose deformation causes a change in its resistance. With capacitive sensors the cantilever acts as one electrode, with an electrode strip acting as the other. As the cantilever is deformed it is brought closer to the electrode strip, which in turn affects the capacitance between the two electrodes.

Resistive and capacitive accelerometers can be used to measure constant acceleration, such as that of Earth's gravity. They are generally used for measuring low-frequency vibrations.

2.4.12 Piezoelectric Accelerometers

Piezoelectric accelerometers are based on the piezoelectric effect. This means that an electric charge is created when the sensing material is squeezed or strained. Several methods of straining of the material can be used, three of the basic being: compression, flexural, and shear, with the shear being the most common one. These accelerometers are generally durable, protected from contamination, and impervious to extraneous noise influences.

2.5 Temperature Sensors

Temperature is the most widely sensed of all parameters. Temperature sensors detect a change in a physical parameter (resistance or output voltage) that corresponds to a temperature change. Three basic types of temperature sensors are electromechanical, electronic, and thermo-resistive [3].

2.5.1 Electromechanical Temperature Sensors

These sensors are based on expanding or contracting properties of materials when subjected to a temperature change. Bi-metal thermostats are created by bonding two metals into a single strip of material. Different expansion rates of the metals create electromechanical motion when the material is subjected to a temperature change. In capillary thermostats the capillary motion of expanding or contracting fluid is used to make or break a number of electrical contacts.

2.5.2 Electronic Temperature Sensors

Thermocouples: Thermocouples are based on the Seed-back effect. When a pair of dissimilar metals is joined at one end, and there is a temperature difference between the joined end and the open end, thermal electromagnetic force is generated. This will create a flow of current through the wires that is proportionate to the temperature difference. The open ends must be kept at a constant reference temperature. Several standard types of thermocouples are use.

2.5.3 Silicon Sensors

Silicon sensors make use of the bulk electrical resistance properties of semiconductor materials, rather than the junction of two differently doped areas. Especially at low temperatures, silicon sensors provide a nearly linear increase in resistance versus temperature or a positive temperature coefficient.

2.5.4 Resistive Temperature Sensors

Resistive temperature sensors are devices whose resistance changes with the temperature.
Thermistors: A thermistor is a type of resistor with resistance varying according to its temperature. They typically consist of a combination of two or three metal oxides that are sintered in a ceramic base material.

Thermistors can be classified into two types: positive temperature coefficient (PTC) and negative temperature coefficient (NTC). PTC devices exhibit an increase in resistance as temperature rises, while NTC devices exhibit a decrease in resistance when temperature increases.

The main disadvantage of the thermistor is its strong nonlinearity. Cheap thermistors have large spread of parameters ("tolerance") and calibration is usually necessary.

2.5.5 Resistive Temperature Detectors (RTDs)

Unlike thermistors that use a combination of metal oxides and ceramics, resistive temperature detectors are made from pure metal (copper, nickel, or platinum are usually used). RTDs are useful over larger temperature ranges, while thermistors typically achieve a higher precision within a limited temperature range.

As a RTD is a resistance device, it needs measuring current to generate a useful signal. Because this current heats the element above the ambient temperature ($P = I^2R$), errors can occur, unless the extra heat is dispersed. This forces us to choose a small-sized resistance device with a quick response or a larger resistance device and better heat release.

A second solution is to keep the measuring current low (usually between 1 and 5 mA).

2.6 Humidity Sensors

Humidity is the amount of water vapor in the given substance (usually a gas). It is an important parameter in a variety of fields, including room air humidity in patient monitoring and exhibit perseveration in museums, meteorological observations, soil humidity in agriculture, and process control in industrial applications.

Humidity can be measured as the absolute humidity (ratio of water vapor to the volume of substance), relative (compared to the saturated moisture level) or dew point (temperature and pressure at which the observed gas starts to turn into liquid). Most common humidity sensors are based on capacitive, resistive, and thermal conductivity measurement techniques.

