Mechatronic Systems Design

MEC301

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Lecture 6: **Sensors and Transducers**

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Transducers

- A ***transducer*** is defined as a device that converts a signal from one physical form to a corresponding signal, which has a different physical form.

- In a control system, the ***transducer*** senses the magnitude or intensity of the controlled output and produces a proportional signal in an energy form suitable for transmission along the feedback path to the comparator.

Sensors

- A ***sensor*** is defined as a device that produces an output signal for the purpose of sensing of a physical phenomenon.

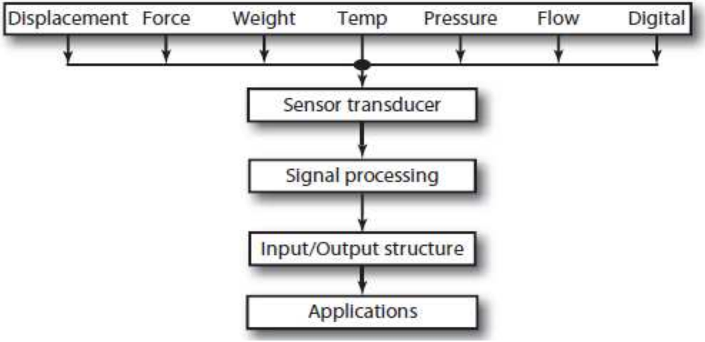
- The element of the transducer which senses the controlled output is called the ***sensor***; the remaining elements of a transducer serve to convert the sensor output to the energy form required by the feedback path

Transducers

Transducers are usually considered in two groups:

- **Motion** and **force transducers**, which are mainly associated with **servomechanisms**
- **Process transducers**, which are mainly associated with **process control** systems

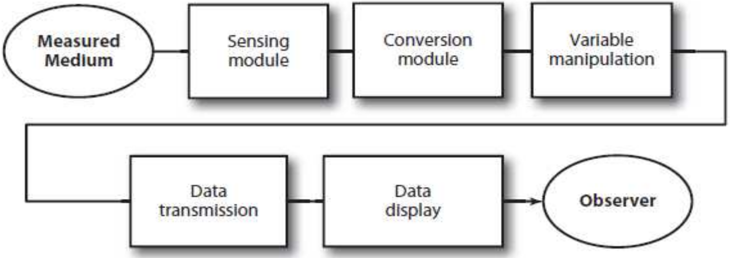
General Instrumentation System



Sensor Classification

Classification	Sensor Type
Signal Characteristics	Analog Digital
Power Supply	Active Passive
Mode of Operation	Null type Deflection type
Subject of Measurement	Acoustic Biological Chemical Electric Mechanical Optical Radiation Thermal Others

Elements of Instrumentation System



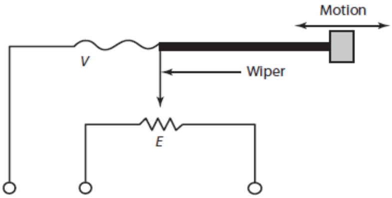
Sensor Types

- Position sensors
- Velocity sensors
- Acceleration sensors
- Proximity sensors
- Load and Pressure sensors
- Temperature sensors
- Flow sensors
- Liquid-level sensors

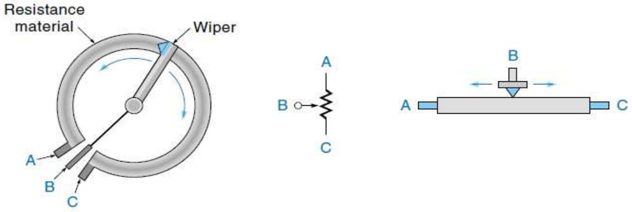
Position Sensors

POTENTIOMETERS
OPTICAL ROTARY ENCODERS
LVDT

Potentiometer



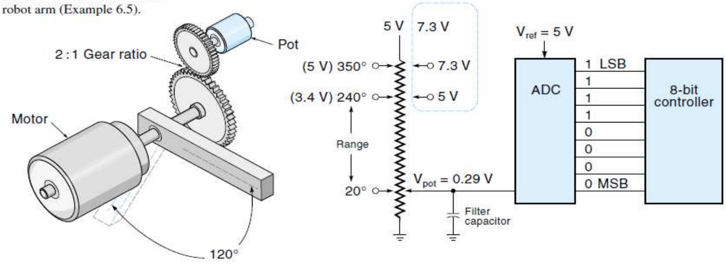
$$V = E\frac{d}{L}$$



(a) Rotary pot (b) Symbol (c) Linear-motion pot

Potentiometer as Position Sensor

Pot sensor position system for robot arm (Example 6.5).



(a) Hardware setup (b) Sensor circuit

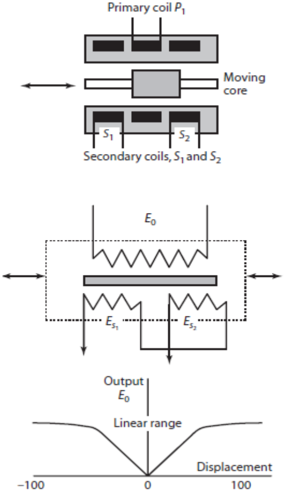
System Values for Various Angles of Robot Arm

Arm angle (degrees)	Pot angle (degrees)	Pot voltage (V)	ADC output (binary states)
0	0	0	00000000
10	20	0.29	00001111
120	240	3.43	10110000
175	350	5	11111111

Potentiometers Features and Applications

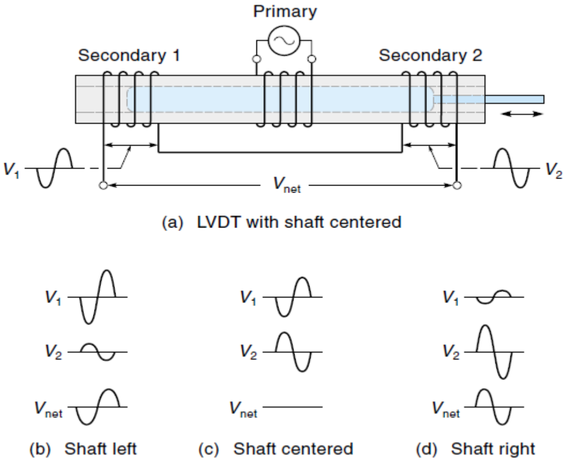
- Features
  - Linear potentiometers are often considered when an electrical signal proportional to displacement is required, but also where cost should be kept low and high accuracy is not critical.
  - Typical rotary potentiometers have a range of +-170°. Their linearity varies from 0.01 to 1.5%.
- Applications
  - Used for position monitoring of products on assembly lines and checking dimensions of the product in quality control systems.
  - Rotary potentiometers are used in applications involving rotational measurement for applications ranging from machine tools to aircraft.

Linear Variable Displacement Transformer (LVDT)

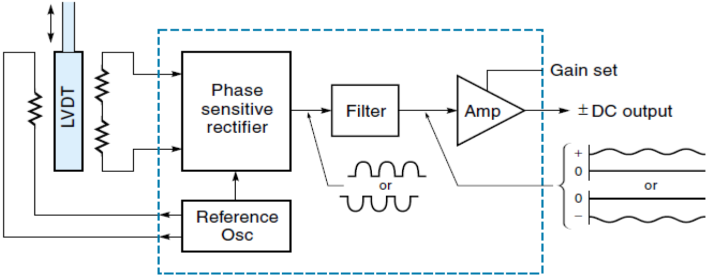


$$V = N\frac{d\phi}{dt}$$

Linear Variable Displacement Transformer (LVDT)



LVDT Interface Circuit



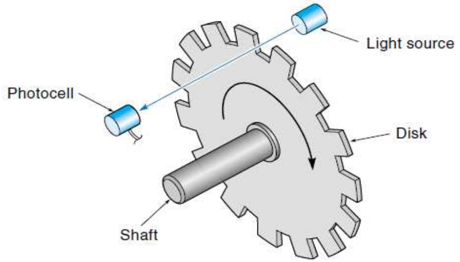
LVDT Features and Applications

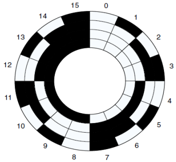
- **Features:**
  - High resolution, high accuracy, and good stability make them an ideal for applications involving short displacement measurements.
  - Sensitive transducers provide resolution down to about 0.05 mm. They have operating ranges from about 0.1 to 300 mm.
  - Accuracy is 0.5 mm of full-scale reading.
  - Less sensitive to wide ranges in temperature than potentiometers.
- **Applications**
  - Measurement of precision gap between weld torch and work surface in welding applications.
  - Measurement of the thickness of plates in rolling mills.
  - Detection of surface irregularity of parts after they are machined.
  - Angular speed measurement of a rotating device.
  - Precise detection of specimen size.
  - Liquid level applications.

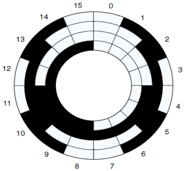
Rotary Encoders Applications

- Encoders are used for measurement of linear or angular position, velocity, and direction of movement.
- Used in computerized manufacturing machines, motion-control applications, and quality assurance of equipment.
- Used in tensile-test instruments to precisely measure the ball screw position.
- Used in automated test stands used when angular positions of windshield wiper drives and switch positions are tested.
- Incremental encoders commonly are used for counting applications.

