Introduction to Sensors

Sensors

Learning Objectives

- Describe and define performance criteria for sensors (e.g., linearity, sensitivity, resolution, noise)
- Explain the operating mode for some common IoT transducers and sensors (strain gage, accelerometer, gyros, temperature, pressure sensors…)
- Interpret a specification sheet and extrapolate missing performance data

What is Sensor?

Force or
Displacement

Perception
of Topography or
Stiffness

Rodin's Cathedral

Reference : Stanford University. Stanford online

skin mechanics

external load

↓

stress/strain at neuron

↓ neuron mechanics, channel id & biophysics, cell physiology

electrochemical response

↓ neural circuit past/current stimuli

behavioral response

Reference : Stanford University. Stanford online

Quantifying touch sensation

- Dynamic Range – what range of force or deformation can you feel?

- Bandwidth – what frequency or on/off rate can you detect?

- Sensitivity – how strong is the output signal relative to the input? Is it the relationship linear?

- Resolution – what is the smallest feature or smallest force you can detect?

Sensors

- To sense physical parameter
- To convert physical quantity into electrical signal
- To make the physical signal compatible with the processing system

- A sensor detects (senses) changes in the ambient conditions or in the state of another device or a system and forwards or processes this information in a certain manner
- A device which detects or measures a physical property and records , indicates, or otherwise responds to it
- The output of a sensor is a signal, which is converted to human reliable form

Sensors

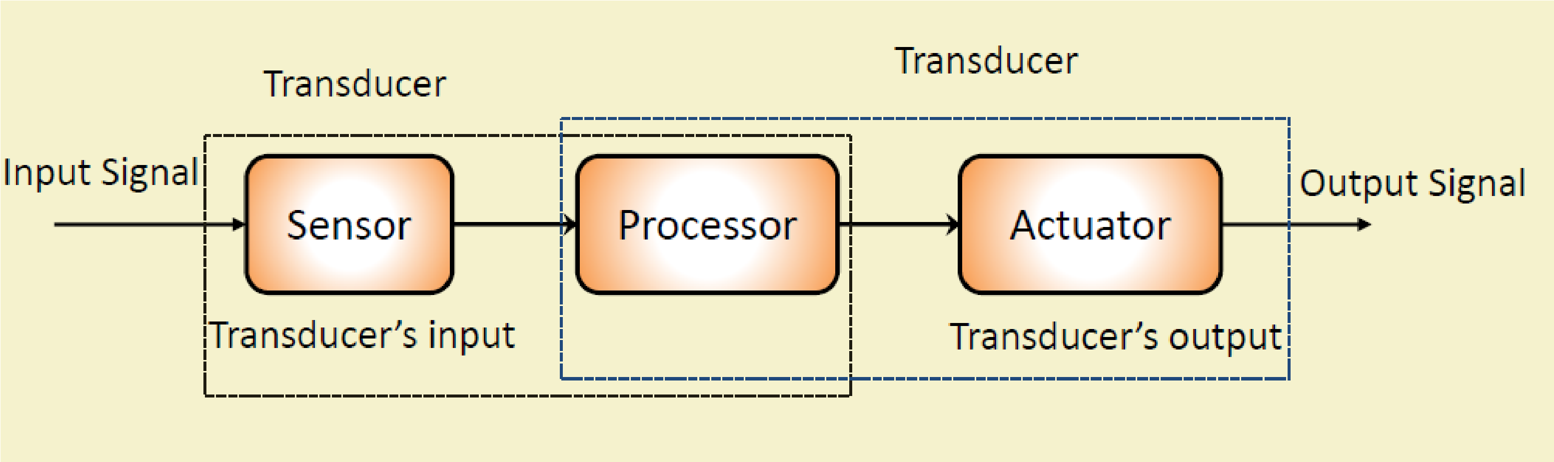
- The characteristic of any device or material to detect the presence of a particular physical quantity
- Performs some function of input by sensing or feeling the physical changes in the characteristic of a system in response to stimuli
- Input: Physical parameter or stimuli
  - Example: Temperature, light, gas, pressure, and sound
- Output: Response to stimuli

