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ME319 MECHATRONICS

Part III: The Senses – Sensors and Signals

Lecture 3: Survey of Sensors

Spring 2020

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Lesson Objectives

- Be able to select a specific sensor for a given measurement application
- Be able to explain the different types of displacement, speed, proximity, temperature, and acceleration sensors
- Be able to explain the operating principle of each of the sensors discussed in this lecture

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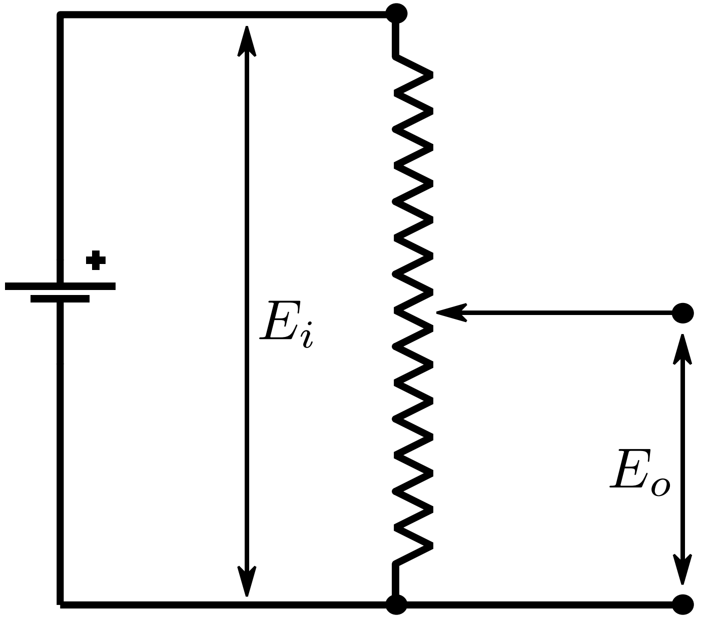
- Contact-type sensor that provides displacement measurement by measuring voltage drop across resistor

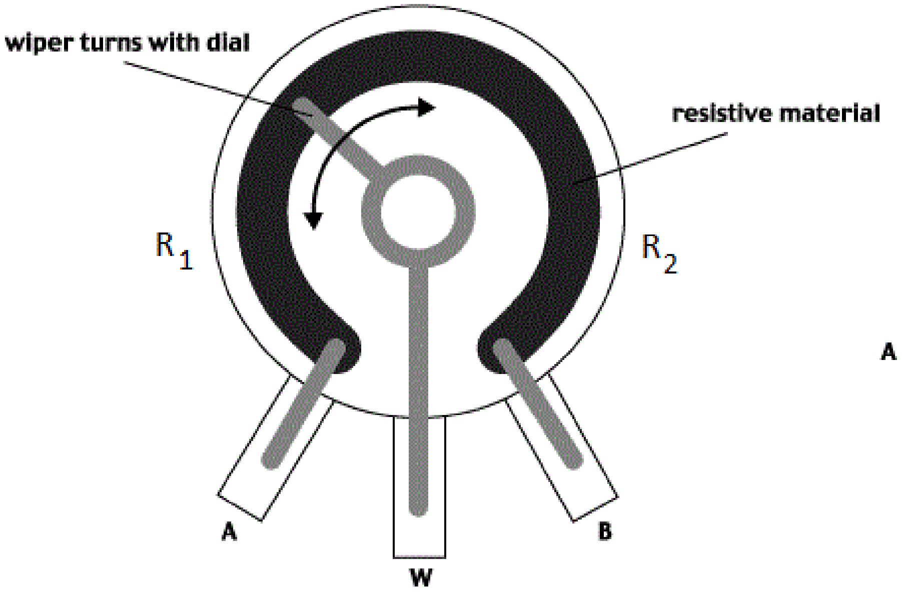


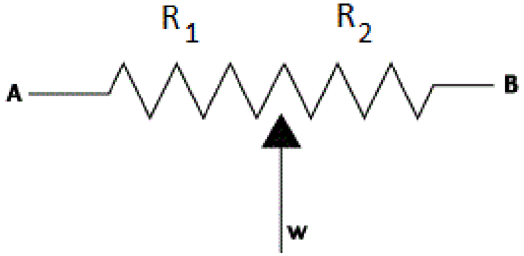
- Linear slider (*B*) attached to object whose displacement is to be measured
- Slider displacement changes resistance between *B* and *C*
- DC voltage applied across *A* and *C* (E_i)
- Voltage drop E_o increases linearly as *B* moves farther from *C*
- E_o can be measured with ADC to measure displacement

B is called the wiper of the potentiometer.