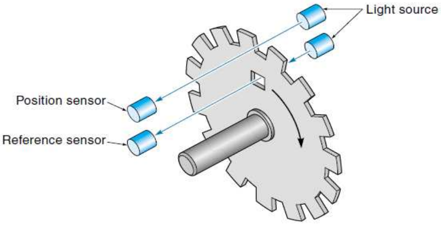
Optical Encoding: Absolute

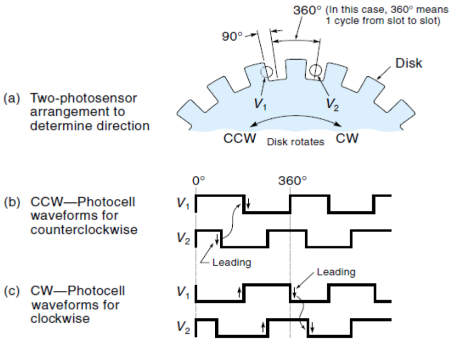




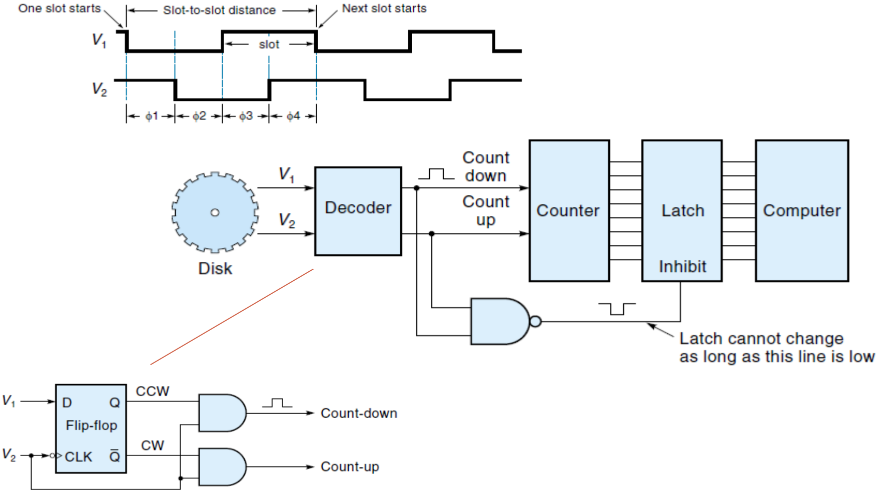


Optical Encoding: Incremental





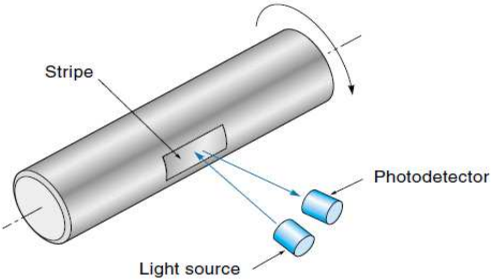
Encoder Interface Circuit



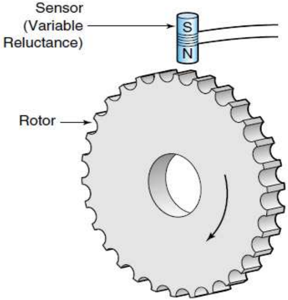
Velocity Sensors

OPTICAL AND DIRECT CURRENT TACHOMETERS

Tachometer



Stripe
Photodetector
Light source



Sensor
(Variable
Reluctance)
S
N
Rotor

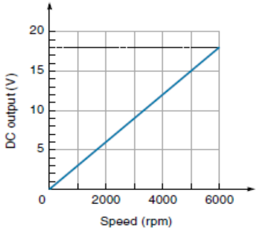
Tachometer Example

The model CK20 is a moving coil tachometer designed for use in applications requiring velocity feedback with minimum system inertia load.

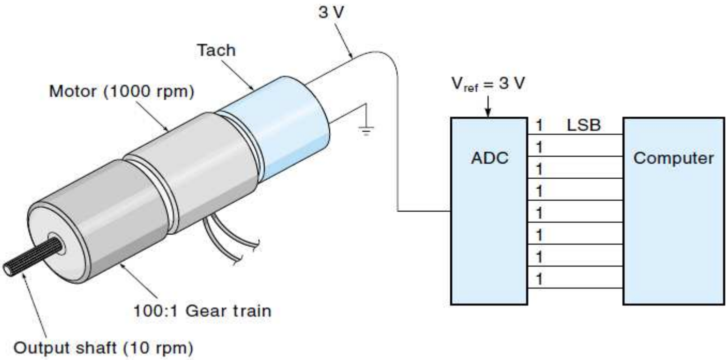
Parameter	Value	Units
Linerity	.2	% max. deviation
Ripple	1.5	max, % peak to peak AC
Ripple Frequency	19	Cycles per revolution
Speed Range	1-6000	RPM
Armature Inertia	$9x10^{-6}$	in-oz-sec^2
Friction Torque	.25	in-oz, max.
Rated Life	10,000	Hours at 3000 RPM

WINDING VARIATIONS

	CK20-A	CK20-B	CK20-C
Output Voltage Gradient (V/KRPM)	3.0	2.5	1



Tachometer Interface



Acceleration Sensors

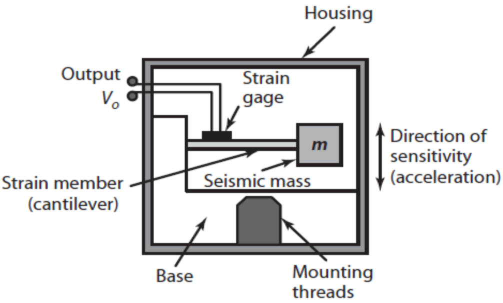
Vibration and piezoelectric

Acceleration Sensors

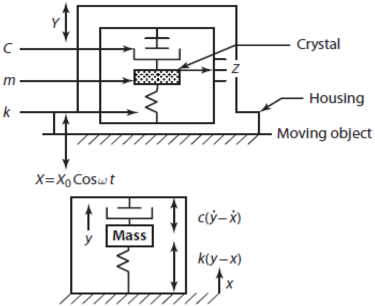
- Measurement of acceleration is important for systems subject to shock and vibration.

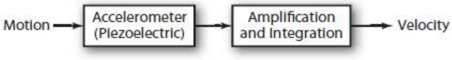
- *Seismic mass*
  - The seismic mass type accelerometer is based on the relative motion between a mass and the supporting structure. The natural frequency of the seismic mass limits its use to low to medium frequency applications.
- *Piezoelectric* accelerometer.
  - The piezoelectric accelerometer, however, is compact and more suitable for high frequency applications

Vibration Sensors: Seismic Mass



Vibration Sensors: Piezoelectric





Accelerometer

- An **accelerometer** is a device that measures indirect acceleration. Rather than measuring the coordinate acceleration (rate of change of velocity), the accelerometer sees the acceleration associated with the phenomenon of weight experienced by any test mass at rest in the frame of reference of the accelerometer device.
  - For example, an accelerometer at rest on the surface of the earth will measure an acceleration $g = 9.81\ m/s^2$ straight upwards, due to its weight. By contrast, accelerometers in free fall or at rest in outer space will measure zero.
  - Another term for the type of acceleration that accelerometers can measure is g-force acceleration.
- Accelerometers have multiple applications in industry and science.
  - Highly sensitive accelerometers are components of inertial navigation systems for aircraft and missiles.
  - Accelerometers are used to detect and monitor vibration in rotating machinery.

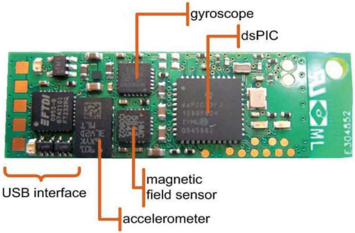
Gyroscope

- A **gyroscope** is a device for measuring or maintaining orientation, based on the principles of angular momentum. Mechanically, a gyroscope is a spinning wheel or disc in which the axle is free to assume any orientation.
  - Although this orientation does not remain fixed, it changes in response to an external torque much less and in a different direction than it would with the large angular momentum associated with the disc's high rate of spin and moment of inertia.

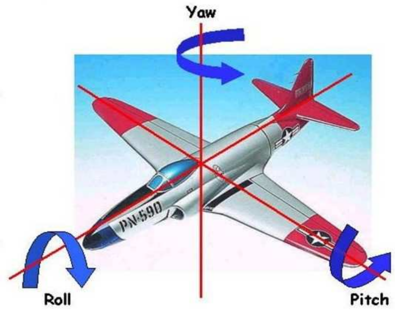
- Electronic, microchip-packaged MEMS gyroscope devices found in consumer electronic devices, solid-state ring lasers, fibre optic gyroscopes, and the extremely sensitive quantum gyroscope.

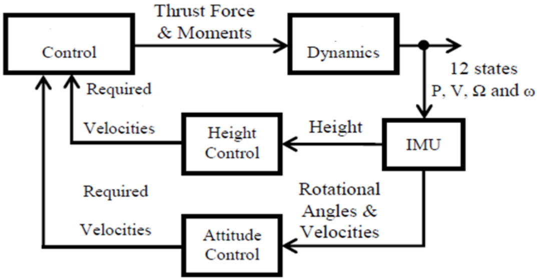
Inertial Measurement Unit (IMU)

- An **inertial measurement unit (IMU)** is an electronic device that measures and reports on a craft's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes, sometimes also magnetometers. IMUs are typically used to maneuver aircraft, including unmanned aerial vehicles (UAVs) and spacecrafts



Flight Control





Proximity Sensors

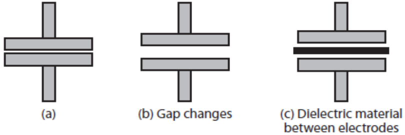
LIMIT SWITCHES
HALL-EFFECT SWITCHES
OPTICAL
CAPACITIVE
INDUCTIVE
ULTRASONIC

Proximity Sensors

- They are used to sense the proximity of an object relative to another object. They usually provide ON/Off signal indicating the presence or absence of an object.
- Examples: *Capacitance, inductance, photoelectric*, and *hall effect*
- **Capacitance** types are similar to inductance except the proximity of an object changes the gap and affects the capacitance.
- **Inductance** proximity sensors consist of a coil wound around a soft iron core. The inductance of the sensor changes when a ferrous object is in its proximity. This change is converted to a voltage-triggered switch.

