Interfacing Techniques

Dr. Wasel Ghanem
Email: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

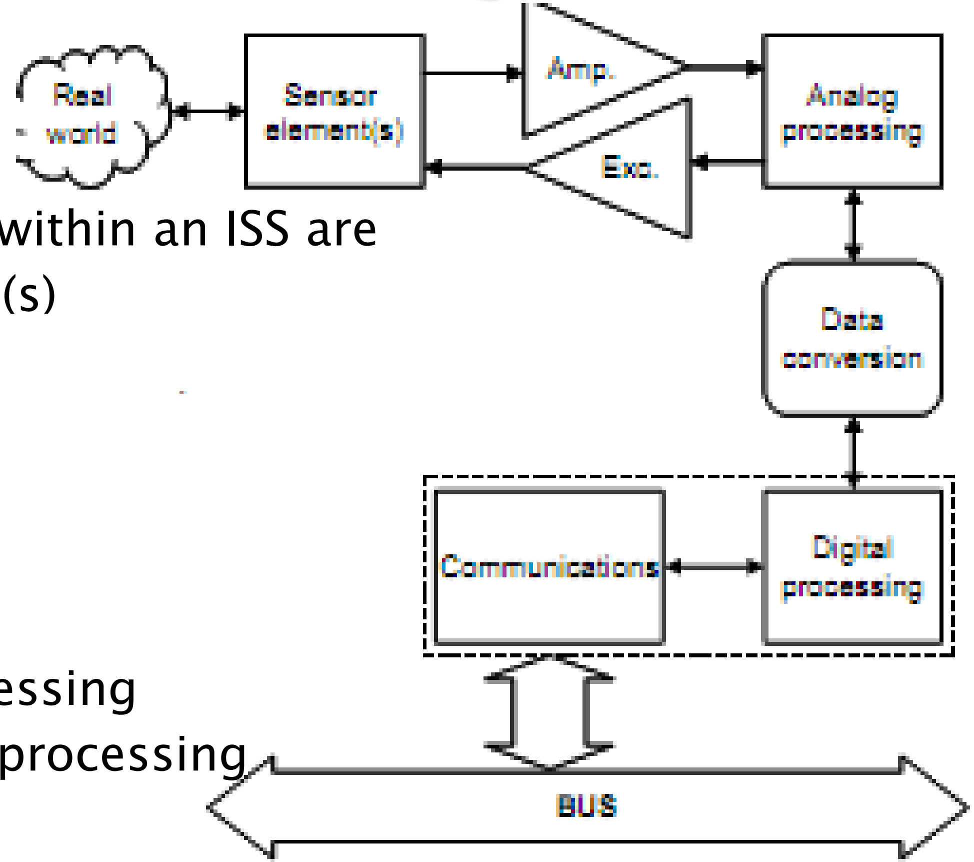
Intelligent Sensor Systems

- 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

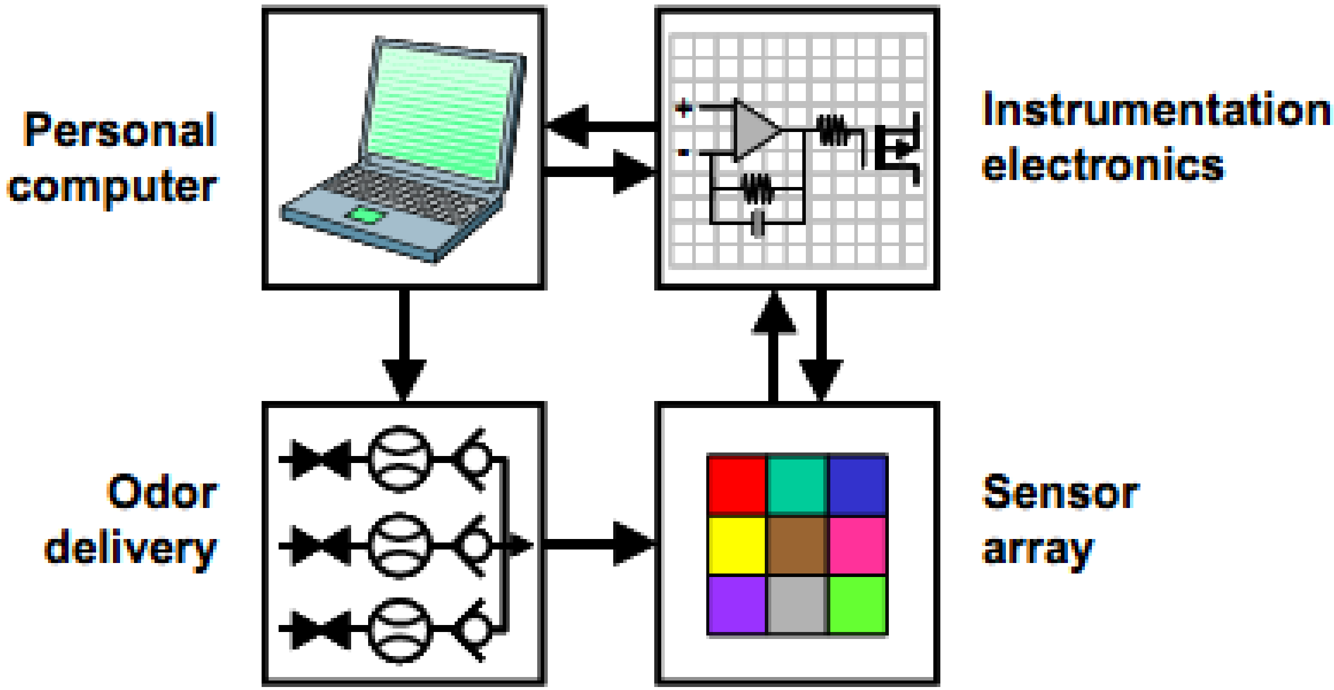
- Several definitions are available
  - A sensor that is capable of modifying its internal behavior to optimize the collection of data from the external world
