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CITS 5506
The Internet of Things
Lecture 08 (Recording)

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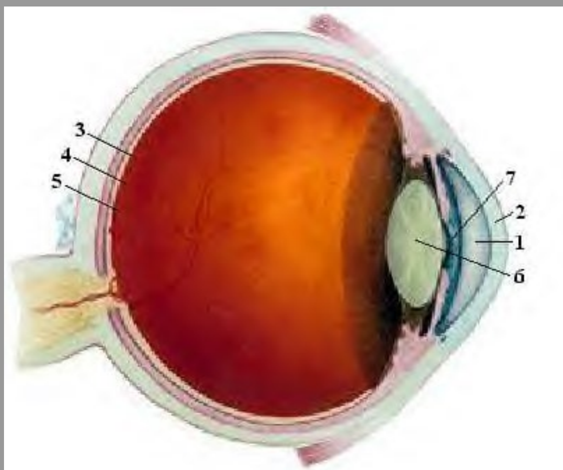
Lecture Overview

- What is Sensor?
  - Transducer, Sensor, Actuator
- Categorization of Sensors
  - Analog & Digital Sensors
  - Active & Passive Sensors
- Sensor’s Specifications
- Attributes of Sensor
- MEMS
- Sensors Examples

Our 5 Senses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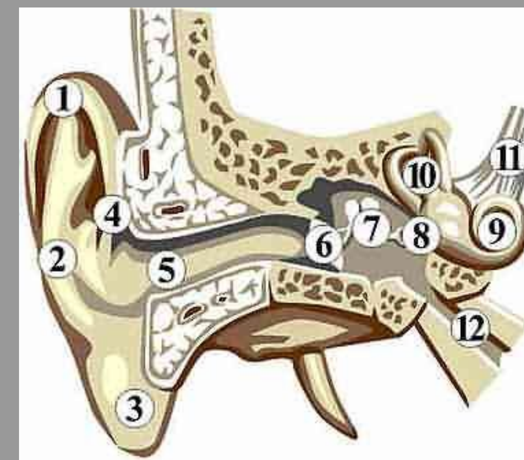
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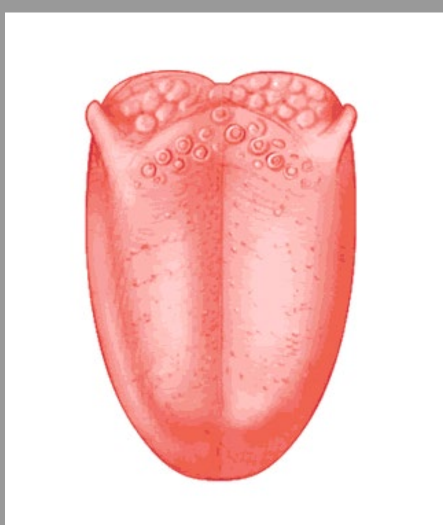
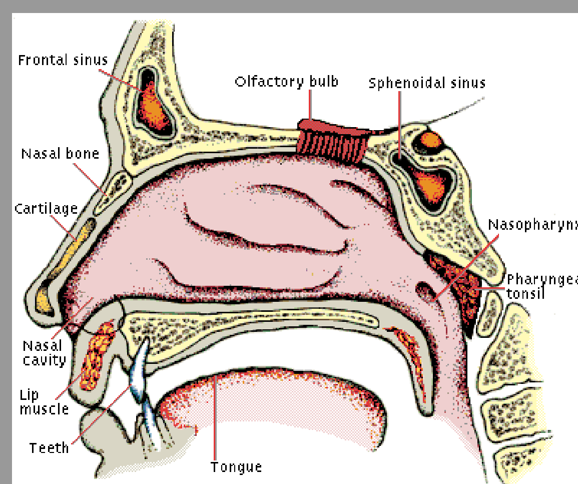



Frontal sinus
Olfactory bulb
Sphenoidal sinus
Nasal bone
Cartilage
Nasopharynx
Pharyngeal tonsil
Nasal cavity
Lip muscle
Teeth
Tongue

Sensor

- A sensor is a device that detects and responds to some type of input from the physical environment.
- The input can be light, heat, motion, moisture, pressure or any number of other environmental phenomena.
- The output is generally a signal that is converted to a human-readable display at the sensor location or transmitted electronically over a network for reading or further processing.

