BFF3302 SENSOR AND INSTRUMENTATION SYSTEM

Introduction to the sensor & instrumentation

By

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Chapter Description

- Aims
  - Obtain basic knowledge about electronic, measurement, sensors, and instrumentation
  - Able to analyse particular sensor, instrument, and measurement situation.
- Expected Outcomes
  - Determine general treatment of instrument elements and their characteristic
  - Analyse transducer elements, intermediate elements, and data acquisition system (DAQ)
  - Determine principles of the work and derive mathematical model of sensors for measuring motion and vibration, dimensional metrology, force, torque and power, pressure, temperature, flow and acoustics
- References

  - Introduction to signal processing, instrumentation, and control : an integrative approach / Joseph Bentsman Hackensack, NJ : World Scientific Pub., 2016
  - Transducers for instrumentation / M. G. Joshi, New Delhi, India : Infinity, 2017
  - Instrumentation and measurement in electrical engineering / editor : Harinirina Randrianarisoa, New York : Arcler Press, 2017

What you will learn?

- Fundamentals of Instrumentation & Measurement System
- Fundamentals of Sensors and their characteristic
- Fundamentals of Data Analysis
- Project Integration

Main topics

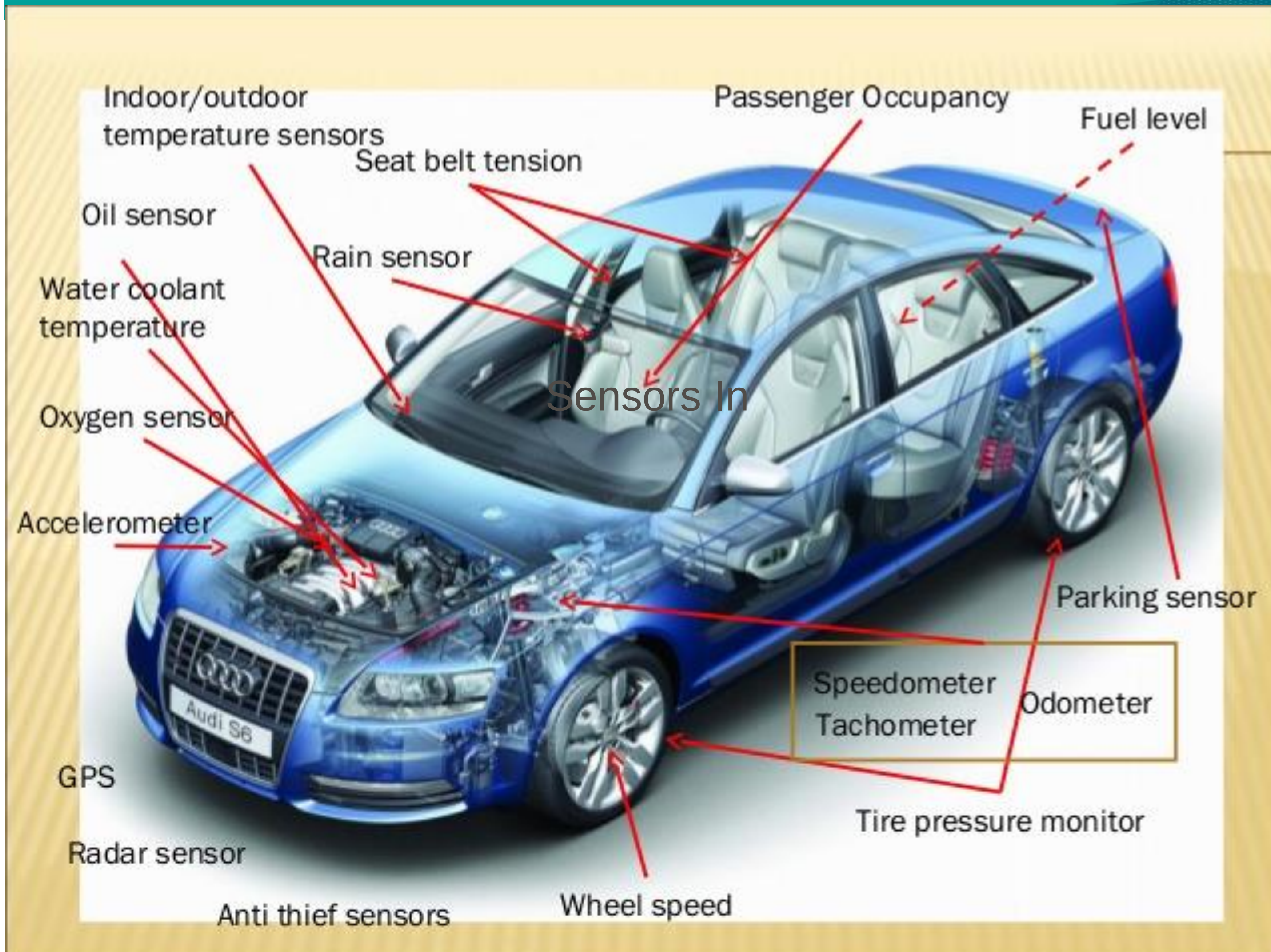
- Chp 1: Fundamental of sensors and instrumentation system
- Chp 2: (Static) performance instrument characteristic
- Chp 3: Transducer elements: analog and digital
- Chp 4: Intermediate components/elements:
  - Op-amp
  - Differential & integral components/elements
  - Filtering
  - AD/DA converters
  - Conversion & terminology

- Chp 5: Temperature transducer
  - Resistance temperature detector (RTC)
  - PTC & NTC
- Chp 6: Distance/proximity sensor
  - Ultrasonic sensor
  - Capacitive & inductive sensors
- Chp 7: Force, torque, power measurement tranducer
  - Balance
  - Hydraulic load cell and Pneumatic load cell
- Chp 8: Motion and vibration measurements
  - Relative motion or vibration measuring devices
  - Absolute motion or vibration devices
  - Calibration of motion / vibration measuring devices
- Chp 9: Actuators

Introduction

- Significant improvement: field of instrumentation
- Area: detection, acquisition, control and analysis of data in science & technology.
- E.g.; an ordinary watch – an instrument for measuring time. Car air-cond; washing machine.
- Modern automobiles are equipped with a variety of sensors and indicators.
- E.g.: sensors for knock detection, manifold pressure, coolant level & temperature, oil level & flow rate, brake fluid level, fuel levels,
- E.g.: throttle position & speeds of the engine, crank shaft & wheel, MEMS for safety airbags for passengers, GPS for geographically information and on-board computers/micro-processors for controlling air-conditioning systems and engine operations at different loads and speeds.

Sensors In



Slideshare:
Patil Sanket, 2014.
Sensors in Automobiles
(https://www.slideshare.ne

Area of applications

- Military and Aerospace Systems
- Heavy Construction Engineering
- General Industrial Applications
- Environmental Engineering
- Automobile and consumer markets
- Laboratory test and scientific study
- Medical and biological systems
- Weather data and measurements
- Data communication

