Principle Operation of Measuring Instruments

Lecture ONE

Reference:

A.K. Sawhney, A *Course in* Electrical *and* Electronic Measurements *and* Instrumentation, DHANPAT RAI & Co. (Pvt.) Ltd, 2011.

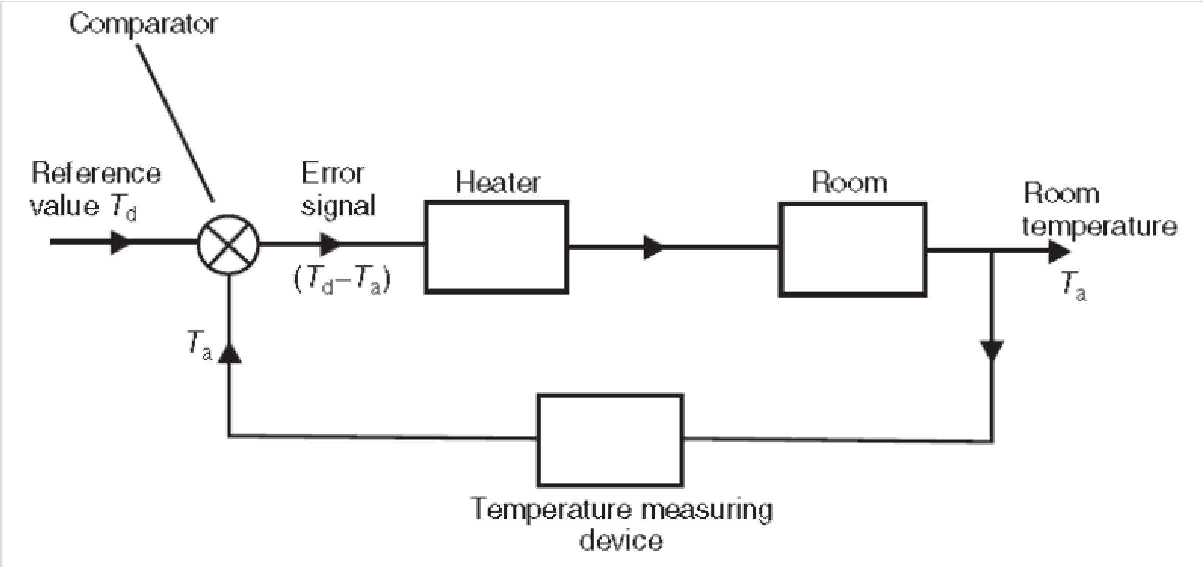
Related Tasks	Assessment Criteria	Assessment Methods
• Identify measuring instruments • Operate measuring instruments • Explain application of each measuring instrument • Use manufacturer’s manual	Operation principles of measuring instruments are clearly described	• Assignments • Hands-on activities

Measuring Instruments

- **MEASUREMENTS**
- The measurement of a given quantity is essentially an act or the result of comparison between the quantity (whose magnitude is unknown) and a predefined standard.
- Since two quantities are compared, the result is expressed in numerical values.
- In order that the results of the measurement are meaningful, there are two basic requirements :
    1. the standard used for Comparison purposes must be accurately defined and should be commonly accepted, and
    2. the apparatus used and the method adopted must be provable.

- Electronic test equipment is used to create signals and capture responses from electronic devices under test (DUTs).

- Measurements are needed in various functions of engineering during design and processes, operations and maintenance of equipment, and monitoring
- This is due to the fact that, the design, operation and maintenance require a feedback of information.



Methods of Measurements

- The methods of measurements may be broadly classified into two categories :
  1) Direct Methods and
  2) Indirect Methods.

Direct Methods

- In these methods, the. unknown quantity (measurand) is directly compared against a standard. The , result is expressed as a numerical number and a unit.
- Direct methods are quite common for the measurement of physical quantities like length, mass and time.

Indirect Methods

- In engineering applications Measurement Systems are used which require need of indirect methods for measurement purposes.
- In some cases, method uses more than one parameter.

The *three* phases of instruments *:*

1. Mechanical instruments,
2. Electrical instruments, and
3. Electronic instruments.

Mechanical Instruments

- These instruments are very reliable for static and stable conditions.
- But, they are unable to respond rapidly to measurements of dynamic and transient conditions.

Electrical Instruments

- Electrical methods of indicating the output of detectors are more rapid than mechanical methods.
- It is unfortunate that an electrical system normally depends upon a mechanical meter movement as indicating device.
- This mechanical movement has some inertia and therefore these instruments have a limited time (and hence, frequency) response.

Electronic Instruments

- These instruments require use of semi-conductor devices.
- Since in electronic devices, the only movement involved is that of electrons, the response time is extremely small on account of very small inertia of electrons.

Classification of Instruments

- Broadly, instruments are classified into *two* categories :
  - Absolute Instruments, and
  - Secondary Instruments.

  - **Absolute instruments.** These instruments give the magnitude of the quantity under measurement in terms of physical constants of the instrument.
  - **Secondary instruments.** These instruments are so constructed that the quantity being measured can only be measured by observing the output indicated by the instrument.

Deflection and Null Type Instruments

- **Deflection Type.** The Instruments Of This Type, The Deflection Of The Instrument Provides A Basis For Determining The Quantity Under Measurement.
- **Null Type.** In A Null Type Of Instrument, A Zero Or Null Indication Leads To Determination Of The Magnitude Of Measured Quantity.