2.6.1 Capacitive RH Sensors

In a capacitive RH sensor, change in dielectric constant is almost directly proportional to relative humidity in the environment. Relative humidity sensors have three-layer capacitance construction and consist of thermoset polymer, platinum electrodes, and a silicon chip with integrated voltage output signal conditioning.

These sensors have low temperature coefficient, and response times that range from 30 to 60 s. They offer near-linear voltage outputs, wide RH ranges and condensation tolerance, and are stable over long-term use. However, the capacitive effect of the cable connecting the sensor to the signal conditioning circuitry is large compared to the small capacitance changes of the sensor. This limits the distance from sensing element to signal conditioning circuitry.

2.6.2 Resistive Humidity Sensors

Resistive humidity sensors measure the resistance change in a medium such as a conductive polymer or a salt. Resistance usually has an inverse exponential relationship to humidity. Response times of these sensors are 10–30 s.

Resistive humidity sensors are small size, low cost, and are usable from remote locations.

2.7 Chemical Sensors

Chemical sensors detect the presence or concentration of particular chemical elements or compounds in a given sample. A chemical sensor usually consists of a chemically sensitive film or a membrane and a transducer.

A chemical process occurring in or on a chemically sensitive film or membrane causes a signal to be generated at the transducer. Examples of mechanisms commonly employed include host–guest binding, catalytic reactions, or a redox process.

Chemical sensors have a vast variety of applications ranging form medical diagnostics and nutritional sciences, through security to automotive industry (Fig. 2.2).

Based on the principal of operation, several types of chemical sensors can be identified.

2.7.1 Interdigital Transducer Sensors

Interdigital transducers using capitative measurement are often used in chemical sensors. Sensitive layer is used as the dielectric between two electrodes. The dielectric properties of the sensitive layer are changed when it interacts with certain substances, affecting the capacitance between the two electrodes.

2.7.2 Conductivity Sensors

In these sensors the sensitive layer is used as a conductor of electricity. Interactions with certain chemicals (e.g., absorption of gasses) modify the conductivity of this layer. There are two types of sensing layers: Metal Oxide and Conducting Polymers.

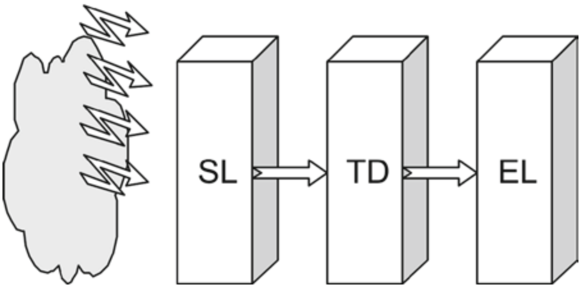

Fig. 2.2 Structure of a chemical sensor. Legend: CS – Chemical substance, SL – Sensitive layer, TD – Transducer, EL – Electronics. Explanation: Chemical substance reacts with the chemical layer. Reaction causes a signal to be generated at the transducer. The signal is then processed by electronics and converted into a format suitable for further processing

Metal Oxide sensitive layers are typically made of SnO_2 doped with Pt or Pd. These sensors can operate at high temperatures (300–5,000°C), which makes them especially suitable for combustion gases.

Conductive Polymer sensitive layers are usually based on pyrrole, aniline, or thiophene. These sensors operate best at room temperatures. Compared to Metal Oxide sensors these sensors have lower power consumption, and faster response and recovery times. However, they are have lower sensitivity and are sensitive to humidity.

2.7.3 Optical Chemical Sensors

In optical sensors, an optical waveguide is used as the sensitive layer. Chemical reactions between the waveguide and the target chemical substance cause a change in the optical properties of the waveguide (e.g., the index of reflection). As a result the amount (or the wavelength) of the light striking the sensor on the end of the waveguide varies.

These sensors are highly sensitive, can handle small quantities, are inexpensive, and easy to sterilize.

Majority (about 60%) of chemical sensors are gas sensors. Most commonly used chemical sensors include O_2, pH, CO, CO_2, NO_X, Methane, etc. Table 2.1 gives an overview of the range of characteristics for some of these sensors available on the market.