Sensor

A device which provides a usable output in response to a specified measurand.

A sensor acquires a physical quantity and converts it into a signal suitable for processing (e.g. optical, electrical, mechanical).

Nowadays common sensors convert measurement of physical phenomena into an electrical signal

Transducer

Active element of a sensor is called a transducer.

A device which converts one form of energy to another.

Sensors detect by receiving a signal from a transducer, then responding to that signal by converting it into an output that can easily be read and understood.

The output can be analog or digital.

Transducer

A transducer converts one form of energy to another, but does not quantify the conversion, e.g. a light bulb converts electrical energy into light and heat; however, it does not quantify how much light or heat. Similarly, battery converts chemical energy into electrical energy.

If the purpose of a device is to quantify an energy level, it is a sensor.

When input is a physical quantity and output electrical reading → Sensor

When input is electrical and output a physical quantity → Actuator

Sensor

A thermometer senses and converts temperature into a readable output, thus it is a sensor. This output can be direct or indirect.

A mercury thermometer that uses a level of mercury against a fixed scale is a direct output.

A digital thermometer is an indirect output using a thermocouple and then quantification.

Magnetic Sensors

Perhaps one of the first sensors used by man was a compass, which is essentially a magnetic sensor. The compass needle, which is steel, aligns itself with the earth's magnetic field lines and points toward the north.

Terminologies

Transducer is a device which transforms energy from one type to another.

- Typical energy domains are mechanical, electrical, chemical, magnetic, optical and thermal.

Transducer can be further classified into Sensors, which monitors a system and Actuators, which impose an action on the system.

Categorization of Sensors

Classification based on physical phenomena

- Mechanical: strain gage, displacement, velocity, accelerometer, tilt meter, viscometer, pressure, etc.
- Thermal: thermo-couple measuring temperature, heat
- Optical: camera, infrared sensor
- Electro-magnetics: voltage, current, frequency phase
- Chemical quantities: moisture, pH value
- Others …

Classification based on measuring mechanism

- Resistance sensing, capacitance sensing, inductance sensing, piezoelectricity, etc.

Conversion Methods

- Physical
  - thermo-electric, thermo-elastic, thermo-magnetic, thermo-optic
  - photo-electric, photo-elastic, photo-magnetic,
  - electro-elastic, electro-magnetic
  - magneto-electric
- Chemical
  - chemical transport, physical transformation, electro-chemical
- Biological
  - biological transformation, physical transformation

Measuring Quantities

Stimulus	Quantity
Acoustic	Wave (amplitude, phase, polarization), Spectrum, Wave Velocity
Biological & Chemical	Fluid Concentrations (Gas or Liquid)
Electric	Charge, Voltage, Current, Electric Field (amplitude, phase, polarization), Conductivity, Permittivity
Magnetic	Magnetic Field (amplitude, phase, polarization), Flux,Permeability
Optical	Refractive Index, Reflectivity, Absorption
Thermal	Temperature, Flux, Specific Heat, Thermal Conductivity
Mechanical	Position, Velocity, Acceleration, Force, Strain, Stress, Pressure, Torque

Physical Principles: Examples

Amperes's Law

– A current carrying conductor in a magnetic field experiences a force (e.g. galvanometer)

• **Curie-Weiss Law**

– There is a transition temperature at which ferromagnetic materials exhibit paramagnetic behavior

• **Faraday's Law of Induction**

– A coil resist a change in magnetic field by generating an opposing voltage/current (e.g. transformer)

• **Photoconductive Effect**

– When light strikes certain semiconductor materials, the resistance of the material decreases (e.g. photoresistor)

Type of Sensors

Active

- send signal into environment and measure interaction of signal with environment/ target
- e.g. radar, sonar

Passive

- record signals already present in environment
- e.g. video cameras
- A passive infrared sensor (PIR motion sensor) is an electronic sensor that measures infrared (IR) light radiating from objects in its field of view.

Types of Sensors

Analog

The output of these sensors is analog and to use with digital hardware an A/D converter is required. Example, the temperature sensor (specifically LM35) is an analog sensor.