- Rotary potentiometers operate using same principle

- Circuit constructed to measure voltage drop similar to linear potentiometer
- Available as single-turn or multi-turn devices





- To read voltage drop across potentiometer, must use a measuring device such as ADC
  - Finite impedance of measuring device (ADC) can cause significant nonlinearities

x = displacement

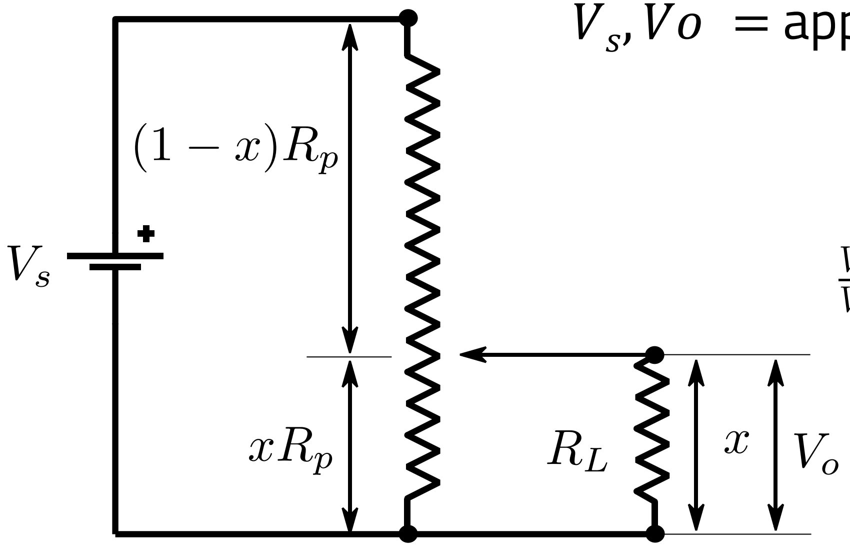
R_p = potentiometer resistance

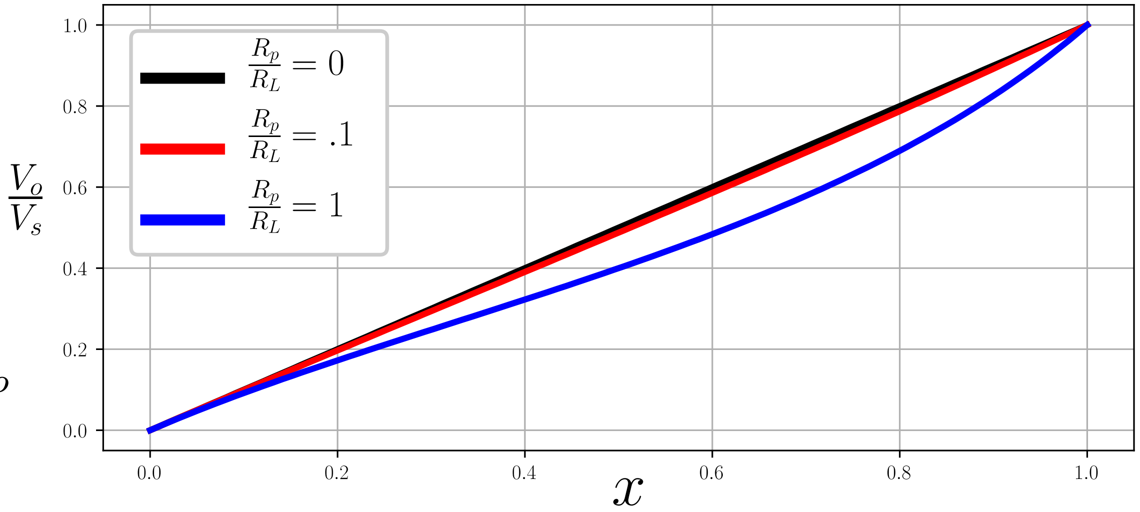
R_L = load resistance (ADC impedance)

V_s, Vo = applied and measured voltages

Voltage output at any position *x*:

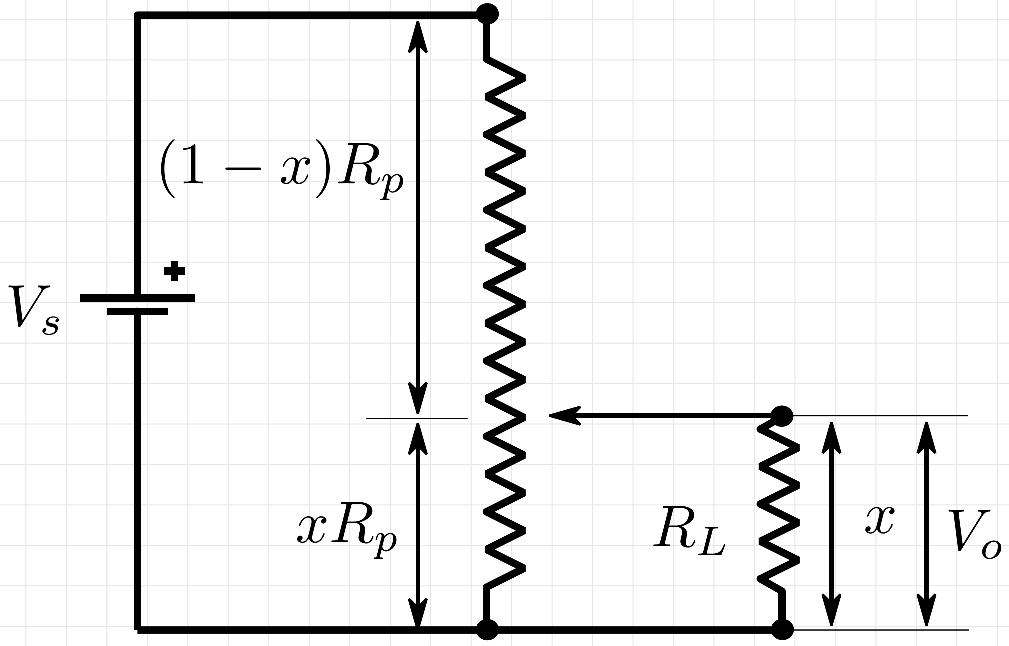
$$V_o = \frac{xV_s}{1 + x(1-x)\frac{R_p}{R_L}} \quad (0 \le x \le 1)$$