Area of applications

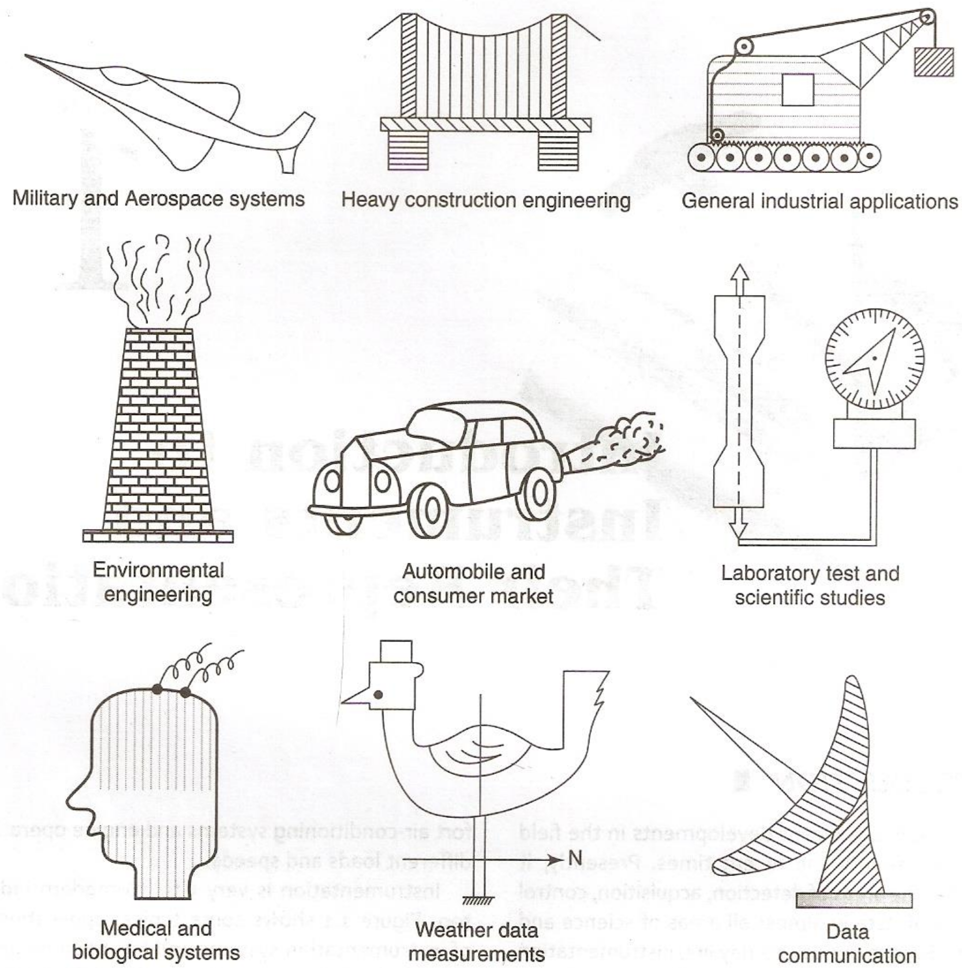


Fig. 1.1 *Typical application areas of instrumentation systems*

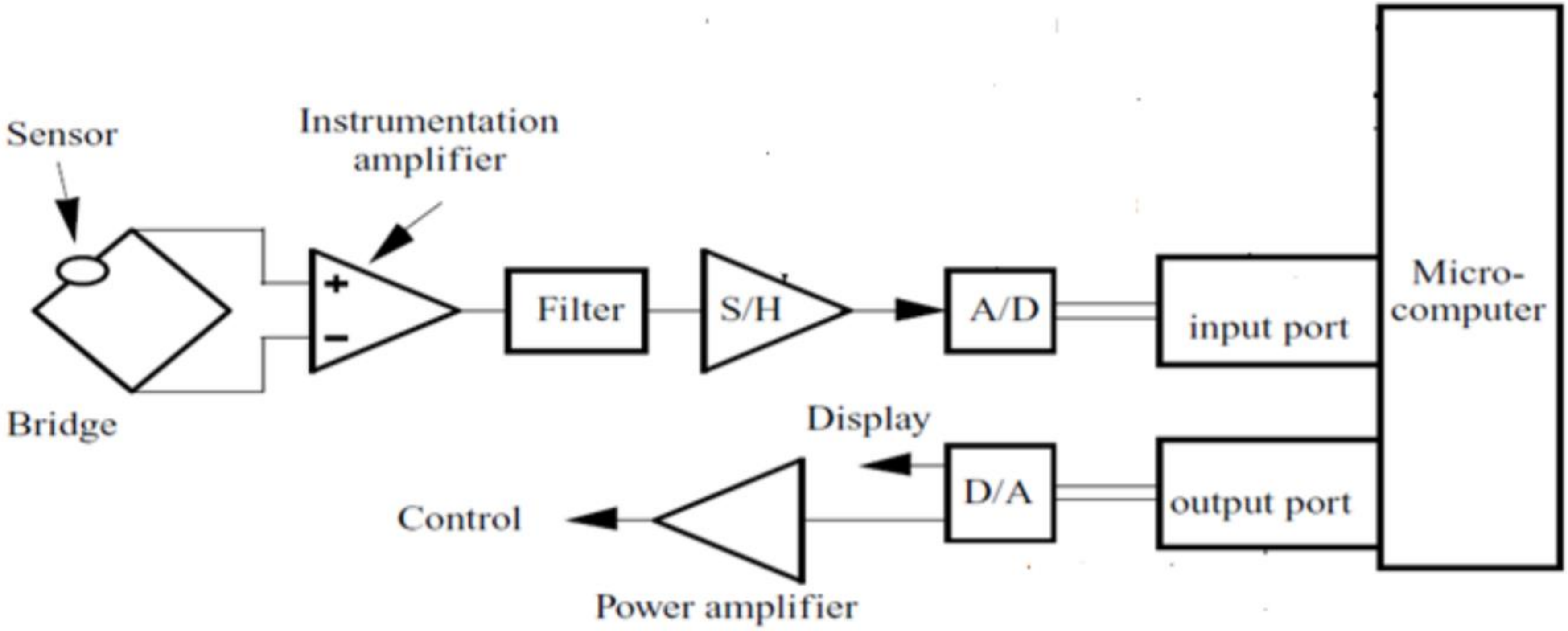
Instrumentation system: applications

1. **Measurement of system parameters**
   - present the information regarding the condition of the system
   - Form: visual indication/registering/recording/monitoring/ transmission according to the requirements of the system.

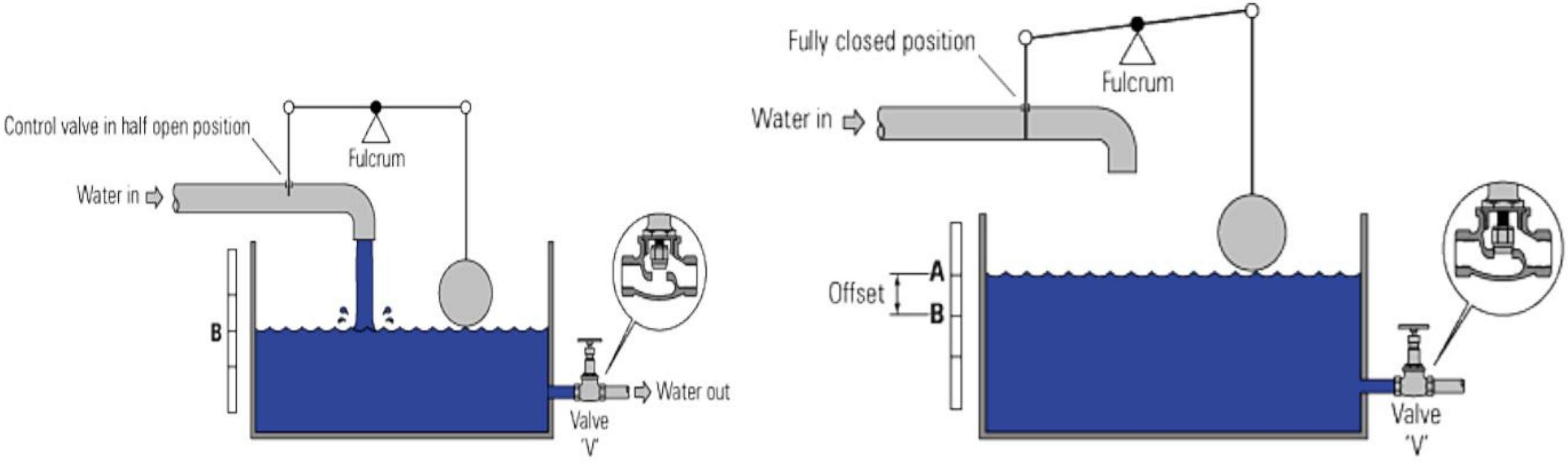
2. **Control of process or operations**
   - used in process industries - oil refineries, chemical plants, textile mills, etc. for controlling variables like temperature, pressure, flow rate and other parameters

3. **Simulation of system conditions**
   - simulate experimentally the actual conditions of complex situations for revealing the true behaviour of the system under different governing conditions.
   - lift, drag and other relevant parameters of aerodynamic bodies are usually obtained by testing the models in controlled air streams generated in wind tunnels that simulate the flow conditions.

System response to sensor and instruments signal



E.g. Water level control system



Instrumentation system: applications

4. **Experimental design studies**
   - For the purpose of the design and development of a new product.
   - The prototype test data is used to improve the design calculations till the desired design performance is achieved.

5. **To perform various manipulations**
   - The instruments are employed to perform operations like signal addition, subtraction, multiplication, division, differentiation, integration, signal linearization, signal sampling, signal averaging, multi-point correlations, ratio controls, etc.
   - Also to determine the solution of complex differential equations or other mathematical manipulations.

6. **Testing of materials, maintenance of standards and specifications of products**
   - To ensure that the material/products meet the specified requirements so that they function properly and enhance the reliability of the system.

