

A Survey on Sensor Classifications for Industrial Applications

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UUCS-95-009

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June 12, 1995

Abstract

The importance of sensors in industrial applications is a result of the introduction of many robotics, automation, and intelligent control techniques into factory floors. Research and improvements need to be continuously performed to meet the challenges in automation and manufacturing applications in industry. Manufacturing processes are becoming extensively dependent on robotic and automation systems, and are requiring more reliable and accurate sensors to be integrated with the manufacturing systems. Sensors are selected depending on the type of process, the expected precision, the operational environment, and many other factors. In this report we survey the different classifications of sensors, and the various sensor applications in industry.

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The importance of sensors in industrial applications is a result of the introduction of many robotics, automation, and intelligent control techniques into factory floors. Research and improvements need to be continuously performed to meet the challenges in automation and manufacturing applications in industry. Manufacturing processes are becoming extensively dependent on robotic and automation systems, and are requiring more reliable and accurate sensors to be integrated with the manufacturing systems. Sensors are selected depending on the type of process, the expected precision, the operational environment, and many other factors. In this report we survey the different classifications of sensors, and the various sensor applications in industry.

A sensor is a device that receives a signal or stimulus and responds with an electric signal. The purpose of a sensor is to respond to some kind of an input physical property and to convert it into an electrical value. A sensor does not function by itself. It is always a part of a larger system which may incorporate many other detectors, signal conditioner, signal processors, memory devices, data recorders, and actuators. The sensor's place in a device is either intrinsic or extrinsic. It may be positioned at the input of a device to perceive the outside effects and to signal the system about variations in the outside stimuli. Also, it may be an internal part of a device which monitors the device's own state to cause the appropriate performance. A sensor is always a part of some kind of a data acquisition system.

Sensors, Signals, and Systems

All sensors may be of two kinds: passive and active. The passive sensors directly generate an electric signal in response to an external stimulus. The examples are a thermocouple, a pyroelectric detector, and a piezoelectric sensor. The active sensors require external power for their operation, which is called an excitation signal. Figure 1 shows a block diagram of a data acquisition and control device to illustrate a place of sensors in a larger system. Any material object may become a subject of some kind of a measurement. Data are collected from an object by a number of sensors. Some of them (2,3, and 4) are positioned directly on or

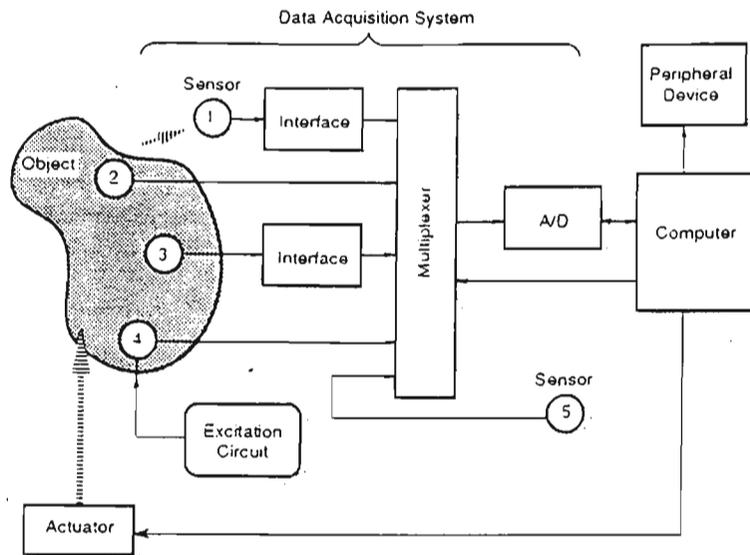


FIG. 1 - Positions of Sensors in a Data Acquisition System

inside the object. Sensor 1 perceives the object without a physical contact and therefore, is called a non-contact sensor. Examples of such a sensor is a radiation detector and a TV camera. Sensor 5 serves a different purpose. It monitors internal conditions of a data acquisition system it self. Some sensors (1 and 3) can not be directly connected to standard electronic circuits because of inappropriate output signal formats. They require the use of interface device (signal conditioners). Sensors 1, 2, 3, and 5 are passive. They generate electric signals without energy consumption from the electronic circuits. Sensor 4 is active. It requires an operating signal which is provided by an excitation circuit. An example of an active sensor is the thermistor which is a temperature sensitive resistor. It may operate with a

constant current source which is an excitation circuit. Depending on the complexity of the system, the total number of sensors may vary from as little as one (a home thermostat) to many thousands (a space shuttle). Electric signals from the sensors are fed into a multiplexer (MUX), which is a switch or a gate. Its function is to connect sensors one at a time to an analog-to-digital (A/D) converter or directly to a computer (if a sensor produces signal in a digital format). The computer controls a multiplexer and an A/D converter for the appropriate timing. Also, it may send control signals to the actuator which acts on the object. Examples of actuators are an electric motor, a solenoid, a relay, and a pneumatic valve. The system contains some peripheral devices (for instance, a data recorder, a display, an alarm, etc.) and a

number of components which are not shown in the block diagram. These may be filters, sample-and-hold circuits, amplifiers, etc.

