Lecture 3: Introduction to Sensor Systems

EE213 – Introduction to Signal Processing

Semester 1, 2021

Outline

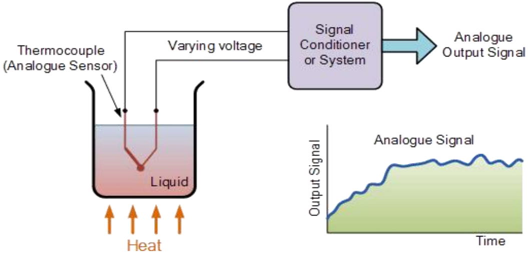
- Basic principles of sensor systems.
  - How an analogue signal is captured and converted to a readable output.
- Classifications of sensors.
- Explain basic working principles of various types of sensors.

Sensors and Signals

- A broad definition of sensors.
  - A sensor is often defined as a "device that receives and responds to a signal or stimulus."
  - This definition is so broad that it covers almost everything.
- A narrower definition of sensors.
  - A sensor is a device that receives a **stimulus** and responds with an electrical signal.
  - According to this definition, the mercury thermometer, in which a reservoir of mercury is sealed in a glass container under vacuum is NOT a sensor!(the mercury thermometer does not generate an electronic signal.)
  - The stimulus is the quantity, property, or condition that is received and converted into an electrical signal.
- We may say that a sensor is a translator of a generally nonelectrical value into an electrical value.
- The sensor's output signal may be in the form of voltage, current, or charge.

Sensors and Signals

- Example for sensors:
  - microphone: a microphone converts sound waves into an electrical signal.
  - thermocouple: A thermocouple produces a temperature-dependent voltage as a result of the thermoelectric effect, and this voltage can be interpreted to measure temperature.

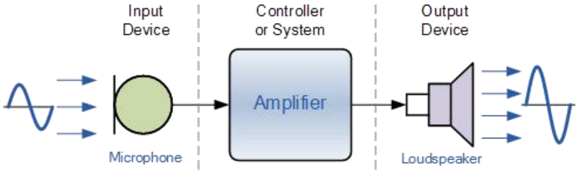


Thermocouple used to produce an analogue signal

- Any sensor is an energy converter: Energy transfer from the object of measurement to the sensor.

Transducers

- The term sensor should be distinguished from transducer.
  - Transducer: converts any one type of energy into another.
  - Transducers have nothing to do with perception or sensing.
  - Transducers may be used as *actuators* in various systems. An actuator may be described as an opposite to a sensor; it converts electrical signal into generally nonelectrical energy (e.g. an electric motor is an actuator; it converts electric energy into mechanical action.).

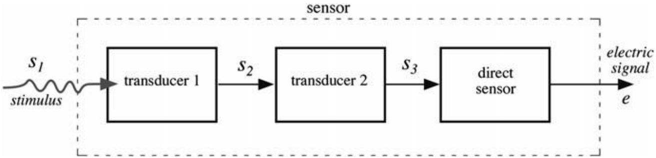


Simple Input/Output System using Sound Transducers

- Identify sensor(s) and transducer(s) in the above figure.

Sensors v.s. Transducers...

- Transducers may be parts of complex sensors.



A sensor may incorporate several transducers. s1, s2, and so on are various types of energy. Note that the last part is a direct sensor producing electrical output e.

Example

A chemical sensor may have a part, which converts the energy of a chemical reaction into heat (transducer) and another part, a thermopile, which converts heat into an electrical signal. The combination of the two makes a chemical sensor, a device which produces electrical signal in response to a chemical reagent.

Sensors and Signals...

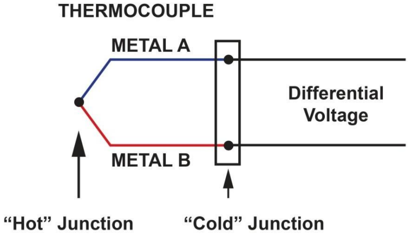
- A sensor does not function by itself
  - it is always a part of a larger system that may incorporate many other detectors, signal conditioners, signal processors, memory devices, data recorders, and actuators.
- The sensor's input signals (stimuli) may have almost any conceivable physical or chemical nature.
  - light, temperature, pressure, vibration, displacement, position, velocity, ion concentration, etc.

Sensor Classification

- There are different ways to classify sensors, depending on the classification purpose.
- All sensors may be of two kinds: passive and active.
  - A passive sensor does not need any additional energy source and directly generates an electric signal in response to an external stimulus.
    - Examples: thermocouples, piezoelectric sensors
  - An active sensor requires **external power** for their operation.
    - Examples: thermistor, light dependent resistor
- Another way to classify sensors:
  - Based on **detection means** used in sensors:
    - Examples: Biological, chemical, electric, magnetic or electromagnetic wave, heat, temperature, etc.
  - Based on **conversion phenomena**:
    - Examples: Thermoelectric, photoelectric, photomagnetic, etc.
  - Based on **stimulus**:
    - Examples: acoustic, biological, chemical, etc.