Instrumentation system: applications

7. Verification of physical phenomena/scientific theories

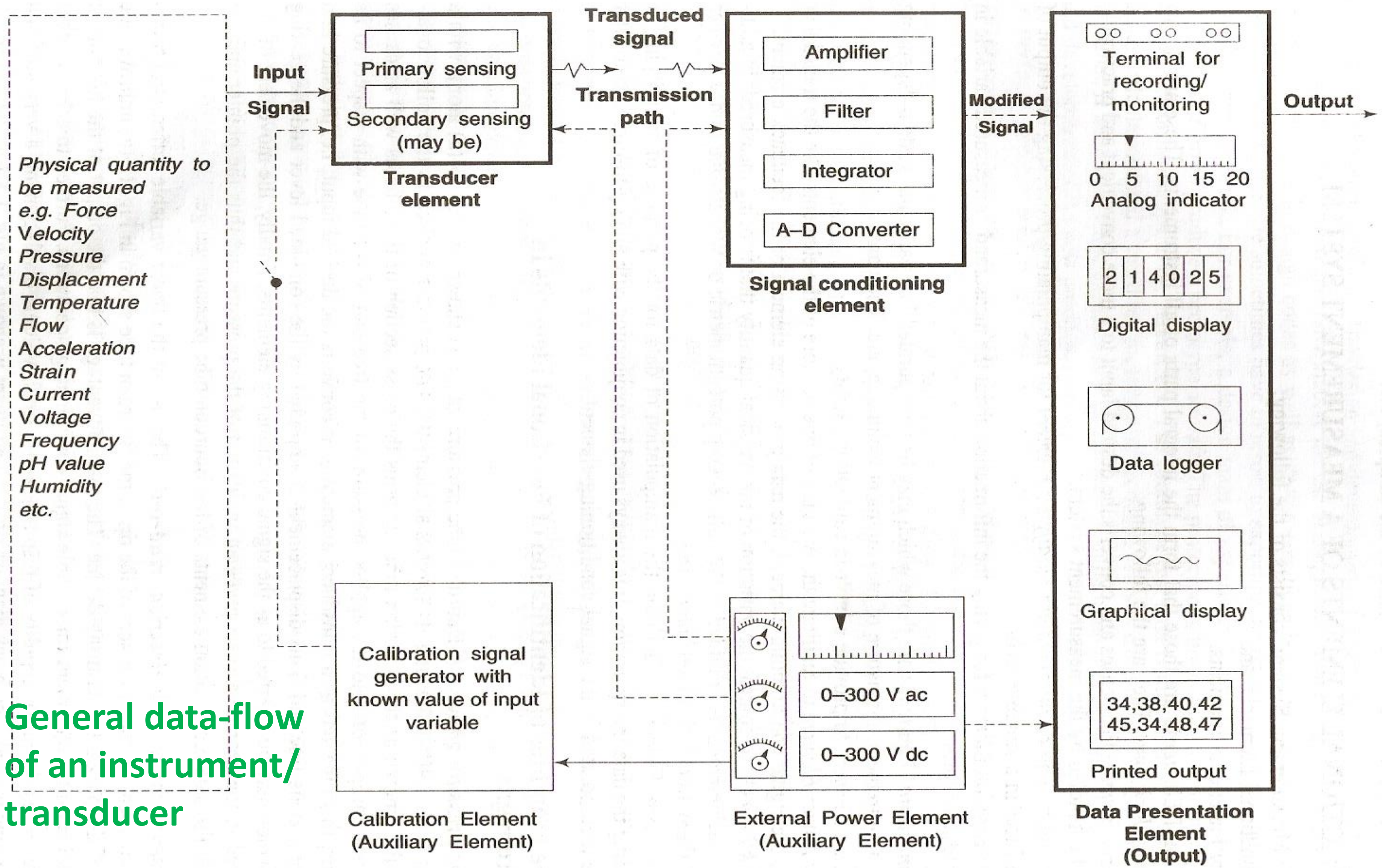
- Generate experimental data to verify a certain physical phenomenon or developing new theories or checking the validity of a certain hypothesis which may have been developed using some simplifying assumptions.

8. Quality control in industry

- To have continuous quality control tests of mass produced industrial products.
- To discover defective components that are outright rejected at early stages of production.
- The various test are: X-ray examination of the plate for defects like blow holes, cracks, etc.; metallurgical examination for metallurgical defects; periodic strength tests of the samples, etc.

Functional elements of a measurement system

- **Basic functional elements** - form the integrated parts of instruments.
  1. Transducer element - senses & converts desired input to a more convenient and practicable form to be handled by measurement system.
  2. Signal conditioning element/ intermediate modifying element - manipulate/process the transducer output in a suitable form.
  3. Data presentation element - give information about the measurand / measured variable in the quantitative form.



General data-flow of an instrument/ transducer

Fig. 1.3 *Basic and auxiliary functional elements of a measurement system*

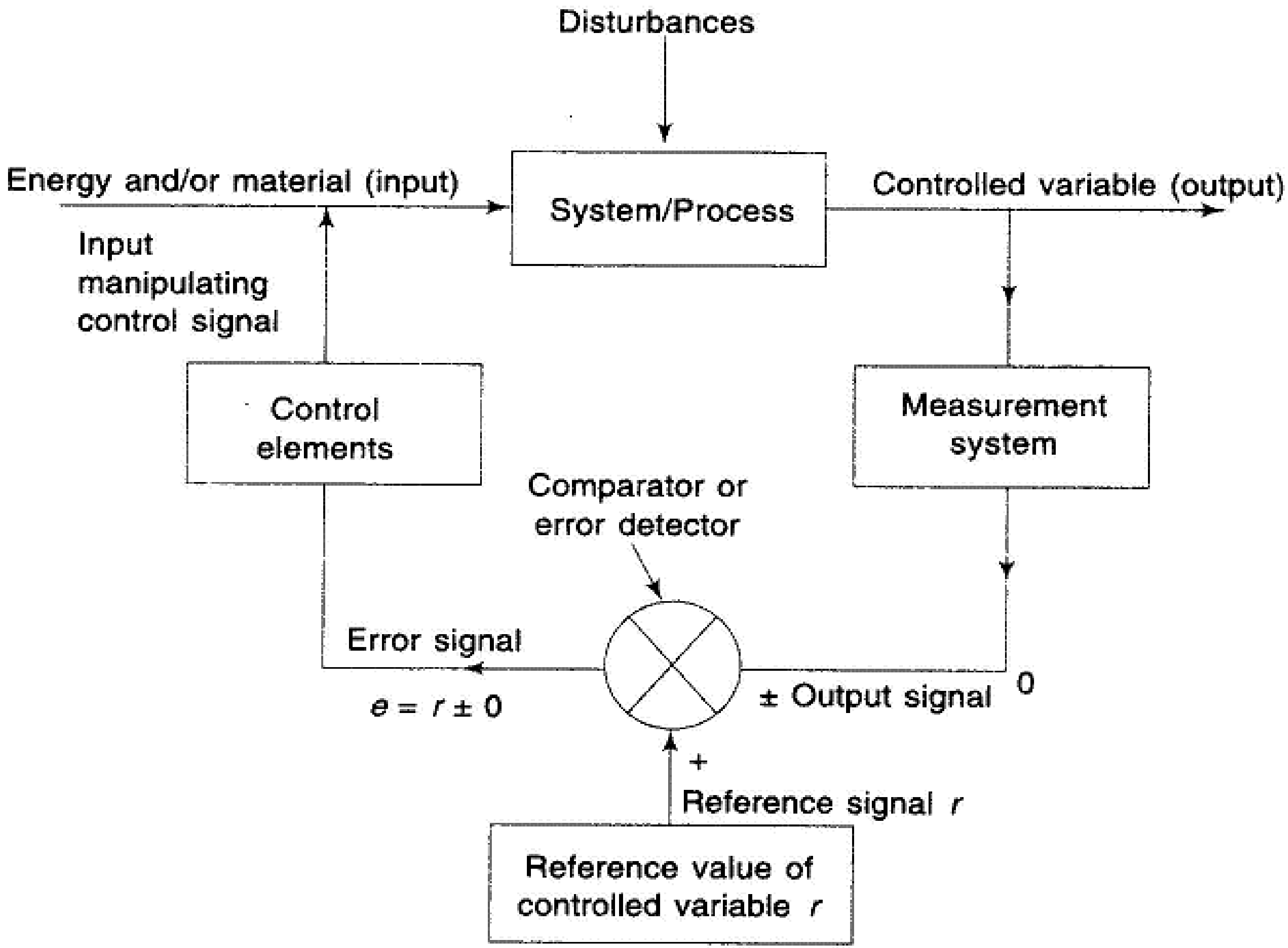
Functional elements of a measurement system

- **Auxiliary functional elements** - those incorporated in particular system based on the requirement type, nature of measurement technique, etc.
  1. **Calibration element** - provide built-in calibration facility.
  2. **External power element** - facilitate the working of one or more of the elements (e.g. transducer, the signal conditioning, the data processing or the feedback element).
  3. **Feedback element**