A single turn rotary potentiometer with 330° measurement range is selected to provide angular position information. A 10V DC voltage is applied across potentiometer leads, and output is connected to 12-bit ADC with 0-20V input range. Potentiometer resistance is 50Ω.

- Calculate effective resolution of sensor (in deg).
- Calculate power dissipated by potentiometer.



Number of possible ADC outputs $= 2^{12} = 4096$

Integrated sensor resolution: $\frac{(20-0)V}{4096Bins} \times \frac{330^o}{10V} = 0.161^o$

Assume load impedance is infinite ($R_L = \infty$), Then all current

is passed through potentiometer: $10V/50\Omega = 0.2A$

Power dissipated by potentiometer:

$$P = I^2R = (0.2A)^2 \times 50\Omega = 2W$$

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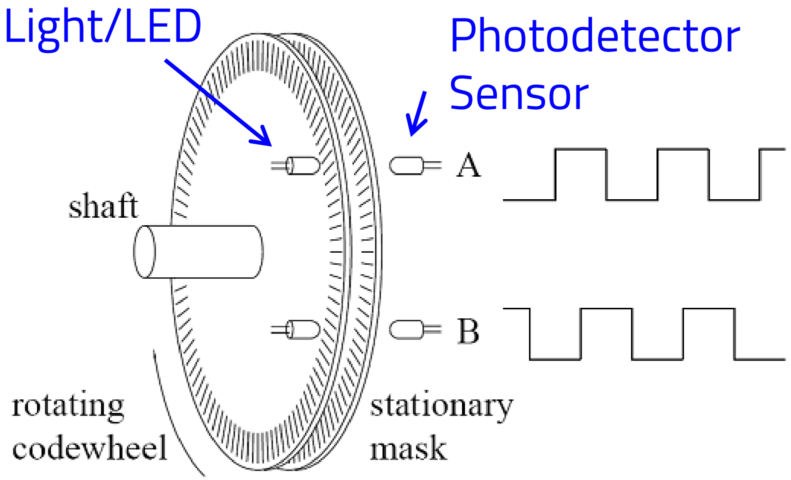
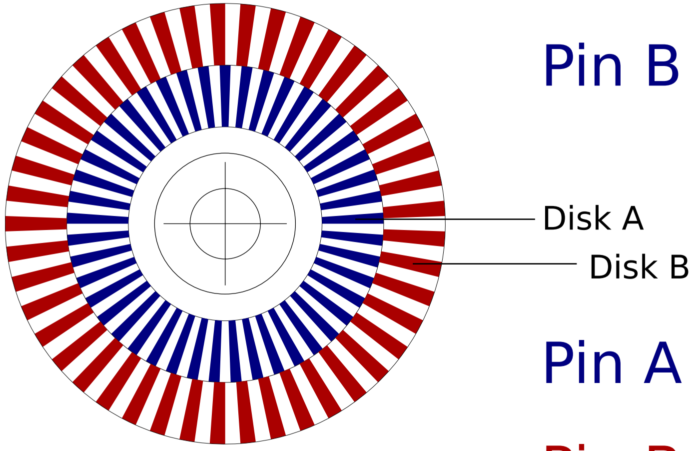
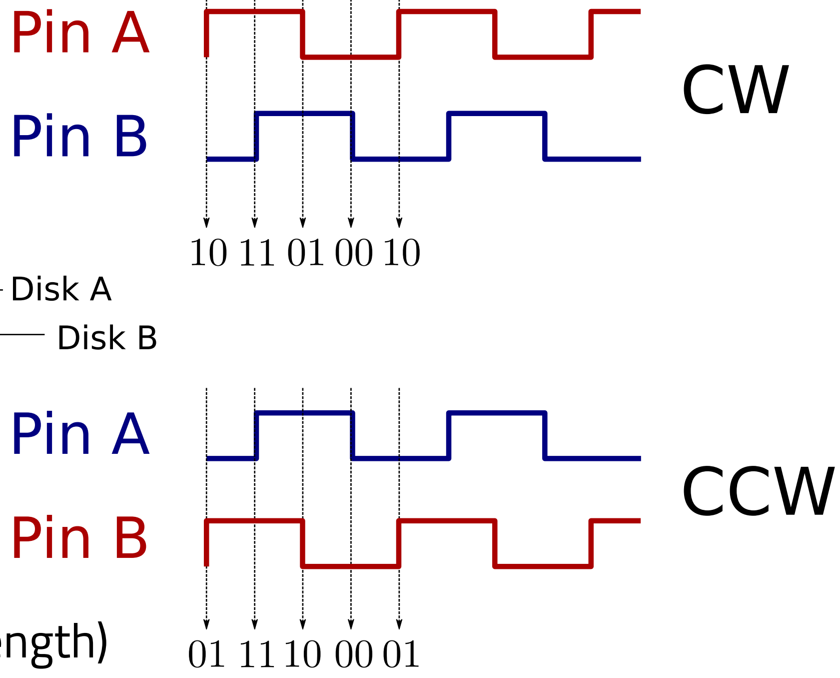
- Incremental encoders measure rotational changes from a datum position
    - Linear encoders also exist for translation measurements
- Devices use two light sources/sensors and disk with slots