2.7.4 Ion-Sensitive FET Sensor

An ion-sensitive field effect transistor (ISFET) is an ion-sensitive field effect transistor used to measure ion concentrations in solution; when the ion concentration (such as pH) changes, the current through the transistor will change accordingly. Here, the solution is used as the gate electrode. A voltage between substrate and oxide surfaces arises due to an ions sheath.

An ISFET's source and drain are constructed as for a MOSFET. The gate electrode is separated from the channel by a barrier which is sensitive to hydrogen ions and a gap to allow the substance under test to come in contact with the sensitive barrier. An ISFET's threshold voltage depends on the pH of the substance in contact with its ion-sensitive barrier.

Table 2.1 Overview of important characteristics for some chemical sensors

Sensor type	Response time	Range	Accuracy	Temperature range
Oxygen	4 s	0–150 mm-Hg		
CO	20 s	0–5,000 ppvmol	±5%	
NO_x	<40 s	0–100 ppm		−20°C to 50°C
H_2S	<60 s	0–200 ppm	±2%	

The surface hydrolization of OH groups of the gate materials varies in aqueous solutions due to pH value. Typical gate materials are Si_3N_4, Al_2O_3, and Ta_2O_5.

ISFET sensors are used in devices for continuous measurements like those for continuous measurement of pH value and gases in blood (O_2, CO_2).

2.7.5 Piezoelectric Chemical Sensors

Piezoelectric effect is the generation of an electric charge in a crystalline material upon subjecting it to stress. A piezoelectric chemical sensor is a piezoelectric oscillator that responds to changes in the chemical composition of its environment with changes of the resonant frequency, or wave speed [4].

The complex nature of these sensors makes them unsuitable for a brief overview of operating principals, as is suitable for this book. However, as these sensors are undergoing a rapid expansion, readers are encouraged to turn to references for more detailed explanations.

2.8 Biosensors

Detection of presence and concentrations of bacteria, viruses, or molecules and molecular complexes like proteins, enzymes, antibodies, DNA, etc. is essential to a wide range of applications. Traditionally, this has been done through time-consuming chemical analysis methods that require laboratory conditions and employ expensive reagents and equipment. Technological advancements and introduction of micro-sensor technology to this field has led to development of biosensors.

Much like a chemical sensor, biosensor consists of three parts: a sensitive layer, transducer, and electronic circuitry to process the signal from the transducer.

Sensitive layer in a biosensor is a biosensitive biological component, like enzymes, antibodies, cell membrane receptors, tissue slices, etc.

One example of biosensors is imunno-sensors. These sensors use specific antibodies as the sensitive layer. These immobilized antibody molecules bond with antigen molecules in the substance. Concentration of antigens can then be measured using, for example, interferometric method.

Biosensors are under constant and rapid development. Currently, design and production of a biosensor face serious difficulties, most related to immobilization of proteins and long-term stability of proteins.

2.8.1 Radiation Sensors

Ionizing radiation consists of subatomic particles or waves that are energetic enough to detach electrons from atoms or molecules, ionizing them. Exposure to radiation causes microscopic damage to living tissue, resulting in skin burns and radiation sickness at high doses and cancer, tumors, and genetic damage at low doses. Therefore, monitoring radiation levels is imperative in many industrial applications where human interaction with radioactive materials exists, as well as in guarding against intentional or accidental exposure of wider population to radiation. Wireless sensor networks provide ideal infrastructure for these kinds of systems.

2.8.2 Geiger–Müller Counter

Geiger counters are used to detect radiation usually gamma and beta radiation, but certain models can also detect alpha radiation. The sensor is a Geiger–Müller tube, an inert gas-filled tube (usually helium, neon, or argon with halogens added) that briefly conducts electricity when a particle or photon of radiation temporarily makes the gas conductive. The tube amplifies this conduction by a cascade effect and outputs a current pulse.

2.8.3 Quartz Fiber Dosimeter

A quartz fiber dosimeter is a pen-like device that measures the cumulative dose of ionizing radiation received by the device. The device is mainly sensitive to gamma and X-rays, but it also detects beta radiation above 1 MeV. Neutron-sensitive versions have been made.

