

Interfacing Techniques

Instructor

Dr. Wasel Ghanem

[Email:ghanem@birzeit.edu](mailto:ghanem@birzeit.edu)

The content of these slides is a collection of different resources

Objectives of the Course

- ▶ Introduce the fundamentals of intelligent sensor systems:
 - sensors, instrumentation, interfacing techniques and pattern analysis
- ▶ Provide the students with an integrative and **multidisciplinary** experience by building a complete multi-sensor intelligent system
- ▶ Allow the students to develop data acquisition and software using modern interfacing techniques and software tools required

Intelligent Sensor Systems

▶ System

- A combination of two or more elements, subsystems and parts necessary to carry out one or more functions
- To interact with the real world, a system requires
 - Sensors: inputs devices
 - Actuators: output devices
 - Processing: signals, information and knowledge

▶ Sensor

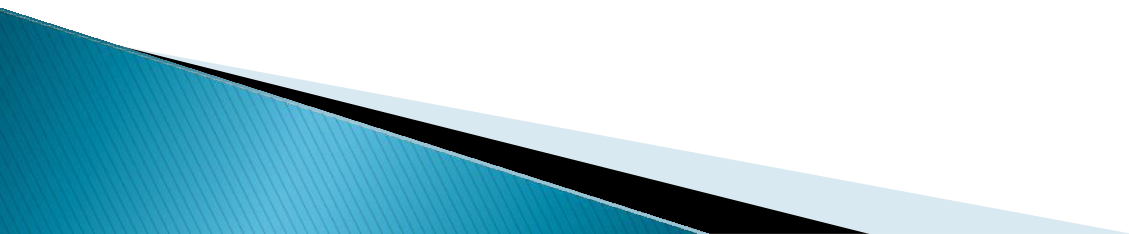
- A device that receives and responds to a stimulus
 - Stimulus: mechanical, thermal, magnetic, electric, optical, chemical...
 - Response: an electrical signal (in most cases)

▶ Intelligence

- The ability to combine
 - A priori knowledge (available before experience) and
 - Adaptive learning (from experience)

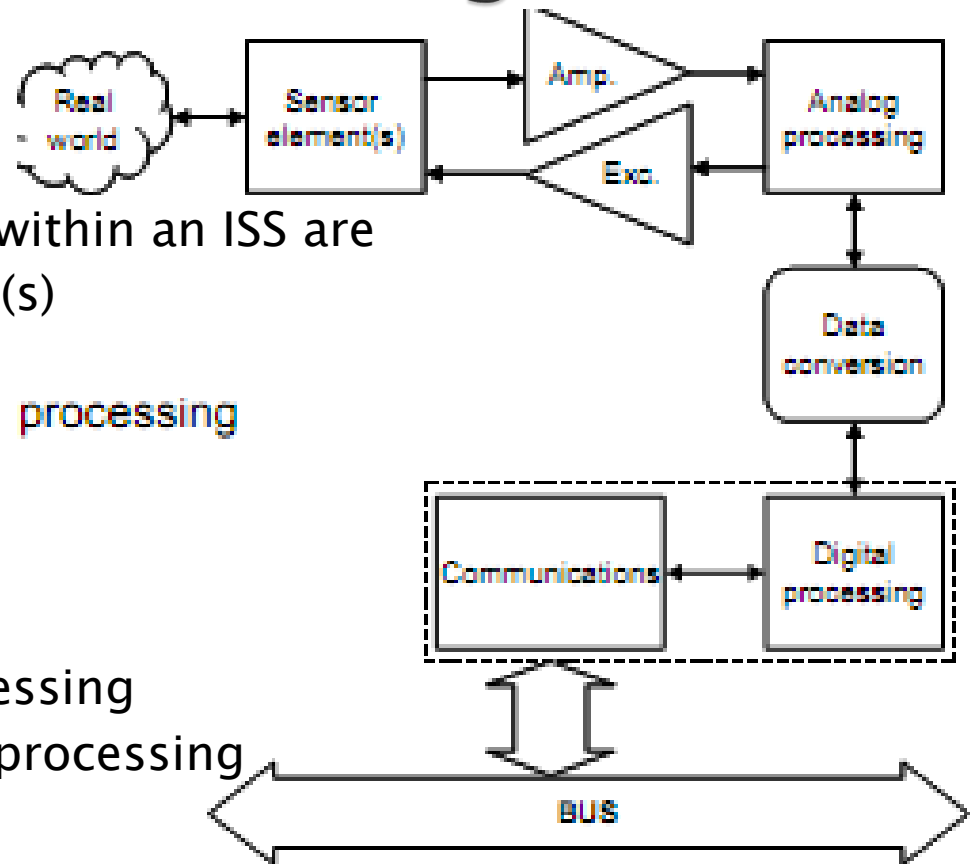
Intelligent Sensor System

- ▶ Several definitions are available
 - A sensor that is capable of modifying its internal behavior to optimize the collection of data from the external world
 - The concepts of adaptation and compensation are central to the Intelligent Sensor philosophy
 - A device that combines a sensing element and a signal processor on a single integrated circuit
 - The minimum requirements of the signal processor are not clear
 - Basic integrated electronics (signal conditioning, ADC)
 - A micro-processor
 - Logic functions and decision making
 - A smart sensor is a sensor that provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity (IEEE 1451.2)
 - This function typically simplifies the integration of the transducer into applications in a networked environment
 - “Intelligent” or “Smart” Sensors?