Classification of Sensors

When an engineer realizes that a certain variable has to be monitored, he/she faces a dilemma: what would be the best sensor for the job? Any sensor operation is based on a simple concept - a physical property of a sensor must be alerted by an external stimulus to cause that property either to produce an electric signal or to modulate (to modify) an external electric signal. Quite often, the same stimulus may be measured by using quite different physical phenomena, and, subsequently, by different sensors. It is, therefore, a matter of an engineering choice to select the best sensor for the particular application. Selection criteria depend on many factors, such as availability, cost, power consumption, environmental conditions, etc. The best choice can be done only after all variables are considered. It is, therefore, not a correct question to ask, "What sensor should I use to measure X?". The proper question must include a wide spectrum of conditions to narrow the choice to one or two options.

Sensor classification schemes range from very simple to very complex. One good way to look at a sensor is to consider all of its properties, such as what it measures (stimulus), what its specifications are, what physical phenomenon it is sensitive to, what conversion mechanism is employed, what material it is fabricated from and what is its field of application.

Sensors could be classified according to their principles of sensing. Some of these principles could depend on motion, forces, strain, temperature, and others.

The study of all different types of sensors in details is not the objective of this paper.

Instead, sensors will be grouped in different types as follows:

- 1- Position, Level, and displacement
- 2- Occupancy and motion detectors
- 3- Velocity and Acceleration
- 4- Force and Strain
- 5- Pressure
- 6- Flow
- 7- Acoustic
- 8- Humidity and moisture
- 9- Light Detectors
- 10- Radiation Detectors
- 11- Electromagnetic field detectors
- 12- Temperature
- 13- Chemical

More elaborate description of some types of sensors will follow, with an example of a specific application for a position, level, and displacement sensors.

1- Position, Level, and displacement

The measurement of position and displacement of physical objects is essential for many applications: process feedback control, performance evaluation, transportation traffic, control, robotics, security systems-just to name the few. By position, we mean the determination of the object's coordinates (linear or angular) with respect to a selected reference. Displacement means moving from one position to another for a specific distance or angle. A critical distance is measured by proximity sensors. In effect, a proximity sensor is a threshold version of a position detector. In other words, a position sensor is a linear device whose output signal represents the distance to the object from a reference point. A proximity sensor may be a somewhat simpler device which generates the output signal when the distance to the object becomes essential for an indication. For instance, many moving mechanisms in process control and automation use a very simple but highly

reliable proximity sensor - the end switch. It is an electrical switch having normally open or normally closed contacts. When a moving object activates the switch by a physical contact, the latter sends a signal to a control circuit. The signal is an indication that the object has reached the end position. Obviously, such contact switches have many drawbacks, for example, high mechanical load on the moving object and hysteresis.

A displacement sensor may be a part of a more complex sensor where the detection of movement is one of the steps in a signal conversion. An example is a capacitive pressure sensor where pressure is translated to displacement of a diaphragm, and the diaphragm displacement is subsequently converted into an electrical signal representing pressure. Therefore, the position sensors are essential for design of many other sensors. An example of the position sensors is the thermal sensors.

Thermal Sensors,

It is possible to apply temperature measurement techniques to measure the liquid level in a tank by employing thermal conductivities and thermal capacitances of different phases: gases and liquids. One way to fabricate a fluid level sensor is to use a temperature difference between liquid and a gas. A liquid might have a temperature quite different from the environment. For instance, a water boiler may contain water at a temperature near 100C. A temperature sensor placed outside on the tank wall will register temperature which is a function of several factors: thermal conductivity of the tank walls, pressure inside the tank, water and ambient temperatures. There is a substantial gradient in the temperature of the wall across the water line. ($T_2 - T_1$). The temperature is lower above the water line, even if the vapor has the same temperature, because of the thermal

conductivity of the tank walls. This thermal gradient can be detected by an array of temperature detectors placed along the water tank wall (fig. 2). The detectors can be RTDs or thermistors whose outputs are multiplexed by a gate circuit (MUX), converted into a digital format (A/D) and analyzed by a microprocessor to detect the water level. Naturally, a level resolution of the arrangement is equal to the distance between two adjacent temperature detectors. For better accuracy, the sensors should be thermally insulated from the outside environment.