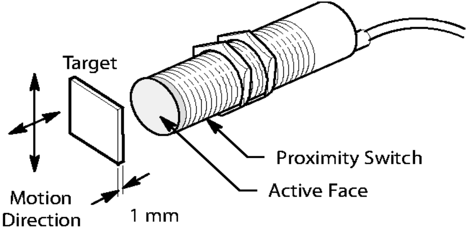
Capacitive Transducer

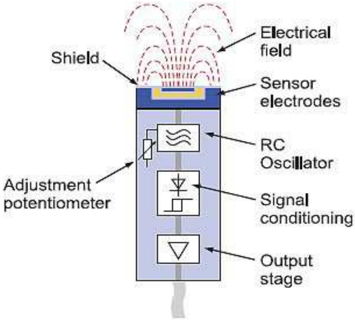
- A change in capacitance can be brought about by varying the following parameters.
  - Changing the distance between the two parallel electrodes.
  - Changing the dielectric constant, permittivity, of dielectric medium .
  - Changing the area of the electrodes, A.
- Features
  - Capacitance transducers can be used in high humidity, high temperature, or nuclear radiated zones.
  - They are very sensitive and have high resolution. They can be expensive and need significant signal conditioners.
- Applications
  - Capacitance transducers are generally only suitable for measuring small displacements. Examples of these are surface profile sensing, wear measurement, or crack growth.



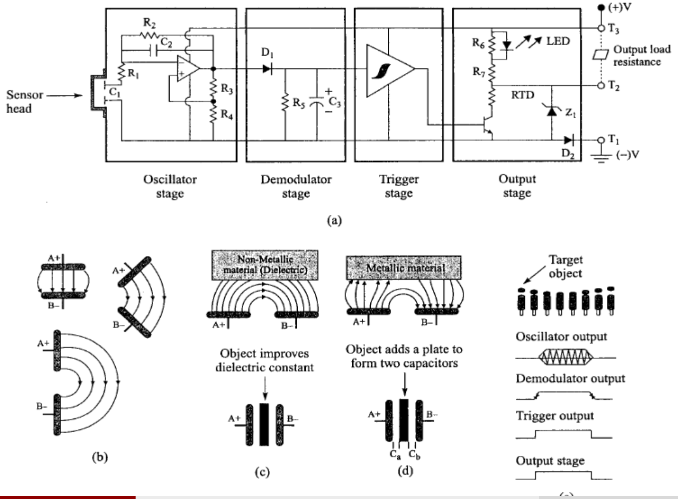
$$C = \frac{\varepsilon A}{d}$$

Capacitive Proximity





Capacitive Proximity Sensor



Specifications

Housing Dimension (mm)	Material	Shielded Unshielded	Sn (mm)	Operating Voltage	Wires
18	Plastic	Shielded	5	10-65 VDC	3
30	Metal	Shielded	10	20-250 VAC	3
	Plastic	Shielded	10	20-250 VAC	2
	Metal	Shielded	10	10-65 VDC	4
	Plastic	Shielded	10	10-65 VDC	4
40	Plastic	Shielded	20	20-250 VAC	2
	Plastic	Shielded	20	10-65 VDC	4

Inductive Transducer

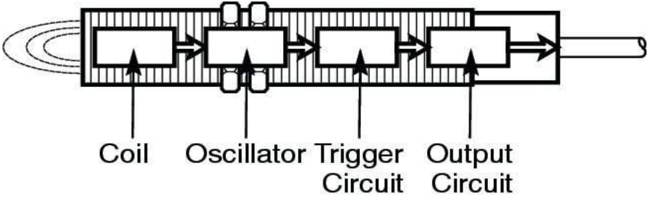
- An **inductive sensor** is an electronic proximity sensor, which detects metallic objects without touching them.

- The sensor consists of an induction loop. Electric current generates a magnetic field, which collapses generating a current that falls asymptotically toward zero from its initial level when the input electricity ceases.

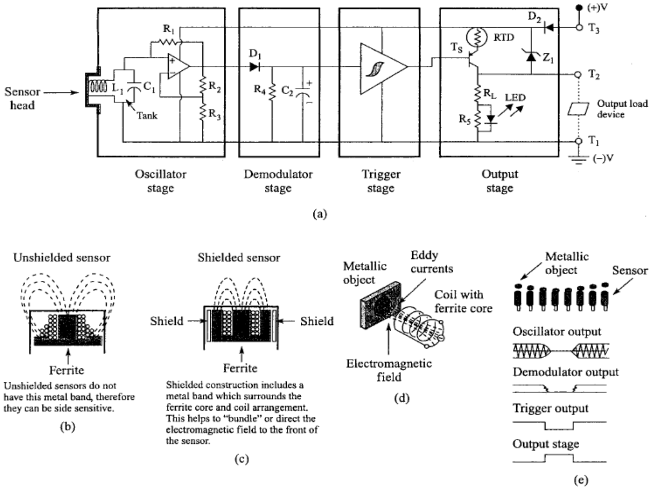
- The inductance of the loop changes according to the material inside it and since metals are much more effective inductors than other materials the presence of metal increases the current flowing through the loop. This change can be detected by sensing circuitry, which can signal to some other device whenever metal is detected.

Inductive Sensors

Fig-Inductive proximity sensors



Inductive Proximity Sensor



Capacitive vs. Inductive

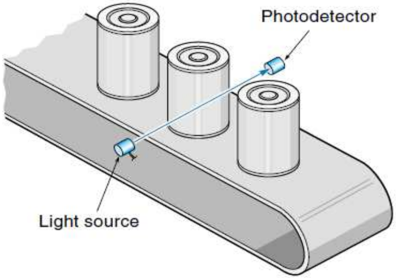
- Capacitive and inductive proximity sensors are similar in size, shape, and concept to inductive proximity sensors.
  - The main difference between the two types is that capacitive proximity sensors produce an electrostatic field instead of an electromagnetic field
- Capacitive sensing is suitable for detecting metals, nonmetals, solids, and liquids.
- Inductive sensing is best suited for metallic targets because it is both a reliable and a more affordable technology.

Proximity Sensors

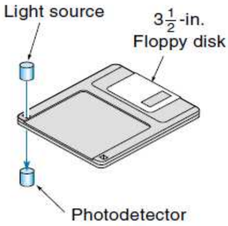
- **Photoelectric** sensors are normally aligned with an infrared light source. The proximity of a moving object interrupts the light beam causing the voltage level to change.

- **Hall effect** voltage is produced when a current-carrying conductor is exposed to a transverse magnetic field. The voltage is proportional to transverse distance between the hall effect sensor and an object in its proximity

Photo-detectors

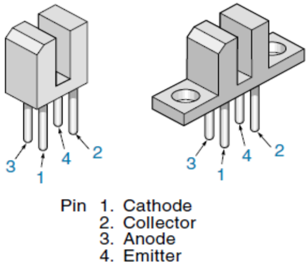


(a) Counting cans on a conveyor belt

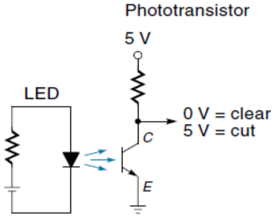


(b) Detecting "read only" hole in a floppy disk

Optical Slotted Coupler



(a) Case types



(b) Circuit

Hall Effect

- Hall effect transducers are used to measure position, displacement, level, and flow.
  - They can be used as an analog motion sensing device as well as a digital device.

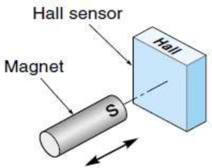
- The Hall effect occurs when a strip of conducting material carries current in the presence of a transverse magnetic field.
  - Hall-Effect Sensors utilise semiconductor Hall chips and a magnet mounted to a shaft or push rod. As the chips change their output in response to the proximity of the magnetic field, changes in its position can be measured.

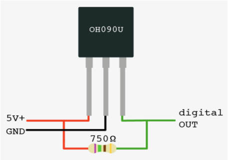
- Principle of operation: An external voltage source is used to establish a current *(I) in the semiconductor crystal. The output voltage (VH) is* sensed across the sides of the crystal, perpendicular to the current direction. When a magnetic field is brought near, the negative charges are deflected to one side producing a voltage.