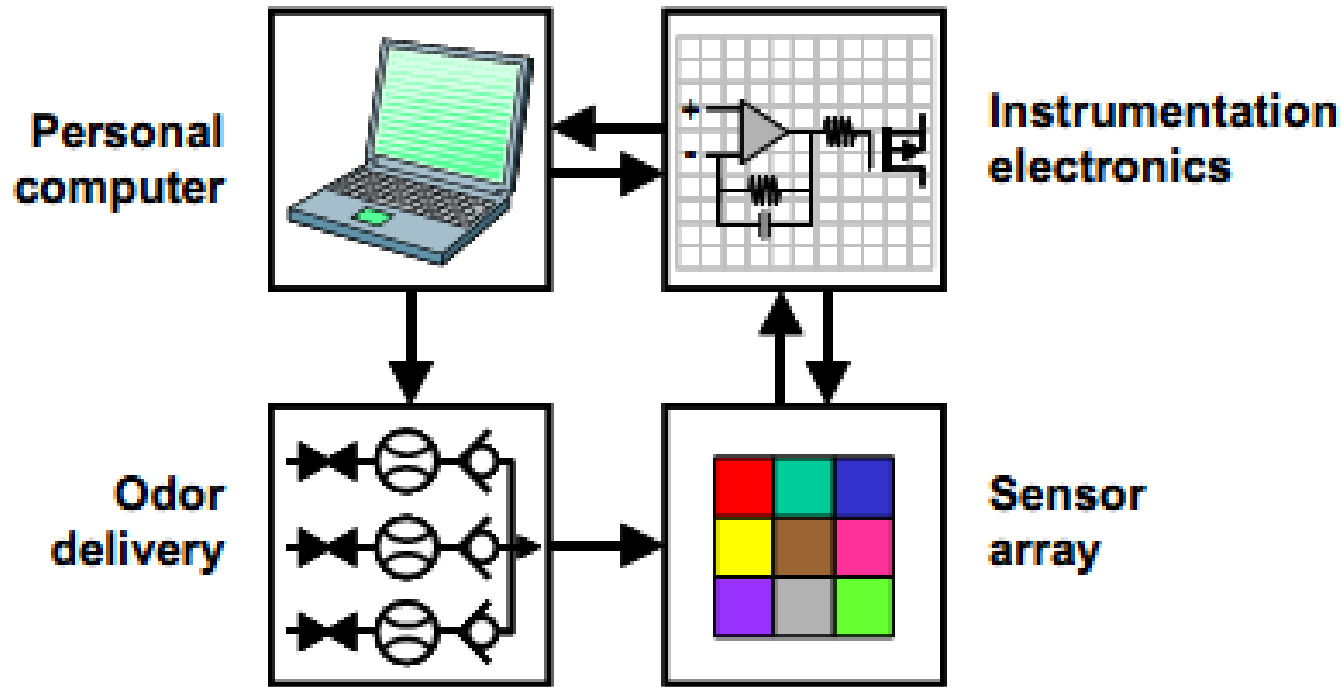


Building blocks of Intelligent Sensors

- ▶ The principal sub-systems within an ISS are
 - Primary sensing element(s)
 - Excitation control
 - Amplification
 - Analogue filtering
 - Data conversion
 - Compensation
 - Digital information processing
 - Digital communications processing



The E-nose: a model ISS

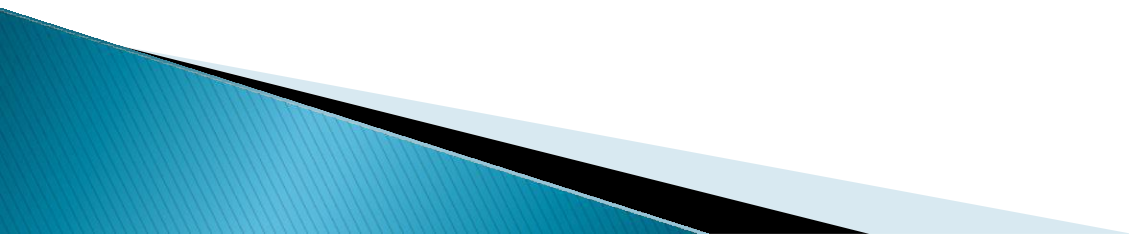


An electronic nose (e-nose) is a device that identifies the specific components of an odor and analyzes its chemical makeup to identify it. An electronic nose consists of a mechanism for chemical detection, such as an array of electronic sensors, and a mechanism for pattern recognition, such as a [neural network](#)

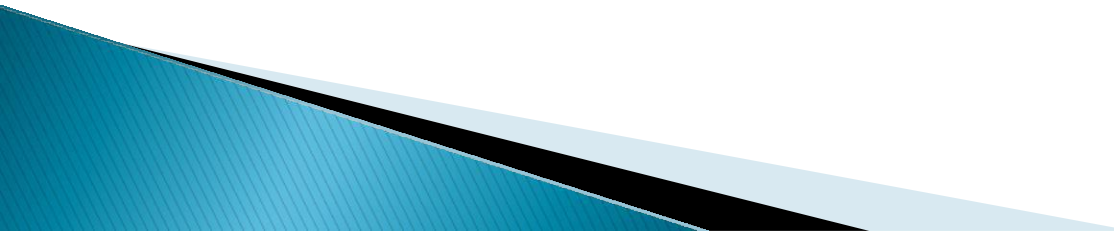
Applications.....

Need to diagnose an illness in a hurry? Scientists are developing an 'electronic nose' app for smart phones

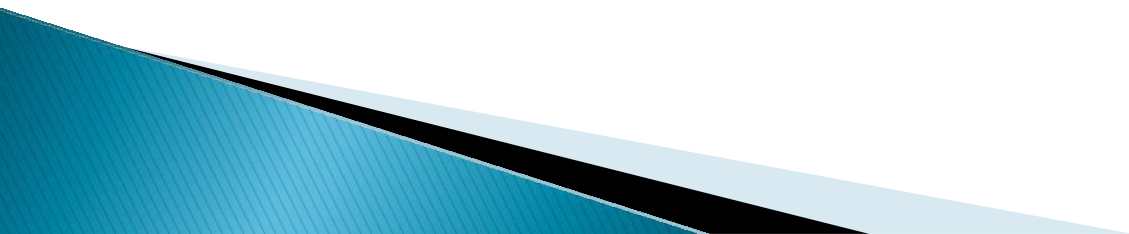
Researchers are working to manufacture a smart phone attachment that works when used in conjunction with what they call sensory vapour technology