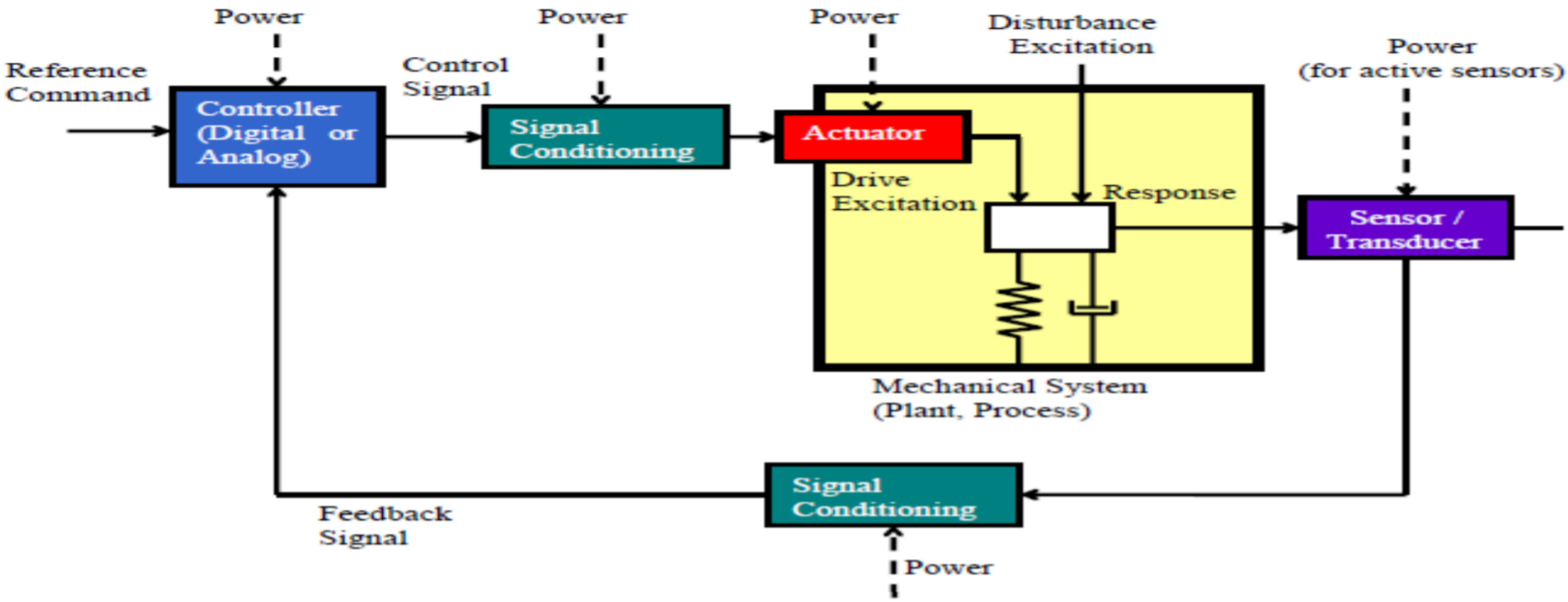
     - control the variation of physical quantity that is being measured.

     - feedback element is provided in the null-seeking potentiometric or Wheatstone bridge devices to make them automatic or self-balancing.
  4. **Microprocessor element** - facilitate the manipulated data for the purpose of simplifying or accelerating the data interpretation.

     - Used in conjunction with ADC which is incorporated in the signal conditioning element.

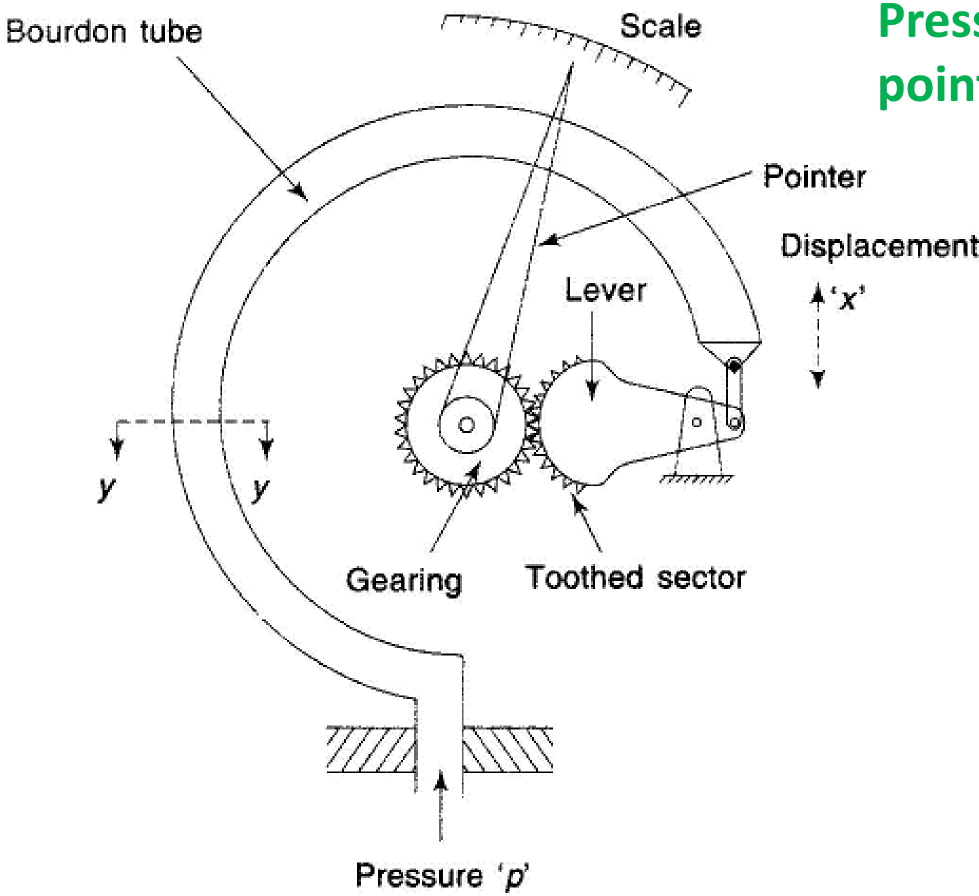


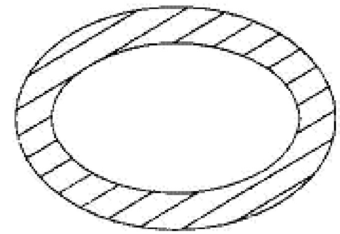
A typical block diagram of automatic (feedback-type) control system


Power
Power
Power
Disturbance Excitation
Power (for active sensors)
Reference Command
Controller (Digital or Analog)
Control Signal
Signal Conditioning
Actuator
Drive Excitation
Response
Sensor / Transducer
Mechanical System (Plant, Process)
Signal Conditioning
Feedback Signal
Power

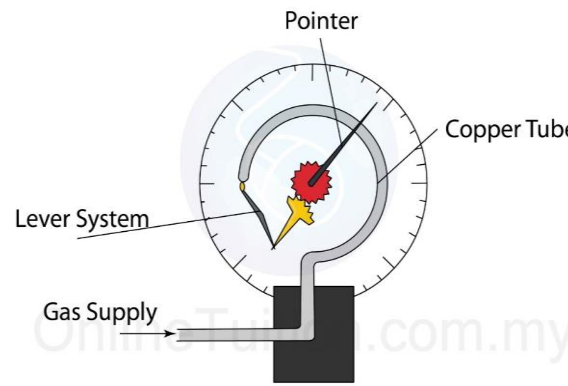
Identification examples of functional elements in instrument