The quartz fiber dosimeter is a rugged form of a device called a Lauritsen electroscope. It consists of a sealed air-filled cylinder called an ionization chamber. Inside it is a metal electrode strip that is attached to a terminal on the end of the pen for recharging. The other end of the electrode has a delicate gold-plated quartz fiber attached to it, which at rest lies parallel to the electrode.

During recharging, the charger applies a high DC voltage, to the electrode, charging it with electrostatic charge. The quartz fiber, having the same charge, is repelled by the surface of the electrode due to the coulomb force and bends away from the electrode. After charging, the charge remains on the electrode because it is insulated.

When a particle of ionizing radiation passes through the chamber, it collides with molecules of air, knocking electrons off them and creating positively and negatively charged atoms (ions) in the air. The ions of opposite charge are attracted to the electrode and neutralize some of the charge on it.

Since each radiation particle allows a certain amount of charge to leak off the electrode, the position of the fiber at any time represents the cumulative radiation that has passed through the chamber since the last recharge. Recharging restores the charge that was lost and returns the fiber to its original deflected position.

2.8.4 Film Badge Dosimeter

The film badge dosimeter, or film badge, is a dosimeter used for monitoring cumulative exposure to ionizing radiation. The badge consists of two parts: photographic film, and a holder.

The film is sensitive to radiation and, once developed, exposed areas increase in optical density (i.e., blacken) in response to incident radiation. One badge may contain several films of different sensitivities or, more usually, a single film with multiple emulsion coatings. This allows for separate measurement of neutron, beta, and gamma exposure, and estimation of energy spectra. The holder may contain a number of filters that attenuate certain types of radiation, such that only the target radiation is monitored. To monitor gamma rays or X-rays, the filters are metal, usually tin or lead. To monitor beta particle emission, the filters use various densities of plastic.

2.8.5 Thermoluminescent Dosimeter

A thermoluminescent dosimeter, or TLD, is a type of radiation dosimeter. A TLD measures ionizing radiation exposure by measuring the amount of visible light emitted from a crystal in the detector when the crystal is heated. The amount of light emitted is dependent upon the radiation exposure.

A TLD is a phosphor, such as lithium fluoride (LiF) or calcium fluoride (CaF), in a solid crystal structure. When a TLD is exposed to ionizing radiation at ambient temperatures, the radiation interacts with the phosphor crystal and deposits all or part of the incident energy in that material. Some of the atoms in the material that absorb that energy become ionized, producing free electrons and areas lacking one or more electrons, called holes. Imperfections in the crystal lattice structure act as sites where free electrons can become trapped and locked into place.

Heating the crystal causes the crystal lattice to vibrate, releasing the trapped electrons in the process. Released electrons return to the original ground state, releasing the captured energy from ionization as light, hence the name thermoluminescent. Released light is counted using photomultiplier tubes and the number of photons counted is proportional to the quantity of radiation striking the phosphor.

Instead of reading the optical density (blackness) of a film, as is done with film badges, the amount of light released versus the heating of the individual pieces of thermoluminescent material is measured.

2.9 Medical Sensing Devices

This book puts a special emphasis on medical applications of wireless sensor networks. Therefore, a section of this chapter is devoted to devices used for monitoring human vital parameters.

2.9.1 Pulse Oximetry

A pulse oximeter is a medical device that indirectly measures the oxygen level in a patient's blood and changes in blood volume in the skin, producing a photoplethysmograph. As noninvasive measurement instruments they are particularly convenient for wide use.

Typically a pulseoximeter has a pair of small light-emitting diodes (LEDs) facing a photodiode through a translucent part of the patient's body, usually a fingertip or an earlobe. One of the LEDs is red, with wavelength of 660 nm, and the other is infrared, 905, 910, or 940 nm. Absorption at these wavelengths differs significantly between oxyhemoglobin and its deoxygenated form; therefore, from the ratio of the absorption of the red and infrared light, the oxy/deoxyhemoglobin ratio can be calculated. The absorbance of oxyhemoglobin and deoxyhemoglobin is the same (isosbestic point) for the wavelengths of 590 and 805 nm.