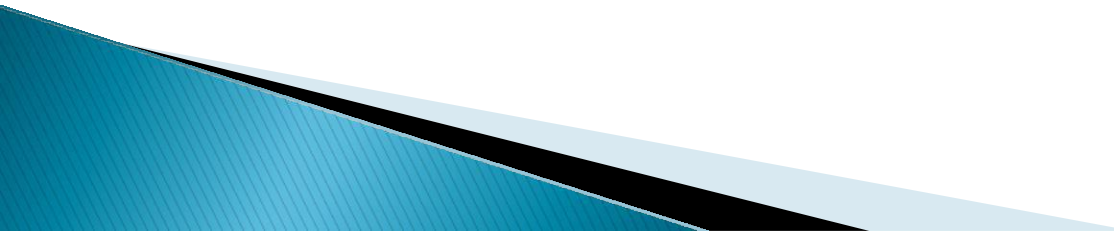
List of videos about ISS

- ▶ **Track Everything– the Internet of Things**
 - ▶ **The Internet of Things**
 - ▶ **System of Systems**
- 

NEW Part...



Sensor characteristics

- ▶ Transducers, sensors and measurements
 - ▶ Calibration, interfering and modifying inputs
 - ▶ Static sensor characteristics
 - ▶ Dynamic sensor characteristics
- 

Transducers: sensors and actuators

▶ Transducer

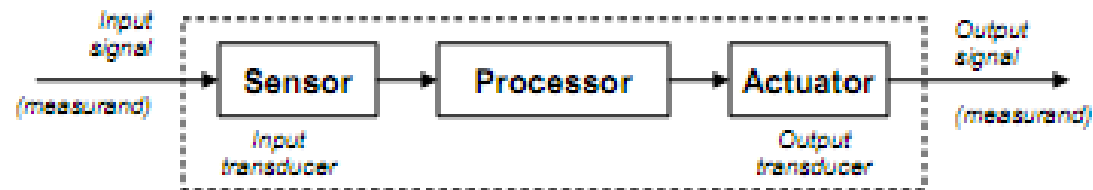
- A device that converts a signal from one physical form to a corresponding signal having a different physical form
 - Physical form: mechanical, thermal, magnetic, electric, optical, chemical...
- Transducers are ENERGY CONVERTERS or MODIFIERS

▶ Sensor

- A device that receives and responds to a signal or stimulus
 - This is a broader concept that includes the extension of our perception capabilities to acquire information about physical quantities

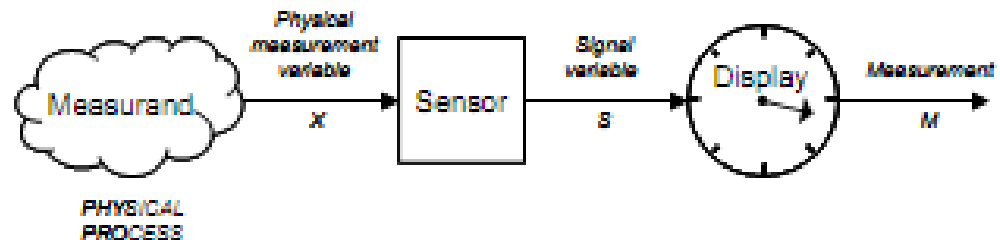
▶ Transducers: sensors and actuators

- Sensor: an input transducer (i.e., a microphone)
- Actuator: an output transducer (i.e., a loudspeaker)



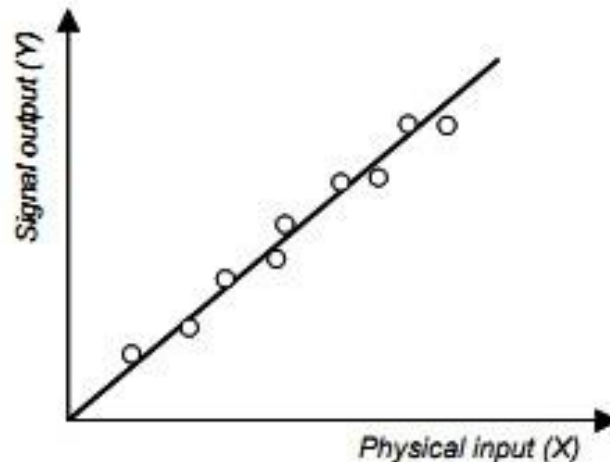
Measurements

- ▶ A simple instrument model
 - A observable variable X is obtained from the measurand
 - X is related to the measurand in some KNOWN way (i.e., measuring mass)
- ▶ The sensor generates a signal variable that can be manipulated:
 - Processed, transmitted or displayed
- ▶ In the example above the signal is passed to a display, where a measurement can be taken
- ▶ Measurement
 - The process of comparing an unknown quantity with a standard of the same quantity (measuring length) or standards of two or more related quantities (measuring velocity)



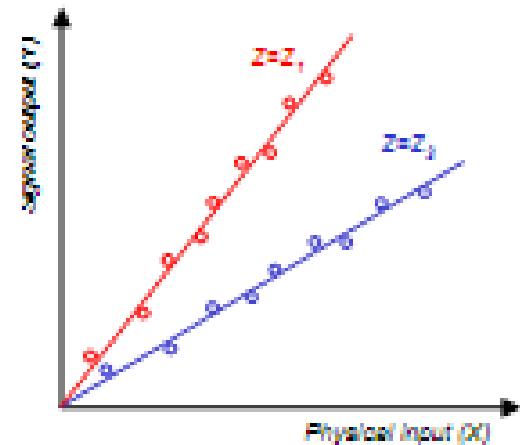
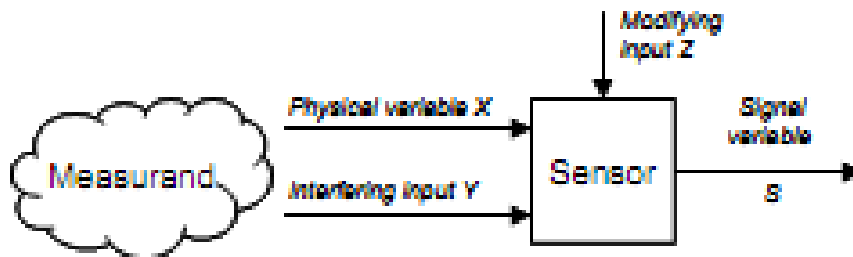
Calibration

