Sensor technology

Sensor

A *sensor* is a device that converts a physical phenomenon into an electrical signal. As such, sensors represent part of the interface between the physical world and the world of electrical devices, such as computers. The other part of this interface is represented by *actuators*, which convert electrical signals into physical phenomena.

Sensor Performance Characteristics Definitions

Transfer Function

The transfer function shows the functional relationship between physical input signal and electrical output signal. Usually, this relationship is represented as a graph or calibration curve showing the relationship between the input and output signal, and the details of this relationship may constitute a complete description of the sensor characteristics.

Sensitivity

The sensitivity is defined in terms of the relationship between input physical signal and output electrical signal. It is generally the ratio between a small change in electrical signal to a small change in physical signal. Typical units are volts/kelvin, millivolts/kilopascal, etc. A thermometer would have “high sensitivity” if a small temperature change resulted in a large voltage change.

Span or Dynamic Range

The range of input physical signals that may be converted to electrical signals by the sensor is the dynamic range or span. Signals outside of this range are expected to cause unacceptably large inaccuracy. This span or dynamic range is usually specified by the sensor supplier. Typical units are kelvin, pascal, newtons, etc.

Accuracy or Uncertainty

Uncertainty is generally defined as the largest expected error between actual and ideal output signals. Typical units are kelvin. “Accuracy” is generally considered by metrologists to be a qualitative term, while “uncertainty” is quantitative. For example one sensor might have better accuracy than another if its uncertainty is 1% compared to the other with an uncertainty of 3%.

Noise

All sensors produce some output noise in addition to the output signal. In some cases, the noise of the sensor is less than the fluctuations in the physical signal, in which case it is not important. Many other cases exist in which the noise of the sensor limits the performance of the system based on the sensor.

Resolution

The resolution of a sensor is defined as the minimum detectable signal fluctuation.

Classification of sensors

A logical way to classify sensors is with respect to the physical property the sensor is designed to measure. Thus, we have temperature sensors, force sensors, pressure sensors, motion sensors, etc.

However, sensors which measure different properties may have the same type of electrical output.
We must consider the environment of the sensor. Environmental effects are perhaps the biggest contributor to measurement errors in most measurement systems. The environment includes not only such parameters as temperature, pressure and vibration, but also, the electromagnetic and electrostatic effects, and the rates of change of the various environments. For example, a sensor may be little affected by extreme temperatures, but may produce huge errors in a rapidly changing temperature.

Temperature sensors

Because temperature can have such a significant effect on materials and processes at the molecular level, it is the most widely sensed of all variables. Temperature is defined as a specific degree of hotness or coldness as referenced to a specific scale. It can also be defined as the amount of heat energy in an object or system.

Temperature sensors detect a change in a physical parameter such as resistance or output voltage that corresponds to a temperature change. There are two basic types of temperature sensing:
■ **Contact** temperature sensing requires the sensor to be in direct physical contact with the media or object being sensed. It can be used to monitor the temperature of solids, liquids or gases over an extremely wide temperature range.
■ **Non-contact** measurement interprets the radiant energy of a heat source in the form of energy emitted in the infrared portion of the electromagnetic spectrum. This method can be used to monitor non-reflective solids and liquids but is not effective with gases due to their natural transparency.

Sensor Types and Technologies

Temperature sensors comprise three families: electro-mechanical, electronic, and resistive.

Electro-mechanical

Bi-metal thermostats are exactly what the name implies: two different metals bonded together under heat and pressure to form a single strip of material. By employing the different expansion rates of the two materials, thermal energy can be converted into electro-mechanical motion.
Bi-metal thermostats are also available in adjustable versions. By turning a screw, a change in internal geometry takes place that changes the temperature setpoint.

Bulb and capillary thermostats make use of the capillary action of expanding or contracting fluid to make or break a set of electrical contacts. The fluid is encapsulated in a reservoir tube. This allows for slightly higher operating temperatures than most electro-mechanical devices.