Digital

The output of these sensors is digital data that you can read via serial or parallel communication buses (as UART, SPI, I2C, etc). The typical format for the data is demonstrated exactly in the sensor’s datasheet.

Specifications of Sensor

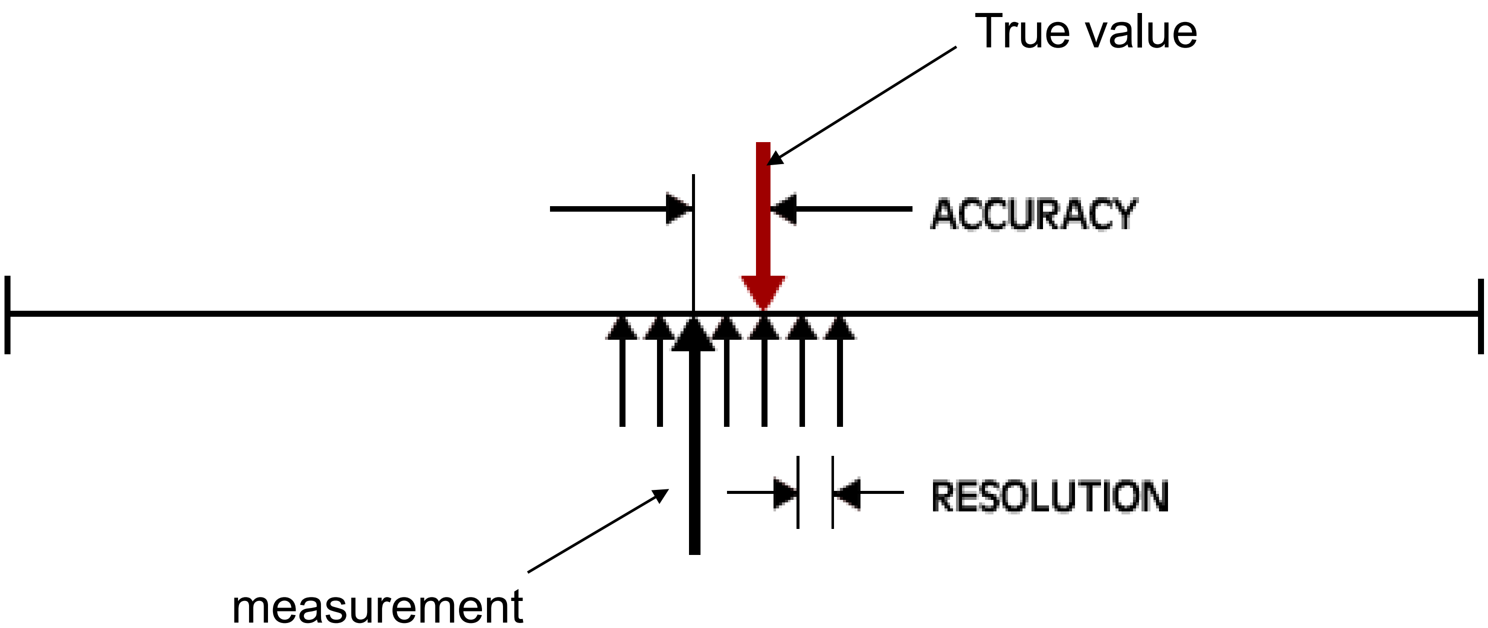
Accuracy: Error between the result of a measurement and the true value being measured.

Resolution: The smallest increment of measure that a device can make.

Sensitivity: The ratio between the change in the output signal to a small change in input physical signal. Slope of the input-output fit line.

Repeatability/Precision: The ability of the sensor to output the same value for the same input over several trials.

Accuracy vs Resolution



Accuracy

- Accuracy is the capacity of a measuring instrument to give RESULTS close to the TRUE VALUE of the measured quantity
- Accuracy is measured by the absolute and relative errors

Absolute Error = Result – True Value

Relative Error = Absolute Error / True Value

Specifications of Sensor

Dynamic Range: the ratio of maximum recordable input amplitude to minimum input amplitude,

i.e. D.R. = 20 log (Max. Input Ampl./Min. Input Ampl.) dB

Linearity: the deviation of the output from a best-fit straight line for a given range of the sensor

Transfer Function (Frequency Response): The relationship between physical input signal and electrical output signal, which may constitute a complete description of the sensor characteristics.