Pressure measurement – pointer display

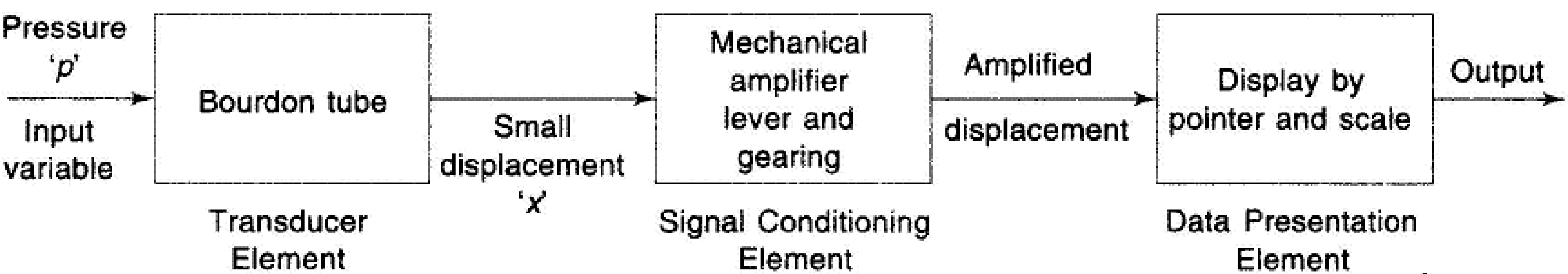




Elliptic-shaped section yy

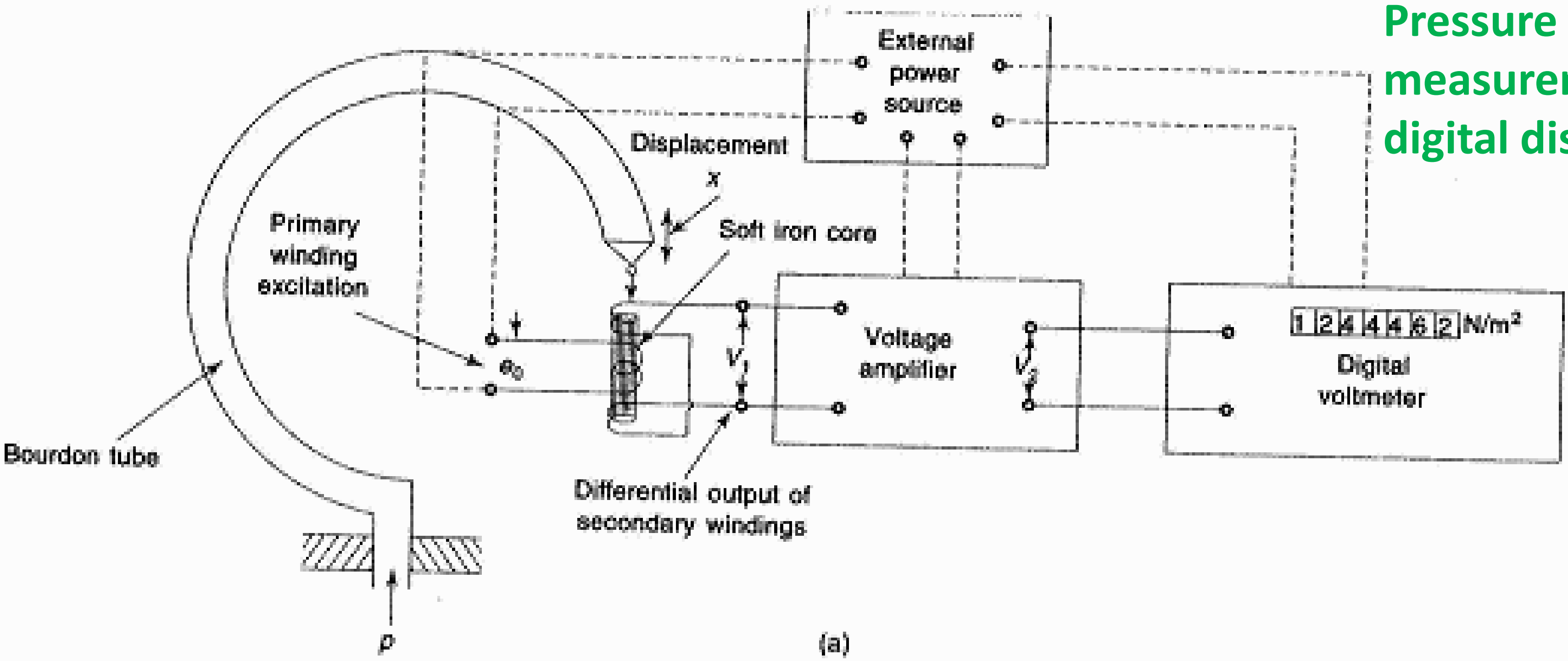


Bourdon tube pressure gauge



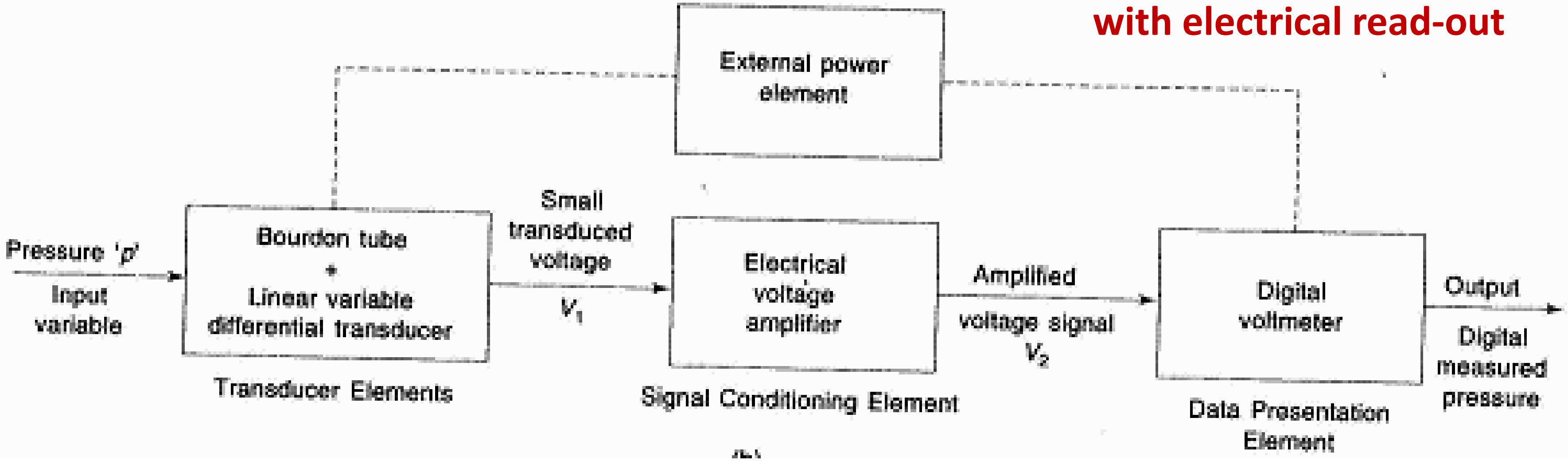
- **Bourdon tube pressure gauge**
  - ❑The **pressure** - hollow oval shaped bent tube
  - ❑**deforms the cross-section** - causes a relative motion, proportional to the applied pressure at the free end of the tube with respect to its fixed end.
  - ❑Acts as **transducer element** → converts the input (pressure into a displacement *x*) at its free end.
  - ❑Combined **lever and the gearing** arrangement (signal conditioning elements) → amplify signal.
  - ❑**Pointer movement** (data presentation elements) (at the gear on a scale) → indication of the pressure.

Pressure measurement – digital display



(a)

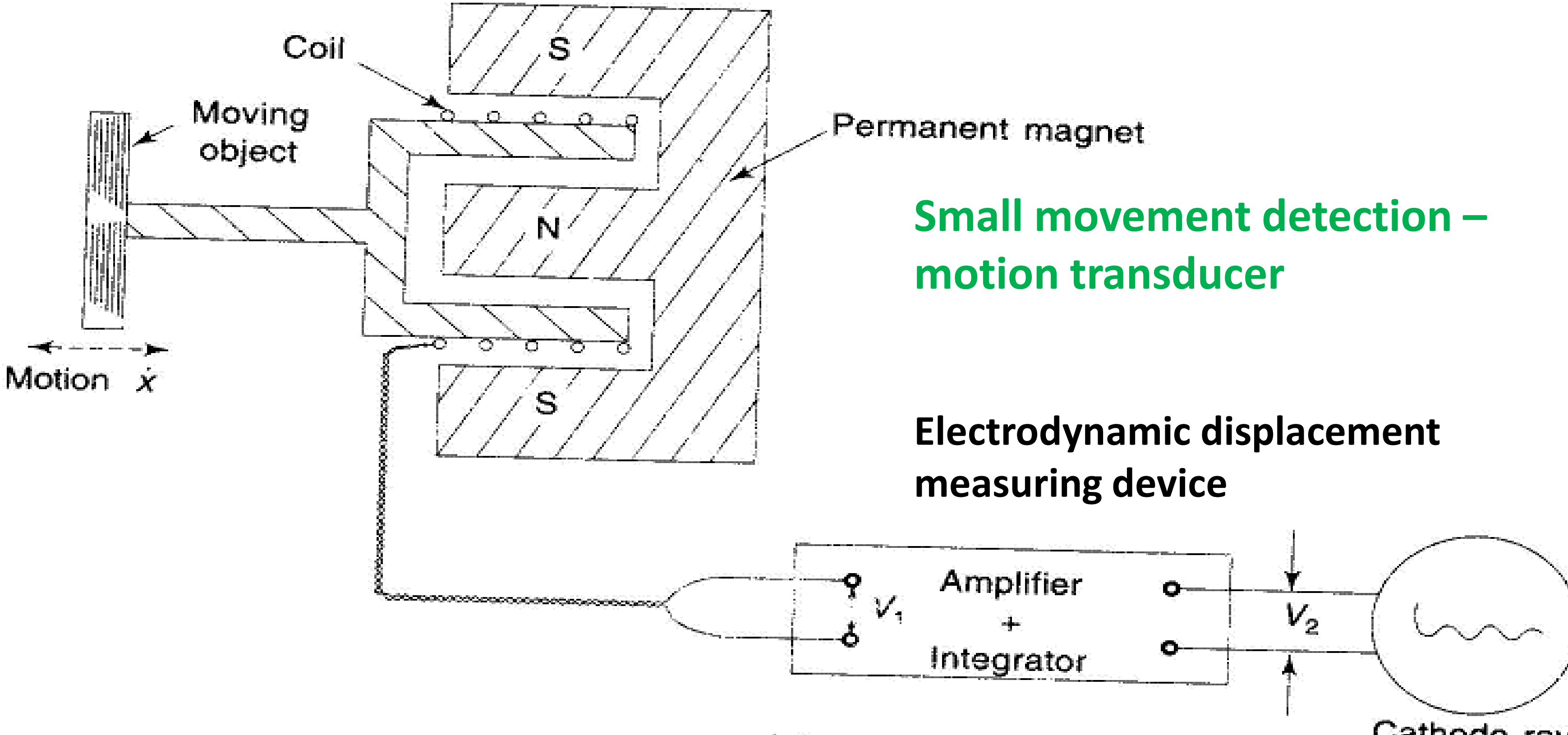
Bourdon pressure gauge with electrical read-out