    - The concepts of adaptation and compensation are central to the Intelligent Sensor philosophy
  - A device that combines a sensing element 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

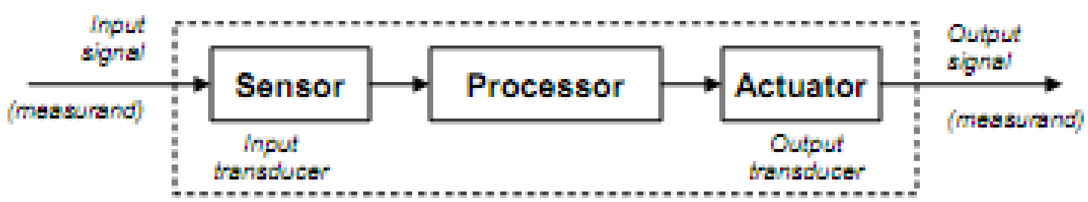
NEW Part…

Sensor characteristics

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

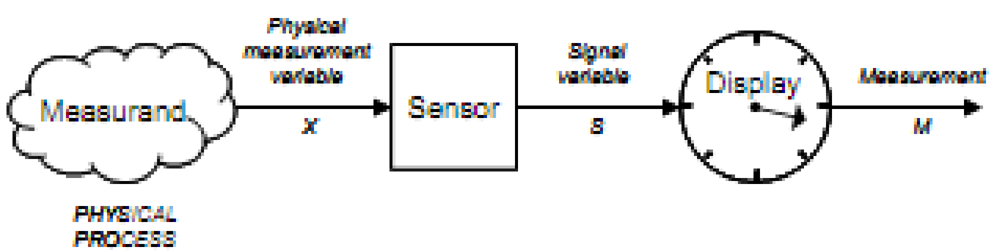
Transducers: sensors and actuators

- 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)