Specifications of Sensor

Bandwidth: the frequency range between the lower and upper cutoff frequencies, within which the sensor transfer function is constant gain or linear.

Noise: Random fluctuation in the value of input that causes random fluctuation in the output value.

Attributes of Sensor

Operating Principle: Embedded technologies that make sensors function, such as electro-optics, electromagnetic, piezoelectricity, active and passive ultraviolet.

Dimension of Variables: The number of dimensions of physical variables.

Size: The physical volume of sensors.

Data Format: The measuring feature of data in time; continuous or discrete/analog or digital.

Attributes of Sensor

Intelligence: Capabilities of on-board data processing and decision-making.

Active versus Passive Sensors: Capability of generating vs. just receiving signals.

Physical Contact: The way sensors observe the disturbance in environment.

Environmental durability: The sensor robustness under its operation conditions

Sensor Calibration

- The relationship between the physical measurement variable(X) and the signal variable (S) may need calibration.

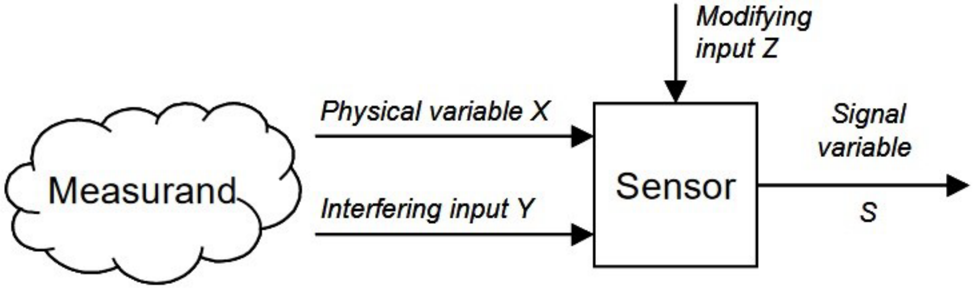
- A sensor or instrument is calibrated by applying a number of KNOWN physical inputs and recording the response of the system.

Additional Inputs

Interfering inputs (Y):

Those that the sensor to respond as the linear superposition with the measurand variable X

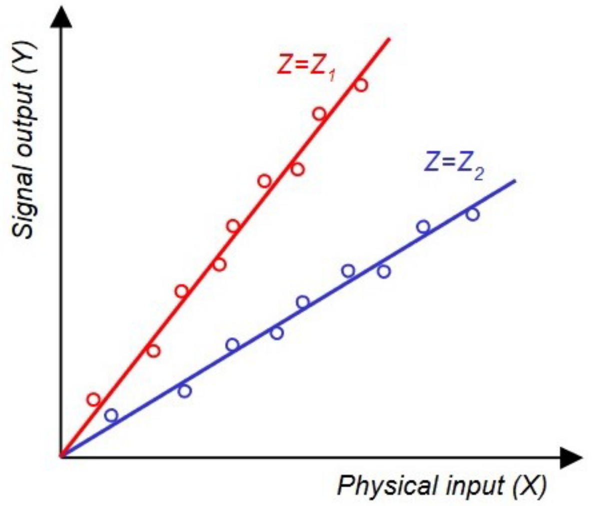
Linear superposition assumption: $S(aX+bY)=aS(X)+bS(Y)$



Additional Inputs

Modifying inputs (Z):

Those that change the behaviour of the sensor and, hence, the calibration curve, eg Temperature is a typical modifying input



MEMS Technology

What is MEMS?