Another approach is based on the active thermal detection where thermal sensor measures heat dissipation through a tank wall (fig. 3). A long sensing strip is positioned over the outside surface of the tank, from bottom to top. The strip contains two resistive components. One possess properties of a thermistor, that is, its resistance is a function of temperature. It serves as a temperature sensor. The other component in a strip is a heating element. The strip is connected into a resistive bridge and an amplifier, which controls electric current through the heating element. This results in temperature increase of the strip, including the embedded temperature sensor. Quickly, after applying power, the bridge comes into an equilibrium state which corresponds to a specific constant temperature set by the bridge's fixed resistors. A voltage across the heater depends mainly on three factors: the set temperature, the tank temperature and the liquid level in the tank. Since liquid is a better thermal conductor than a gaseous phase, the higher the liquid level, the higher the thermal loss from the strip through the tank wall and the tank contents. A combined heat flow Q_2 through the wall, and Q_3 through the liquid, is much higher than Q_1 through the wall above the liquid level.

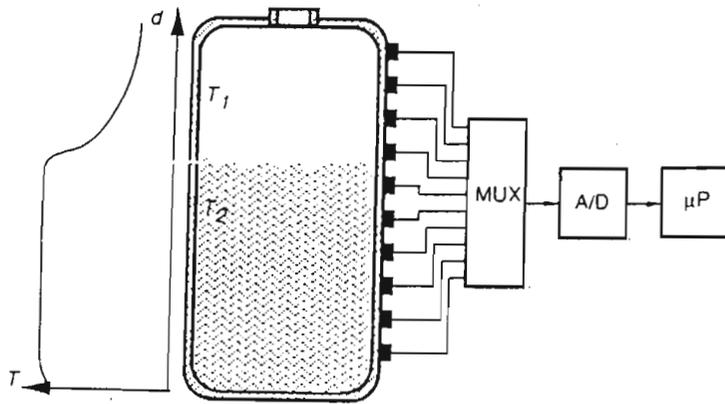


FIG. 2 - An Array Thermal Detector of Liquid Level

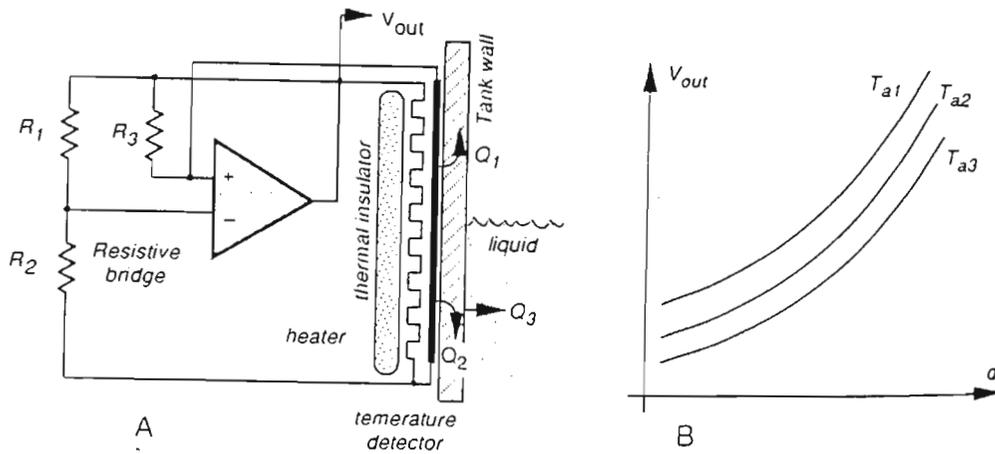


FIG. 3 - Active Thermoresistive Liquid Level Sensor

A: Simplified Circuit Diagram

B: Voltage Across Heating Elements For Three Different Tank Temperatures

Therefore, to maintain the fixed temperature of the strip, the amplifier must deliver a higher voltage for a higher fluid level. Fig. 4 shows a family of curves establishing a relationship between the liquid level and the voltage across the heating element. The higher temperature of the tank the lower the curve. Hence, for practical purposes, the circuit must incorporate an additional temperature compensating sensor. Naturally, the strip should not necessarily incorporate a thermistor-like sensor. Semiconductors, RED, and other temperature sensitive devices may be successfully employed. However, a distributed thermistor is more attractive for many applications due to its simplicity and lower cost.