Analog and Digital Modes of Operation

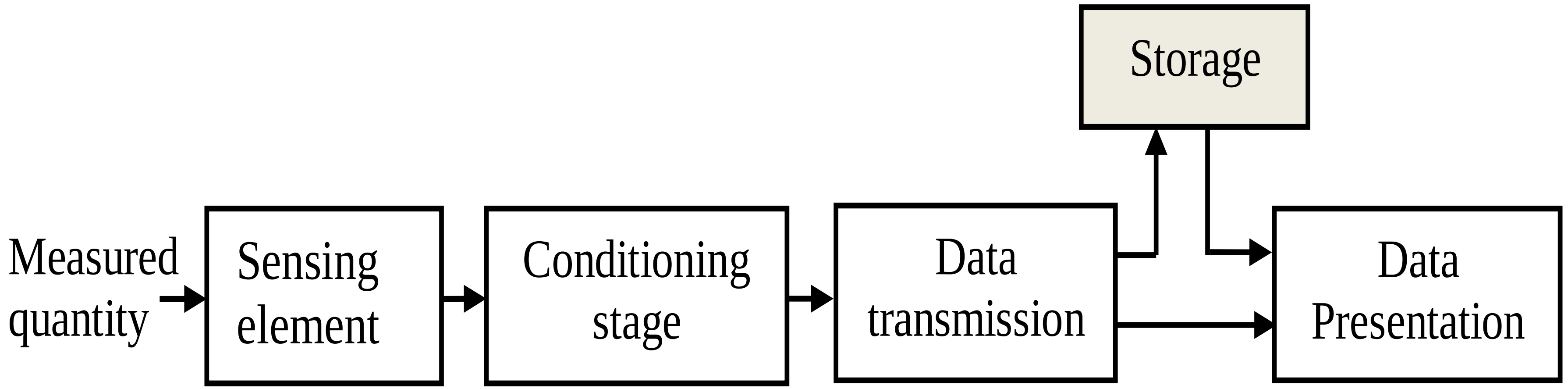
Secondary instruments work in either Analog mode, and Digital mode.

- **Analogue Mode.** Signals that vary in a continuous fashion and take on an infinite number of values in any given range.
- **Digital Mode.** Signals vary in discrete steps and thus take up only finite different values in a given range.

Applications of Instruments and Measurement Systems

- **Monitoring function.** For supplying information concerning the variable quantity under measurement.
- **Experimental engineering analysis.** For solution of engineering problems, theoretical and experimental methods are available:
  i. Testing the validity of theoretical predictions.
  ii. Formulations of generalized empirical relationships in cases where no proper theoretical backing exists.
- **Controlling function.** This is one of the most important functions especially in the field of industrial control processes.

ELEMENTS OF A GENERALIZED MEASUREMENT SYSTEM



Choosing appropriate measuring instruments

- Choosing the suitable instrument to use for measurement of a particular quantity is the specification of the instrument characteristics required, especially parameters like the desired measurement accuracy, resolution, sensitivity, and dynamic performance.
- It is also essential to know the environmental conditions that the instrument will be subjected to.

Choosing appropriate measuring instruments

- Then, a skilled instrument engineer will be able to evaluate the possible list of instruments in terms of their accuracy, cost, and suitability for the environmental conditions and thus choose the most appropriate instrument.
- The better the characteristics, the higher the cost. However, in comparing the cost and relative suitability of different instruments for a particular measurement situation, considerations of durability, maintainability, and constancy of performance are also very important.

Characteristics of Instruments and Measurement Systems

Static Characteristics and Dynamic Characteristics

Static characteristics:

(i) Accuracy and precision
(ii) Sensitivity
(iii) Reproducibility, repeatability and Drift
(iv) Range and span
(v) Linearity
(vi) Hysteresis
(vii) Threshold
(viii) Static error
(ix) Dead Zone and Dead Time

Brief discussion on Static characteristics

Several terms of static characteristic include the following:

- **Accuracy** measured in terms of its *error.*

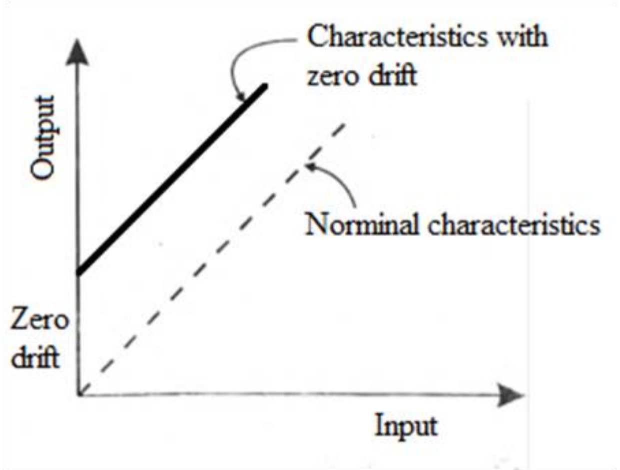
$$\delta A = A_m - A_t$$

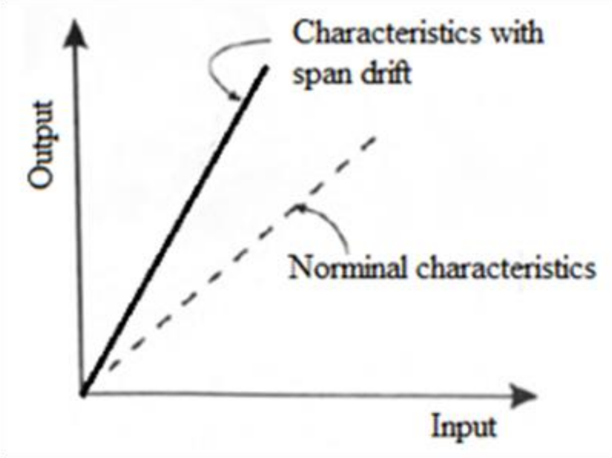
relative static error, $\varepsilon_r = \dfrac{\text{Absolute error}}{\text{true value}} = \dfrac{\delta A}{A_t} = \dfrac{\varepsilon_0}{A_t}$