- ▶ The relationship between the physical measurement variable (X) and the signal variable (S)
 - 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: $S(aX+bY)=aS(X)+bS(Y)$
- ▶ Modifying inputs (Z)
 - Those that change the behavior of the sensor and, hence, the calibration curve
 - Temperature is a typical modifying input



Sensor characteristics

▶ Static characteristics

- The properties of the system after all transient effects have settled to their final or steady state
 - Accuracy
 - Discrimination
 - Precision
 - Errors
 - Drift
 - Sensitivity
 - Linearity
 - Hysteresis (backslash)

▶ Dynamic characteristics

- The properties of the system transient response to an input
 - Zero order systems
 - First order systems
 - Second order systems

Accuracy, discrimination and precision

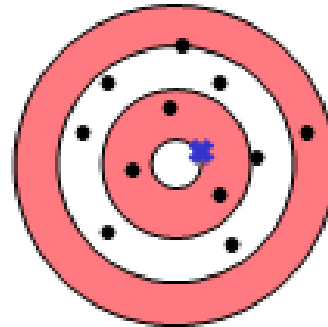
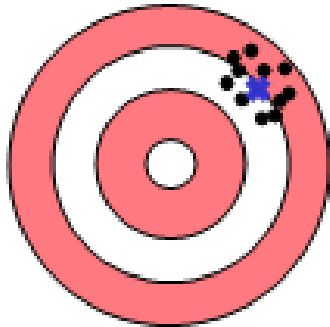
- ▶ Accuracy is the capacity of a measuring instrument to give RESULTS close to the TRUE VALUE of the measured quantity
 - Accuracy is related to the bias of a set of measurements
 - (IN)Accuracy is measured by the absolute and relative errors
- ▶ Discrimination is the minimal change of the input necessary to produce a detectable change at the output
 - Discrimination is also known as RESOLUTION
 - When the increment is from zero, it is called THRESHOLD

Precision

- ▶ The capacity of a measuring instrument to give the same reading when repetitively measuring the same quantity under the same prescribed conditions
 - Precision implies agreement between successive readings, NOT closeness to the true value
 - Precision is related to the variance of a set of measurements
 - Precision is a necessary but not sufficient condition for accuracy
- ▶ Two terms closely related to precision
 - Repeatability
 - The precision of a set of measurements taken over a short time interval
 - Reproducibility
 - The precision of a set of measurements BUT
 - taken over a long time interval or
 - Performed by different operators or
 - with different instruments or
 - in different laboratories

▶ Shooting darts

- Discrimination
 - The size of the hole produced by a dart
- Which shooter is more accurate?
- Which shooter is more precise?



 mean

Accuracy and errors

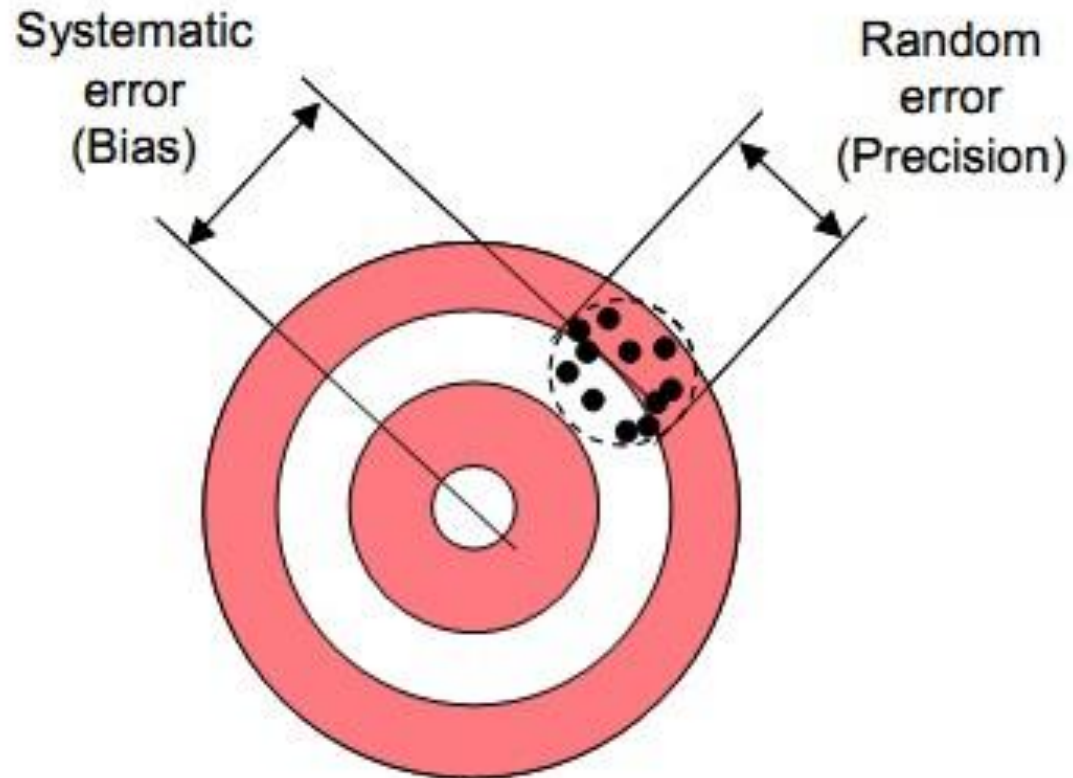
▶ Systematic errors

- Result from a variety of factors
 - Interfering or modifying variables (i.e., temperature)
 - Drift (i.e., changes in chemical structure or mechanical stresses)
 - The measurement process changes the measurand (i.e., loading errors)
 - The transmission process changes the signal (i.e., attenuation)
 - Human observers (i.e., parallax errors)
- Systematic errors can be corrected with COMPENSATION methods (i.e.,
 - feedback, filtering)