2- Occupancy and motion detectors

The occupancy sensors detect the presence of people in a monitored area. Motion detectors respond only to moving objects. A distinction between the two is that the occupancy sensors produce signals whenever an object is stationary or not, while the motion detectors are selectively sensitive to moving objects. The applications of these sensors include security, surveillance, energy management (electric light control), personal safety, friendly home appliances, interactive toys, novelty products, etc. Depending on the applications, the presence of humans may be detected through any means that is associated with some kind of a human body's property or body's actions. For instance, a detector may be sensitive to body weight, heat, sounds, dielectric constant, etc.

One of the major aggravations in detecting the occupancy or intrusions is a false positive detection. The term "false positive" means that the system indicates an intrusion when there is none. In some noncritical applications, where false positive detections occur once in

a while, for instance, in a toy or a motion switch controlling electric lights in a room, this may be not a serious problem: the lights will be erroneously turned on for a short time, which unlikely do any harm. In other systems, especially used for the security purposes, the false positive detections, while generally not as dangerous as false negative ones (missing an intrusion), may become a serious problem. While selecting a sensor for critical applications, considerations should be given to its reliability, selectivity, and noise immunity. It is often a good practice to form a multiple sensor arrangement with symmetrical interface circuits. It may dramatically improve a reliability of a system, especially in the presence of external transmitted noise. Another efficient way to reduce erroneous detections is to use sensors operating on different operating principles, for instance, combining capacitive and infrared detectors is an efficient combination as they are receptive to different kinds of transmitted noise.

3- Velocity and Acceleration

Acceleration is a dynamic characteristic of an object, because according to Newton's second law it essentially requires application of a force. In effect, displacement, velocity, and acceleration are all related-velocity is a first derivative of displacement and acceleration is the second derivative. However, in a noisy environment, taking derivatives may result in extremely high errors, even if complex and sophisticated signal conditioning circuits are employed. Therefore, velocity and acceleration are not derived from position or proximity detectors, but rather measured by a special sensors. As a rule of thumb, in low-frequency applications (less than 1 kHz), velocity measurement is usually favored. In measuring high-frequency motions with appreciable noise levels, acceleration

measurement is preferred. However a basic idea behind any sensor for transduction of velocity or acceleration is a measurement of a displacing object with respect to some reference object. That is, any such sensor must contain components which are sensitive to a displacement. Such components, while being adapted for conversion of velocity and acceleration, rather than just displacement, their design and fabrication methods are specifically geared to the dynamic measurements.

4- Force and Strain

The SI unit of force is derived from Newton's second law and is one of the fundamental quantities of physics. The measurement of force is required in mechanical and civil engineering, for weighing objects, designing prosthesis, etc. Whenever pressure is measured, it requires the measurement of force. It could be said that force is measured when dealing with solids, while pressure - when dealing with fluids. That is, force is considered when action is applied to a spot, and pressure is measured when force is distributed over a relatively large area.

Force sensors can be divided into two classes: quantitative sensor actually measures the force and represents its value in terms of an electrical signal. Examples of these sensors are strain gauges and load cells. The qualitative sensors are threshold devices which are not concerned with good fidelity of representation of the force value. Their function is merely to indicate whether there is a sufficiently strong forces applied or not. That is, the output signal indicates when force magnitude exceeds a predetermined threshold level. An example of these detectors is a computer keyboard where a key makes a contact only when it is pressed sufficiently hard.

The various methods of sensing force can be categorized as follows:

- * By balancing the unknown force against the gravitational force of a standard mass.
- * By measuring the acceleration of a known mass to which the force is applied.
- * By balancing the force against an electromagnetically developed force.
- * By converting the force to a fluid pressure and measuring the pressure.
- * By measuring the strain produced in an elastic member by the unknown force.

In most sensors, force is not directly converted into an electric signal. Some intermediate steps are usually required. For instance, a force sensor can be fabricated by combining a position sensor and a force-to-displacement converter. The latter may be a simple coil spring, whose compression displacement x can be defined through the spring coefficient k and compressing force F as

$$x = kF$$

The sensor shown in fig. 5a is comprised of a spring and LVDT displacement sensor within the linear range of the spring, the LVDT sensor produces voltage which is proportional to the applied force. A similar sensor can be constructed with other types of springs and pressure sensors, such as the one shown in fig. 5b. The pressure sensor is combined with a fluid filled bellows which is subjected to force. The fluid-filled bellows functions as a force-to-pressure converter by distributing a localized force at its input over the sensing membrane of the pressure sensor.