Electro-mechanical sensors are typically the simplest components to interface with their applications. Since they are capable of either opening or closing with increasing temperature, they are capable of interrupting a power circuit to control or shut down a circuit or of closing a circuit to sound an alarm, turn on a fan, etc.

In most circumstances, thermostats are connected to one leg of the power source. When the application temperature is reached, the device will function to either make or break the circuit.

Electronic sensors

Silicon sensors make use of the bulk electrical resistance properties of semiconductor mate-rials, 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 (PTC). IC-type devices can provide a direct, digital temperature reading, so there's no need for an A/D converter.

Infrared (IR) pyrometry. All objects emit infrared energy provided their temperature is above absolute zero (0 Kelvin). There is a direct correlation between the infrared energy an object emits and its temperature.
IR sensors measure the infrared energy emitted from an object in the 4–20 micron wavelength and convert the reading to a voltage. Typical IR technology uses a lens to concentrate radiated energy onto a thermopile. The resulting voltage output is amplified and conditioned to provide a temperature reading.

Thermocouples produces a voltage when the temperature of one of the spots differs from the reference temperature at other parts of the circuit. Thermocouples can also convert a temperature gradient into electricity. They are formed when two electrical conductors of dissimilar metals or alloys are joined at one end of a circuit. Thermocouples do not have sensing elements, so they are less limited than resistive temperature devices (RTDs) in terms of materials used and can handle much higher temperatures. Typically, they are built around bare conductors and insulated by ceramic powder or formed ceramic.

All thermocouples have what are referred to as a "hot" (or measurement) junction and a "cold" (or reference) junction. One end of the conductor (the measurement junction) is exposed to the process temperature, while the other end is maintained at a known reference temperature. The cold junction can be a reference junction that is maintained at 0°C (32°F).

Resistive temperature Devices

Thermistors (or thermally sensitive resistors) are devices that change their electrical resistance in relation to their temperature. They typically consist of a combination of two or three metal oxides that are sintered in a ceramic base material.

Thermistors are available in two different types: **positive temperature coefficient** (PTC) and **negative temperature coefficient** (NTC). PTC devices exhibit a positive change or increase in resistance as temperature rises, while NTC devices exhibit a negative change or decrease in resistance when temperature increases. The change in resistance of NTC devices is typically quite large, providing a high degree of sensitivity.

They also have the advantage of being available in extremely small configurations for extremely rapid thermal response.

In addition to metal oxide technology, PTC devices can also be produced using conductive polymers. These devices make use of a phase change in the material to provide a rapid increase in electrical resistance. This allows for their use in protection against excessive electrical current as well as excessive temperature.

Selecting Temperature Sensors

Each sensor type has its advantages and disadvantages. For example:

- Bimetallic thermostats have direct interface with application for fast response, high current carrying capacity, small operating temperature range (–85 to 371°C), application/market-based pricing but are less accurate than most electronic-based systems, larger size than electronic-based systems, Creepage-type device cannot interface with electronic components

- Thermocouples have the broadest temperature range (–200°C to 2315°C) and are durable for high vibration and high-shock applications, but require special extension wire.

- Thermistors provide high resolution, have the widest range of applications, are the most sensitive, fast thermal response and are low cost, but are nonlinear and have limited temperature range (–100 to 500°C). Self heating can effect accuracy.

- Resistive Temperature Devices are nearly linear and are highly accurate and stable, but they are large and expensive.

- Silicon types are low cost and nearly linear, but have a limited temperature range.

For cryogenic temperatures, RTDs and some silicon-based devices are capable of approaching absolute zero (0K). Maximum temperatures range from 150°C to 200°C.

For non-contact (infrared) devices, temperatures below –18°C or above 538°C would require a custom unit.

For certain medical applications or processes involving chemical reactions, tolerances of ±0.1°C or less may be required. For any application requiring tolerances of less than ±1.7°C, an electronic system will be required. Silicon, RTD, thermocouple or thermistor-based systems can all be designed to maintain these extremely tight tolerances. Typically RTDs will provide the greatest overall accuracy.