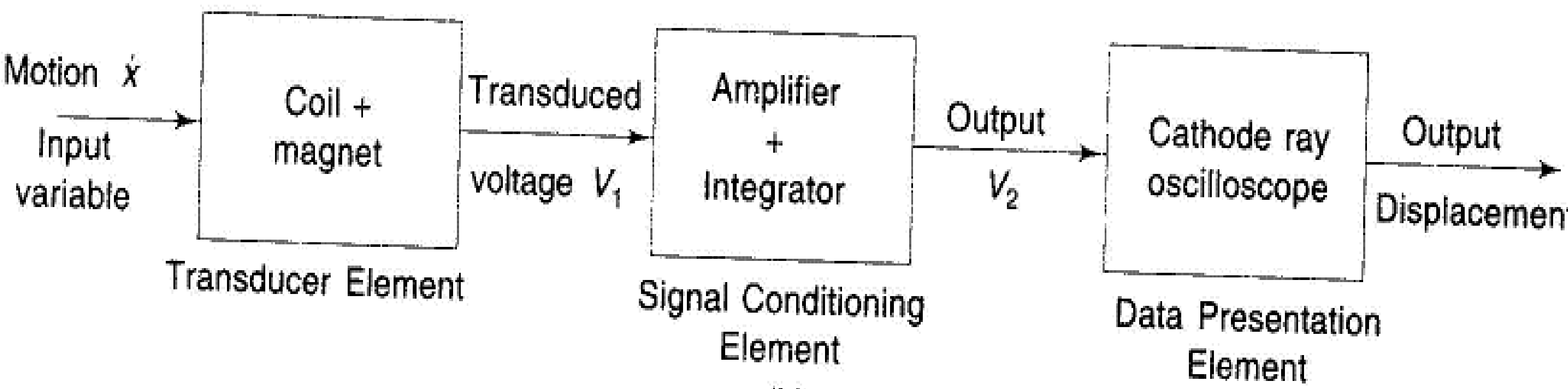
- **Bourdon pressure gauge with electrical read-out**
    1. The use of linear variable differential transducer (LVDT) for sensing the movement of the tip of the Bourdon tube improves the performance of the pressure measuring device.
    2. Advantage: the output of the instrument is electrical and is quite convenient for suitable signal conditioning operations.
    3. A very stiff and short Bourdon tube is used to achieve features of linearity, rapidity of response and a small volume displacement.

Small movement detection – motion transducer

Electrodynamic displacement measuring device

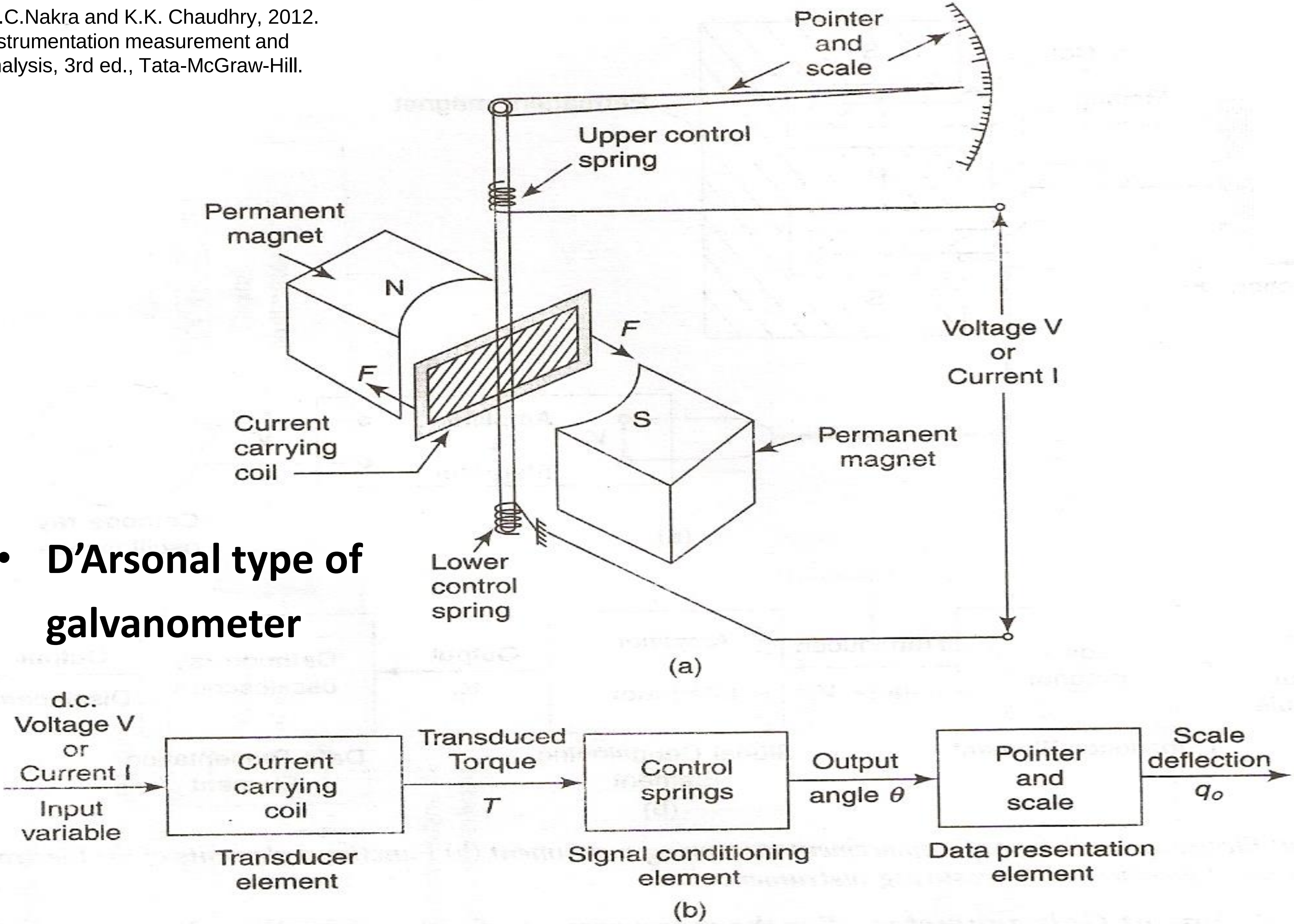


(a)



B.C.Nakra and K.K. Chaudhry, 2012. Instrumentation measurement and analysis, 3rd ed., Tata-McGraw-Hill.

- **D'Arsonal type of galvanometer**



- **D’Arsonal type of galvanometer**
  1. A permanent magnet moving coil (PMMC) type of galvanometer to measure dc voltage, V or current, I.
  2. The input current I, (or current proportional to voltage V) flows in the coil suspended in the magnetic field causes a tangential force on the axial conductors of the coil.
  3. This generates a torque, T proportional to the input current, I.
  4. This torque is balanced by means of twin spiral springs; the upper and lower spiral springs.
  5. This results in the output θ of the pointer, attached to the shaft, which gives the output indication q_0 on the circular scale.

D’Arsonal type of galvanometer

The transfer functions K_T, K_S and K_D can be expressed as follows:

$$\text{Input current } I \text{ (A)} \times K_T = \text{Torque } T\text{(N.m)} \tag{1.1}$$

$$\text{Torque (N}\cdot\text{m)} \times K_S = \text{Angle } \theta \tag{1.2}$$

and

$$\text{Angle } \theta \times K_D = \text{scale deflection } q_o \text{ (mm)} \tag{1.3}$$

From the above equations, we get,

$$\text{Input current } (I) \times (K_T) \times (K_S) \times (K_D) = \text{Scale deflection } q_o \tag{1.4}$$

$$\text{Alternatively, } \frac{dq_o}{dI} = (K_T) \times (K_S) \times (K_D) \text{ mm/A} \tag{1.5}$$

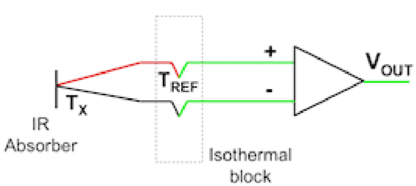
It may be noted that the transfer functions K_T, K_S and K_D are generally constants for steady–state conditions. These values are generally referred as sensitivities or gain or amplifications of the respective functional elements. Further, the overall sensitivity or transfer function of any instrument can be represented as

$$[K]_{\text{overall}} \text{ of the instrument} = (K_T) \times (K_S) \times (K_D) \tag{1.6}$$

B.C.Nakra and K.K. Chaudhry, 2012. Instrumentation measurement and analysis, 3rd ed., Tata-McGraw-Hill.