▶ Random errors

- Also called NOISE: a signal that carries no information
- True random errors (white noise) follow a Gaussian distribution
- Sources of randomness:
 - Repeatability of the measurand itself (i.e., height of a rough surface)
 - Environmental noise (i.e., background noise picked by a microphone)
 - Transmission noise (i.e., 60Hz hum)
- Signal to noise ratio (SNR) should be $\gg 1$
 - With knowledge of the signal characteristics it may be possible to interpret a signal with a low SNR (i.e., understanding speech in a loud environment)

Example: systematic and random errors

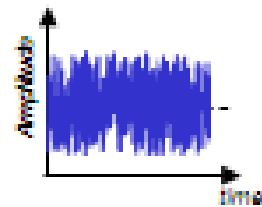
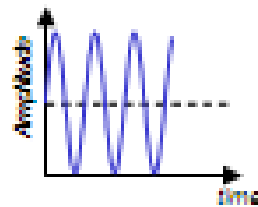
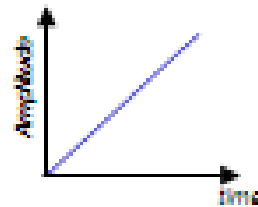
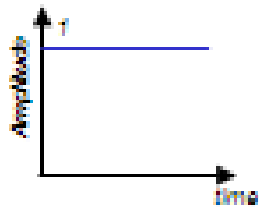
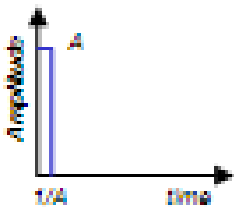


More static characteristics

- ▶ **Input range**
 - The maximum and minimum value of the physical variable that can be measured (i.e., $-40^{\circ}\text{F}/100^{\circ}\text{F}$ in a thermometer)
 - Output range can be defined similarly
- ▶ **Sensitivity**
 - The slope of the calibration curve $y=f(x)$
 - An ideal sensor will have a large and constant sensitivity
 - Sensitivity-related errors: saturation and “dead-bands”
- ▶ **Linearity**
 - The closeness of the calibration curve to a specified straight line (i.e., theoretical behavior, least-squares fit)
- ▶ **Monotonicity**
 - A monotonic curve is one in which the dependent variable always increases or decreases as the independent variable increases
- ▶ **Hysteresis**
 - The difference between two output values that correspond to the same input depending on the trajectory followed by the sensor (i.e., magnetization in ferromagnetic materials)
 - Backslash: hysteresis caused by looseness in a mechanical joint

Dynamic characteristics

- ▶ The sensor response to a variable input is different from that exhibited when the input signals are constant (the latter is described by the static characteristics)
- ▶ The reason for dynamic characteristics is the presence of energy-storing elements
 - Inertial: masses, inductances
 - Capacitances: electrical, thermal
- ▶ Dynamic characteristics are determined by analyzing the response of the sensor to a family of variable input waveforms:
 - Impulse, step, ramp, sinusoidal, white noise...



Dynamic models

- ▶ The dynamic response of the sensor is (typically) assumed to be linear
- Therefore, it can be modeled by a constant-coefficient linear differential equation

$$a_k \frac{d^k y(t)}{dt^k} + \dots + a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = x(t)$$

- In practice, these models are confined to zero, first and second order. Higher order models are rarely applied
- ▶ These dynamic models are typically analyzed with the Laplace transform, which converts the differential equation into a polynomial expression
- Think of the Laplace domain as an extension of the Fourier transform
 - Fourier analysis is restricted to sinusoidal signals
 - $x(t) = \sin(\omega t) = e^{-j\omega t}$
 - Laplace analysis can also handle exponential behavior
 - $x(t) = e^{-\sigma t} \sin(\omega t) = e^{-(\sigma + j\omega)t}$

The Laplace Transform (review)

- ▶ The Laplace transform of a time signal $y(t)$ is denoted by
 - $L[y(t)] = Y(s)$
 - The s variable is a complex number $s = \sigma + j\omega$
 - The real component σ defines the real exponential behavior
 - The imaginary component defines the frequency of oscillatory behavior
- ▶ The fundamental relationship is the one that concerns the transformation of differentiation