CW Rotation (*B* leads *A* by 1/4 wavelength)



CCW Rotation (*A* leads *B* by 1/4 wavelength)

- As disk rotates, channels *A* and *B* output square waves
- Sensors *A* and *B* misaligned by half of slot spacing so square waves are offset by 1/4 wavelength

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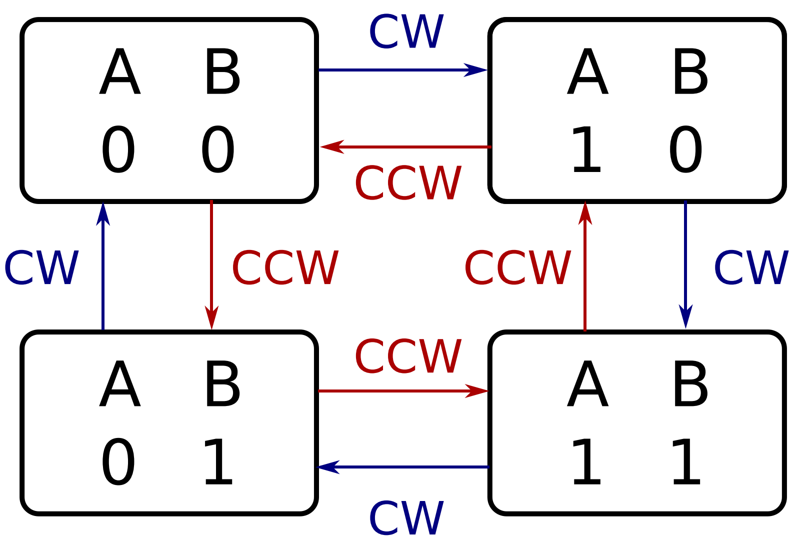
- Thus using two sensor/emitter pairs, encoders can provide both:
  - Speed / Position information (by measuring: frequency of square wave / number of pulses)
  - Direction information (by measuring direction of state transitions)



- Algorithm can monitor which states follow which to determine direction of rotation

- With use of two sensors, we get four distinct states per slot on the disk
- If encoder has 1000 slots (or lines), we get 4000 distinct states per revolution
- Thus using 2 sensors improves resolution of encoder by factor of 4 (over using a single sensor)
- This mode of encoder operation is called quadrature mode

Example

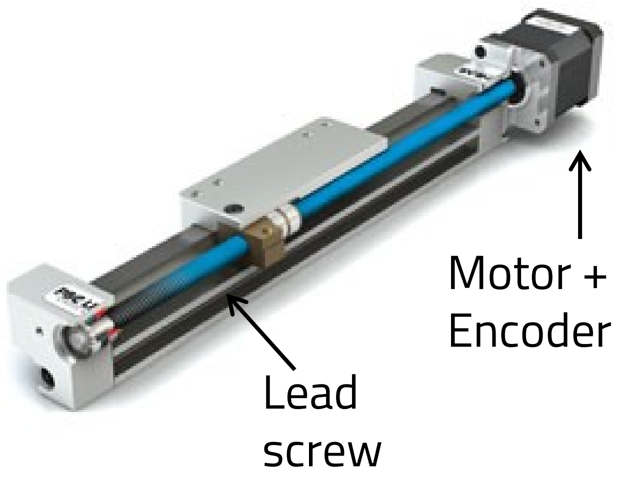
DC motor equipped with incremental optical encoder used to drive a lead positioning screw. Screw has lead of 0.1 in./rev. Encoder has 1000 lines and is operated in quadrature mode. Determine measurement resolution (in mm/count).

Table travels distance of 0.1 in (2.54 mm) per revolution of motor.

For each revolution of motor, encoder produces 4000 counts.