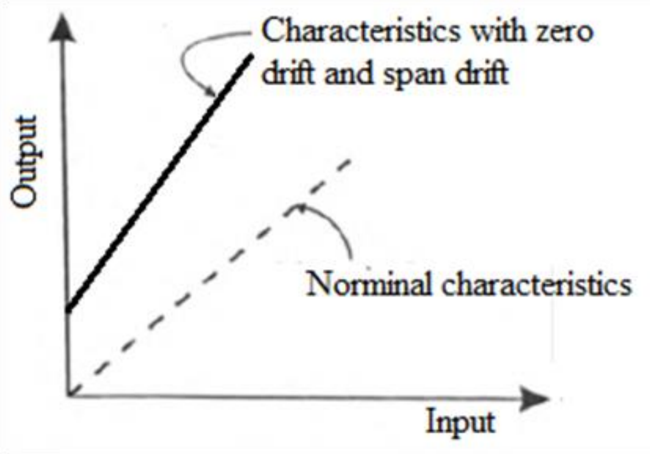
- Static correction is the difference between the true value and the measurement value of the quantity

Repeatability and Reproducibility

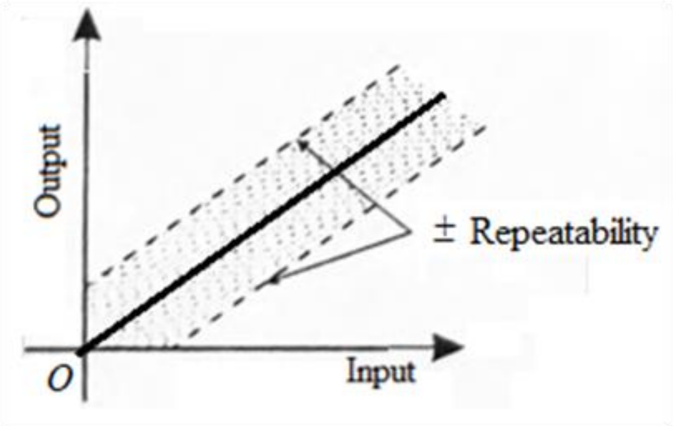
- Perfect reproducibility means that the instrument has no drift.
- Drift may be classified into three categories:
    - zero drift,
    - span drift (or sensitivity drift), and
    - zonal drift. Zero drift:







Input-output relationship with **± repeatability**



Precision: Is a measure of consistency or repeatability of measurements.

given that,

x_n is the measured value and

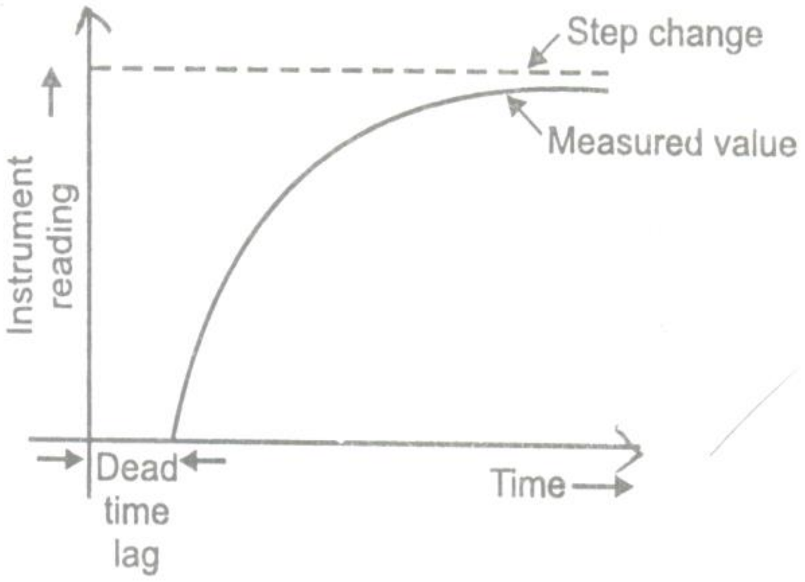
$\overline{x}$ is the average value or expected value.

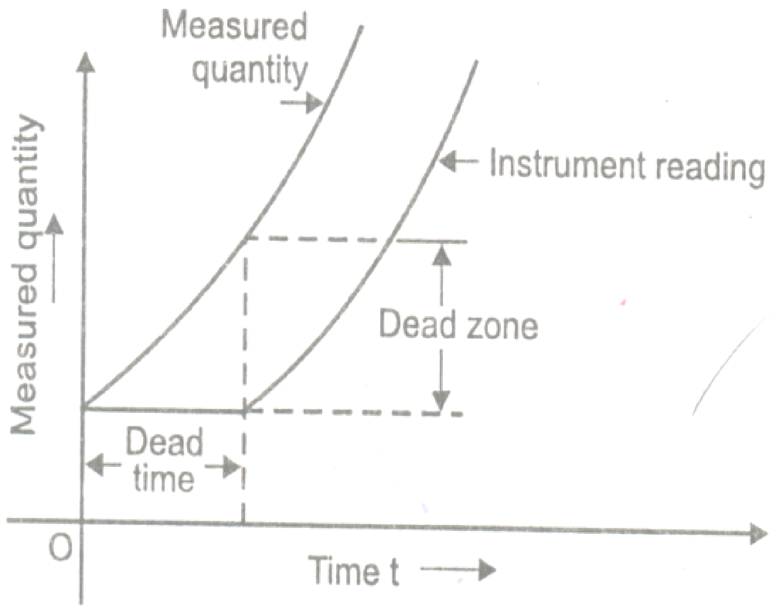
$$\text{Precision} = 1 - \left| \frac{x_n - \overline{x}}{\overline{x}} \right|$$