Light or Photo-sensors

Photovoltaic or Solar cells

Solar cells produce direct current electricity from sun light which can be used to power equipment or to recharge a battery. The first practical application of photovoltaics was to power orbiting satellites and other spacecraft, but today the majority of photovoltaic modules are used for grid connected power generation. In this case an inverter is required to convert the DC to AC. Photovoltaic power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulfide.

Photoelectric effect

In the **photoelectric effect**, electrons are emitted from solids, liquids or gases when they absorb energy from light. Electrons emitted in this manner are called *photoelectrons*. The photoelectric effect requires photons with energies from a few electronvolts to over 1 MeV in high atomic number elements.

In 1905 Albert Einstein published a paper that explained experimental data from the photoelectric effect as being the result of light energy being carried in discrete quantized packets. This discovery led to the quantum revolution. Einstein was awarded the Nobel Prize in 1921 for his discovery of the law of the photoelectric effect.

Infrared automatic door sensors

The principle behind infrared automatic door sensors is the transmission and receiving of infrared light. An element known as a light emitting diode (LED) transmits active infrared light, which is reflected on the floor and received by an optical receiver known as a photo diode (PD). As long as there is no movement or object in the path of the light beam, the light pattern is static and the sensor remains in stand-by.

When a person or object crosses the beam, the reflection of the light is distorted. This is registered by the PD, which gives off an impulse for opening the door. Sensors differ in the number of rows of active infrared spots. These spots are collectively referred to as the detection area. Because objects cause a distortion in the reflected light pattern, active infrared sensors also react to shopping carts and other moving objects.

Active infrared sensors are excellent as a safeguard at the door opening because of their ability to continue recognizing changes that occur in the detection area. As long as there is a person or object in the detection area, the sensor remains active, preventing the door from closing.

Active infrared door sensors are generally immune to the effects of external factors such as rain, snow and falling leaves. Although the sensor registers this type of movement, intelligent software is employed to screen such factors out.

Magnetic sensors

Magnetic sensors detect changes and disturbances in a magnetic field like flux, strength and direction.There are several types of technologies used to make a magnetic sensor work. Fluxgate, Hall Effect, Magnetoresisitive, Magnetoinductive, nuclear precession, and SQUID (superconducting quantum interference devices) each have a different approach to using magnetic sensors. Magnetoresistive devices record electrical resistance of the magnetic field. Magnetoinductive are coils surrounding magnetic material whose ability to be permeated changes within the Earth's magnetic field. Fluxgate measures magnetic fields against a known internally created magnetic based response that runs through a continually fluxing set of parameters. Each type of technology focuses on a particular area for detection, a measurement to be detected and way of recording changes.

Magnetometers can be made in several ways, and here we will review a couple of specific devices that are of widest commercial use.

The flux gate magnetometer relies on measurement of the behavior of a ferromagnet filled inductor. In the absence of external magnetic fields, current passed through the coil causes the formation of a magnetic field, which acts to polarize the ferromagnetic material. In general, the memory of the ferromagnetic material causes a hysteresis ***(The lagging of an effect behind its cause, as when the change in magnetism of a body lags behind changes in the magnetic field or in general the delay between the action and reaction of a measuring instrument. Hysteresis is the amount of error that results when this action occurs.)*** in the relation between the applied field and the polarization of the ferromagnet. We can see this by thinking about the starting situation, where the ferromagnet is unpolarized and there is no current. If a current is applied, it polarizes the ferromagnet. As the current is increased, the polarization increases until saturation. Now, the current may be reduced to zero, and the resulting situation will include some residual polarization of the ferromagnet. If a current in the opposite direction is applied, the polarization is reversed, eventually saturated, and retains some residual reverse polarization when the current is again turned off. The applied magnetic field is proportional to the current through the electromagnetic field and we see that the magnetization of the core responds to the applied field with hysteresis.