Transducer

- **Converts a signal from one physical form to another physical form**
- **Physical form: thermal, electric, mechanical, magnetic, chemical, and optical**
- **Energy converter**
- **Example:**
  - **Microphone : Converts sound to electrical signal**
  - **Speaker : Converts electrical signal to sound**
  - **Antenna : Converts electromagnetic energy into electricity and vice versa**
  - **Strain gauge : Converts strain to electrical**

Sensors Vs Transducers

- **The word transducer is a collective term used for both sensors which can be used to sense a wide range of different energy forms, and actuators which can be used to switch voltages and currents.**
- **Sensors are only sensitive to the measured property**
- **Sensors does not influence the measured property (measuring temp does not reduce or increase the temp.**



Sensors Vs Transducers

Transducer : Any device by which variations in one physical quantity (e.g. pressure, brightness) are quantitatively converted into variations in another (e.g. voltage, position).

OR…a device for which changes in **input** quantity A produce corresponding, predictable changes in **output** quantity B

For our purposes, Sensors convert **physical** to **electrical** signals

Sensor Characteristics

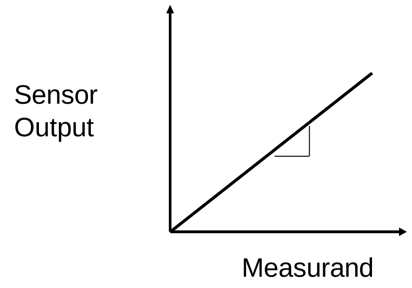
- **Static characteristics**
  - After steady state condition, how the output of a sensor change in response to an input change
- **Dynamic characteristics**
  - The properties of the system's transient response to an input

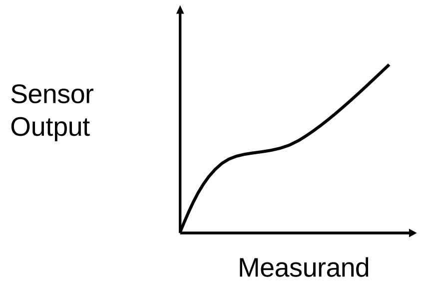
Static Characteristics

- Accuracy
  - Represents the correctness of the output compared to a superior system
  - The difference between the standard and the measured value
- Range
  - Gives the highest and the lowest value of the physical quantity within which the sensor can actually sense
  - Beyond this value there is no sensing or no kind of response
- Resolution
  - Provides the smallest change in the input that a sensor is capable of sensing
  - Resolution is an important specification towards selection of sensors.
  - Higher the resolution better the precision
- Errors
  - The difference between the standard value and the value produced by

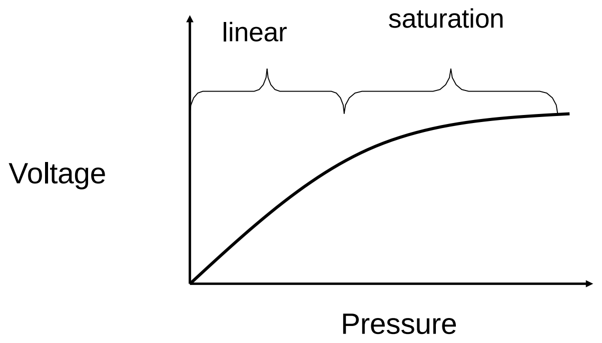
- **Sensitivity**
  - Sensitivity indicates ratio of incremental change in the response of the system with respect to incremental change in input parameter.
  - It can be found from slope of output characteristic curve of a sensor
  - Sensitivity drift - Change in sensitivity of an instrument temperature or other external factors.
- **Linearity**
  - The deviation of sensor value curve from a particular straight line
  - The degree to which variations in the o/p follows i/p variations
- **Drift**
  - The difference in the measurements of sensor from a specific reading when kept at that value for a long period of time
- **Repeatability/Precision**
  - The deviation between measurements in a sequence under same conditions