$$L\left[\frac{d}{dt}y(t)\right] = sY(s) - f(0)$$

■ Other useful relationships are

Impulse: $L[\delta(t)] = 1$

Decay: $L[\exp(at)] = (s - a)^{-1}$

Step: $L[u(t)] = \frac{1}{s}$

Sine: $L[\sin(\omega t)] = \frac{\omega}{s^2 + \omega^2}$

Ramp: $L[r(t)] = \frac{1}{s^2}$

Cosine: $L[\cos(\omega t)] = \frac{s}{s^2 + \omega^2}$

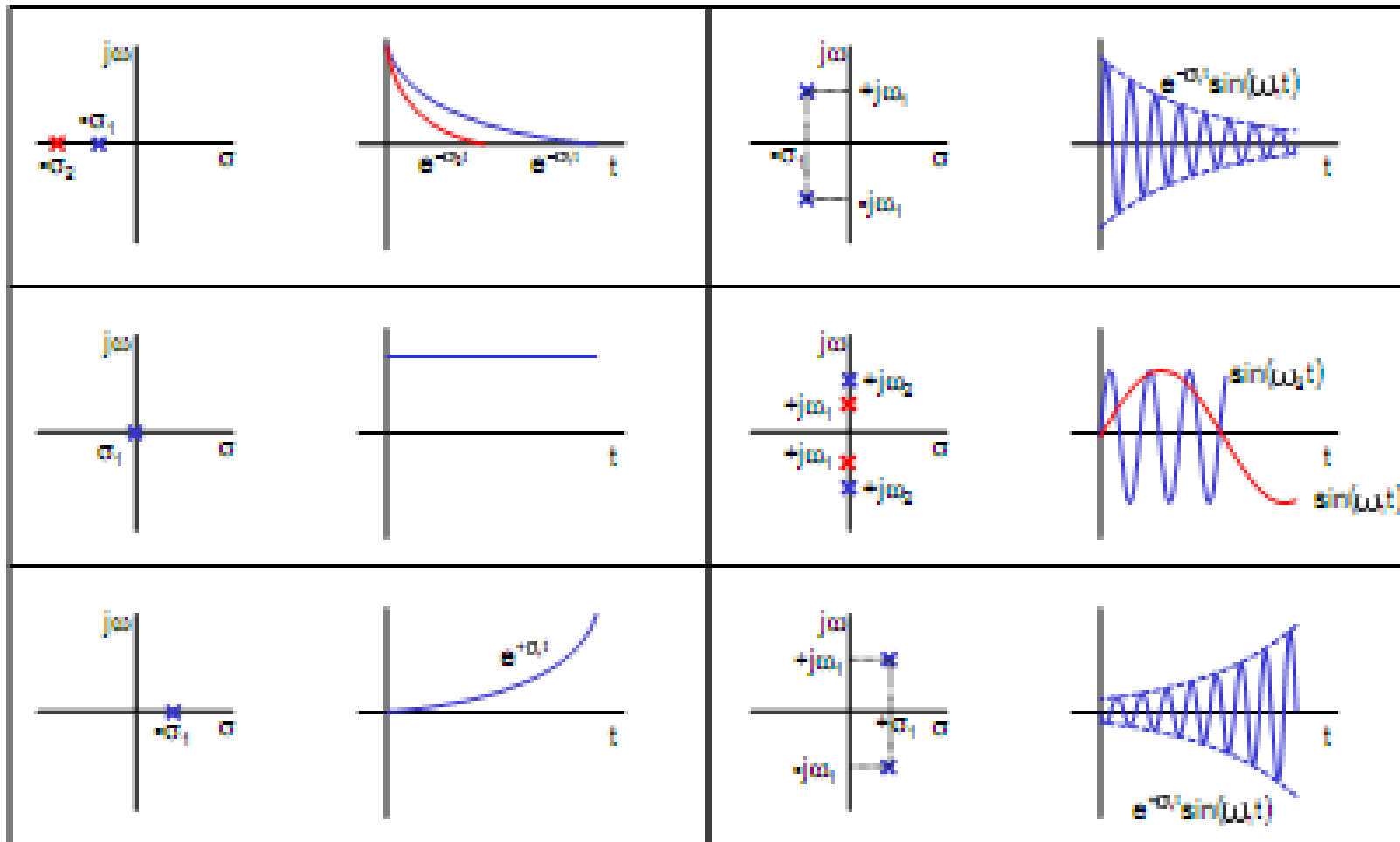
The Laplace Transform (review)

- ▶ Applying the Laplace transform to the sensor model yields

$$\begin{aligned} & \mathcal{L} \left[a_k \frac{d^k y}{dt^k} + \dots + a_2 \frac{d^2 y}{dt^2} + a_1 \frac{dy}{dt} + a_0 y(t) = x(t) \right] \\ & \quad \Downarrow \\ & (a_k s^k + \dots + a_2 s^2 + a_1 s + a_0) Y(s) = X(s) \\ & \quad \Downarrow \\ & G(s) = \frac{Y(s)}{X(s)} = \frac{1}{a_k s^k + \dots + a_2 s^2 + a_1 s + a_0} \end{aligned}$$

- $G(s)$ is called the transfer function of the sensor
- The position of the poles of $G(s)$ – zeros of the denominator – in the s -plane determines the dynamic behavior of the sensor such as
 - Oscillating components
 - Exponential decays
 - Instability

Pole location and dynamic behavior

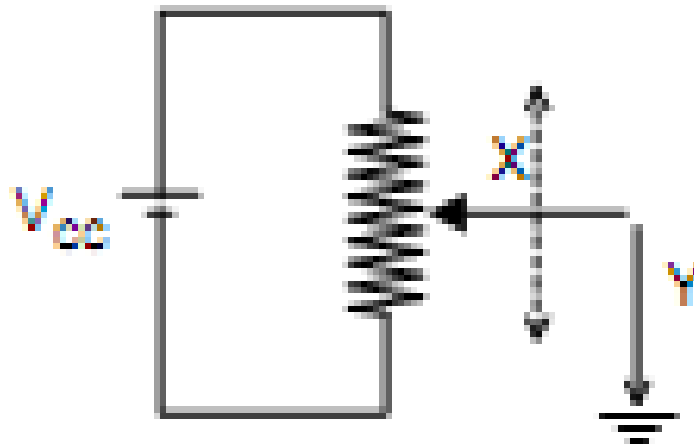


Zero-order sensors

- ▶ Input and output are related by an equation of the type
 - Zero-order is the desirable response of a sensor

$$y(t) = k \cdot x(t) \Rightarrow \frac{Y(s)}{X(s)} = k$$

- No delays
- Infinite bandwidth
- The sensor only changes the amplitude of the input signal
- Zero-order systems do not include energy-storing elements
- Example of a zero-order sensor
 - A potentiometer used to measure linear and rotary displacements
 - This model would not work for fast-varying displacements