Input variable to transducer	*Output variable of transducer*	*Principle of operation*	*Type of device*
(2)	(3)	(4)	(5)
Temperature	Voltage	An emf is generated across the junctions of two dissimilar metals or semiconductors when that junction is heated	Thermocouple or Thermopile
Temperature	Displacement	There is a thermal expansion in volume when the temperature of liquids or liquid metals is raised and this expansion can be shown as displacement of the liquid in the capillary	Liquid in Glass Thermometer
Temperature	Resistance change	Resistance of pure metal wire with positive temperature coefficient varies with temperature	Resistance Thermometer
Temperature	Pressure	The pressure of a gas or vapour varies with the change in temperature	Pressure Thermometer

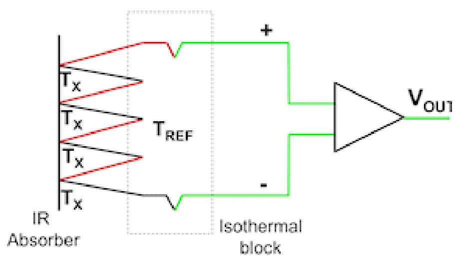
Thermocouple



$V_{OUT} = S \cdot (T_X - T_{REF})$

S: Seebeck coefficient

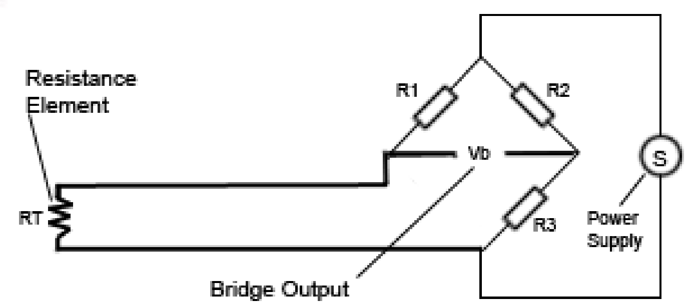
Thermopile



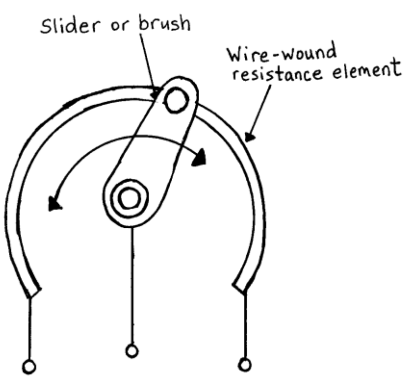
$V_{OUT} = N \cdot S \cdot (T_X - T_{REF})$

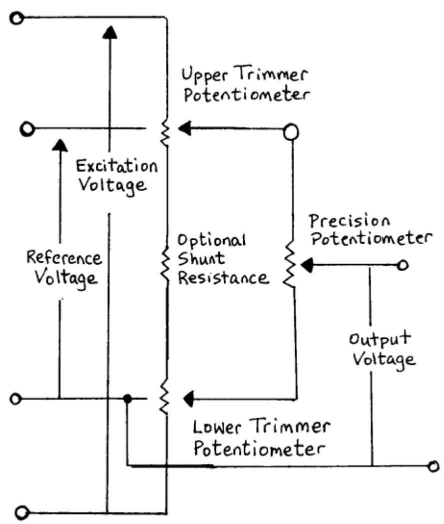
S: Seebeck coefficient

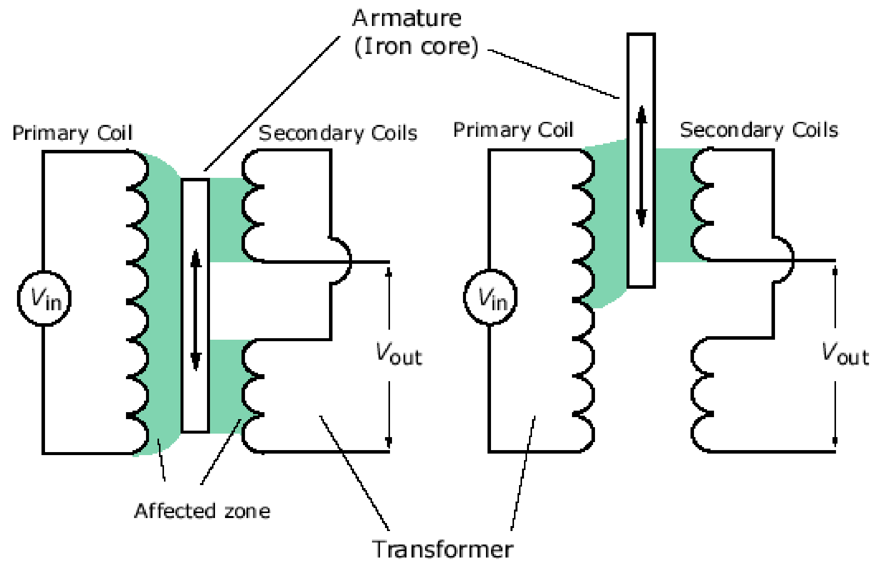
N: Number of thermocouples



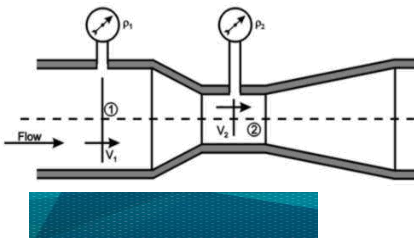
Input variable to transducer	*Output variable of transducer*	*Principle of operation*	*Type of device*
(2)	(3)	(4)	(5)
Displacement	Inductance change	The differential voltage of the two secondary windings varies linearly with the displacement of the magnetic core	Linear Variable Differential Transducer (LVDT)
Displacement	Resistance change	Positioning of a slider varies the resistance in a potentiometer or a bridge circuit	Potentiometric Device
Motion	Voltage	Relative motion of a coil with respect to a magnetic field generates a voltage	Electrodynamic Generator

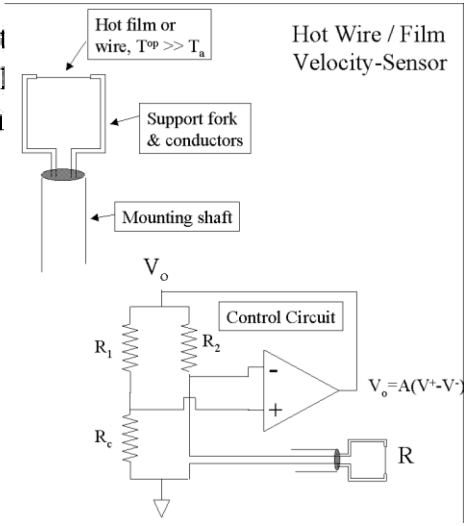




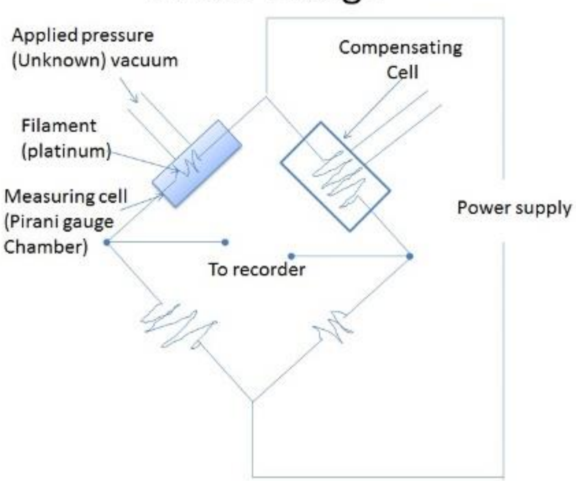


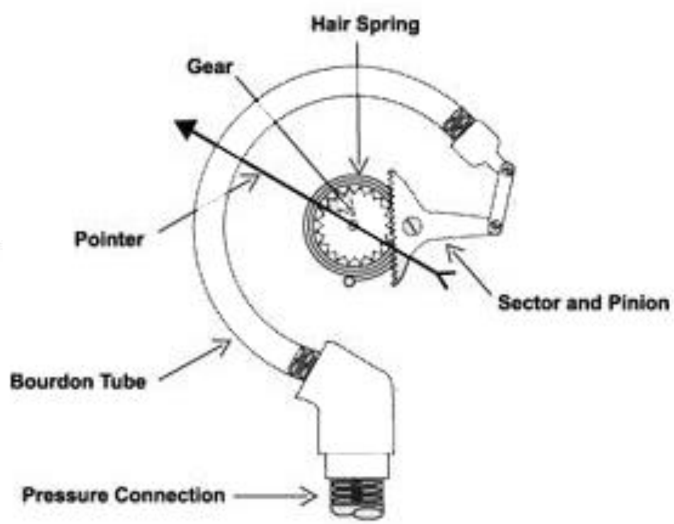
Input variable to transducer	Output variable of transducer	Principle of operation	Type of device
(2)	(3)	(4)	(5)
Flow rate	Pressure	Differential pressure is generated between the main pipe-line and throat of the Venturimeter/Orificemeter	Venturimeter/Orifice-meter
Flow velocity	Resistance change	Resistance of a thin wire/film is varied by convection cooling in stream of gas/liquid flows	Hot Wire Anemomet (gas flows). Hot Fil Anemometer (liqu flows)
Pressure	Movement of a liquid column	The impressed pressure is balanced by the pressure generated by a column of liquid	Manometer
Pressure	Displacement	The application of pressure causes displacement in elastic elements	Bourdon Gauge
Gas pressure	Resistance change	Resistance of a heating element varies by convection cooling	Pirani Gauge