Temperature Sensors - Thermocouples

- Thermocouples convert a change in temperature into an electrical signal.
- When two wires with dissimilar electrical properties are joined at both ends and one junction is made hot and the other cold, a small electric current is produced proportional to the difference in the temperature.
- Seebeck discovered this effect.
- The cold end may be joined at a sensitive millivolt meter and the hot junction forms the sensor end.



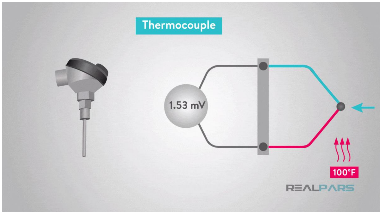


Illustration of a thermocouple

Temperature Sensors - Resistance Type Sensors

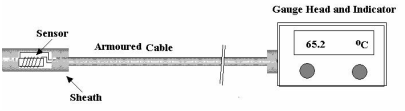
- Physical principle: the electrical resistance of a conductor change with temperature.
  - If a constant voltage is applied to the conductor then the current flowing through it will change with temperature. The resistivity of the conductor change with temperature.
  - This usually means the resistance gets bigger as the conductor gets hotter.
  - The following law relates the resistance and temperature.

$$R = R_0(1 + \alpha\theta) \quad (1)$$

    where α is the temperature coeffcient of resistance and R_0 is the resistance at $0^\circ\mathrm{C}$.
  - The main type of wire used is *PLATINUM*.(unaffected by the temperature of the gauge end)

Temperature Sensors - Resistance Type Sensors

- A special type of resistance sensor is called a thermistor.



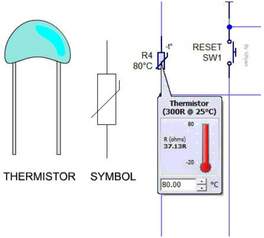


Illustration of a thermistor

- Made from a small piece of semiconductor material.
- The resistance changes a lot for a small change in temperature.
- Can be made into a small sensor and it costs less than platinum wire.

Pressure Sensors

Pressure Sensors can be divided into three types:

- Deflection type
- Strain gauge type
- Piezoelectric type

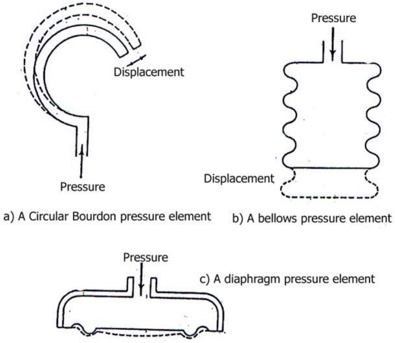
Pressure Sensors - Deflection Type

- This sensor uses an elastic material to convert pressure to displacement (e.g. stainless steel, brass.).
- The working principle of this class of sensors is based on the following relationship:

$$\boxed{\text{pressure} \rightarrow \text{displacement} \rightarrow \text{electrical signal}}$$

- The displacement will be proportionate to the value of pressure exerted.
- Suitable to be used in an automatic control system.
- The main element used is in the shape of **Bourdon tube, bellow** or **diaphragm**.
- The secondary element is the element that will convert the displacement to electrical signals where the displacement can be detected through resistivity change, inductance or capacitance.

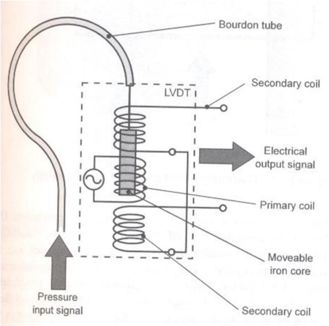
Pressure Sensors - Deflection Type

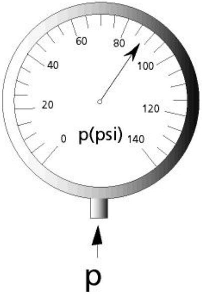


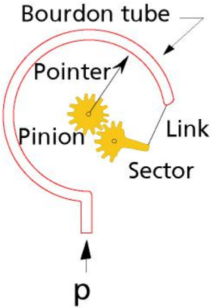
The Main Typical Element Used In A Deflection Type Pressure Sensor

Bourdon tube pressure sensor

- The pressure results in the movement of iron core.
- The movement of the iron core varies the mutual inductance between the coils.
- In this way, the output voltage is a function of the displacement.