- **Sensitivity:**

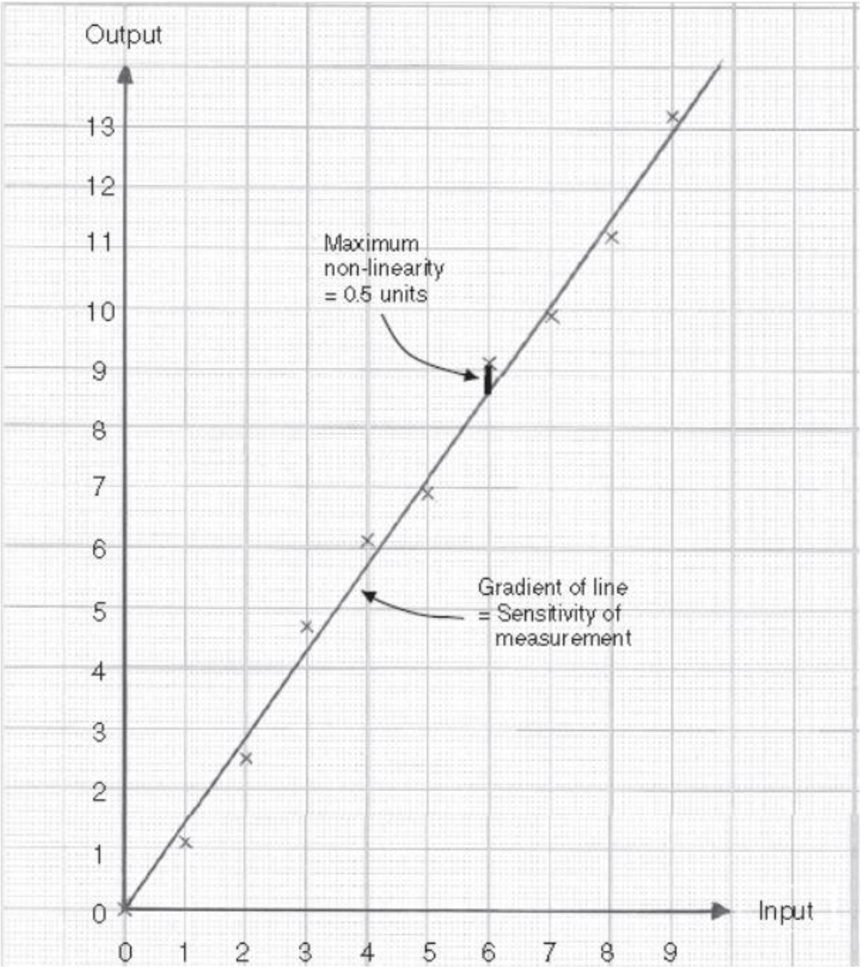
$$\text{Sensitivity (S)} = \frac{\text{change in output}}{\text{change in input}} \qquad \text{Scale factor} = \frac{\text{change in input}}{\text{change in output}}$$

- **Dead Zone:** also known as **dead band** or **dead space**





- **Linearity**



Output
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Maximum
non-linearity
= 0.5 units
Gradient of line
= Sensitivity of
measurement
Input
0 1 2 3 4 5 6 7 8 9

Loading Effect

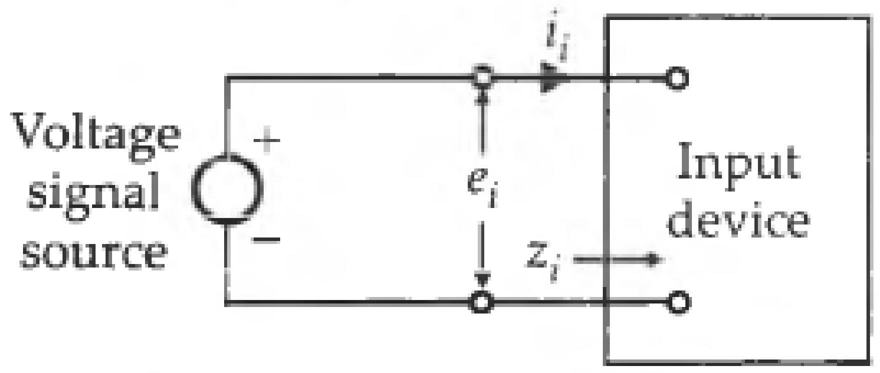
- Under practical conditions, introduction of any element in a system results, invariably, in extraction of energy from the system there by distorting the original signal.
- This distortion may take the form of attenuation, waveform distortion, phase shift and many a time all these undesirable features put together.

- The loading effects are due to impedances of various elements connected in a system and hence it is desirable at this stage to analyze their effects.

- Two types of impedances:
  input impedance and output impedance

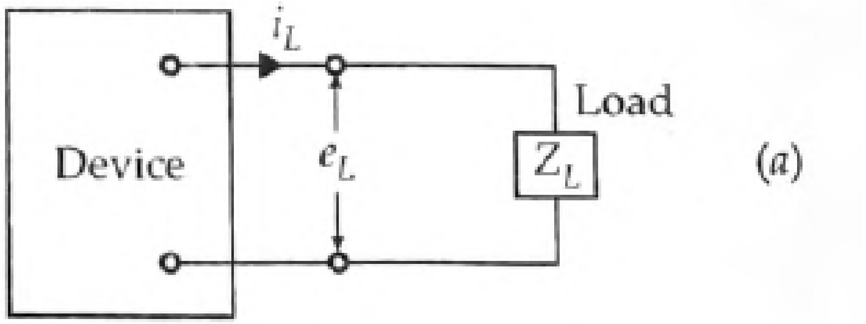
Input Impedance

- In the figure showing voltage signal source and input device connected across it, the magnitude of the impedance of element connected across the signal source is called **Input Impedance.**