- Acronym for Microelectromechanical Systems
- "MEMS is the name given to the practice of making and combining miniaturized mechanical and electrical components."
  – *K. Gabriel, SciAm, Sept 1995.*

Synonym to:

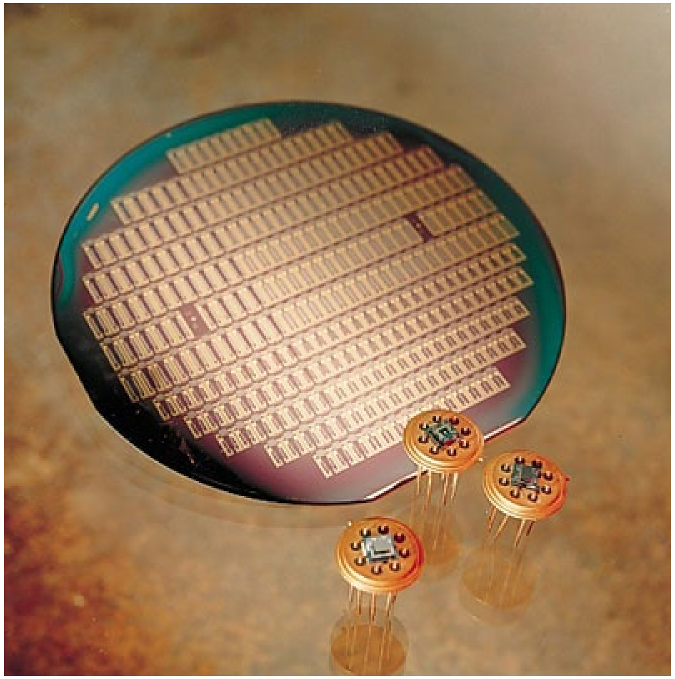
- Micromachines (in Japan)
- Microsystems technology (in Europe)

Leverage on existing IC-based fabrication techniques (but now extend to other non IC techniques)

- Potential for low cost through batch fabrication
- Thousands of MEMS devices (scale from ~ 0.2 μm to 1 mm) could be made simultaneously on a single silicon wafer

MEMS Technology

- Co-location of sensing, computing, actuating, control, communication & power on a small chip-size device
- High spatial functionality and fast response speed
  - Very high precision in manufacture
  - miniaturized components improve response speed and reduce power consumption



HP Planar, with their own foundry for wafer production, uses proprietary electronics capabilities to bring MEMs chip production processes to new sensor applications.

Sensor selection

Environmental Factors	Economic Factors	Sensor Characteristics
Temperature range	Cost	Sensitivity
Humidity effects	Availability	Range
Corrosion	Lifetime	Stability
Size		Repeatability
Overrange protection		Linearity
Susceptibility to EM interferences		Error
Ruggedness		Response Time
Power consumption		Frequency Response
Self-test capability		

Important Sensor Properties Critical to the Sensor Performance

Response time	Recovery time
Reproducibility	Aging
Stability (short term, long term)	
Sensitivity	Resolution
Dynamic range	Selectivity
Size and weight	Cost

Consideration for Sensor Choice

Application to Problem

Sensor technology

Sensor data collection topologies

Data communication

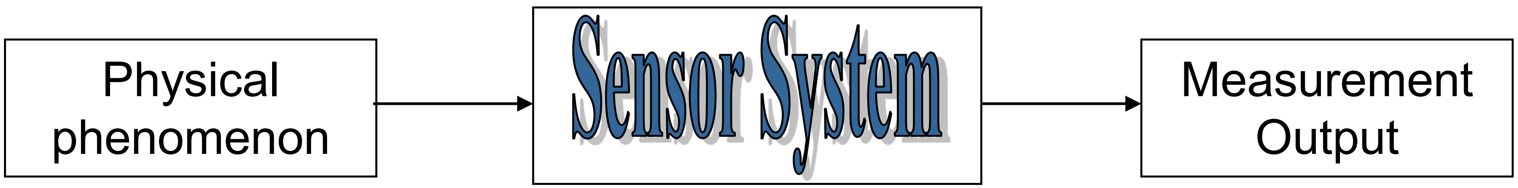
Power supply

Data synchronization

Environmental parameters and influence

Remote data analysis

Measurements



Measurement output:
• Interaction between a sensor and the environment surrounding the sensor
• Compound response of multiple inputs

Measurement errors:
• System errors: imperfect design of the measurement setup and the approximation, can be corrected by calibration
• Random errors: variations due to uncontrolled variables. Can be reduced by averaging.

Strain Gauge: Motion, Stress, Pressure

Strain gauge is used to measure deflection, stress, pressure, etc.

The resistance of the sensing element changes with applied strain.

A Wheatstone bridge is used to measure small changes in the strain gauge resistance.