The monitored signal bounces in time with the heart beat because the arterial blood vessels expand and contract with each heartbeat. By examining only the varying part of the absorption spectrum, a monitor can ignore other tissues or nail polish and discern only the absorption caused by arterial blood. Thus, detecting a pulse is essential to the operation of a pulse oximeter and it will not function if there is none (Fig. 2.3).

A pulse oximeter is useful in any setting where a patient's oxygenation is unstable, including intensive care, operating, recovery, emergency and hospital ward settings, pilots in unpressurized aircraft, for assessment of any patient's oxygenation, and determining the effectiveness of or need for supplemental oxygen. Assessing a patient's need for oxygen is the most essential element to life; no human life thrives in the absence of oxygen (cellular or gross). Although a pulse oximeter is used to monitor oxygenation, it cannot determine the metabolism of oxygen, or the amount of oxygen being used by a patient. For this purpose, it is necessary to also measure carbon dioxide (CO_2) levels.

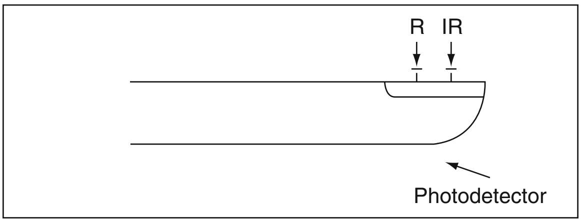

Fig. 2.3 Operating principle of a pulseoximeter. Explanation: Red and infrared light emmitors are positioned above the fingernail. A photodetector is positioned below the finger. Absorption of red and infrared light differs significantly between oxyhemoglobin and its deoxygenated form; therefore, from the ratio of the absorption of the red and infrared light, the oxy/deoxyhemoglobin ratio can be calculated

Because of their simplicity and speed, pulse oximeters are of critical importance in emergency medicine and are also very useful for patients with respiratory or cardiac problems, especially COPD, or for diagnosis of some sleep disorders such as apnea and hypopnea. Portable, battery-operated pulse oximeters are useful for pilots operating in a non-pressurized aircraft above 10,000 ft (12,500 ft in the US), where supplemental oxygen is required.

A pulse oximeter does, however, have a number of drawbacks, limiting their use, or calling for caution when oximetry results are used and interpreted.

First, it should be noted that oximetry is not a complete measure of respiratory sufficiency. A patient suffering from hypoventilation (poor gas exchange in the lungs) given 100% oxygen can have excellent blood oxygen levels while still suffering from respiratory acidosis due to excessive carbon dioxide.

It is also not a complete measure of circulatory sufficiency. If there is insufficient blood flow or insufficient hemoglobin in the blood (anemia), tissues can suffer hypoxia despite high oxygen saturation in the blood that does arrive.

Furthermore, a high level of methemoglobin will tend to cause a pulse oximeter to read closer to 85% regardless of the true level of oxygen saturation. It also should be noted that the inability of two-wavelength saturation level measurement devices to distinguish carboxyhemoglobin due to carbon monoxide inhalation from oxyhemoglobin must be taken into account. To counter this problem, CO-oximeters have recently been developed. These devices use additional wavelengths to distinguish CO from O_2.

2.9.2 Continuous Glucose Monitors

A continuous blood glucose monitor (CGM) determines blood glucose levels on a continuous basis (every few minutes). These devices include a disposable glucose sensor placed just under the skin and worn for a few days until replacement, a link from the sensor to a non-implanted transmitter which communicates to a radio receiver and an electronic receiver worn like a pager (or insulin pump) that displays blood glucose levels on a practically continuous manner.

The sensor can be implanted in the subcutaneous tissue using a specialized tool designed to minimize tissue damage. The tip of the sensor is made of a membrane selectively permeable to glucose. Once the glucose passes through the membrane, it is oxidized by the enzyme glucose oxidase. Reduced glucose oxidase can then be oxidized by reacting with molecular oxygen, forming hydrogen peroxide as a by-product. At the electrode surface, hydrogen peroxide is oxidized into water, generating a current which can be measured and correlated to the glucose concentration outside the membrane (see above right).