Sensitivity

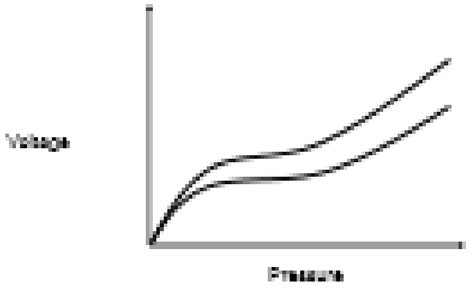




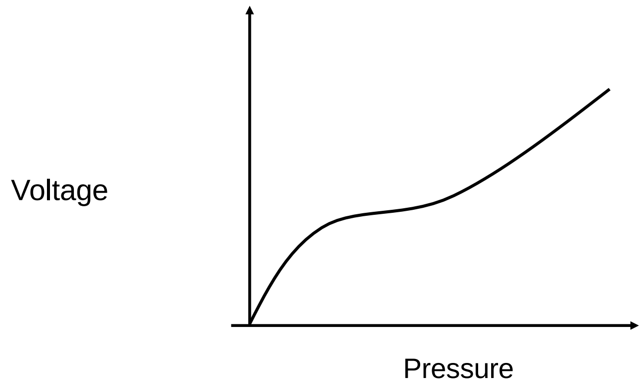
Span / Range



Repeatability



Non-Linearity



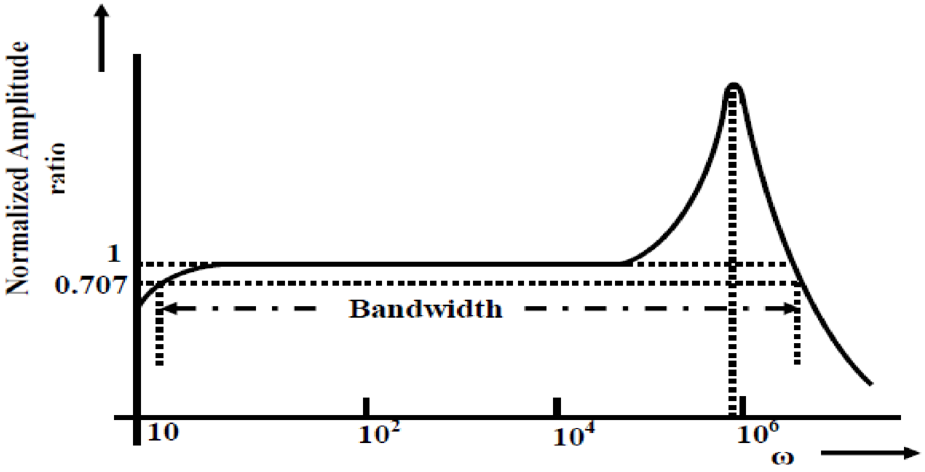
Reference : Stanford University. Stanford online

Dynamic Characteristics

The performance of the instrument when the input variable is changing rapidly with time.

- **Zero order system**
  - Output shows a response to the input signal with no delay
  - Does not include energy-storing elements
  - Example: Potentiometer measures linear and rotary displacements
- **First order system**
  - When the output approaches its final value gradually
  - Consists of an energy storage and dissipation element
- **Second order system**
  - Complex output response
  - The output response of sensor oscillates before steady state

- **Frequency Response Performance**
  - the performance of the system subject to sinusoidal input of varying frequency.
- **Bandwidth and Natural Frequency**
  - The range of frequencies over which amplitude is fairly constant .
  - it is the frequency range in which the normalized amplitude ratio does not fall below 0.707, or -3 dB limit
  - The frequency at which the amplitude ratio attains a peak is called the (damped) *natural frequency of the system*



Linearization and Error

- “All models are wrong, some are useful".

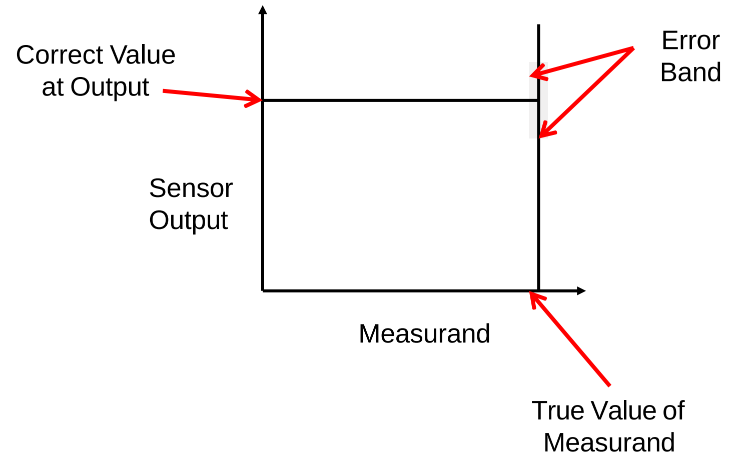
  - *George Box*

- So sensors, all sensors are not ideal, but they're still useful.