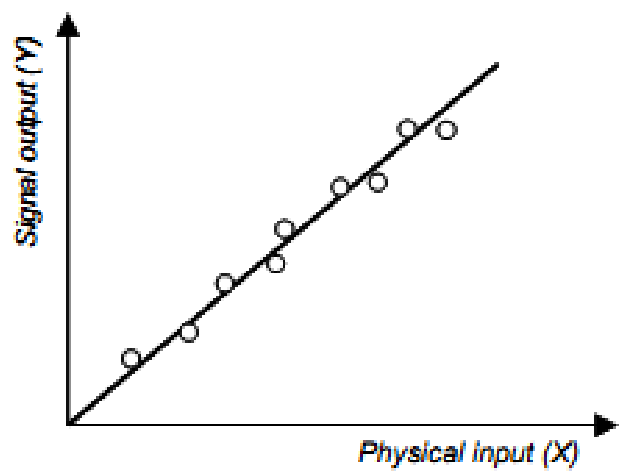
Measurements

- 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)



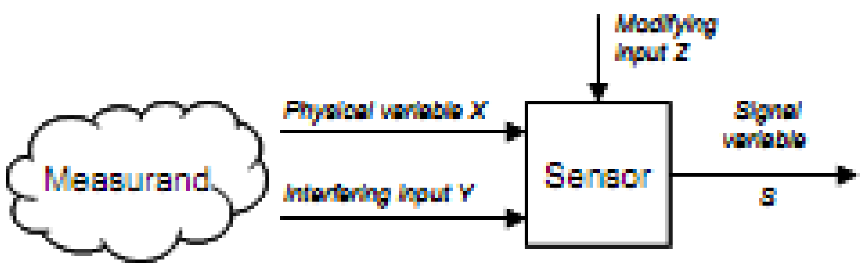
Calibration

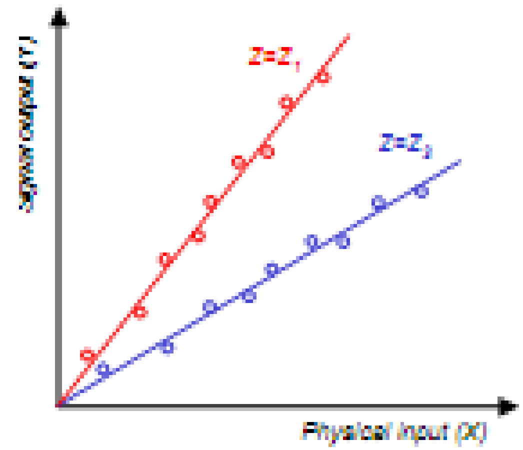
- The relationship between the physical measurement variable (X) and the signal variable (S)
  - A sensor or instrument is calibrated by applying a number of KNOWN physical inputs and recording the response of the system



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
    - Hystheresis (backslash)
- Dynamic characteristics
  - The properties of the system transient response to an input
    - Zero order systems
    - First order systems
    - Second order systems