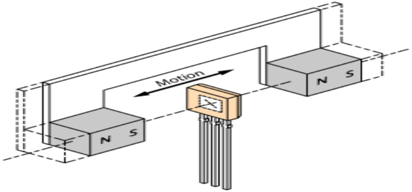
$$V_H = \frac{KIB}{D}$$

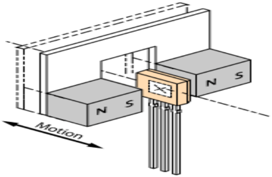
V_H = Hall-effect voltage
K = constant (dependent on material)
I = current from an external source
B = magnetic flux density
D = thickness constant

Hall Effect Proximity Sensor



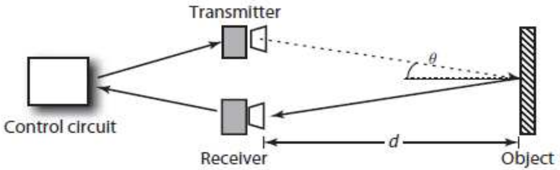






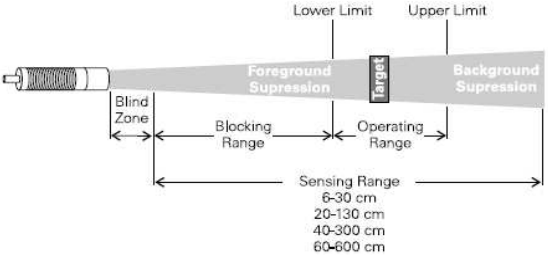
Range Sensors: Ultrasonic

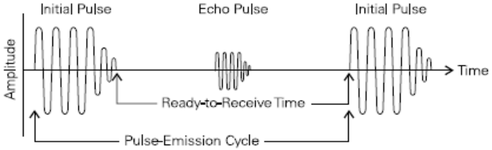
Ultrasonic proximity sensors use a transducer to send and receive high frequency sound signals. When a target enters the beam the sound is reflected back to the switch, causing it to energize or deenergize the output circuit.



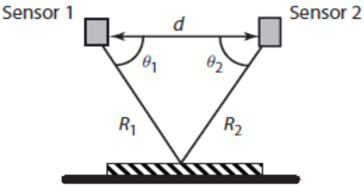
$$\text{Distance: } d = \frac{vt\cos\theta}{2}$$

Ultrasonic Sensors





Range Sensors: Laser



$$R_1 = \frac{d \sin \theta_2}{\sin [180 - (\theta_1 + \theta_2)]}$$

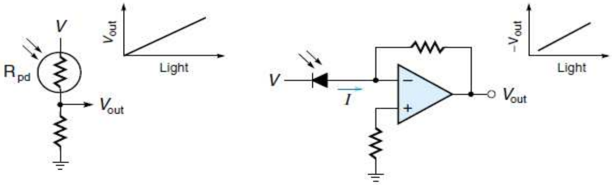
$$R_2 = \frac{d \sin \theta_1}{\sin [180 - (\theta_1 + \theta_2)]}$$

Light Sensors

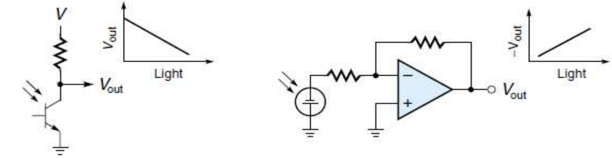
Light Sensors

- Light intensity and full field vision are two important measurements used in many control applications.
- *Phototransistors*, *photoresistors*, and *photodiodes* are some of the more common type of light intensity sensors.
- When the photoresistor is exposed to light, its resistance drops in proportion to the intensity of light. When interfaced with a circuit and balanced, the change in light intensity will show up as change in voltage.
- These sensors are simple, reliable, and cheap, used widely for measuring light intensity.

Light Sensors



(a) Photoresistor (b) Photodiode



(c) Phototransistor (d) Photovoltaic cell

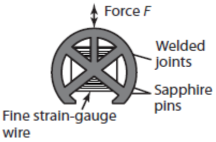
Load Sensors

Bonded-wire strain gauges
Semiconductor force strain gauges
Low-force sensors
Bourdon tubes
Bellows
Semiconductor pressure sensors

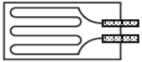
Force, Torque, and Pressure Sensors

- Common force/torque sensors are: *strain gauge* and *piezoelectric*.
- Both are available to measure force and/or torque either in one axis or multiple axes.
- The strain gauge make use of mechanical members that experiences elastic deflection when loaded. These types of sensors are limited by their natural frequency.
- The piezoelectric sensors are particularly suitable for dynamic loadings in a wide range of frequencies. They provide high stiffness, high resolution over a wide measurement range, and are compact.

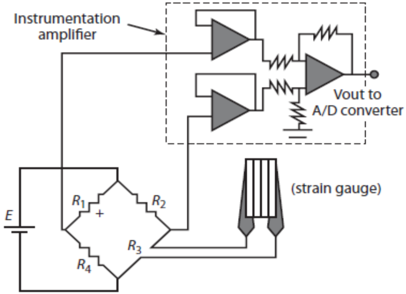
Strain Gauges



(a) Stretched unbonded



(a) Bonded wire strain gauge



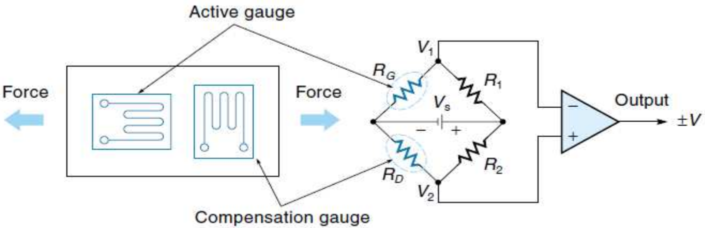
The resistance, R, of a resistance wire depends on its area, length, and electrical resistivity.

$$R_0 = \frac{\rho l}{A_0}$$

where

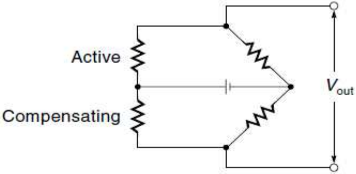
ρ = resistivity, Ω-m
R_0 = sample resistance, Ω
l = length, m
A_0 = cross-sectional area, m^2

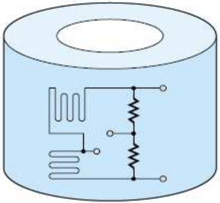
Strain Gauges

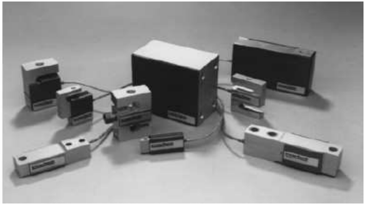


(a) Placement of gauges (b) Interface circuit using a bridge

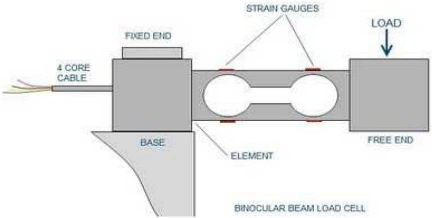
Load Cells

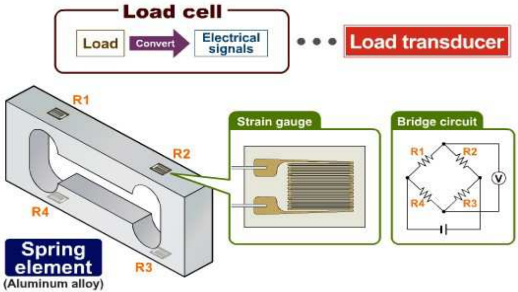






Load Cells


STRAIN GAUGES
LOAD
FIXED END
4 CORE
CABLE
BASE
ELEMENT
FREE END
BINOCULAR BEAM LOAD CELL

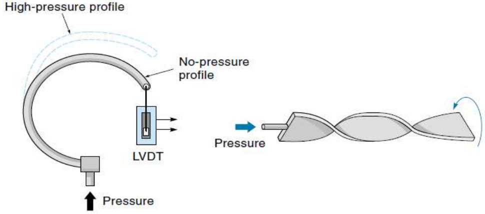

Load cell
Load
Convert
Electrical
signals
Load transducer
R1
R2
R3
R4
Strain gauge
Bridge circuit
R1
R2
R3
R4
V
Spring
element
(Aluminum alloy)

Strain Gauges

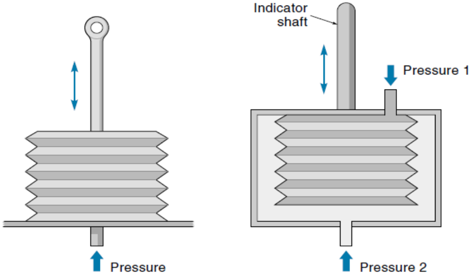
- Features
  - A high gauge factor increases its sensitivity and causes a larger change in resistance for a particular strain.
  - High resistance of the strain gauge minimizes the effect of resistance variation in the signal processing circuitry. Choose gauge characteristics such that resistance is a linear function of strain.
  - For dynamic measurements, the linearity should be maintained over the desired frequency range.
  - Low temperature coefficient and absence of the hysteresis effect add to the precision.

- Applications
  - Strain-gauge transducers are used for measuring strain, force, torque, pressure, and vibration.
  - In some applications, strain gauges are used as a primary or secondary sensor in combination with other sensors.