Motion Sensors

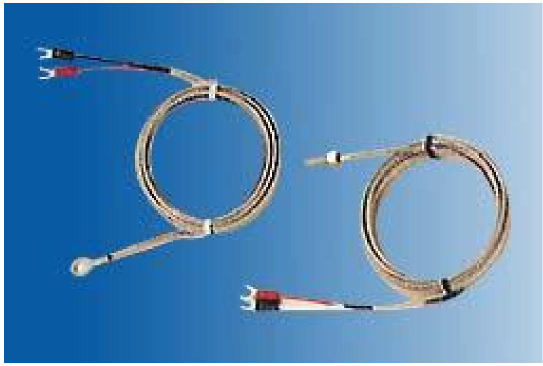
- Monitor location of various parts in a system
  – absolute/relative position
  – angular/relative displacement
  – proximity
  – acceleration
- Principle of operation
  – Magnetic, resistive, capacitance, inductive, eddy current, etc.

Temperature Sensor

- **Resistance temperature device (RTD)**

- **Thermistor (Thermal Resistor)**

Thermocouple: Seeback effect to transform a temperature difference to a voltage difference



Accelerometer

- Accelerometers are used to measure acceleration along one or more axis and are relatively insensitive to orthogonal directions.
- **Applications**

– Motion, vibration, blast, impact, shock wave

- Electromechanical device to measure acceleration forces:

– Static forces like gravity pulling at an object lying at a table

– Dynamic forces caused by motion or vibration

Piezoelectric effect

A permanently-polarized material such as quartz (SiO_2) or barium titanate ($BaTiO_3$) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force.

This phenomenon is known as the piezoelectric effect.

Piezoelectric sensors

Piezoelectric sensors use the piezoelectric effect as the principle of operation.

The piezoelectric effect refers to the appearance of an electric field in a material when it is subjected to a stress force or a strain.

Since it is a reversible effect, if an electric field or voltage is applied to a piezoelectric material, it stresses or strains. This first effect is called the direct piezoelectric effect, the second, the converse piezoelectric effect .

Piezoelectric sensors

- Piezoelectric materials transduct a mechanical measurand such as force, pressure, acceleration, or deceleration directly into an output electrical signal.
- This direct transduction may be considered an inherent intelligence or smartness of the material.
- The importance of piezoelectric materials or what is sometimes referred to as smart materials in the development of sensors has been growing very rapidly.
- The use of the smart materials allows one to simplify sensor design, and hence to eliminate usually complex hybrid signal transduction or conditioning components of the sensor.

Accelerometer: How they work

– **Seismic mass accelerometer**: A seismic mass is connected to the object undergoing acceleration through a spring and a damper;

– **Piezoelectric accelerometers**: a microscopic crystal structure is mounted on a mass undergoing acceleration; the piezo crystal is stressed by acceleration forces thus producing a voltage.

– **Capacitive accelerometer**: consists of two microstructures (micromachined features) forming a capacitor; acceleration forces move one of the structure causing a capacitance changes.

– **Piezoresistive accelerometer:** consists of a beam or micromachined feature whose resistance changes with acceleration

– **Thermal accelerometer**: tracks location of a heated mass during acceleration by temperature sensing

Accelerometer Applications

Automotive: monitor vehicle tilt, roll, skid, impact, vibration, etc., to deploy safety devices (stability control, anti-lock breaking system, airbags, etc.) and to ensure comfortable ride (active suspension)

- Aerospace: inertial navigation, smart munitions, unmanned vehicles
- Sports/Gaming: monitor athlete performance and injury, joystick, tilt
- Personal electronics: cell phones, digital devices
- Security: motion and vibration detection
- Industrial: machinery health monitoring
- Robotics: self-balancing

Electrochemical sensors

Sensors whose response is a result of an interaction between electricity and chemistry— hence the nomenclature **electrochemical** sensors.

Basically, the electrochemical sensors can be divided into three general types:

- conductimetric
- potentiometric
- amperometric

Electrochemical sensors

The **conductimetric** sensors are those whose response relates to the measurement of electrical resistance, impedance, or admittance.

The **potentiometric** sensor response relates to the measurement of voltage,

The **amperometric** sensor response relates to the measurement of electrical current.