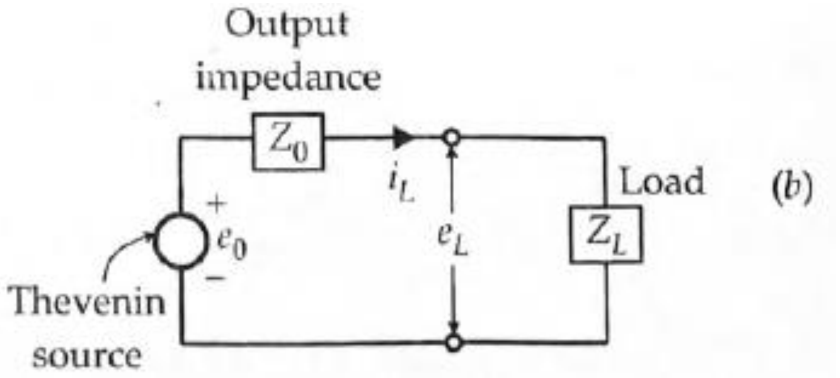


Output Impedance

- The output impedance of a device is defined as its equivalent impedance as seen by the load.



- The *equivalent impedance* implies that the device can be represented by a *Thevenin's equivalent circuit* shown in Fig. (b)



Dynamic characteristics:

- Dynamic characteristics of a measuring instrument refer to the case where the measured variable changes rapidly with time.
- When an input is applied to a system, the energy storage elements do not allow an immediate flow of energy and therefore the measurement system does not respond to the input immediately.
- The measurement system goes through a transient state before it finally settles to its steady state position.
- The dynamic characteristics of any measurement system are:
  - i. Speed of response and Response time
  - ii. Lag
  - iii. Fidelity
  - iv. Dynamic error

Analogous Quantities in Thermal, Liquid Level, Pneumatic and Electrical Systems

	Electrical Systems	Thermal Systems	Liquid-Level Systems	Pneumatic Systems
	Charge ; C	Heat flow ; J	Liquid flow ; m^3	Air flow ; m^3
	Current; A	Heat flow rate ; J/s	Liquid flow rate ; m^3 /s	Air flow rate ; m^3/s
	Voltage ; V	Temperature ; °C	Heat; m	Pressure ; N/m^2
	Resistance ; Ω	Resistance ; °C /(J/s)	Resistance ; $m/(m^3/s)$	Resistance ; $(N/m2)/(m^3/s)$
	Capacitance ; F	Capacitance ; J/°C	Capacitance ; m^2	Capacitance; $m^3/(Nm^2)$

Transfer Function

- In any linear, time-invariant measuring system, the following general relation can be written between input and output for time (*t*) > 0:

$$a_n \frac{d^n q_o}{dt^n} + a_{n-1} \frac{d^{n-1} q_o}{dt^{n-1}} + \cdots + a_1 \frac{dq_o}{dt} + a_0 q_o = b_m \frac{d^m q_i}{dt^m} + b_{m-1} \frac{d^{m-1} q_i}{dt^{m-1}} + \cdots + b_1 \frac{dq_i}{dt} + b_0 q_i$$

where q_i is the measured quantity, q_o is the output reading, and a_o ... a_n, b_o . b_m are constants.

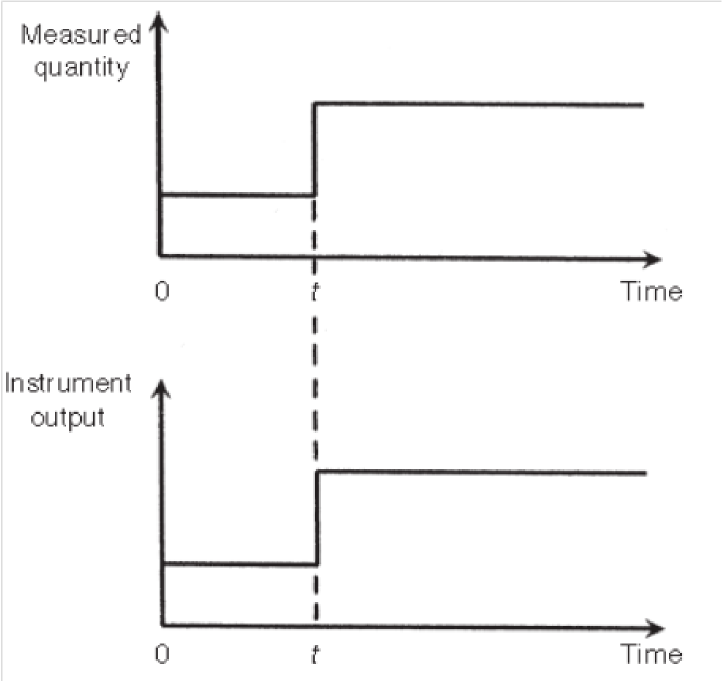
- Transfer function plays an important role in the characterization of linear time invariant systems.
- The transfer function of a linear time invariant system is defined as the ratio of Laplace transform of the output variable to the Laplace transform of the input variable with all initial conditions equal to zero.

Zero Order Systems

- A zero order instrument is one where the highest order of the derivative describing the system behavior is zero.

$$a_0 q_o = b_0 q_i \quad or \quad q_o = b_0 q_i / a_0 = K q_i$$

where *K* is a constant known as the instrument static sensitivity (steady state gain)



First Order Systems

- The highest order of derivative in first order system is one.