Pressure Sensors: Bourdon and Bellows

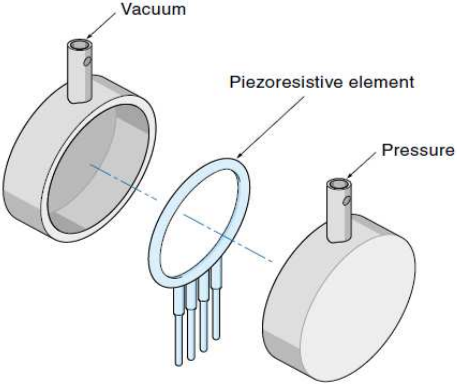


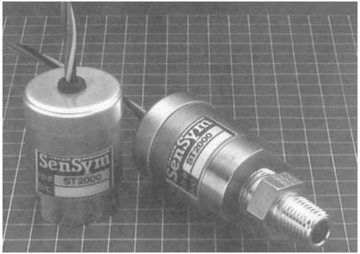
(a) "Unbend" type (b) "Untwist" type



(a) Single-pressure type (b) Differential-pressure type

Semiconductor Pressure Sensor





Temperature Sensors

Bimetallic temperature sensors
Thermocouples
Resistance temperature detectors
Thermistors
IC temperature sensors.

Temperature Sensors

- Temperature measurement is based on one of the following principles.

1. Contact voltage between two dissimilar metals.
2. Change in electrical resistance.
3. Change in radiated energy.

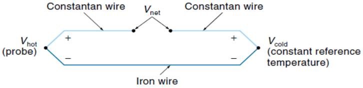
- The most common temperature sensors are:
  - Thermocouples
  - Thermisters
  - Resistance Temperature Detectors (RTD)
  - Infrared types

Thermocouples

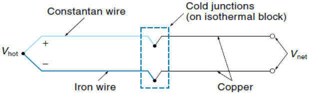
- *Thermocouples* are the most versatile, inexpensive, and have a wide range (up to 1200 C typical). A thermocouple simply consists of two dissimilar metal wires joined at the ends to create the sensing junction.

- When used in conjunction with a reference junction, the temperature difference between the reference junction and the actual temperature shows up as a voltage potential.

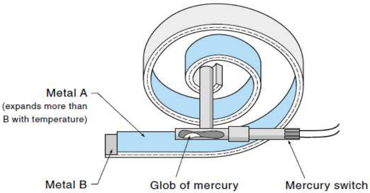
Thermocouple

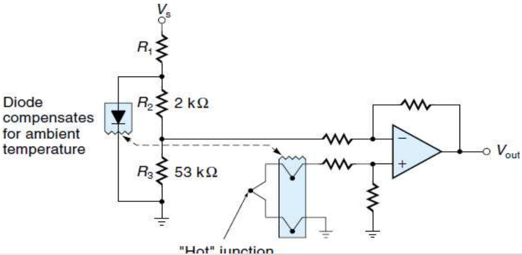


(a) Basic principle

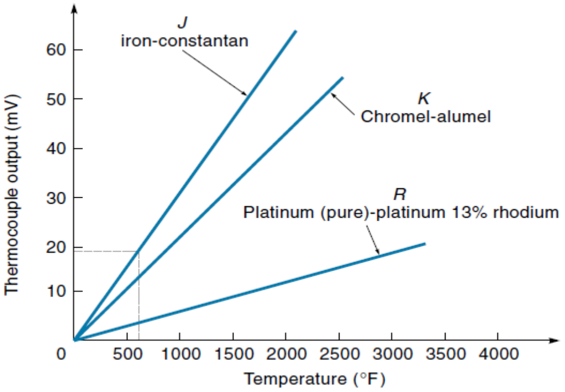


(b) Thermocouple connected to copper wires





Thermocouple Chart



Standard Thermocouple Characteristics

Type	Material	Operating Range	Accuracy
K	Chromel/Alumel	−200 to 1350	+/− 3°C
J	Iron/Constantan	−200 to 800	+/− 3°C
E	Chromel/Constantan	−200 to 1000	+/− 1.5°C
R	Platinum/Platinum Rhodium (10%)	−50 to 1600	+/− 2°C
S	Platinum/Platinum Rhodium (13%)	−50 to 1600	+/− 2°C
T	Copper/Constantan	−200 to 400	+/− 2°C

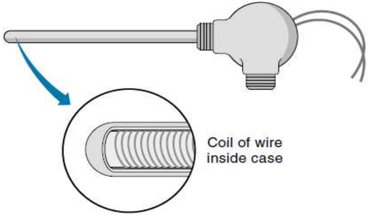
Temperature Sensors

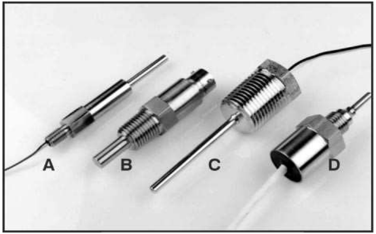
- The *RTDs* use the phenomenon that the resistance of a metal changes with temperature. They are, however, linear over a wide range and most stable
- *Thermistors* are semiconductor devices whose resistance changes as the temperature changes. They are good for very high sensitivity measurements in a limited range of up to 100 C. The relationship between the temperature and the resistance is nonlinear.
- *Infrared type* sensors use the radiation heat to sense the temperature from a distance. These noncontact sensors can also be used to sense a field of vision to generate a thermal map of a surface

RTD

- RTD is a length of wire whose resistance is a function of temperature.

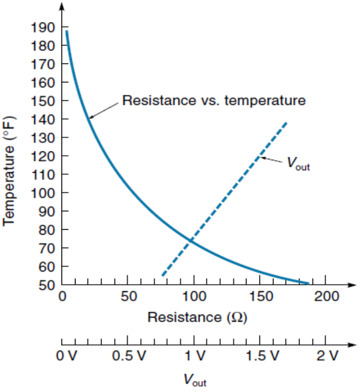
- It consists of a wire that is wound in the shape of a coil to achieve small size and improve thermal conductivity.



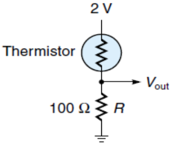


Thermistor

Thermistor operation relies on the principle of change in semiconductor resistance with change in temperature



(a) Thermistor temperature vs. resistance curve



(b) Interface circuit

IC Temperature Sensors: LM35

National Semiconductor

LM35/LM35A/LM35C/LM35CA/LM35D
Precision Centigrade Temperature Sensors

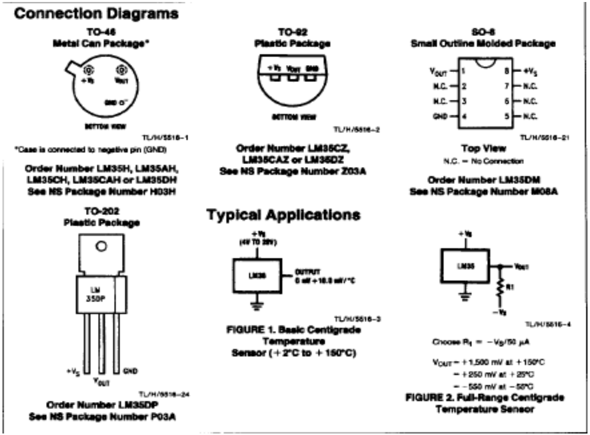
General Description

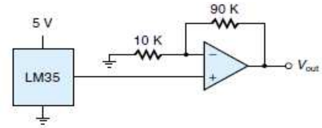
The LM35 series are precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature. The LM35 thus has an advantage over linear temperature sensors calibrated in ° Kelvin, as the user is not required to subtract a large constant voltage from its output to obtain convenient Centigrade scaling. The LM35 does not require any external calibration or trimming to provide typical accuracies of ±¼°C at room temperature and ±¾°C over a full −55 to +150°C temperature range. Low cost is assured by trimming and calibration at the wafer level. The LM35's low output impedance, linear output, and precise inherent calibration make interfacing to readout or control circuitry especially easy. It can be used with single power supplies, or with plus and minus supplies. As it draws only 60 μA from its supply, it has very low self-heating, less than 0.1°C in still air. The LM35 is rated to operate over a −55° to +150°C temperature range, while the LM35C is rated for a −40° to +110°C range (−10° with improved accuracy). The LM35 series is available packaged in hermetic TO-46 transistor packages, while the LM35C, LM35CA, and LM35D are also available in the plastic TO-92 transistor package. The LM35D is also available in an 8-lead surface mount small outline package and a plastic TO-202 package.

Features

- Calibrated directly in ° Celsius (Centigrade)
- Linear + 10.0 mV/°C scale factor
- 0.5°C accuracy guaranteeable (at +25°C)
- Rated for full −55° to +150°C range
- Suitable for remote applications
- Low cost due to wafer-level trimming
- Operates from 4 to 30 volts
- Less than 60 μA current drain
- Low self-heating, 0.08°C in still air
- Nonlinearity only ±¼°C typical
- Low impedance output, 0.1 Ω for 1 mA load

LM35 Temperature Sensor





Temperature Sensors Comparison

Sensor	Temperature range (°C)	Accuracy (±°C)	Cost	Robustness
Thermocouple	−270 to +2600	1	Low	Very high
RTD	−200 to +600	0.2	Medium	High
Thermistor	−50 to +200	0.2	Low	Medium
Integrated circuit	−40 to +125	1	Low	Low

Flow Sensors

Orifice plates
Venturis
Pitot tubes
Turbines
Magnetic flowmeters.

Flow Sensors

- The fluid medium can be liquid, gas, or a mixture of the two.
- The flow could be laminar or turbulent and can be a time-varying phenomenon.

- The *venturi meter* and *orifice plate* restrict the flow and use the pressure difference to determine the flow rate.

- The *rotameter* and the *turbine meters* when placed in the flow path, rotate at a speed proportional to the flowrate.