First-order sensors

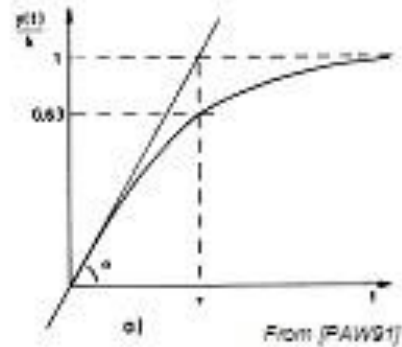
- ▶ Inputs and outputs related by a first-order differential equation

$$a_1 \frac{dy}{dt} + a_0 y(t) = x(t) \Rightarrow \frac{Y(s)}{X(s)} = \frac{1}{a_1 s + a_0} = \frac{k}{\tau s + 1}$$

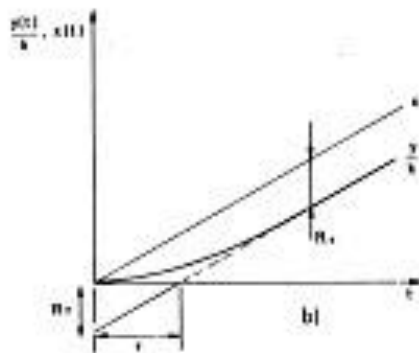
- First-order sensors have one element that stores energy and one that dissipates it
- Step response
 - $y(t) = Ak(1 - \exp(-t/\tau))$
 - A is the amplitude of the step
 - k (=1/a₀) is the static gain, which determines the static response
 - τ (=a₁/a₀) is the time constant, which determines the dynamic response
- Ramp response
 - $y(t) = Akt - Ak\tau u(t) + Ak\tau \exp(-t/\tau)$
- Frequency response
 - Better described by the amplitude and phase shift plots

First-order sensor response

Step response

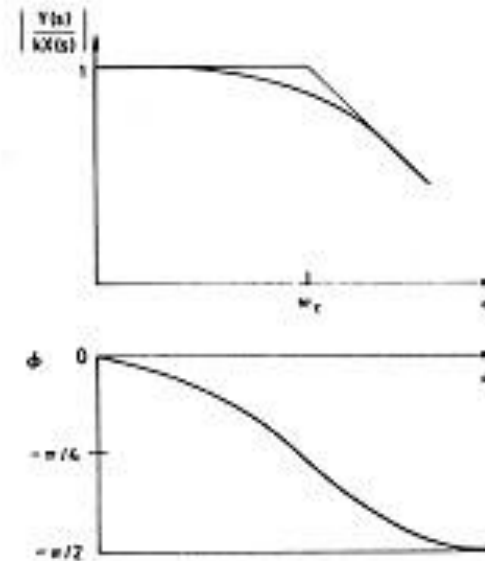


Ramp response



Frequency response

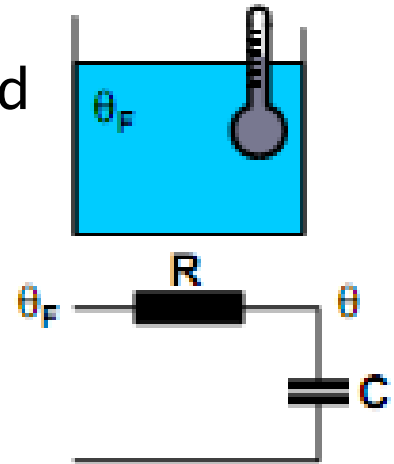
- Corner frequency $\omega_c = 1/\tau$
- Bandwidth



Example of a first-order sensor

- ▶ A mercury thermometer immersed into a fluid

- What type of input was applied to the sensor?
- Parameters
 - C: thermal capacitance of the mercury
 - R: thermal resistance of the glass to heat transfer
 - θ_F : temperature of the fluid
 - $\theta(t)$: temperature of the thermometer
- The equivalent circuit is an RC network



- ▶ Derivation

- Heat flow through the glass $(\theta_F - \theta(t))/R$
- Temperature of the thermometer rises as
- Taking the Laplace transform

$$\frac{d\theta(t)}{dt} = \frac{\theta_F - \theta(t)}{RC}$$

$$\begin{aligned} s\theta(s) &= \frac{\theta_F(s) - \theta(s)}{RC} \Rightarrow (RCs + 1)\theta(s) = \theta_F(s) \Rightarrow \\ &\Rightarrow \theta(s) = \frac{\theta_F(s)}{(RCs + 1)} \Rightarrow \theta(t) = \theta_F(1 - e^{-t/RC}) \end{aligned}$$

Second-order sensors

- ▶ Inputs and outputs are related by a second-order differential equation

$$a_2 \frac{d^2 y}{dt^2} + a_1 \frac{dy}{dt} + a_0 y(t) = x(t) \Rightarrow \frac{Y(s)}{X(s)} = \frac{1}{a_2 s^2 + a_1 s + a_0}$$