- If all coefficients a_2 ... a_n except for a_o and a_1 are assumed to be zero in

$$a_n \frac{d^n q_o}{dt^n} + a_{n-1} \frac{d^{n-1} q_o}{dt^{n-1}} + \cdots + a_1 \frac{dq_o}{dt} + a_0 q_o = b_m \frac{d^m q_i}{dt^m} + b_{m-1} \frac{d^{m-1} q_i}{dt^{m-1}} + \cdots + b_1 \frac{dq_i}{dt} + b_0 q_i$$

$$\boxed{a_1 \frac{dq_o}{dt} + a_0 q_o = b_0 q_i}$$

- If *d/dt* is replaced by the *D*

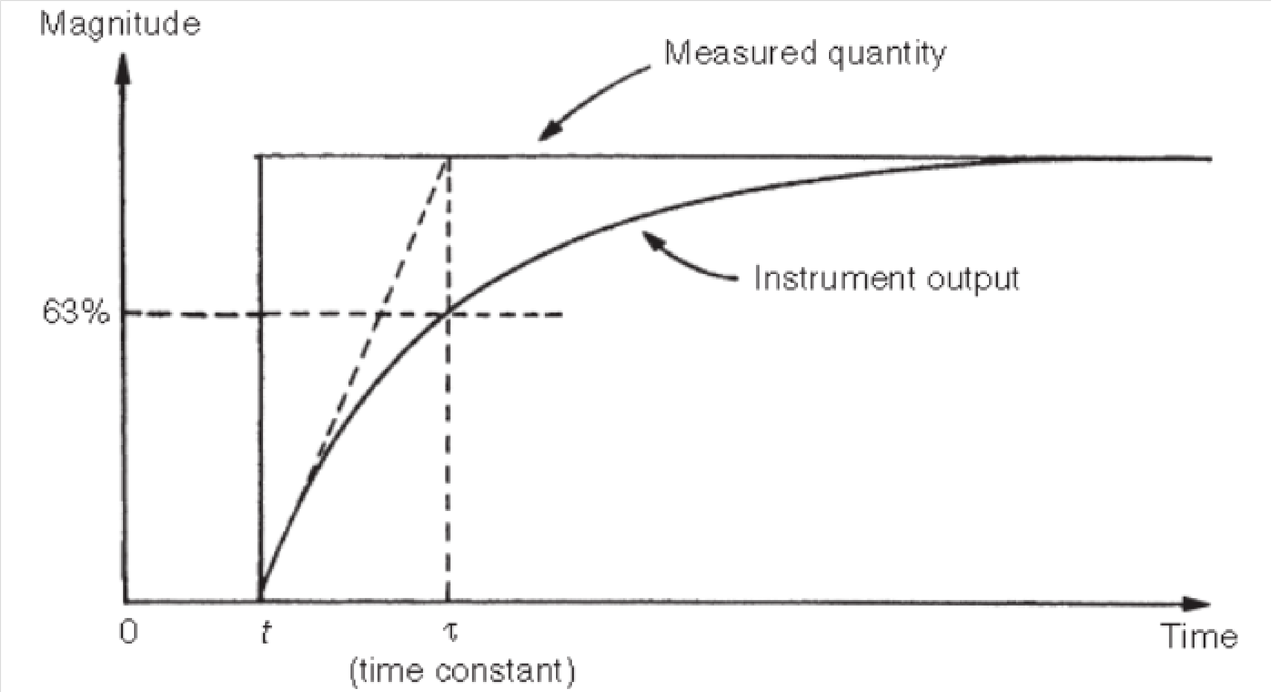
$$a_1 D q_o + a_0 q_o = b_0 q_i$$

$$q_o = \frac{(b_0/a_0) q_i}{[1 + (a_1/a_0) D]}$$

- **First-order instrument characteristic**

Defining $\boldsymbol{K} = b_0/a_0$ as the static sensitivity and $s = a_1/a_0$ as the time constant of the system

$$q_o = \frac{Kq_i}{1 + \tau D}$$



RESPONSE OF SECOND ORDER SYSTEMS

- A second order system may be defined by the following differential equation
  - If all coefficients $a_3 \ldots a_n$ other than a_0, a_1, and a_2 are assumed to be zero, we get:

$$a_2\frac{d^2q_o}{dt^2}+a_1\frac{dq_o}{dt}+a_0q_o=b_0q_i$$

$$q_o=\frac{b_0q_i}{a_0+a_1D+a_2D^2}$$

- It is convenient to express the variables a_0, a_1, a_2, and b_0 in terms of three parameters: ***K*** (static sensitivity), $\boldsymbol{\omega}$ (undamped natural frequency), and ξ (damping ratio), where:

$$K=b_0/a_0 \quad ; \quad \omega=\sqrt{a_0/a_2} \quad ; \quad \xi=a_1/2\sqrt{a_0a_2}$$

- ξ can be written as

$$\xi = \frac{a_1}{2a_0\sqrt{a_2/a_0}} = \frac{a_1\,\omega}{2a_0}.$$

- From

$$q_o = \frac{b_0 q_i}{a_0 + a_1 D + a_2 D^2}$$

$$q_o = \frac{(b_0/a_0) q_i}{1 + (a_1/a_0)D + (a_2/a_0)D^2}$$

$$\frac{b_0}{a_0} = K \quad ; \quad \left(\frac{a_1}{a_0}\right) D = \frac{2\,\xi\,D}{\omega} \quad ; \quad \left(\frac{a_2}{a_0}\right) D^2 = \frac{D^2}{\omega^2}$$

$$\boxed{\frac{q_0}{q_i} = \frac{K}{D^2/\omega^2 + 2\xi D/\omega + 1}}$$

The normalized (dimensionless) transfer function, G(s) is,

$$G(s) = K\frac{q_0}{q_i} = \frac{\omega_n^2}{D^2 + 2\xi D\,\omega_n + \omega_n^2}$$