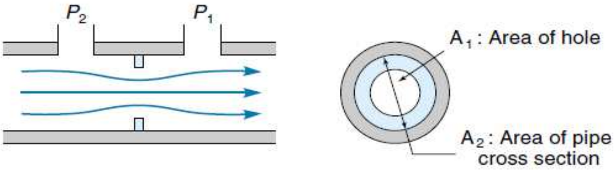
- The *electromagnetic flow meters* use noncontact method. Magnetic field is applied in the transverse direction of the flow and the fluid acts as the conductor to induce voltage proportional to the flow rate.

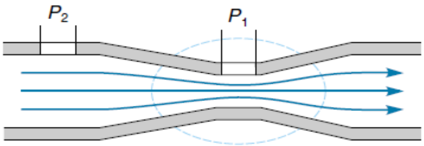
Flow Sensors

- *Ultrasonic flow meters* measure fluid velocity by passing high-frequency sound waves through fluid.
  - Transmitters (T) provide the sound signal source. As the wave travels towards the receivers (R), its velocity is influenced by the velocity of the fluid flow due to the doppler effect.

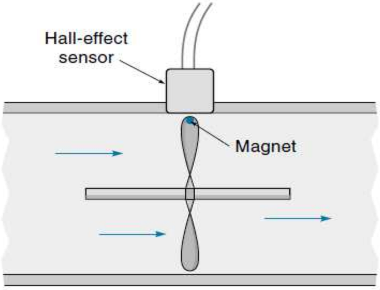
- The control circuit compares the time to interpret the flow rate. This can be used for very high flow rates and can also be used for both upstream and downstream flow. The other advantage is that it can be used for corrosive fluids, fluids with abrasive particles, as it is like a noncontact sensor.

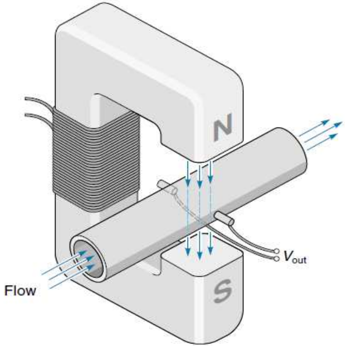
Orifice Plate and Venturi Flow





Turbine and Magnetic

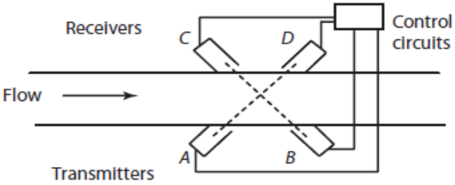




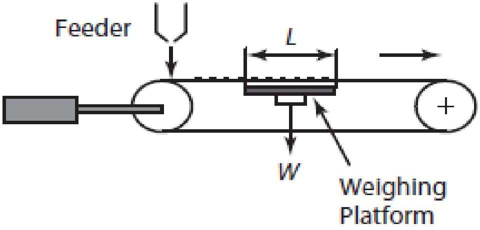
Ultrasonic Flow Sensors

- Ultrasonic flow meters measure fluid velocity by passing high frequency sound waves through the fluid.

- They operate by measuring the transmission time difference of an ultrasonic beam passed through a homogeneous fluid contained in a pipe at both an upstream and downstream location.



Flow Sensors for Solids



$$\text{Flow rate } Q = \frac{WR}{L}$$

Level Sensors

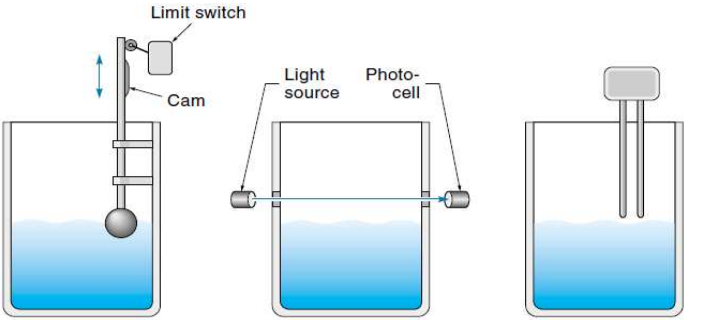
DISCRETE AND CONTINUOUS TYPES

Level Sensors

- Level sensors are used to measure the fluid level in tanks.

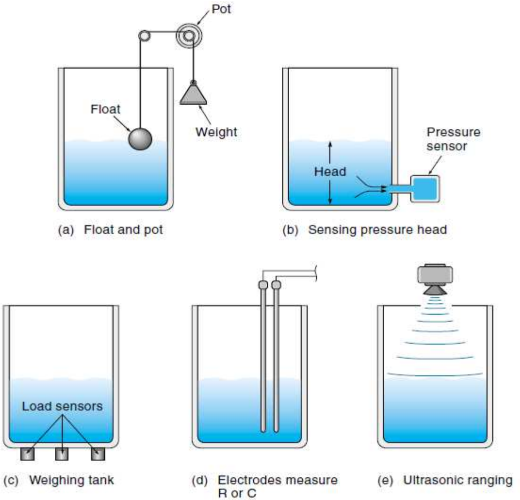
- There are discrete and continuous level sensors

Discrete Level Sensor



(a) Float and switch (b) Photosensor (c) Resistance probe

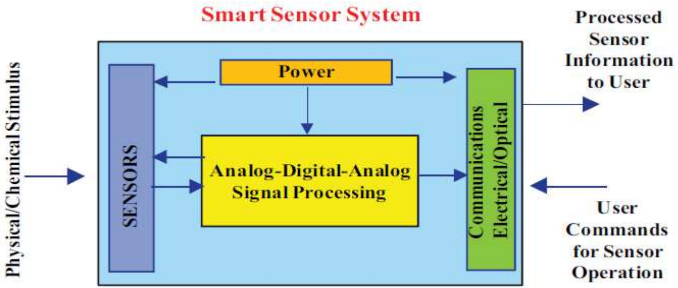
Continuous Level Sensor



Smart Sensors

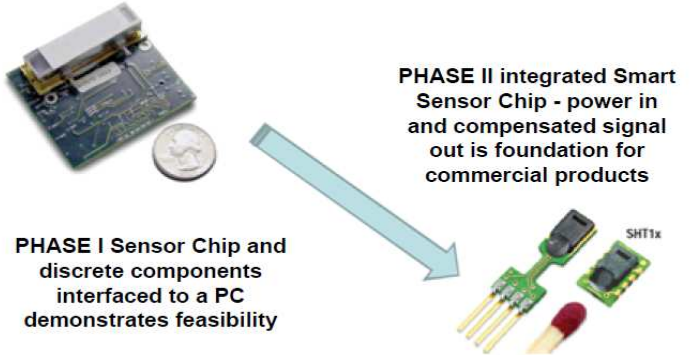
Smart Sensors

- Smart sensors combine the sensing element with microprocessor capabilities that provides embedded intelligence.
- Advantages include: fast signal processing , high signal-to-noise-ratio, self-testing, auto-calibration, failure prevention



Smart Sensors

- Smart sensors have evolved from large size discrete components to small integrated sensory systems



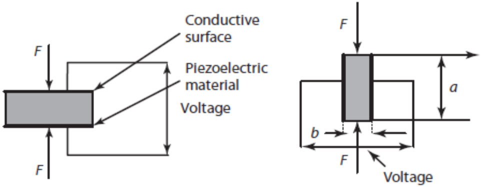
Smart Material Sensors

- New smart materials are being used as sensors.
- Examples are: *Optic fibers, piezoelectric,* and *magnetostrictive* materials
- Optic fibers
  - Can be used to sense strain, liquid level, force, and temperature with very high resolution.
  - They have found numerous applications in smart structure applications such as damage sensors, vibration sensors, and cure-monitoring sensors.
- The basic principle of operation of an embedded optic fiber used to sense displacement, force, or temperature. The relative change in the transmitted intensity or spectrum is proportional to the change in the sensed parameter.

Piezoelectric Transducer

- Piezoelectric materials, when subjected to mechanical force or stress along specific planes, generate electric charge.

- The best-known natural material is quartz crystal (SiO2). Rochelle salt is also considered a natural piezoelectric material.



$$Q = dF \quad \text{(Longitudinal effect)}$$

$$Q = dF\frac{a}{b} \quad \text{(Transverse effect)}$$

Micro Sensors

- Micro Electro Mechanical Systems (MEMS) is a class of systems that are physically small. These systems have both electrical and mechanical parts as an integrated circuit. They include micro-sensors and micro-actuators

- Microsensors are the miniaturized version of the conventional macrosensors with improved performance and reduced cost.

- Silicon micromachining technology has helped the development of many microsensors and continues to be one of the most active research and development topics in this area.

Micro and Nano Sensors

- Microsensors have found applications in medical technology.
  - A *fiberscope* of approximately 0.2 mm in diameter has been developed to inspect flaws inside tubes.
  - A *microtactile sensor*, which uses laser light to detect the contact between a catheter and the inner wall of blood vessels during insertion that has sensitivity in the range of 1 mN.

- Similarly, the progress made in the area of nanotechnology has fuelled the development of nanosensors. These are relatively new sensors that take one step further in the direction of miniaturization and are expected to open new avenues for sensing applications.