Electrochemical sensors

Typical measurands may include chemical species such as gases (O_2 , CO, CO_2 etc.), pH, humidity, or biological quantities such as glucose, cholesterol, enzymes, antibodies, proteins, etc.

As there are many biological applications for these sensors in humans, animals, and plants, these sensors are also referred as bioelectrochemical sensors.

Thermal Sensors

Temperature sensor. This sensor is used in a wide range of applications critical to the medical, agricultural, industrial, and automotive communities.

The particular application may range from measuring temperature within a furnace where accuracies of 10°C may be sufficient to the measurement of temperature associated with tumors, where accuracies of less than 0.01°C are necessary.

Thermal Sensors

The most popular being the resistance thermometer, thermistors, thermocouples, and radiation thermometers. Other, less common varieties include acoustic thermometers, dielectric constant thermometers, refractive index thermometers, and quartz crystal thermometers.

These technologies are typically based on such broad areas as solid state, electromagnetics, acoustics, and optics. Recent advances in microfabrication technology have enabled the realization of miniature temperature sensors that are extremely sensitive and stable.

Temperature Sensor: History

Resistance Thermometer by Ohm in 1827. He realized that the resistance of metals increased in a quasi-linear fashion with temperature. The first commercially available thermometer based on the variation of metal resistance with temperature appeared in 1871.

Semi-Conductor based Thermometer

Thermometers that use semiconductors as the sensing element differ from metal-based thermometers in that the resistance decreases with increasing temperature.

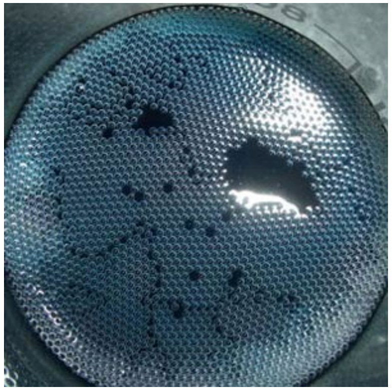
Sensors

Sensors are pervasive. They are embedded in human bodies, automobiles, airplanes, cellular telephones, radios, chemical plants, industrial plants and countless other applications.

• Without the use of sensors, there would be no automation !!