Reference : Stanford University. Stanford online

Error

Overall Error (Error Band)

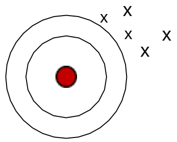


Reference : Stanford University. Stanford online

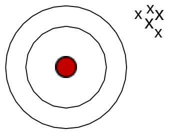
Accuracy vs. Precision

Accuracy vs. Precision

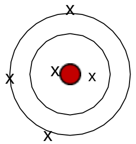
- Accurate
  - Average of sampled output is close to real value (AC errors and noise)
- Precise
  - Sampled output is consistently tightly grouped with consistent offset from real value (DC errors)



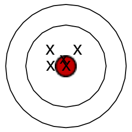
Imprecise and Inaccurate



Precise but Inaccurate



Accurate but Imprecise



Precise and Accurate

Reference : Stanford University. Stanford online

Noise

Electronic Noise Sources

- EMF - capacitive & inductive pickup
- Johnson noise
  - All resistors and dissipative systems
  - Thermal/Brownian random molecular interactions
- 1/f noise (shot, flicker, Hooge)
  - Semiconductor based electronics, amplifiers, instruments
  - Seminconductor resistors, Hooge noise
- Drift
  - Accumulated offset errors
  - Very low frequency fluctuations?

$$V_J = \sqrt{4k_B TR}$$

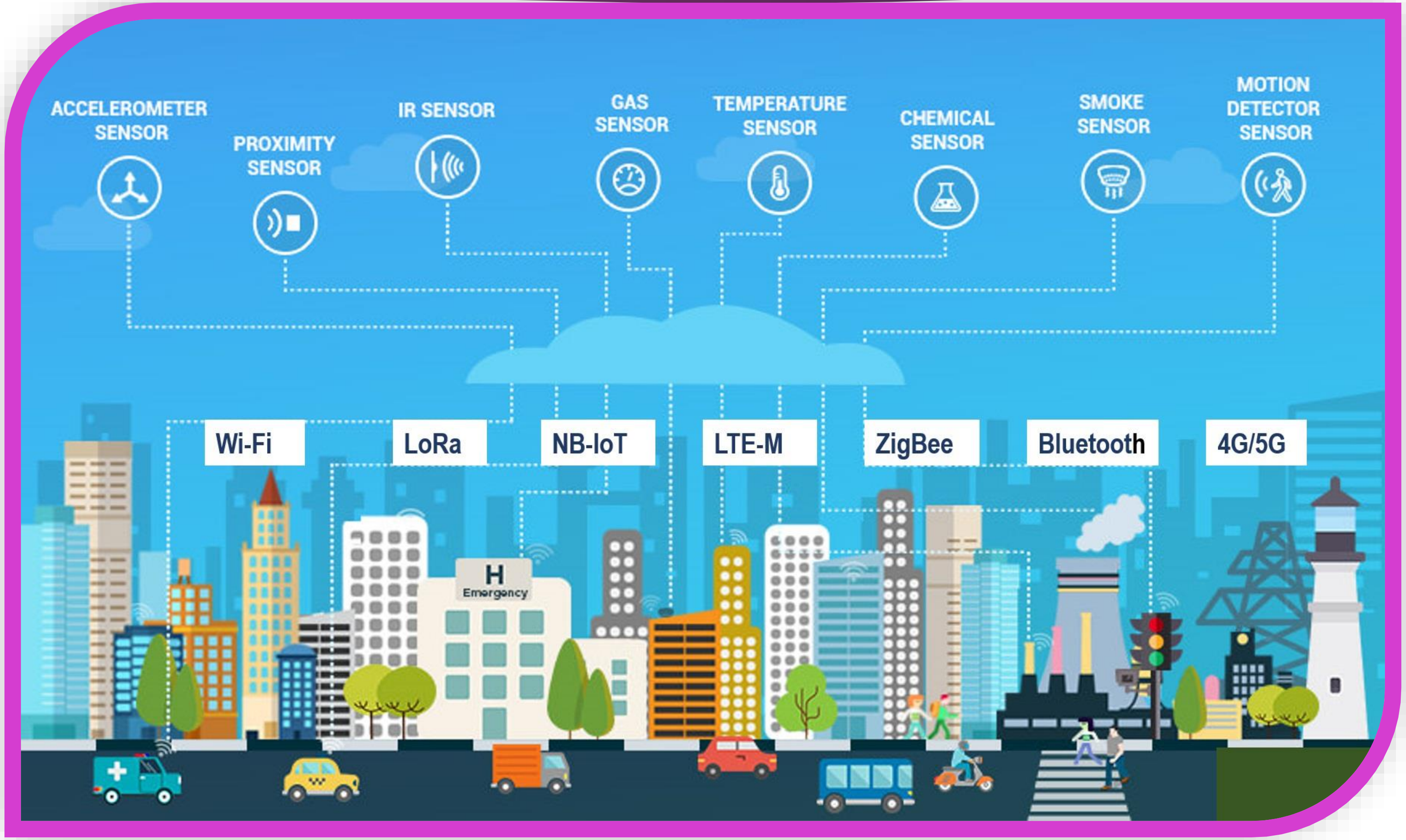
$$V_H = \sqrt{\frac{\alpha V_R^2}{Nf}}$$