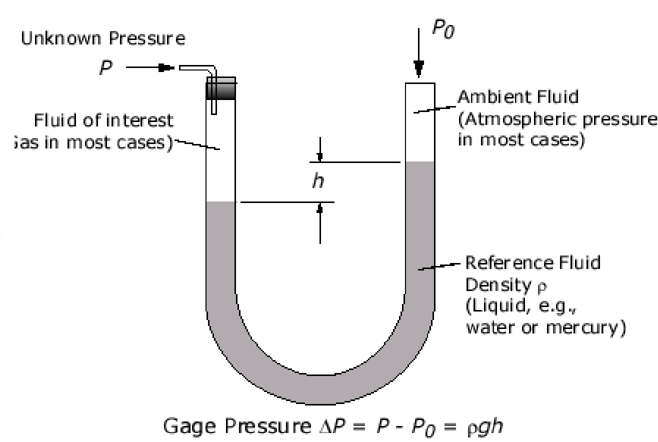




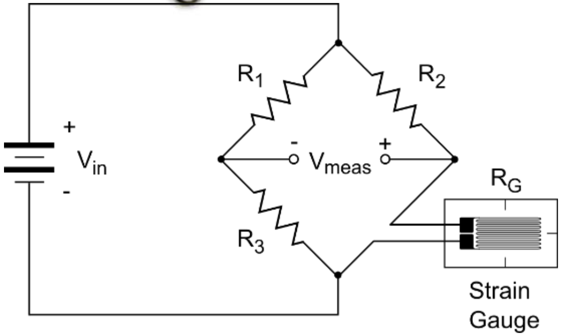
Pirani Gauge

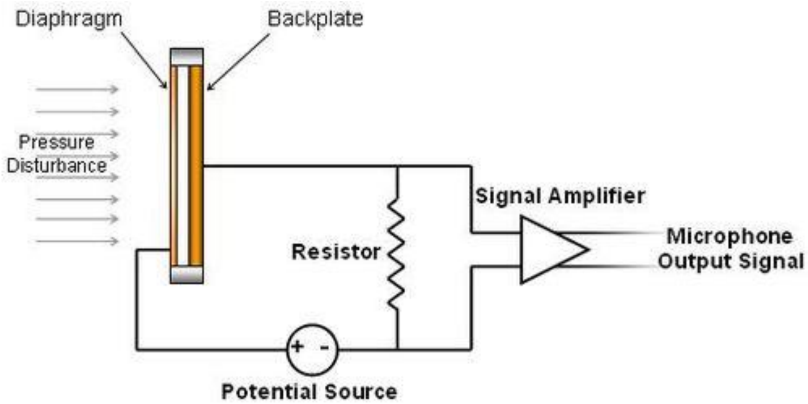


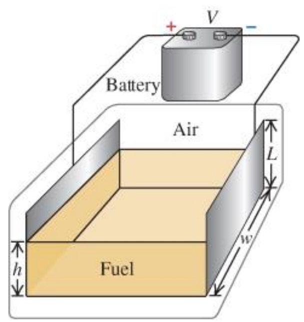


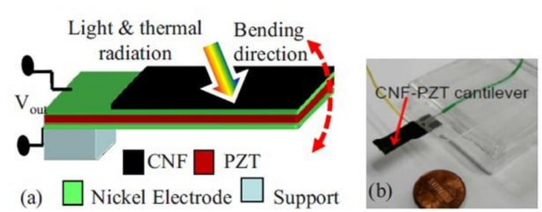


Input variable to transducer	*Output variable of transducer*	*Principle of operation*	*Type of device*
(2)	(3)	(4)	(5)
Force	Displacement	The application of force against a spring changes its length in proportion to the applied force	Spring Balance
Force/torque	Resistance change	The resistance of metallic wire or semiconductor element is changed by elongation or compression due to externally applied stress	Resistance Strain Gauge
Force	Voltage	An emf is generated when external force is applied on certain crystalline materials such as quartz	Piezo-electric Device
Liquid level/thickness	Capacitance change	Variation of the capacitance due to the changes in effective dielectric constant	Dielectric gauge
Speech/music/noise	Capacitance change	Sound pressure varies the capacitance between a fixed plate and a movable diaphragm	Condenser Microphone

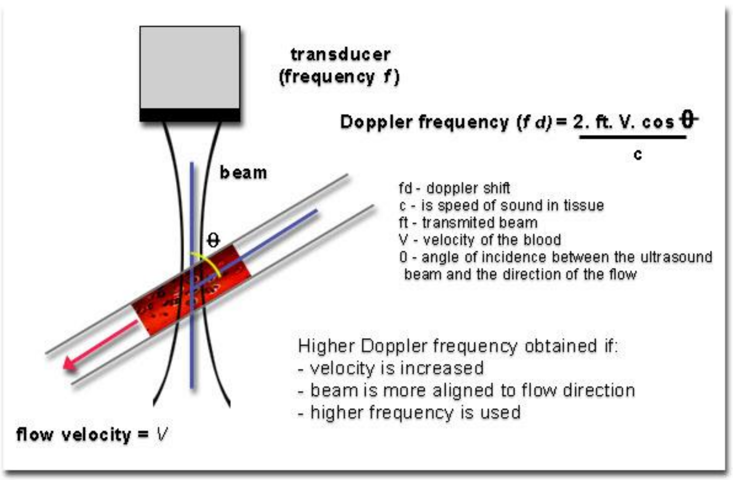


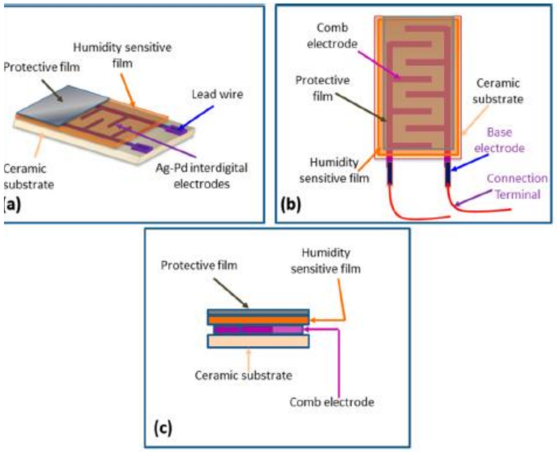






Input variable to transducer	*Output variable of transducer*	*Principle of operation*	*Type of device*
(2)	(3)	(4)	(5)
Light	Voltage	A voltage is generated in a semi-conductor junction when radiant energy stimulates the photoelectric cell	Light Meter/Solar Cell
Light radiations	Current	Secondary electron emission due to incident radiations on the photo-sensitive cathode causes an electronic current	Photomultiplier tube
Humidity	Resistance change	Resistance of a conductive strip changes with the moisture content	Resistance Hygrometer
Blood flow/any other gas or liquid or two-phase flow	Frequency shift	The difference in the frequency of the incident and reflected beams of ultrasound known as Doppler's frequency shift is proportional to the flow velocity of the fluid	Doppler Frequency Shift Ultrasonic Flow Meter





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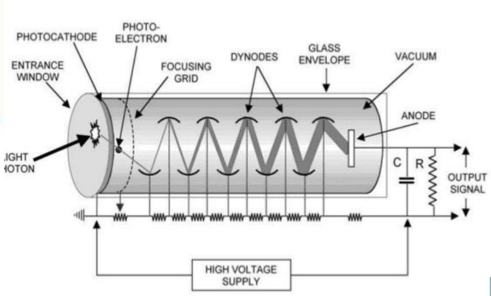

Transducer	Measurand	Measurand Frequency Max/Min	Output Impedance	Typical Resolution	Accuracy	Sensitivity
Potentiometer	Displacement	5 Hz/DC	Low	0.1 mm	0.1%	200 mV/mm
LVDT	Displacement	2,500 Hz/ DC	Moderate	0.001 mm or less	0.3%	50 mV/mm
Resolver	Angular displacement	500 Hz/ DC (limited by excitation freq)	Low	2 min.	0.2%	10 mV/deg
Tachometer	Velocity	700 Hz/ DC	Moderate (50 Ω)	0.2 mm/s	0.5%	5 mV/mm/s 75 mV/rad/s
Eddy current proximity sensor	Displacement	100 kHz/ DC	Moderate	0.001 mm 0.05% full scale	0.5%	5 V/mm
Piezoelectric accelerometer	Acceleration (and velocity, etc.)	25 kHz/ 1Hz	High	1 mm/s^2	1%	0.5 mV/m/s^2
Semiconductor strain gage	Strain (displacement, acceleration, etc.)	1 kHz/ DC (limited by fatigue)	200 Ω	1 - 10 με (1 με = 10^{-6} unity strain)	1%	1 V/ε, 2,000 με max
Loadcell	Force (10 - 1000 *N*)	500 Hz/ DC	Moderate	0.01 N	0.05%	1 mV/N
Laser	Displacement/ Shape	1 kHz/ DC	100 Ω	1.0 μm	0.5%	1 V/mm
Optical encoder	Motion	100 kHz/ DC	500 Ω	10 bit	±½ bit	10^4/rev.

Example of sensors and standard specification

Conclusion

- Aims
  - Obtain basic knowledge about electronic, measurement, sensors, and instrumentation
  - Able to analyse particular sensor, instrument, and measurement situation.

- Students should be able to:
  - Determine general treatment of instrument elements and their characteristic
  - Analyse transducer elements, intermediate elements, and data acquisition system (DAQ)
  - Determine principles of the work and derive mathematical model of sensors for measuring motion and vibration, dimensional metrology, force, torque and power, pressure, temperature, flow and acoustics