Smoke Detectors

Wearable Health Care System



Temperature
Respiration
Movement

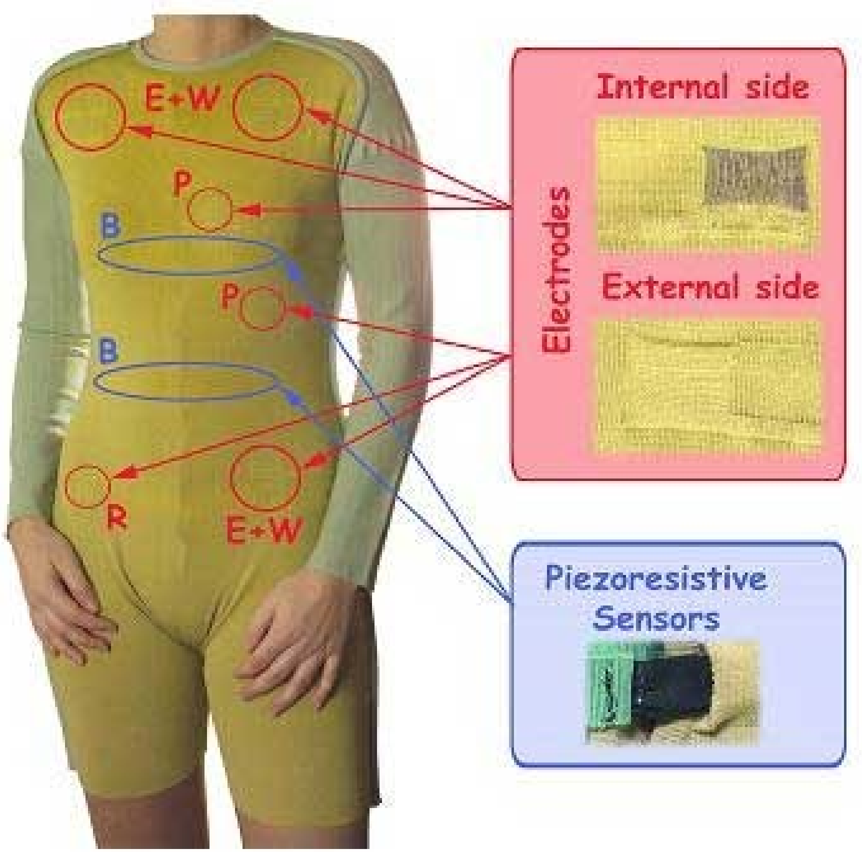
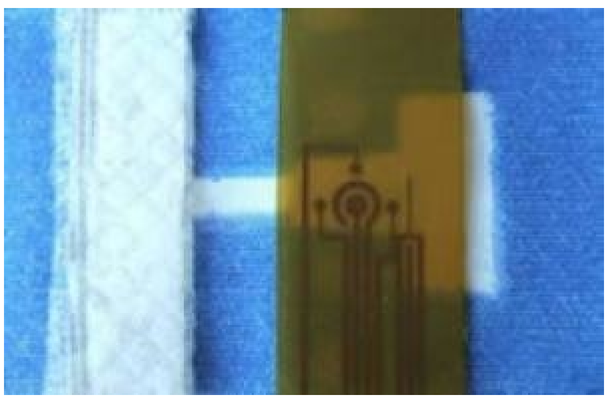
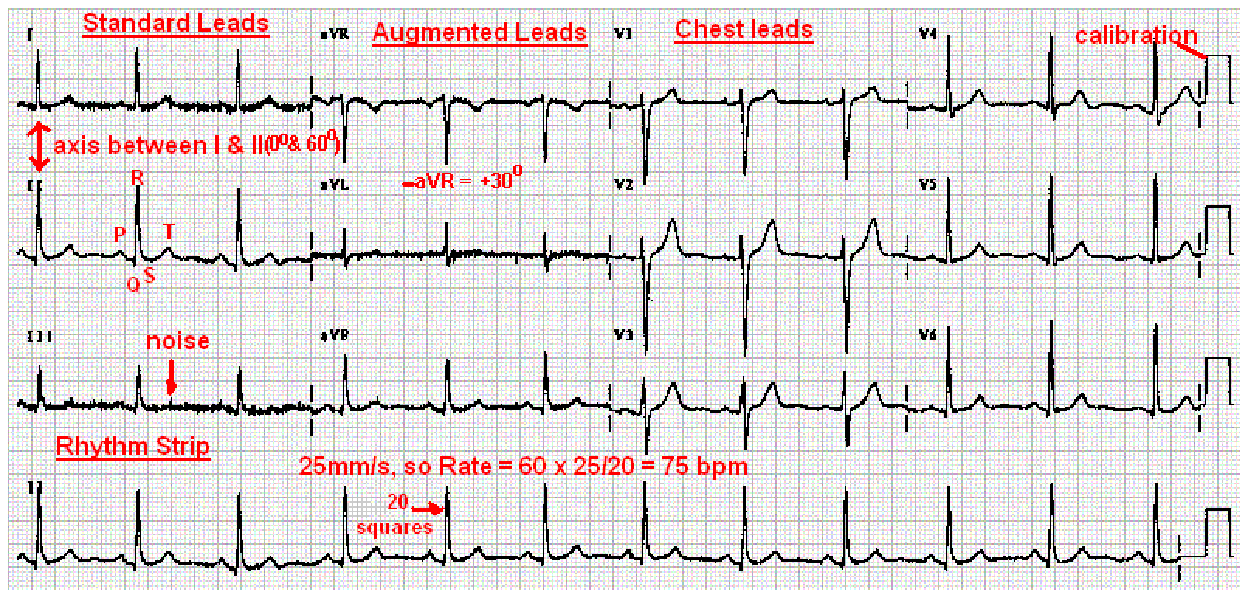


Figure 1. Prototype model, E+W Einthoven and Wilson , R Referee, P Precordial leads, B Breathing sensors. (Prototype A)

Smart Sweat

Miniaturized biosensors in a textile patch can now analyze body fluids, even a tiny drop of sweat, and provide a much better assessment of someone's health.





Smart Shoe