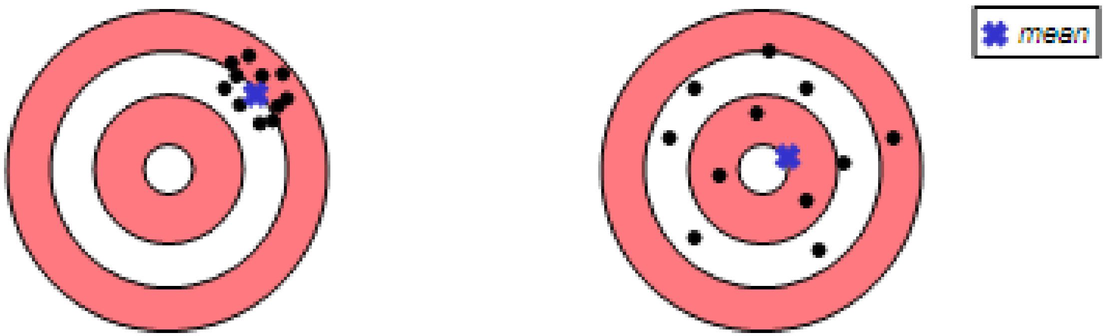
Accuracy, discrimination and precision

- 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

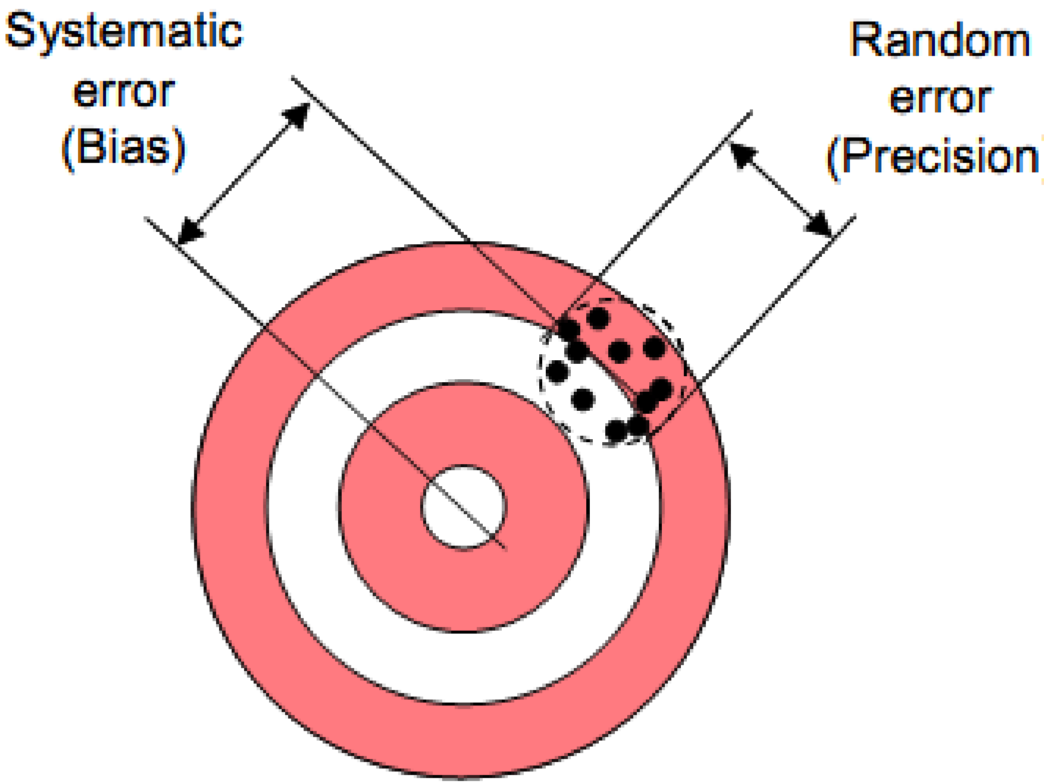
- Shooting darts
  - Discrimination
    - The size of the hole produced by a dart
  - Which shooter is more accurate?
  - Which shooter is more precise?



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 >>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

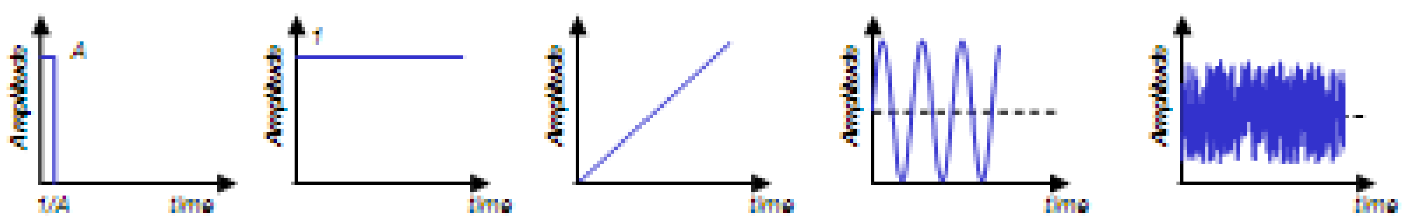


More static characteristics

- Input range
  - The maximum and minimum value of the physical variable that can be measured (i.e., -40F/100F 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
- Hystheresis
  - 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: hystheresis 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