5- Pressure

The pressure concept was primarily based on the pioneering work of Evangelista Torricelli who for a short time was a student of Galileo. During his experiments with mercury filled dishes, in 1643, he realized that the atmosphere exerts a pressure on earth.

Another great experimenter Blaise Pascal, in 1647, conducted an experiment with the help of his brother-in-law, Perier, on the top of the mountain *Puy de Domme* and at its base. He observed that pressure exerted on the column of mercury depends on elevation. He named a mercury-in-vacuum instrument they used in the experiment the *barometer*. In 1660, Robert Boyle stated his famous relationship: "The product of the measures of pressure and volume is constant for a given mass of air at fixed temperature". In 1738 Daniel Bernoulli developed an impact theory of gas pressure to the point where Boyle's law could be deduced analytically. Bernoulli also anticipated the Charles-Gay-Lussac law by stating that the pressure is increased by heating gas at a constant volume. For a detailed description of gas and fluid dynamics a reader should be referred to one of the many books on the fundamentals of physics.

In general terms, matter can be classified into solids and fluids. The word fluid describes something which can flow. That includes liquids and gases. The distinction between liquids and gases are not quite definite. By varying pressure it is possible to change liquid into gas and vice versa. It is impossible to apply pressure to fluid in any direction except normal to its surface. At any angle, except 90, fluid will just slide over, or flow. Therefore, any force applied to fluid is tangential and the pressure exerted on boundaries is normal to the surface. For a fluid at rest, pressure can be defined as the force F exerted perpendicularly on a unit area A of a boundary surface:

$$p = dF / dA$$

Pressure is basically a mechanical concept that can be fully described in terms of the primary dimensions of mass, length, and time. It is familiar fact that pressure is strongly affected by position within the boundaries, however at a given position it is quite independent of

direction. We note the expected variations in pressure with elevation

$$dp = -wdh,$$

where w is the specific weight of the medium, and h represents the vertical height.

A pressure sensor operating principle is based on the conversion of a result of the pressure exertion on a sensitive element into an electrical signal. Virtually in all cases, pressure results in the displacement of an element, having a defined surface area. Thus, a pressure measurement may be reduced to a measurement of a displacement or a force, which results from a displacement. Thus, we recommend that the reader also familiarizes oneself with displacement sensors.

7- Acoustic

Acoustic sensors are generally called microphones. In essence, a microphone is a pressure transducer adapted for the transduction of sound waves over a broad spectral range. The microphones differ by their sensitivity, directional characteristics, frequency bandwidth, dynamic range, sizes, etc. Also, their designs are quite different depending on the media from which sound waves are sensed. For the perception of the air waves or vibrations in solids, the sensor is called a microphone, while for the operation in liquids, it is called hydrophone. The main difference between a pressure sensor and an acoustic sensor is that the latter does not need to measure constant or very slow changing pressures. Its operating frequency range usually starts at several hertz, while the upper operating frequency limit is quite high - up to several megahertz for the ultrasonic applications.

Since acoustic waves are mechanical waves, any microphone or hydrophone has the same basic structure as a pressure sensor: it is comprised of a moving diaphragm and a

displacement sensor which converts the diaphragm's deflection into an electrical signal. That is, they may include some additional parts such as mufflers, focusing reflectors, etc., however, in this chapter we will review only the sensing parts of some of the most interesting acoustic sensors.

11- Electromagnetic field detectors

Magnetic field measurements are extensively used in geomagnetic studies, navigation, manufacturing processes, medicine, etc. The instruments which measure magnetic fields are called magnetometers. Most of them employ electronics and usually contain no moving parts.

The magnetic field is one of the most important characteristics of earth. Its strength is in the average of 0.5 gauss. The field consists of two parts. The inner part is 90% of total. It is attributed to a differential rotation between the earth's core and its mantle. The outer part is 10% of the total and attributed to ionospheric ring currents. The field can be represented by a dipole which fluctuates both in time and space. The best-fit dipole location is about 440 km off center and is inclined about 11 degrees to the earth axis rotation.