Thus measurement resolution of this setup is:

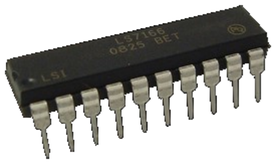
2.54 mm / 4000 counts = 0.635 μm per count

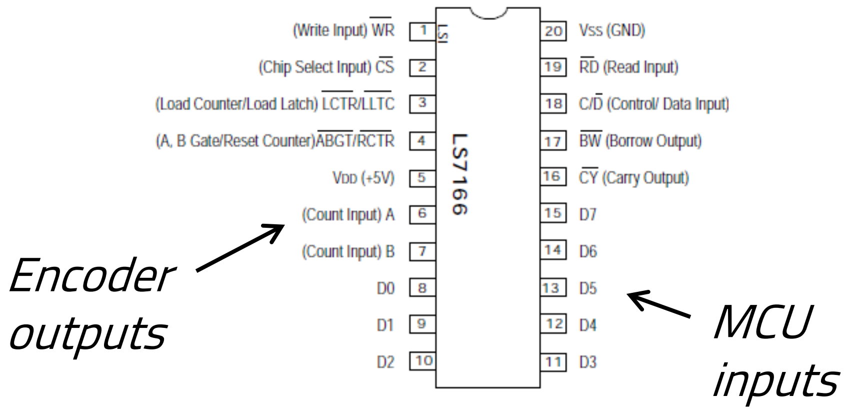


Displacement Measurement - Incremental Encoders

- Number of counts can be very large and they can occur at very fast rate
  - For instance, 1000 line encoder at 1000 rpm → 66,666 counts per sec in quadrature mode → > 133 kHz sampling rate required (Sampling $f > 2x$ encoder f)
  - Typically too fast for MCU's
- Dedicated hardware counters used for this purpose
  - Keep track of encoder count and MCU reads counter at slower rate
    - IC keeps track of encoder count
    - MCU reads count using 8 bit output
    - 24-bit value read in three 1-byte chunks.

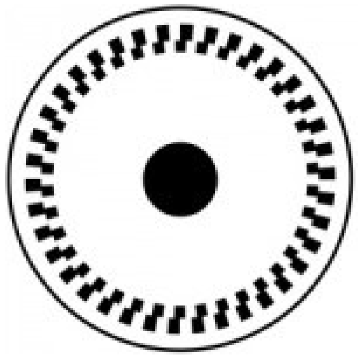
LS1766 24-bit Quadrature Counter for Encoders



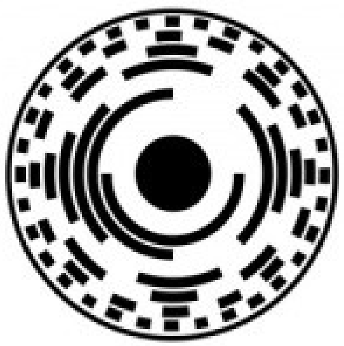


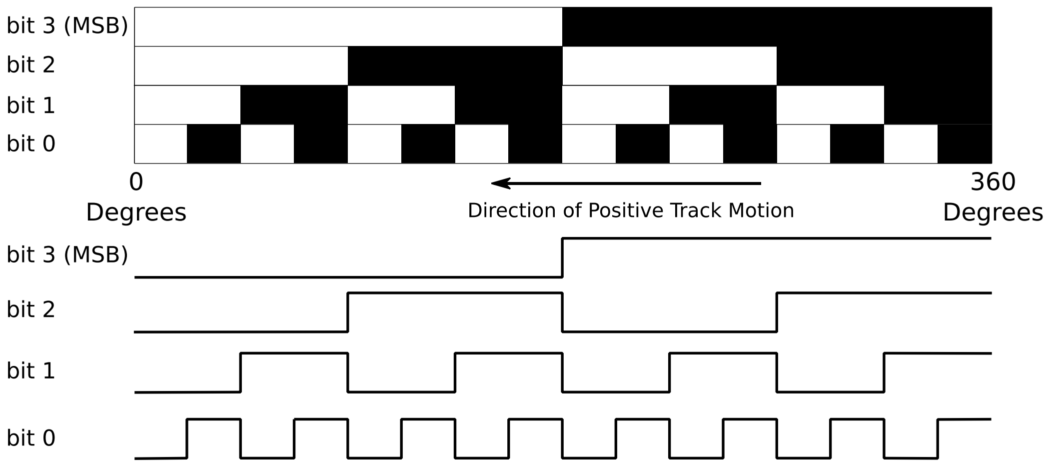
- Absolute encoders provide absolute positioning information
  - Angular position of absolute encode disk has unique output
    - As encoder disk rotates, sensors provide unique binary output corresponding to rotational position
    - Two methods of encoding this information are called natural binary (normal binary counting) and gray code (only 1 bit changes at a time)

Incremental Encoder Disk

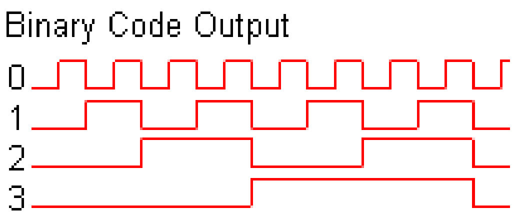


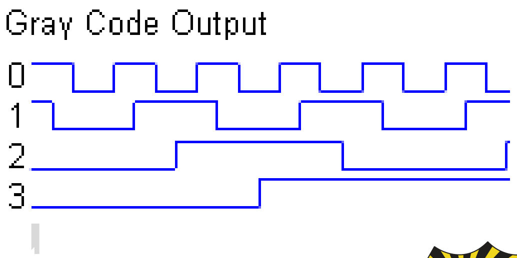
Absolute Encoder Disk (8-bit)