Other electronic noise

- Shot noise
  - Associated with pn junctions $S_n(f) = 2q_e I_{DC}$
- Flicker noise (also 1/f)
  - Associated with trap charge states in diodes and FETs
- Amplifier noise
  - Multiple factors, depends on op-amp type, see Senturia
  - Example: AD624 instrumentation amplifiers have
    - 4nV/rtHz voltage noise at low frequencies
    - 200fA/rtHz current noise above 10Hz

Reference : Stanford University. Stanford online

IoT Sensor Deployment



IoT Sensor Deployment - Challenges

- **Variety of sensors and chipsets**
  - There is an increasing number of commercial launches of cellular technologies like NB-IoT, Cat-M1/M2, LTE-M, LoRa, etc.
  - Each of these technologies has specific electronics for sensing endpoints.
  - Although the cost of mobile chipsets has been declining over time, currently there's no cost-effective solution that can work with the widespread in electronics of the cellular-connected IoT sensors to measure connectivity parameters.

IoT Sensor Deployment - Challenges

- **Identify an optimal location to deploy sensor**
  - Whether it is factory floor or a smart building, it's never easy to identify the perfect spot to deploy IoT sensor
  - Sensor must be located near the input source and also where the network signal strength is reliable
  - Unreliable connectivity results in a poor sensor performance which in turn affects the performance overall IoT solution and impacts the customer experience

Picking sensors

Automotive Applications:

- What might you want to measure for each?
- What sensors might you use?
- How will you use the data?
  - Seat occupancy
  - Airbag deployment
  - Tire pressure monitoring system
  - Cruise control

Seat Occupancy

- Required for Seat belt alarm
- Strain gauge or a load cell to identify weight
- What if, we put some stuff on seat
  - Put electric plates in seat which can measure relative permittivity
  - Person has relative permittivity 80 times more that air

Airbag Deployment

- Accelerometer – during crash, it might experience a large transition in the direction of motion. So it's good for forward motion crashes.
- What if someone hits you from side?
  - Pressure Sensor
- For side curtain airbags and door airbags?
  - Gyroscopes

Reference : Stanford University. Stanford online

Tire Pressure

- Only pressure sensor?
- Valve stem – radio, pressure Sensor and a battery
- All the four wheels should rotate at the same speed
- Can we use this information for detecting pressure change wrt one of the tire?

Cruise control

- Measure the difference between desired speed and actual speed
- Use some kind of actuator that moves the underneath pedal

Thank you!