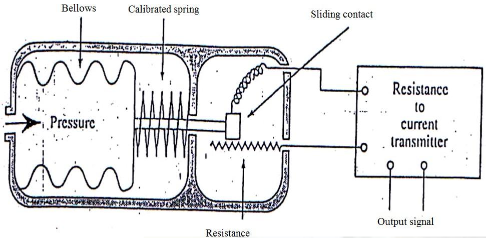


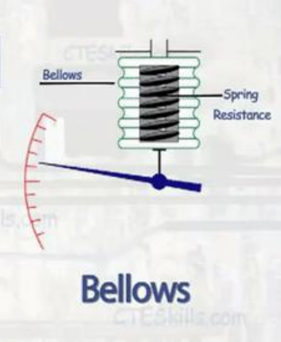
A pressure sensor based on Bourdon tube

Pressure Sensors - Deflection Type ...

Bellow-resistance pressure sensor

- The pressure is proportional to the resistivity.
- The resistance change is detected by displacement of sliding contact in the resistance element.

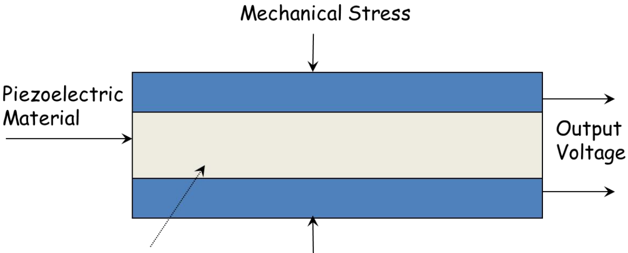


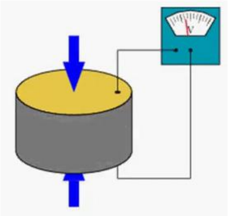


Bellow-resistance pressure sensor

Pressure Sensors - Piezoelectric Type

- This sensor consists of a piezoelectric crystal (made from quartz) or piezoelectric ceramics which functions as a force-sensitive voltage source where the piezoelectric will be in between two plates.
- Pressure exerted on the crystal surface is proportionate to the voltage produced by the crystal.
- This sensor does not require any voltage supply. This sensor is suitable for fast changing pressure measurement.





Piezoelectric Pressure Sensor

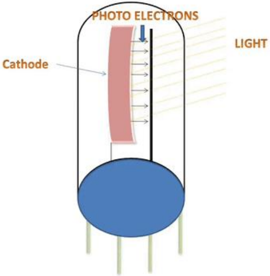
Light Sensors

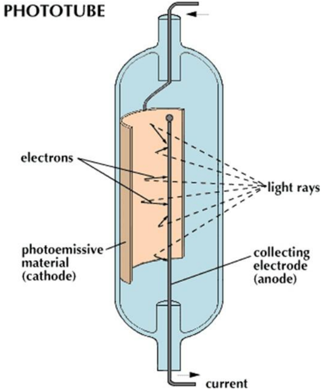
- Light sensors indicate light intensity by measuring radiant energy of photons in a range of frequencies.
- Light sensors are passive devices and thus should be part of an electric circuit to generate an electrical signal.
- There are 2 main categories of light sensors, each with its own operating principle(s).
  - Generates electricity when illuminated.
    - Photo-emissive.
    - Photo-voltaic.
  - Changes electrical properties when illuminated.
    - Photo-conductive.

Light Sensors - Photo-emissive Sensors

Operation:

- Photons hit a light-sensitive material, releasing free electrons.
- Electrons are collected in anode, forming a current.
- The current is measured, and is dependent on photon intensity and frequency.

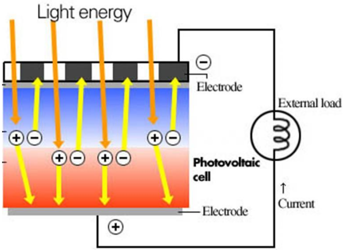




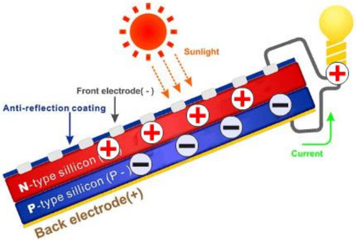
Photo–emissive (phototube) operation

Operation:

- Photons hit a light-sensitive semiconductor, producing electron-hole pairs.
- Electrons move across the semiconductor's p-n junction, producing a voltage across it.
- The current produced by this voltage is measured.

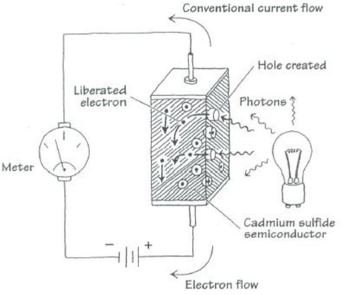


Photo–voltaic cell operation



Operation:

- Photons hit a light-sensitive semiconductor, producing electron-hole pairs.
- Instead of accumulating a voltage (as in the photo-voltaic process), this semiconductor reduces its resistance.
- This increases the amount of current flowing through the semiconductor, which is then measured.