In the absence of an external magnetic field, the hysteresis loop is perfectly symmetric. If there is an external magnetic field, the hysteresis loop is shifted away from the origin. This is because there is a residual applied magnetic field when the current is off, due to the external magnetic field. One result of this is that the symmetry of the hysteresis loop is spoiled. Therefore, this device may be used to sense external magnetic fields. In fact, when properly constructed and wired, this sort of sensor can be very sensitive to small changes in external magnetic field. This class of magnetometers is generally for space science missions, and for all precision terrestrial applications.

Another class of magnetometer is called the **Hall effect sensor**. In the Hall effect sensor, the transport of electrons through an electrical device is affected by the presence of an external magnetic field resulting a measureable voltage across the conductor called Hall voltage. This sort of sensing approach offers ease of fabrication as a substantial advantage, but does not offer the performance of the flux-gate devices discussed above. In general, a Hall effect sensor can measure down to about 5% of the earth's magnetic field.

Hall effect

The **Hall effect** is the production of a voltage difference (the **Hall voltage**) across an electrical conductor, transverse to an electric current in the conductor and a magnetic field perpendicular to the current. It was discovered by Edwin Hall in 1879.

For a simple metal where there is only one type of charge carrier (electrons) the Hall voltage V_H is given by

$$V_H = -\frac{IB}{net}$$

where I is the current across the plate length, B is the magnetic field, t is the thickness of the plate, e is the elementary charge, and n is the charge carrier density of the carrier electrons.

The Hall coefficient is defined as the ratio of the induced electric field to the product of the current density and the applied magnetic field. It is a characteristic of the material from which the conductor is made, since its value depends on the type, number, and properties of the charge carriers that constitute the current.

$$R_H = \frac{E_y}{j_x B}$$

where j is the current density of the carrier electrons, and E_y is the induced electric field. In SI units, this becomes

$$R_H = \frac{E_y}{j_x B} = \frac{V_H t}{IB} = -\frac{1}{ne}.$$

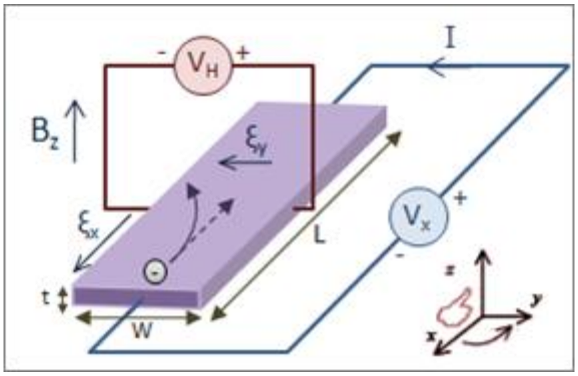

Fig. Schematic Hall Effect setup

Hall Effect measurement setup for electrons. Initially, the electrons follow the curved arrow, due to the magnetic force. At some distance from the current-introducing contacts, electrons pile up on the left side and deplete from the right side, which creates an electric field ξ_y. In steady-state, ξ_y will be strong enough to exactly cancel out the magnetic force, so that the electrons follow the straight arrow (dashed).

Magnetoresistive Sensors

Instead of measuring the build-up of a Hall voltage, it is also possible to measure the increased resistance of the device due to the deflected electrons. In this case, the Hall based sensor is called a Magnetoresistor. **Giant magnetoresistance (GMR)** is a quantum mechanical magnetoresistance effect observed in thin-film structures composed of alternating ferromagnetic and non-magnetic conductive layers. The 2007 Nobel Prize in Physics was awarded to Albert Fert and Peter Grünberg for the discovery of GMR.

The effect is observed as a significant change in the electrical resistance depending on whether the magnetization of adjacent ferromagnetic layers are in a parallel or an antiparallel alignment. The overall resistance is relatively low for parallel alignment and relatively high for antiparallel alignment. The magnetization direction can be controlled, for example, by applying an external magnetic field. The effect is based on the dependence of electron scattering on the spin orientation.