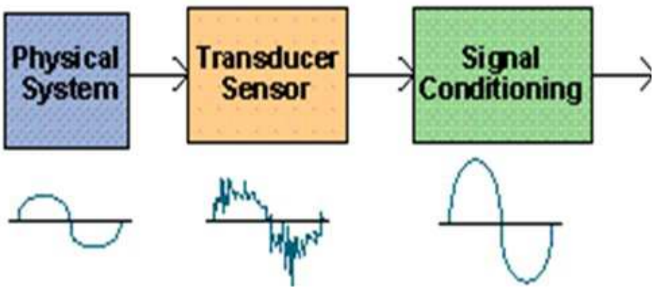
Transducers Classification

- Potentiometric
  - Potentiometric transducers apply the principle of *change in resistance of material in the sensor.*
- Capacitance
  - Capacitance transducers apply the principle of *capacitance variation* between a set of plate assemblies.
- Inductance
  - Inductance transducers are based on the principle of *variation of inductance* by the insertion of core material into an inductor. Inductance variations serve as a measure of displacement.
- Piezoelectric
  - Piezoelectric transducers are based on the principle of *charge generation*. Whenever certain piezoelectric crystals are subjected to mechanical motion, an electric voltage is induced. This effect can be reversed by applying an electric voltage and deforming the crystal.

Signal Conditioning

Signal Conditioning

- Signal conditioning circuits improve the quality of signals generated by transducers before they are converted into digital signals by the PC's data-acquisition hardware.



- Filtering and Amplifying measured signals from sensors

Signal Conditioning

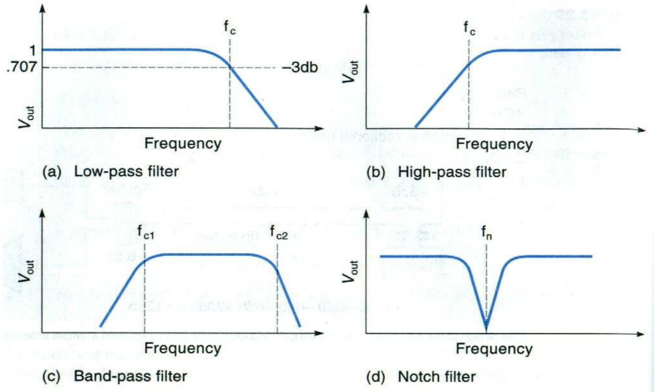
- The **signal conditioner** accepts the electrical output of the transducer and transmits the signal to the comparator in a form compatible with the reference input. The functions of the signal conditioner include:

- **<u>Amplification</u>**
- Isolation
- Sampling
- Noise elimination
- Linearization
- Span and reference shifting
- Math manipulation
  - differentiation, division, integration, multiplication, root finding, squaring, subtraction, or summation
- Signal conversion
  - DC–AC, AC–DC, frequency–voltage, voltage–frequency, digital–analog, analog–digital
- Buffering
- Digitizing
- **<u>Filtering</u>**
- Impedance matching
- Wave shaping
- Phase shifting

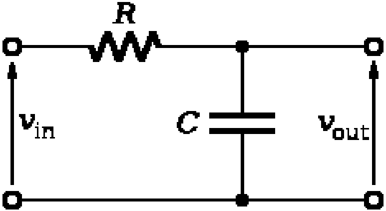
- In a digital control system, many of the signal conditioning functions listed here can also be accomplished by software

Filtering

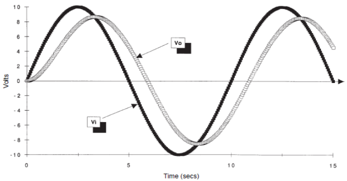
Electronic filters are circuits which perform signal processing functions, specifically to eliminate unwanted frequencies and/or enhance wanted ones



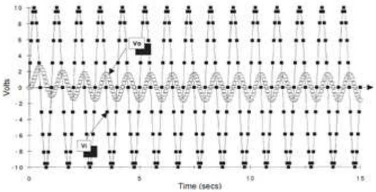
Example: Low Pass Filter



$$H(s) = \frac{Vout}{Vin} = \frac{1/sC}{1/sC + R} = \frac{1}{1 + RCs}$$



Passes low frequencies

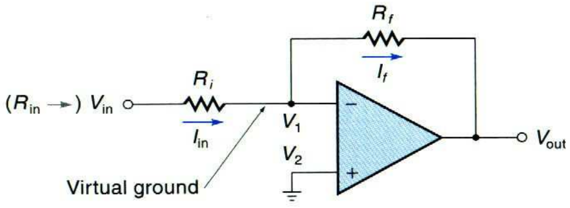


Blocks high frequencies

Amplification

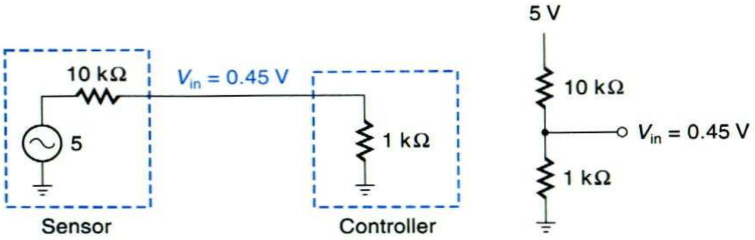
- Amplification expands the range of the transducer signals so that they match the input range of the A/D converter.
  - For example, a x10 amplifier maps transducer signals which range from 0 to 1 V into the range 0 to 10 V before they go into the A/D converter.

Example: Non-inverting amplifier



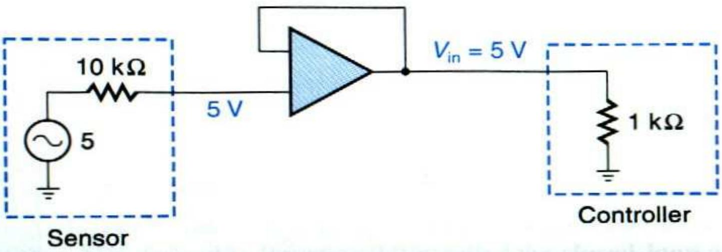
$$Vout = \frac{-R_f}{Ri} Vin$$

Loading effects



(a) Signal experiences voltage drop (b) Equivalent circuit

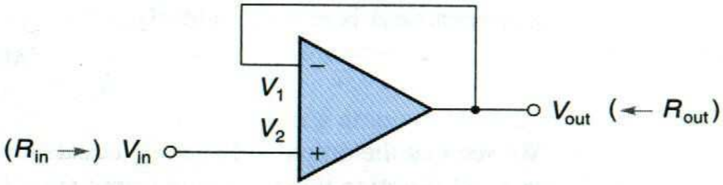
Preventing Loading



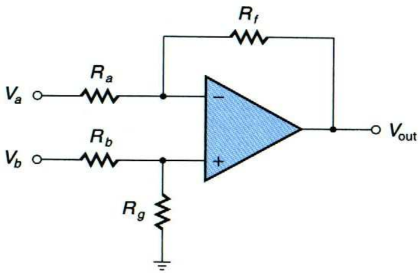
(c) No signal voltage drop

Voltage Follower

- Used to repeat a signal without loading down the sensor.



Difference Amplifier



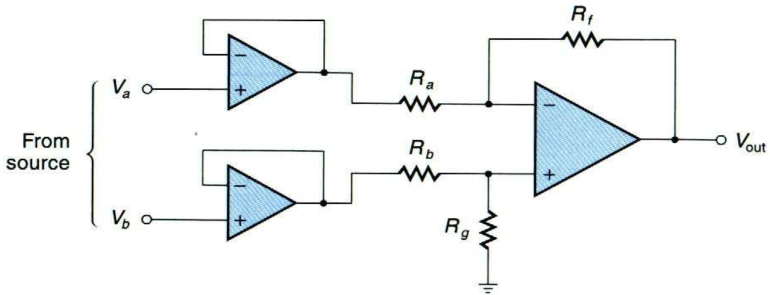
By letting:

- Ra = Rb
- Rf = Rg

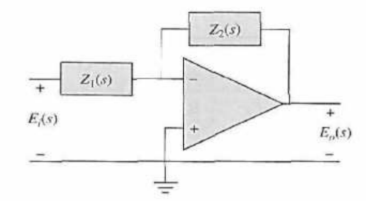
$$V_{OUT} = \frac{R_f}{R_a}(V_b - V_a)$$

Instrumentation Amplifier

- Amplifier with a very good CMRR.
  - Common Mode Rejection Ratio (CMRR) is the ratio of amplified signal to amplified noise



Op Amps

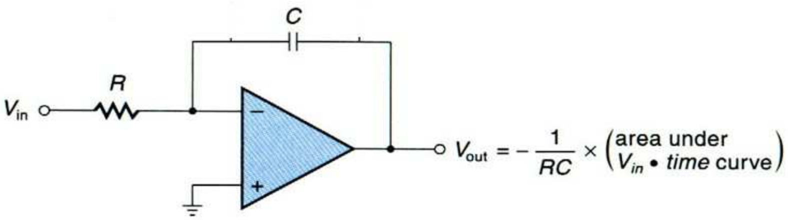


$$G(s) = \frac{E_o(s)}{E_i(s)} = -\frac{Z_2(s)}{Z_1(s)}$$

Input Element	Feedback Element	Transfer Function	Comments
R_1, $Z_1 = R_1$	R_2, $Z_2 = R_2$	$-\frac{R_2}{R_1}$	Inverting gain, e.g., if $R_1 = R_2$, $e_o = -e_1$
R_1, $Z_1 = R_1$	C_2, $Y_2 = sC_2$	$\left(\frac{-1}{R_1 C_2}\right)\frac{1}{s}$	Pole at the origin, i.e., an integrator
C_1, $Y_1 = sC_1$	R_2, $Z_2 = R_2$	$(-R_2 C_1)s$	Zero at the origin, i.e., a differentiator

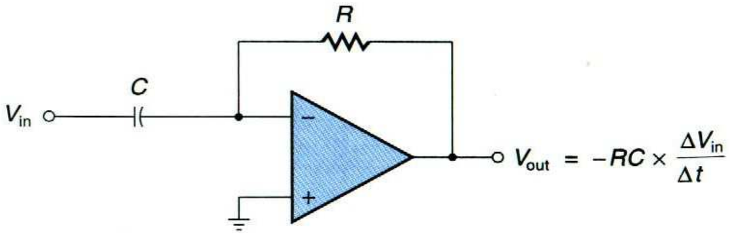
Integrator Circuit

- Output voltage is proportional to the area under a signal curve.