Photo–conductive operation

Chemical Sensors

- Chemical sensors are used to measure and detect chemical substances， are very different from other types of sensors.
- Sensing is usually based on sampling.
- Sample is allowed to react in some fashion with elements of the sensor.
- Chemical sensors may have multiple transduction steps (i.e., indirect sensors).
- In industry, chemical sensors are used for process and quality control. And play a vital role in environment protection by monitoring(e.g., water and air quality.)

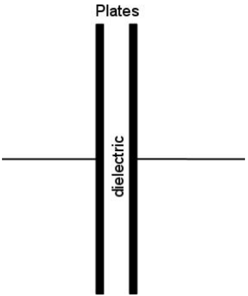
Chemical Sensors...

- Chemical sensors are generally classified into direct or indirect sensors.

- Direct sensor:
  The chemical reaction or the presence of a chemical produces a measured electrical output.

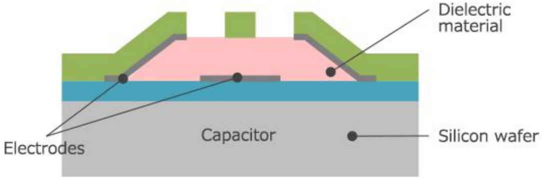
Example (The capacitive moisture sensor)

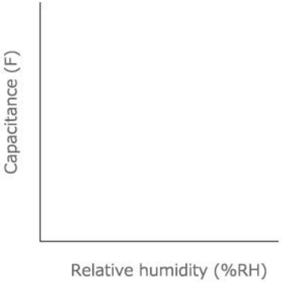
The capacitance of a capacitor is directly proportional to the amount of water present between its plates.



A parallel plate capacitor

Chemical Sensors – Capacitive moisture sensor



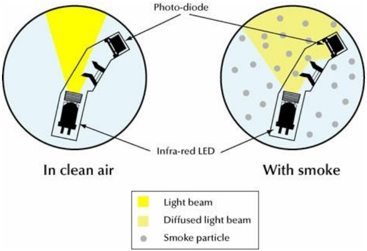


Chemical Sensors...

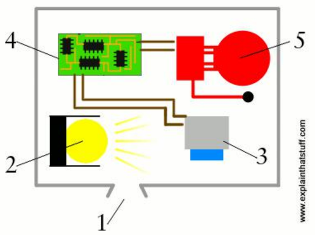
- Indirect sensor:
  - sensor relies on a secondary, indirect reading of the sensed stimulus.

Example (Photo–electric smoke detector)

Photo-electric smoke detectors incorporate a pulsing infra-red LED located in a chamber. The chamber is designed such that the photo-diode does not receive any light energy emitted by the LED in normal situations. In the event of smoke from a fire entering the chamber, the light pulse from the LED will be scattered and hence registered by the photo-diode.



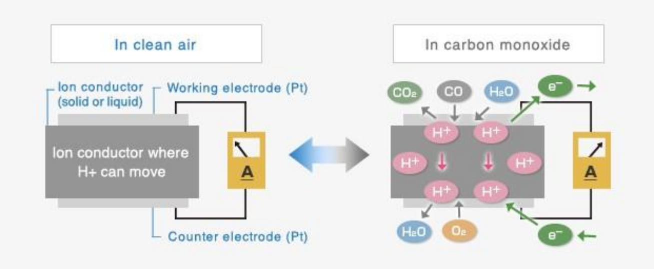
Photo–electric smoke sensor



Chemical Sensors - Electrochemical Sensor

- Electrochemical sensors operate by reacting with the gas of interest and producing an electrical signal proportional to the gas concentration.

Example (CO gas sensor)



Schematic diagrams of electrochemical CO gas sensor

Chemical Sensors - gas sensor

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Chemical Sensors - Electrochemical CO Gas Sensor

- The basic components: a working (sensing) electrode, a counter electrode, and an ion conductor in between them.
- When carbon monoxide (CO) comes in contact with the working electrode, oxidation of CO gas will occur on the working electrode through chemical reaction with water molecules in the air

$$CO + H_2O \rightarrow CO_2 + 2H^+ + 2e^- \qquad (2)$$

- Protons (H+) generated on the working electrode flow toward the counter electrode through the ion conductor. In addition, generated electrons move to the counter electrode through the external wiring. A reaction with oxygen in the air will occur on the counter electrode

$$(1/2)O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad (3)$$

- By measuring the current between the working electrode and the counter electrode, this electrochemical cell can be utilized as a gas sensor.