- We can express this second-order transfer function as

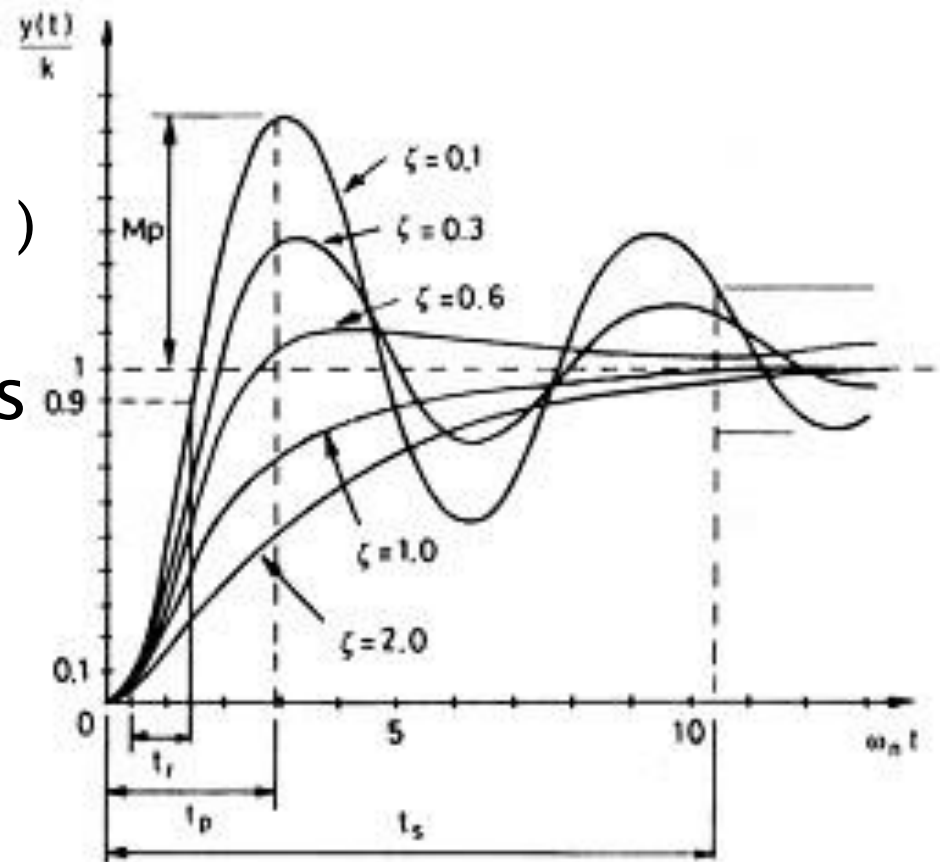
$$\frac{Y(s)}{X(s)} = \frac{k \omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2}$$

$$\text{with } k = \frac{1}{a_0}, \zeta = \frac{a_1}{2\sqrt{a_0 a_2}}, \omega_n = \sqrt{\frac{a_0}{a_2}}$$

- Where
 - k is the static gain
 - ζ is known as the damping coefficient
 - ω_n is known as the natural frequency

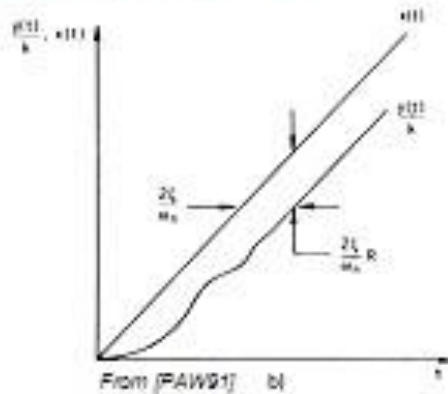
Second-order step response

- ▶ Response types
 - Underdamped ($\zeta < 1$)
 - Critically damped ($\zeta = 1$)
 - Overdamped ($\zeta > 1$)
- ▶ Response parameters
 - Rise time (t_r)
 - Peak overshoot (M_p)
 - Time to peak (t_p)
 - Settling time (t_s)

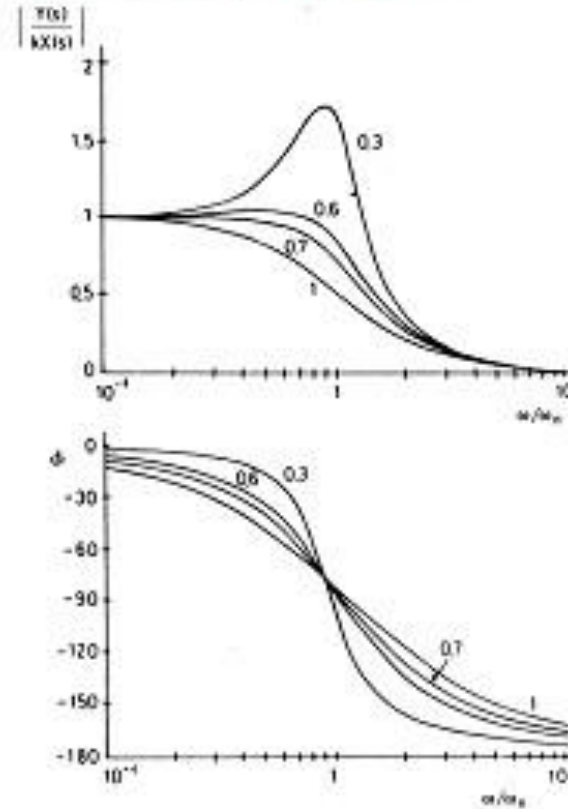


Second-order response

■ Ramp response



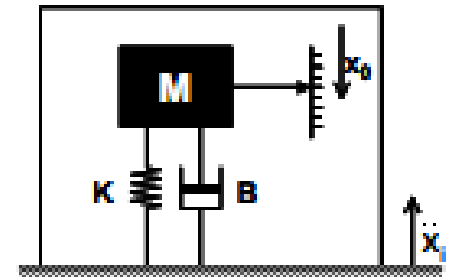
■ Frequency response



Example of second-order sensors

- ▶ A thermometer covered for protection
 - Adding the heat capacity and thermal resistance of the protection yields a second-order system with two real poles (overdamped)
- ▶ Spring-mass-dampen accelerometer
 - The armature suffers an acceleration
 - We will assume that this acceleration is orthogonal to the direction of gravity
 - x_0 is the displacement of the mass M with respect to the armature
 - The equilibrium equation is:

$$\begin{aligned} M(\ddot{x}_1 - \ddot{x}_0) &= Kx_0 + B\dot{x}_0 \\ \Downarrow \\ Ms^2 X_1(s) &= X_0(s) [K + Bs + Ms^2] \\ \Downarrow \\ \frac{X_0(s)}{s^2 X_1(s)} &= \frac{M}{K} \frac{K/M}{s^2 + s(B/M) + K/M} \end{aligned}$$



HOMEWORK: Using Matlab, develop an accelerometer