Natural binary output scheme





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- Resolution of absolute encoder determined by number of bits defined on disk
  - If disk uses N bits (or tracks), resolution is $360/2^N$
  - For instance, commercial 10-bit absolute encoder has 0.35° resolution
- Multi-revolution measurement accomplished by using multiple disks, with gear ratio between disks
  - For instance, to measure 16 revolutions, use 2 disks
  - Second disk has 4 tracks (16 possible values) connected to first disk with 16:1 gear ratio

- To measure rotational speed using an incremental encoder, two possible methods

Pulse Counting Method

- Read encoder counter (IC) twice, divide count difference by elapsed time between readings

$$\omega = \frac{2\pi N}{lT} \quad or \quad \omega = \frac{2\pi N}{4lT}$$

(if quadrature is used)

Pulse Timing Method

- High frequency clock used to measure elapsed time difference between two adjacent lines on encoder disk
- Must handle frequenct timer overflow

$$\omega = \frac{2\pi/l}{m/f} = \frac{2\pi f}{ml}$$

N: Count difference between two readings
l : Number of lines on encoder disk
T: Elapsed time between readings

M: Number of clock cycles recorded
F : Clock frequency
L : Number of lines on encoder disk

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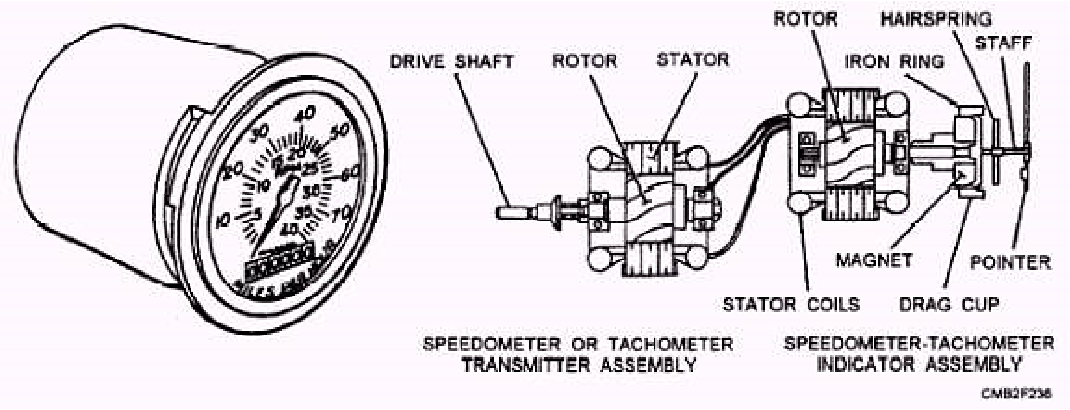
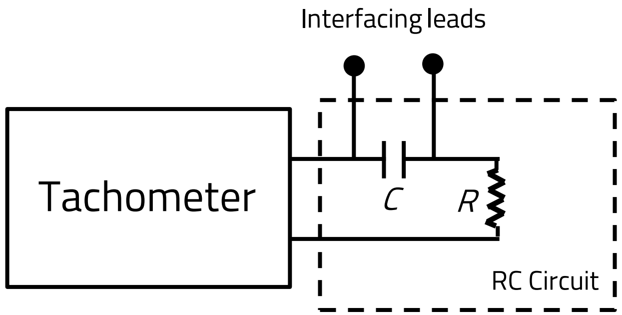
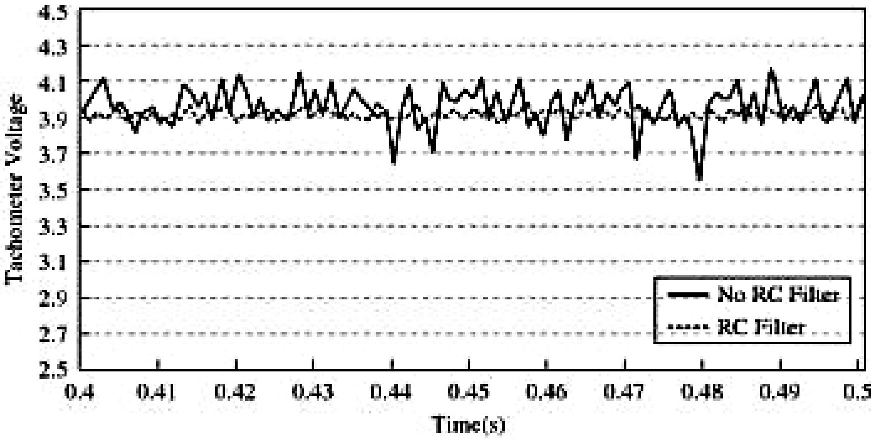
- Another way to measure rotational speed is using a tachometer
  - Tachometer is DC motor, operating in reverse
  - Tachometer outputs voltage which is proportional to rotational speed (opposite of DC motor)





- Because of commutator, voltage signal fluctuates during rotation (there is some AC component)
- This is called ripple
- RC circuit typically used to filter out AC component