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

  - 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(ωt) = e−jωt
    - Laplace analysis can also handle exponential behavior
      - x(t) = e−σtSin(ωt) = e−(σ +jω)

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

$$\text{Impulse: } L[\delta(t)] = 1 \qquad \text{Decay: } L[\exp(at)] = (s-a)^{-1}$$

$$\text{Step: } L[u(t)] = \frac{1}{s} \qquad \text{Sine: } L[\sin(\omega t)] = \frac{\omega}{s^2+\omega^2}$$

$$\text{Ramp: } L[r(t)] = \frac{1}{s^2} \qquad \text{Cosine: } L[\cos(\omega t)] = \frac{s}{s^2+\omega^2}$$

The Laplace Transform (review)

- Applying the Laplace transform to the sensor model yields

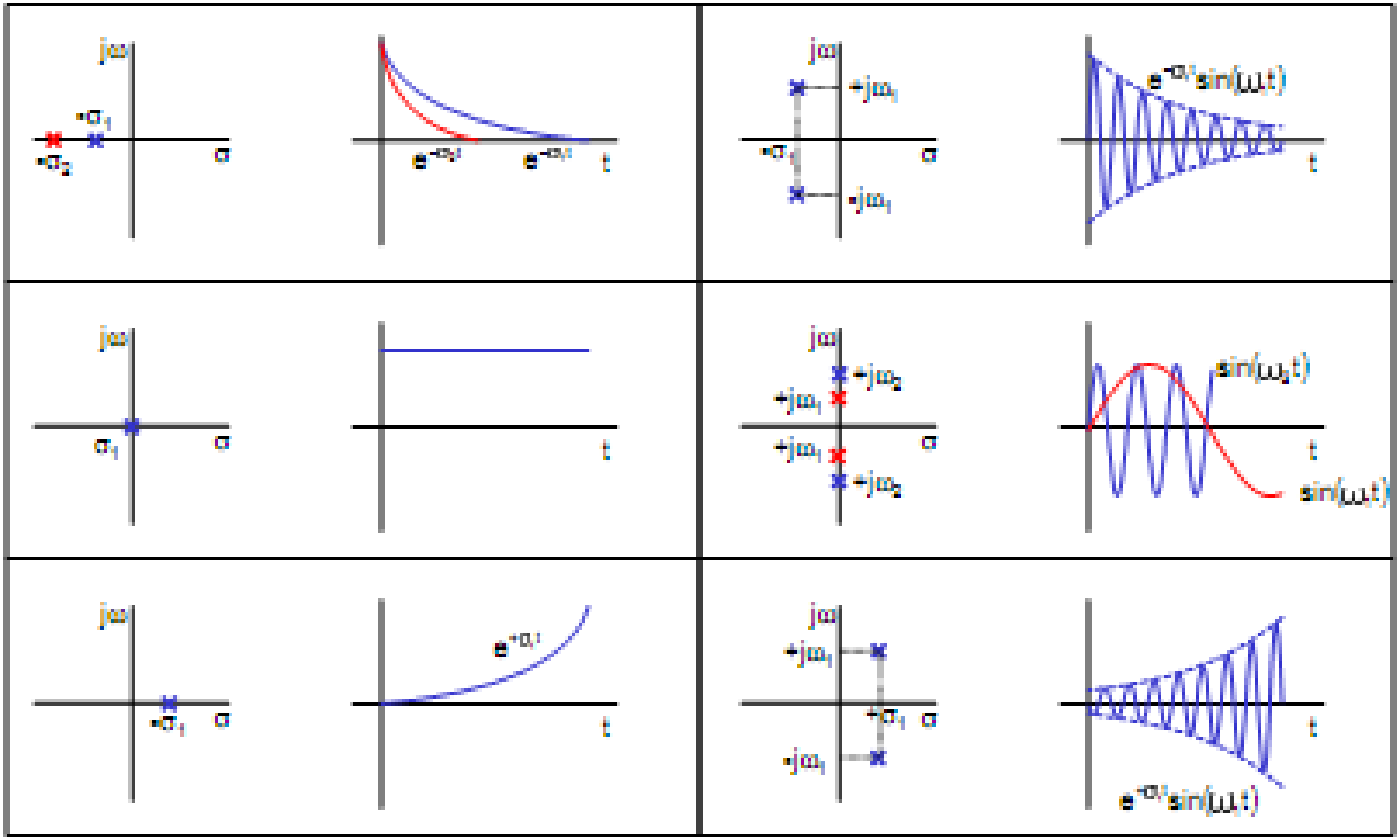
$$L\left[a_k \frac{d^k y}{dt^k} + \cdots a_2 \frac{d^2 y}{dt^2} + a_1 \frac{dy}{dt} + a_o y(t) = x(t)\right]$$
$$\Downarrow$$
$$\left(a_k s^k + \cdots a_2 s^2 + a_1 s + a_o\right) Y(s) = X(s)$$
$$\Downarrow$$
$$G(s) = \frac{Y(s)}{X(s)} = \frac{1}{a_k s^k + \cdots a_2 s^2 + a_1 s + a_o}$$