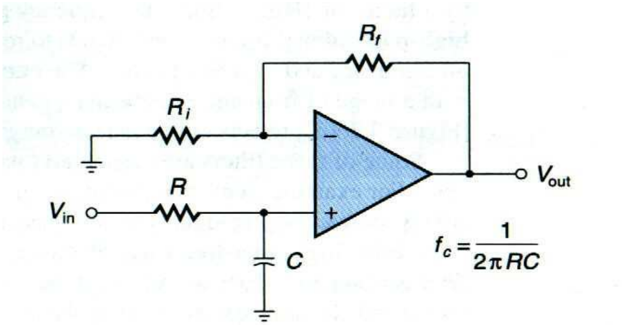


Differentiator Circuit

- Output is proportional to the rate of change of the input.

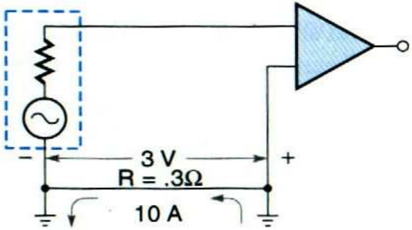


Active Low Pass Filter



Ground-Loop

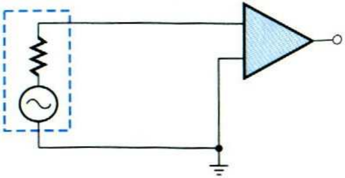
- Source and Load should not be separately grounded because a difference on potential at each ground-point will create a ground-loop of current flow.



(b) Connecting grounds causes a "ground loop"

Ground Loops

- Best solution for connecting to earth-ground.



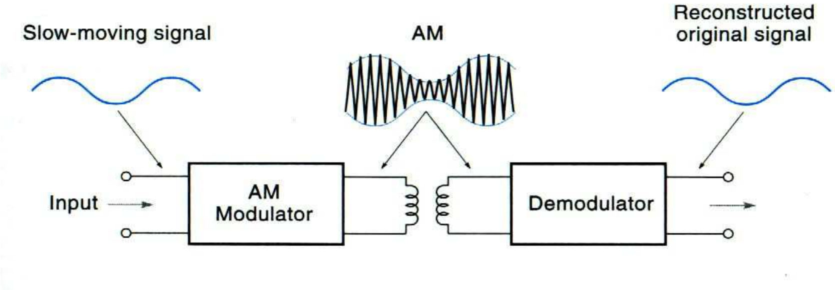
(c) Grounded at one end
(no "ground loop")

Isolation Circuits

- Allow for 2 circuits to have different source voltages and grounds.
  - Ground Isolation
  - Signal Isolation
  - Spike protection

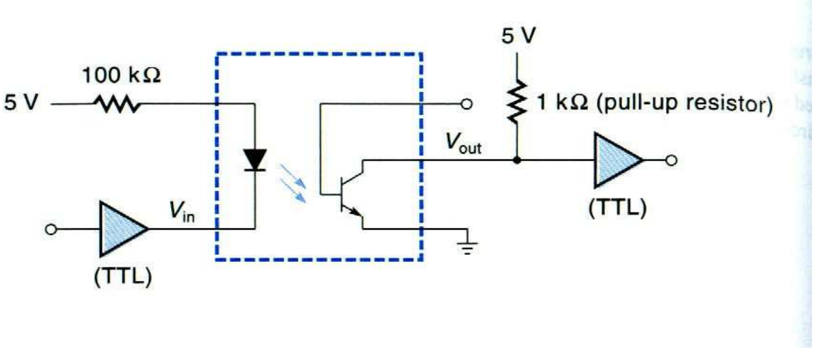
Transformer Coupled

- Good for modulated signals.
- Slow-changing DC signals must be modulated to magnetically couple the transformers.



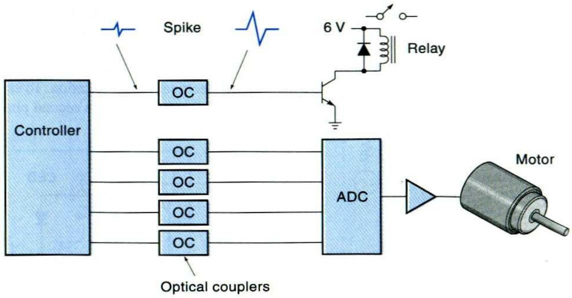
Digital Optocoupler

- Provides isolation of TTL level voltages.
- Also called opto-isolators.



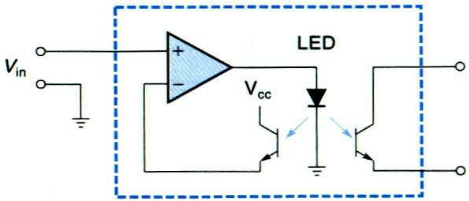
Interface

- Interfacing of high voltage, noisy systems to a controller.
- Signal travels in only one direction.



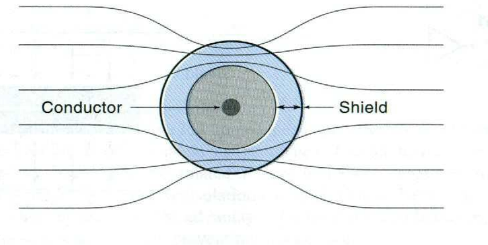
Optical Linear Signal Isolation

- An LED and matched phototransistors are used to provide optical isolation.
- The feedback phototransistor provides feedback due to non-linear response of the LED.



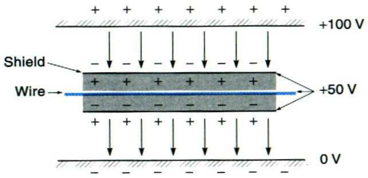
Shielding

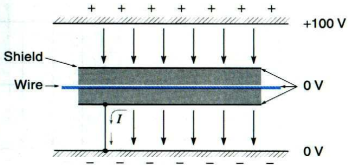
- Changing magnetic fields, such as from AC lines, machinery, or data lines can induce voltage into other lines.
- Shielding cannot block the magnet field noise, but can draw it away from the signal wire



Shielding

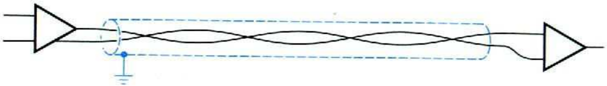
- Magnetic/electric fields can induce a voltage into the shield, which will produce its own electric field.
- Grounding the shield will prevent a voltage buildup.



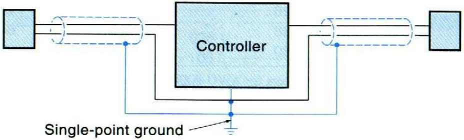


Grouding

- Single-point grounds should be used to prevent ground-loop problems.

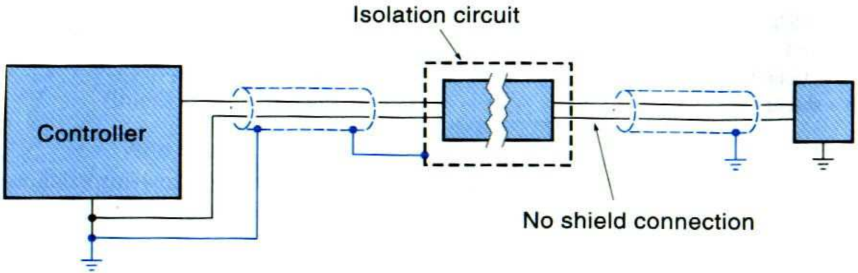


- Best choice is to use a Single-Point Ground at the controller.



Grounding

- When a single point ground cannot be used, an isolation circuit with individually grounds should be used.



Calibration

- The sensor manufacturer usually provides the calibration curves. If the sensors are stable with no drift, there is no need to recalibrate. However, often the sensor may have to be recalibrated after integrating it with a signal conditioning system.

- This essentially requires that a known input signal is provided to the sensor and its output recorded to establish a correct output scale. This process proves the ability to measure reliably and enhances the confidence.

Calibration

- If the sensor is used to measure a time-varying input, dynamic calibration becomes necessary.

- Use of sinusoidal inputs is the most simple and reliable way of dynamic calibration.

- Another test is looking at the transient behavior of step response.

Summary

- Sensors and transducers are essential elements in mechatronic systems because they are used to measure the controlled variable and transmit to the controller as feedback

- Sensors can be divided according to the variable that they measure:
  - Position/Velocity
  - Acceleration
  - Force/Torque/Pressure
  - Flow
  - Temperature
  - Proximity/Range

References

- Mechatronics System Design 2nd edition by Shetty and Kolk. Cenage Learning 2011
- Modern Control Technology: Components and Systems 2nd edition by Kilian. Delmer Publication

Thanks for your attention.

Questions?

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