The main application of GMR is magnetic field sensors, which are used to read data in hard disk drives, biosensors, microelectromechanical systems (MEMS) and other devices. GMR multilayer structures are also used in magnetoresistive random-access memory (MRAM) as cells that store one bit of information.

Flow and Level Sensors

Flow sensors are used in many monitoring and control applications, to measure both air and liquid flows. There are many ways of defining flow (mass flow, volume flow, laminar flow, turbulent flow). Usually the amount of a substance flowing (mass flow) is the most important, and if the fluid's density is constant, a volume flow measurement is a useful substitute that is generally easier to perform. There are numerous reliable technologies and sensor types used for this purpose. Some technologies have been applied to both air and liquid flow measurements, as their principles of operation hold true in either application. Other technologies lend themselves to being airflow or liquid flow specific.

- What accuracy, range, linearity, repeatability, and piping requirements must be considered?
- Is the liquid to be measured clean, viscous, or a slurry?
- Is the liquid to be measured electrically conductive?
- What is the specific gravity or density of the liquid to be measured?
- What flow rates are involved in the application?
- What are the process's operating temperatures and pressures?

Differential Pressure Measurement

Differential pressure measurement sensor technologies can be used for both airflow and liquid flow measurements. A variety of application-specific sensors used for both air flow and pressure measurements are on the market, as well as differential pressure sensors used for liquid measurements. Differential pressure flow-meters are the most common type of unit in use, particularly for liquid flow measurement.

The operation of differential pressure flow-meters is based on the concept that the pressure drop across the meter is proportional to the square of the flow rate; the flow rate is found by measuring the pressure differential and taking the square root.

Differential pressure flow devices, like most flow-meters, have a primary and secondary element. The primary element causes a change in the kinetic energy, to create the differential pressure in the pipe. The unit must be correctly matched to the pipe size, flow conditions, and the properties of the liquid being measured. The secondary element measures the differential pressure and outputs the signal that is converted to the actual flow value.

Venturi tubes are the largest and most expensive differential pressure device. They work by gradually narrowing the diameter of the pipe, and measuring the pressure drop that results. An expanding section of the differential pressure device then returns the flow to close to its original pressure. As with the orifice plate, the differential pressure measurement is converted into a corresponding flow rate. Venturi tubes can typically be used only in those applications requiring a low pressure drop and a high accuracy reading. They are often used in large diameter pipes.

Electromagnetic Flow Sensors

Operation of these sensors is based upon Faraday's Law of electromagnetic induction, which says that a voltage will be induced when a conductor moves through a magnetic field.The liquid is the conductor, and the magnetic field is created by energized coils outside the flow tube. The voltage produced is proportional to the flow rate. Electrodes mounted in the pipe wall sense the induced voltage, which is measured by the secondary element.

Electromagnetic flow meters are applied in measuring the flow rate of conducting liquids (including water) where a high quality, low maintenance system is needed. The cost of magnetic flow meters is high relative to other types of flowmeters. They do have many advantages, including: they can measure difficult and corrosive liquids and slurries, and they can measure reverse flow.

Metal detectors

Metal detectors are useful for finding metal inclusions hidden within objects, or metal objects buried underground. They often consist of a handheld unit with a sensor probe which can be swept over the ground or other objects. If the sensor comes near a piece of metal this is indicated by a changing tone in earphones, or a needle moving on an indicator. Usually the device gives some indication of distance; the closer the metal is, the higher the tone in the earphone or the higher the needle goes. Another common type are stationary "walk through" metal detectors used for security screening at access points in prisons, courthouses, and airports to detect concealed metal weapons on a person's body.

The simplest form of a metal detector consists of an oscillator producing an alternating current that passes through a coil producing an alternating magnetic field. If a piece of electrically conductive metal is close to the coil, eddy currents will be induced in the metal, and this produces a magnetic field of its own. If another coil is used to measure the magnetic field (acting as a magnetometer), the change in the magnetic field due to the metallic object can be detected.