- 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

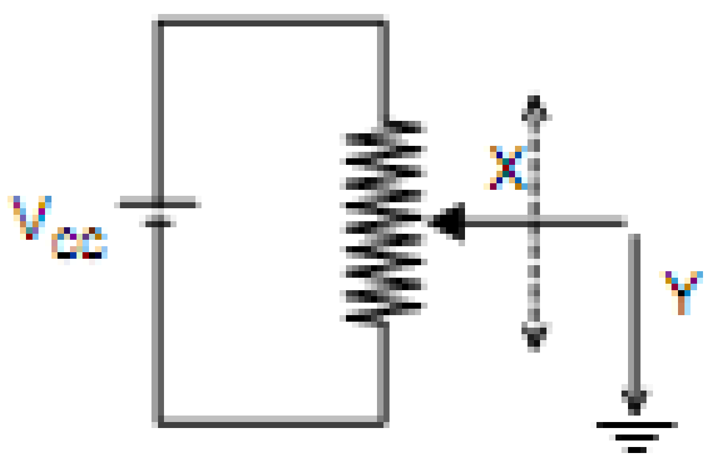


Zero-order sensors

- 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

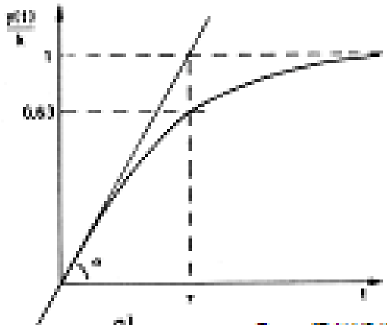
- Inputs and outputs related by a first-order differential equation

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

  - 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

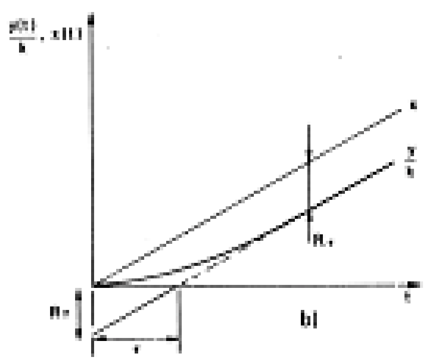
First-order sensor response

- **Step response**

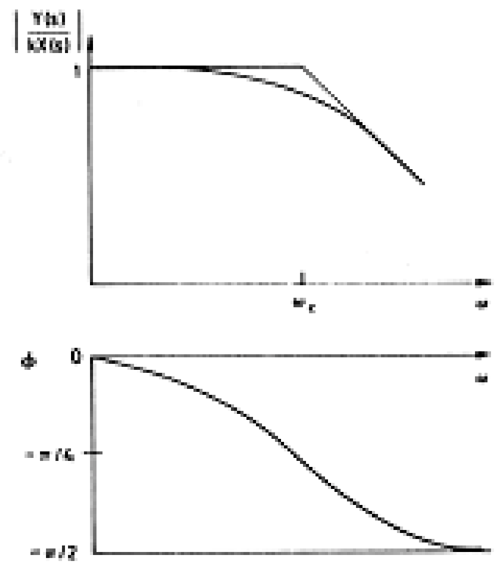


From [PAW91]