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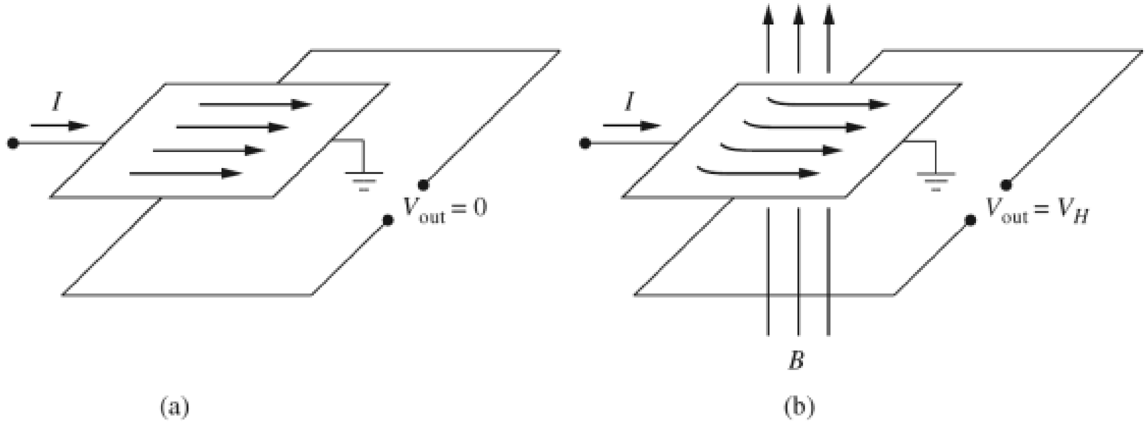
- Proximity sensors used to detect presence of object
  - Examples: Door open/close, end-of-travel detection, obstacle presence under powered doors, etc.
- Hall effect sensors commonly used for this purpose
- Hall effect discovered in 1877
  - Voltage difference is developed in current-carrying conductor when subjected to perpendicular magnetic field



No magnetic field applied

Magnetic field applied

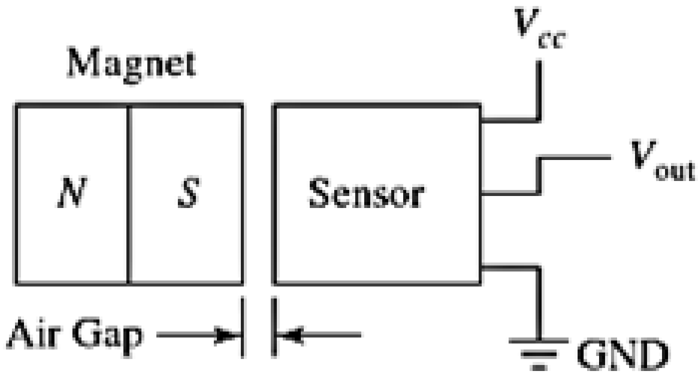
Voltage difference given by Lorentz's Law:

$$\vec{V}_H = \vec{I} \times \vec{B}$$

Hall effect voltage usually small, in μV range.

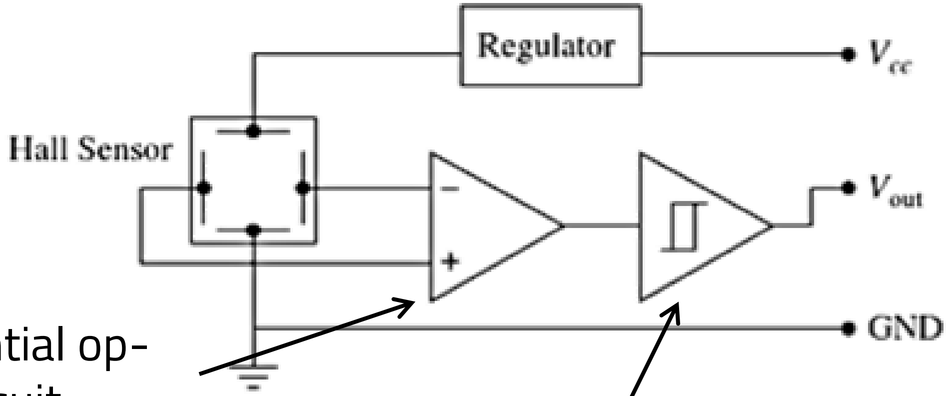
- Hall effect sensor consists of two pieces:
  - Stationary semi-conductor sensor package
  - Magnet attached to device we want to measure proximity from

Unipolar Hall Effect Sensor



- When magnet is within specified distance of sensor, sensor turns ON
- When magnet is removed, sensor turns OFF