- In Laplace transform, substitute ***D*** with ***s***

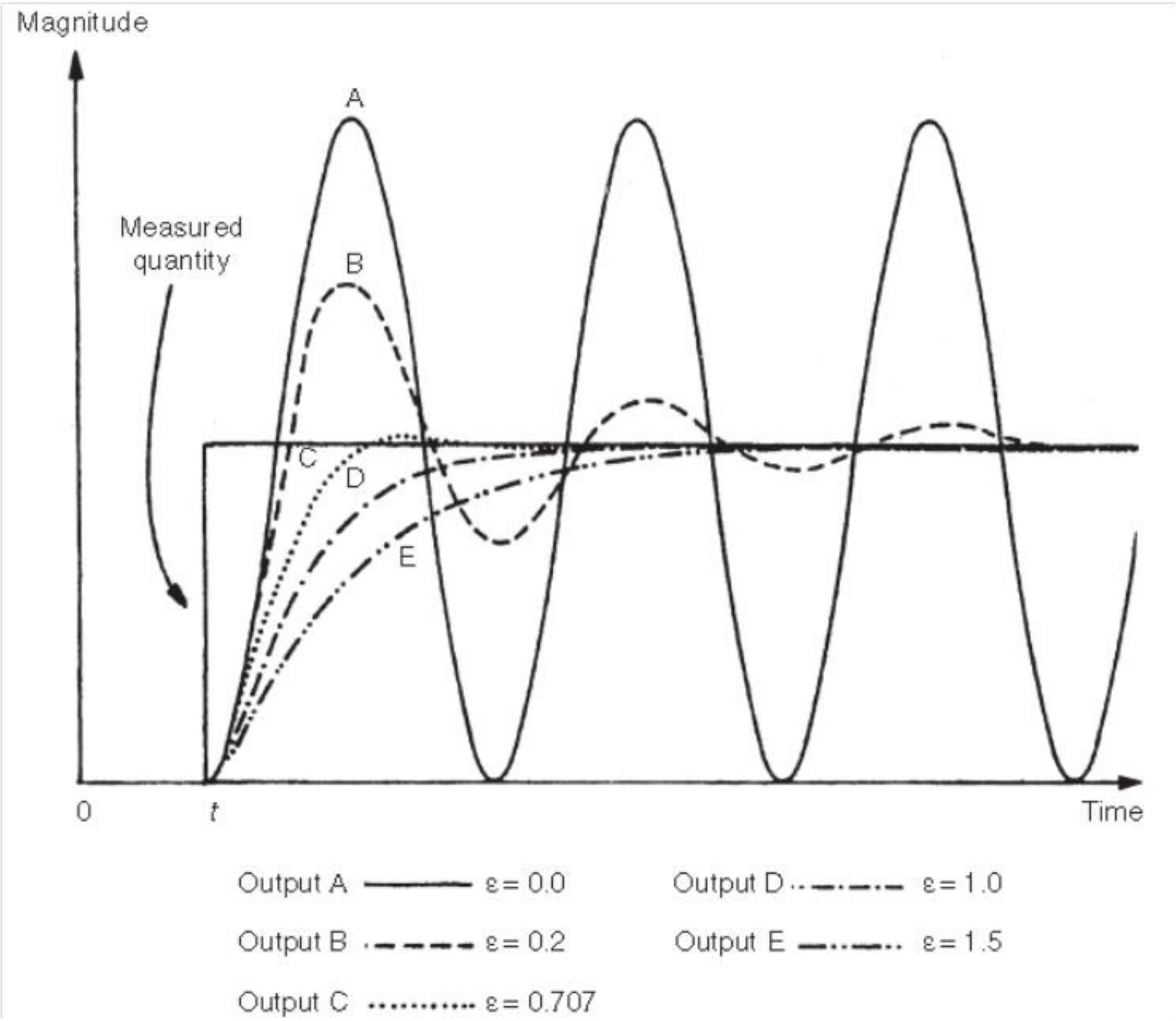
$$G(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

Static sensitivity $S = b_0 / a_0$

Natural frequency

$$\omega_n = \sqrt{a_0 / a_2} \text{ rad/s}$$

$$\xi = \frac{a_1}{2\sqrt{a_0 a_2}}$$



- **Commercial second-order** instruments, of which the accelerometer is a common example, are generally designed to have a damping ratio (ξ) somewhere in the range of 0.6-0.8.

Manufacturer’s Instructions or Manual

- Manufacturer's Instructions or manual is a the written directions provided by the manufacturer or distributor that contain the necessary information for the safe and effective use of the equipment.
- Manufacturer’s manual provides clear work instructions.
- If you have a new or an existing measuring equipment, you’ll want to read the manual carefully before operating it to ensure safe and proper operation.
- This will help you to run it smoothly by assuring the accuracy to avoid measurements to be done wrong as this could lead to faults in production and unsatisfied.

Work instructions for measuring instruments

A work instruction for measuring instruments typically include:

- Brief description of the instrument and its purpose.
- Essential information such as brand and model.
- Safety
- The technical calibration conditions and specifications.
    - information about the environment the instrument should be in,
    - how the instrument is supposed to be set up and
    - how to accurately perform the measurement.

Work instructions for measuring instruments

- Setting up the instrument includes
  - Installation procedures
  - Operation procedures
  - Servicing and maintenance procedures
  - Cleaning process and calibrating it to zero setting.
- The treatment of results and possible information on periodic measurements or auditing.

Check points

The work instruction content for measuring instruments would include:

1) Description and purpose of the measuring instrument
2) Technical specifications
3) Environmental condition of usage
4) Setting up the instrument
5) Measurement procedure
6) Interpretation of the results

Check points

- Do not forget to include information about how to leave the instrument after usage.
- To sum up, you need to think about three main things when preparing work instructions for measuring instruments:

1) How to prepare the instrument,
2) How to use it and
3) What to do with it after you're done measuring.