In modern magnetic compasses, the magnetized needle is replaced by more sensitive magnetic field detectors. The main reason for that is in several disadvantages of needle compasses. First, the motion of the needle assembly of a mechanical compass is particularly difficult to damp, since any damping medium used must be contained in a receptacle attached to the framework of the moving vehicle. Hence, motion of the vehicle are transmitted to the needle assembly through the damping medium. Second, any electromagnetic or ferromagnetic anomalies, occurring in the vehicle, influence the compass in the same way as does the earth's magnetic

field. These local magnetic fields to some extent, can be canceled by the manipulation of small permanent magnets or electromagnets in the vicinity of the compass. Another problem, which is especially evident in aircraft, is the so-called "northerly turning error", which refers to the increase in error when the aircraft is headed north.

There are two classes of magnetometers or magnetic detectors. One is a nondirectional device which is called the "total field magnetometer" which produces an output that is a function of the magnitude of the magnetic field passing through it, no matter what its vector relation to the instrument might be. This class includes the proton-precession magnetometers and optically pumped magnetometers. The second class embraces vector magnetometers which register only the magnitude of that component of the magnetic field which lies parallel to their sensitive axes. This includes a saturable-core, the Hall-effect, and the magneto resistive magnetometers.

The measurement of magnetic fields per se is an important application for the magnetic sensors. However, a really broad area for their use in practical systems are position, force, and pressure measurements, proximity detection, sensing of angular velocity, and strong electric currents.

12- Temperature

From prehistoric times people were aware of heat and trying to assess its intensity by measuring temperature. Perhaps the simplest, and certainly the most widely used phenomenon for temperature sensing is thermal expansion. This forms the basis of the liquid-in-glass thermometers. For electrical transduction, different methods of sensing are employed. Among them are: resistive, thermoelectric, semiconductive, optical, and piezoelectric detectors. Taking a temperature

essentially requires the transmission of a small portion of the object's thermal energy to the sensor, whose function is to convert that energy into an electric signal. When a contact sensor is placed inside or on the object, heat conduction takes place through the interface between the object and the probe. The probe warms up or cools down, i.e., it exchanges heat with the object. Any probe, no matter how small, will disturb the measurement site. This applies to any method of sensing: conductive, convective, and radiative. Thus, it is an engineering task to minimize the error by an appropriate sensor design and a correct measurement technique.

A contact temperature measurement is complete when there is no thermal gradient between the contact surface and the interior of the probe. This process may take significant time, because, after the probe placement, reaching thermal equilibrium between the object and the sensor may be a slow process, especially if the contact area is dry. A typical contact temperature sensor consists of the following components:

- 1- A sensing element ; a material which is responsive to a change in its own temperature. A good element should have low specific heat, high thermal conductivity, strong and predictable temperature sensitivity.
- 2- Contacts are conductive pads or wires which interface between the sensing element and the external electronic circuit. The contacts should have the lowest possible thermal conductivity and electrical resistance. Also they are often used to support the sensor.
- 3- A protective envelop is either a sheath or coating which physically separates a sensing element from the environment. A good envelope must have low thermal resistance and high electrical isolation properties. It must be impermeable to moisture and other factors which may spuriously affect the sensing

element.

A noncontact temperature sensor is a thermal radiation sensor that contains a sensing element which is responsive to temperature. In addition, it may have an optical window and a built-in interface circuit.

13- Chemical

Chemical sensors are sensitive to stimuli produced by various chemical compounds or elements. The most important property of these sensors is selectivity. Another generally important property of a chemical sensor, is its very small output electrical signal. Any electrical loading on such a sensor would distort information. This commonly requires the use of high quality interface electronic devices.

Selectivity can be defined as the ability of a sensor to respond primarily to only one chemical compound or element in the presence of other species. In most biological system, specificity is achieved by shape recognition, which involves a comparison with some kind of stereo-type. High selectivity means that the contribution from the primary species dominates, and that the contribution from the interfering species is minimal. Therefore, one of the most important functions in the evaluation of a chemical sensor performance is the qualification of its selectivity. It is common practice to evaluate the response of a sensor only for increasing the values of activity (concentration) of the primary species. This is mainly due to the fact that it is more convenient to prepare a continuously broad range of the test concentrations by adding increasing amount of a concentrated primary species to the background sample than vice versa. An absolutely selective sensor really does not exist and there is always some interference present.

Conclusion

In this report we surveyed the different types and classifications of sensors used in various industrial applications. This is by no means a comprehensive survey of all sensors that are being used in industry, rather the report is intended to give a flavor of the wide variety of sensory systems in the current complex factory floor environment.

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