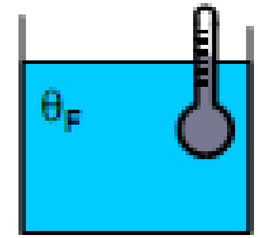
- **Ramp response**



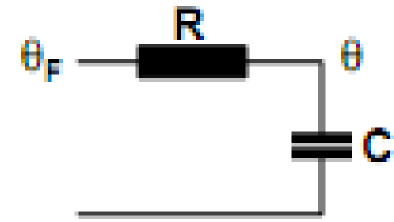
- **Frequency response**
  - Corner frequency $\omega_c = 1/\tau$
  - Bandwidth



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
    - θF: temperature of the fluid
    - θ(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 $\frac{d\theta(t)}{dt} = \frac{\theta_F - \theta(t)}{RC}$
  - Taking the Laplace transform

$$s\,\theta(s) = \frac{\theta_F(s) - \theta(s)}{RC} \Rightarrow (RCs+1)\theta(s) = \theta_F(s) \Rightarrow$$

$$\Rightarrow \theta(s) = \frac{\theta_F(s)}{(RCs+1)} \Rightarrow \theta(t) = \theta_F\left(1 - e^{-t/RC}\right)$$

Second-order sensors

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

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

  - We can express this second-order transfer function as

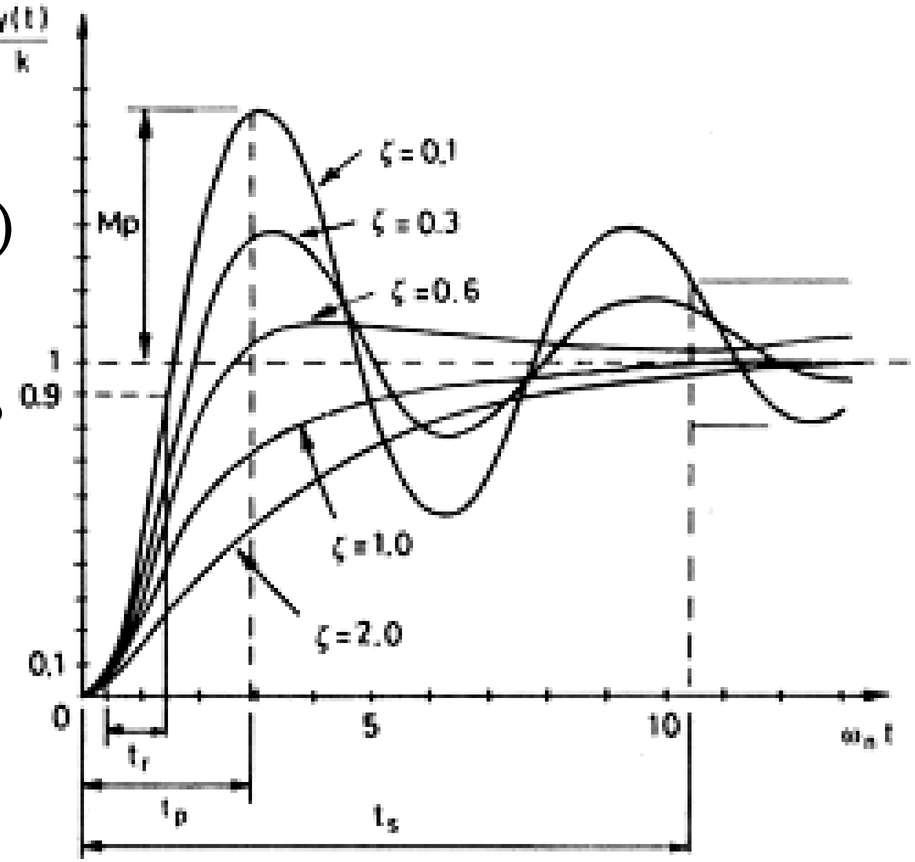
$$\frac{Y(s)}{X(s)} = \frac{k\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