Activity 1.1:

Direct Measurement of Electrical parameters
Visit the Measurement Laboratory

1. Identify measuring instruments and testing equipment
2. Give their functions
3. Orient yourself how to use and operate of the following (participate physically):

(Hint: Obtain Manuals)

   a. Digital Oscilloscope
   b. Analogue Oscilloscope
   c. Spectrum analyser
   d. Frequency counter
   e. Function generator
   f. Logic probe

4. Explain application of each measuring instrument
5. Use manufacturer’s manual of the listed measuring instruments and testing equipment identify the following
    a) Limitations in the operations and ranges.
    b) Safety and precautions

6. Study the use of the following:
    a) Pulse Generators
    b) Video Signal Generators
    c) Digital Pattern Generators

7. Prepare and present the report for the activity 1.1

Activity 1.2:

Measurement of Non-electrical Parameters

1. Study the requirements for designing a 500-grams aerial vehicle (e.g. quadrotors)
2. Identify the designing requirements, parameters and their units

Requirements:

1) Use Arduino
2) Propellers (4)
3) Brushless motors (4)
4) MPU6050 module
5) HMC5883L module
6) Magnetometer module
7) Rechargeable battery
8) Body frame
9) GPS

1. Program Arduino to control speeds of motors (Use PWM) and direction of the movement
2. Estimate the required force required to lift 500-grams drone
3. Discuss the testing points and process for (2).
4. Apply data fusion from the Accelerometer & Gyroscope, and Magnetometer data
5. Compare the data from (4) and data from the offline GPS.
6. Discuss the error obtained after data fusion
7. Prepare and present the report for the activity 1.2

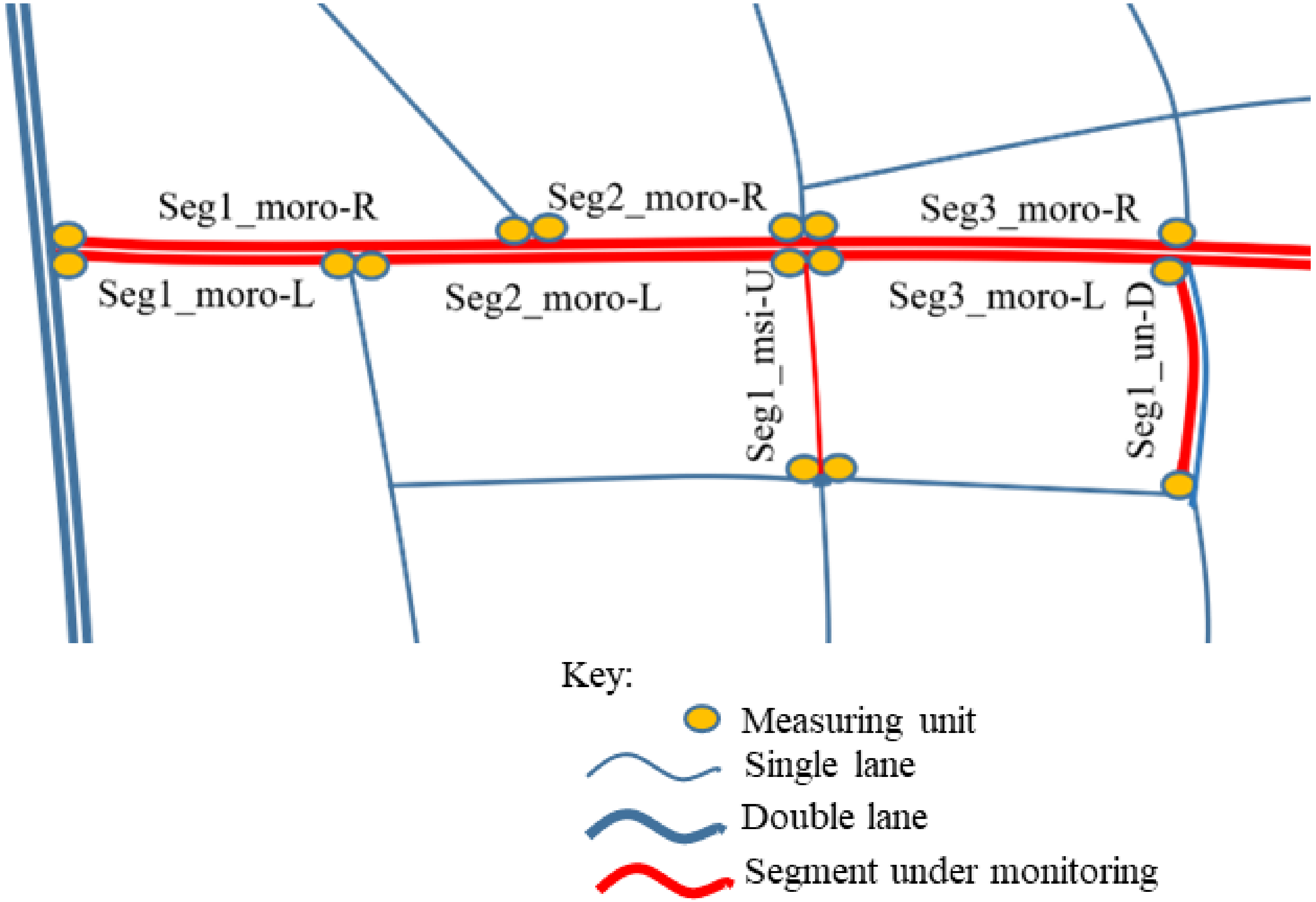
Activity 1.3:

Monitoring Process:

Identify measuring instruments and testing equipment to be used in monitoring the traffic congestion along the road segment.

1. Identify the parameters required for estimating the traffic congestion along the road segments shown in the next slide.

2. Discuss the type of measuring instruments to be used and testing points (locations of the road network).
3. Estimating the road congestion during peak-hours


Seg1_moro-R
Seg2_moro-R
Seg3_moro-R
Seg1_moro-L
Seg2_moro-L
Seg3_moro-L
Seg1_msi-U
Seg1_un-D
Key:
Measuring unit
Single lane
Double lane
Segment under monitoring