This type of device requires at least four finger sticks per day for calibration. Continuous glucose monitors measure glucose levels in the interstitial fluid, not directly the blood. This causes a temporal lag behind actual blood glucose values of about 5 min.

2.10 Electrocardiograph

An electrocardiograph is a device for recording of the electrical activity of the heart over time, usually in a noninvasive recording via skin electrodes.

An electrocardiogram is obtained by measuring electrical potential between various points of the body using a biomedical instrumentation amplifier. A lead records the electrical signals of the heart from a particular combination of recording electrodes which are placed at specific points on the patient's body.

There are two types of leads – unipolar and bipolar. The former has an indifferent electrode at the center of the Einthoven's triangle (which can be likened to the "neutral" of a wall socket) at zero potential. The direction of these leads is from the "center" of the heart radially outward. These include the precordial (chest) leads and augmented limb leads – VR, VL, and VF. The bipolar type, in contrast, has both electrodes at some potential, with the direction of the corresponding lead being from the electrode at lower potential to the one at higher potential, e.g., in limb lead I, the direction is from left to right. These include the limb leads – I, II, and III.

2.10.1 Leads

A lead refers to a combination of electrodes that forms an imaginary line in the body along which the electrical signals are measured. The standard 12-lead ECG consists of 10 electrodes.

2.10.2 Limb Leads

Leads I, II, and III are the so-called limb leads because at one time, the subjects of electrocardiography had to literally place their arms and legs in buckets of salt water in order to obtain signals for Einthoven's string galvanometer. They form the basis of what is known as Einthoven's triangle.

Lead I is a dipole with the negative electrode on the right arm and the positive electrode on the left arm. Lead II is a dipole with the negative electrode on the right arm and the positive electrode on the left leg. Lead III is a dipole with the negative electrode on the left arm and the positive electrode on the left leg.

2.10.3 Augmented Limb

Augmented limb leads (aVR, aVL, and aVF) are derived from the same three electrodes as leads I, II, and III. However, they view the heart from different angles (or vectors) because the negative electrode for these leads is a modification of Wilson's central terminal, which is derived by adding leads I, II, and III together and plugging them into the negative terminal of the EKG machine. This zeroes out the negative electrode and allows the positive electrode to become the "exploring electrode" or a unipolar lead.

2.10.4 Precordial Leads

The precordial leads (V1, V2, V3, V4, V5, and V6) are placed directly on the chest. Because of their close proximity to the heart, they do not require augmentation. Wilson's central terminal is used for the negative electrode, and these leads are considered to be unipolar. The precordial leads view the heart's electrical activity in the so-called horizontal plane. The heart's electrical axis in the horizontal plane is referred to as the Z axis.

Leads V1, V2, and V3 are referred to as the right precordial leads and V4, V5, and V6 are referred to as the left precordial leads.

Lead V1 is placed in the fourth intercostal space to the right of the sternum. Lead V2 is placed in the fourth intercostal space to the left of the sternum. Lead V3 is placed directly between leads V2 and V4. Lead V4 is placed in the fifth intercostal space in the midclavicular line (even if the apex beat is displaced). Lead V5 is placed horizontally with V4 in the anterior axillary line. Lead V6 is placed horizontally with V4 and V5 in the midaxillary line.

2.10.5 Ground

An additional electrode (usually green) is present in modern four-lead and twelve-lead ECGs. This is the ground lead and is placed on the right leg by convention, although in theory it can be placed anywhere on the body. With a three-lead ECG, when one dipole is viewed, the remaining lead becomes the ground lead by default.

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http://www.springer.com/978-1-84996-509-5

Application and Multidisciplinary Aspects of Wireless Sensor Networks
Concepts, Integration, and Case Studies
Gavrilovska, L.; Krco, S.; Milutinovic, V.; Stojmenovic, I.; Trobec, R. (Eds.)
2011, X, 282 p., Hardcover
ISBN: 978-1-84996-509-5