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

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

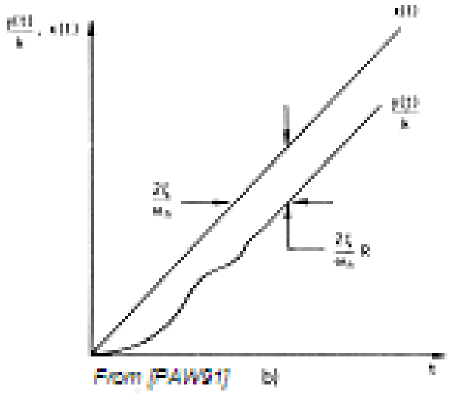
Second-order step response

- Response types
  - Underdamped ($\zeta<1$)
  - Critically damped ($\zeta=1$)
  - Overdamped ($\zeta>1$)
- Response parameters
  - Rise time (tr)
  - Peak overshoot (Mp)
  - Time to peak (tp)
  - Settling time (ts)

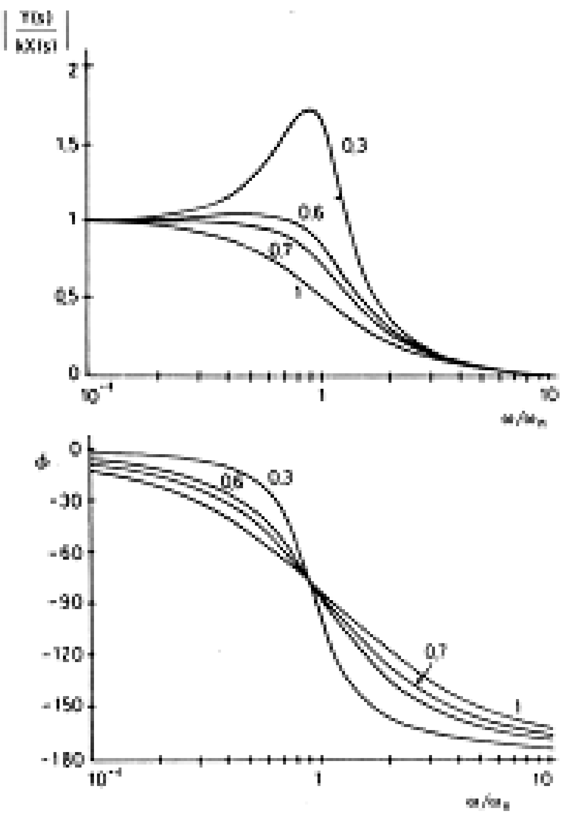


Second–order response

- 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:

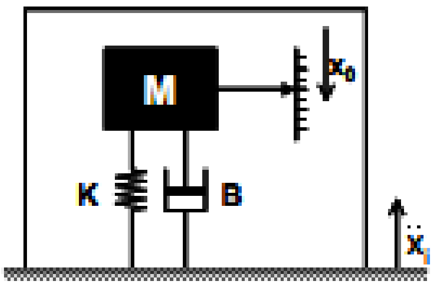
$$M(\ddot{x}_i - \ddot{x}_0) = Kx_0 + B\dot{x}_0$$

$$\Downarrow$$

$$Ms^2X_i(s) = X_0(s)\left[K + Bs + Ms^2\right]$$

$$\Downarrow$$

$$\frac{X_0(s)}{s^2X_i(s)} = \frac{M}{K}\frac{K/M}{s^2 + s(B/M) + K/M}$$



HOMEWORK: Using Matlab, develop an accelerometer

References

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