Hall Effect Proximity Sensor Interfacing

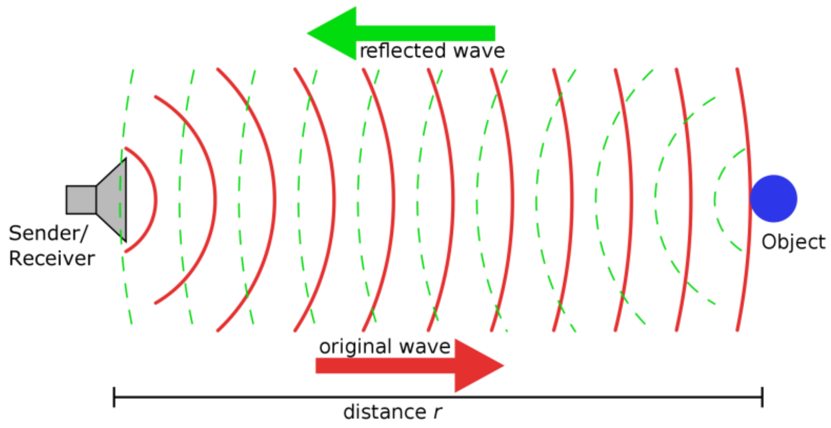


Differential op-amp circuit – amplifies small voltage output

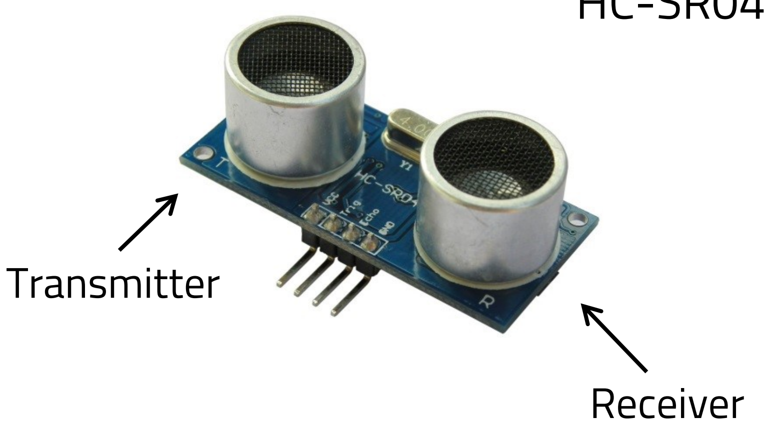
Schmitt trigger:

- If input below a threshold, outputs low
- If input above a threshold, outputs high
- Hysteresis of Schmitt trigger used to guard against noise

- Ultrasonic sensors use “time of flight” measurement scheme to detect distance from an object
  - Emit burst of sound at high frequency over short interval
  - Senses echo signal, computes time between when signal sent and when echo received
  - Using speed of sound, computes distance



HC-SR04 ultrasonic sensor



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- Ultrasonic sensor range limited by two factors:
  - Min range (~several cm): Signal received before it is finished transmitting
  - Max range (~30 ft): Low signal to noise ratio beyond this distance
- Not affected by color, transparency, or lighting conditions of object being detected
- Does not work well detecting “soft” objects (foam, cotton, sponge, etc)

Ultrasonic sensors used often in cars as backup sensors or for collision detection.

Be careful about interference with these sensors: Anything that emits high frequency noise (e.g., motors) may interfere with sensor.

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- Limit switches are commonly used to detect end of travel for a moving axis
  - Used in conveyer systems, elevators, transfer machines, etc.
  - Come in a variety of designs to allow general contact
  - Easy to interface with MCU since they provide digital ON/OFF signal

Roller Lever Design


Short Lever Design

Roller Plunger Design

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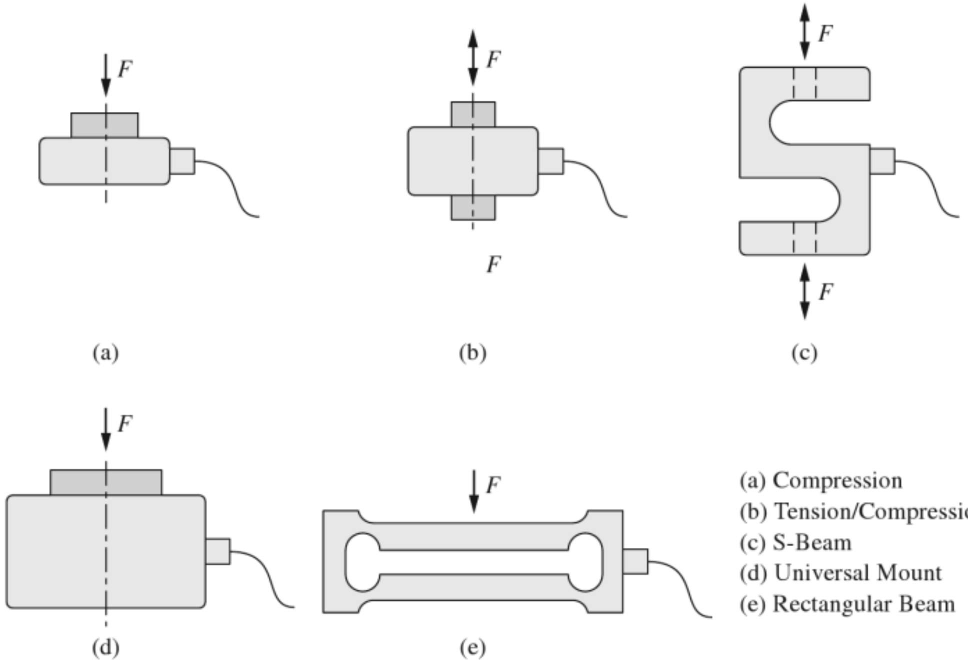
- Transducers for measuring force can be hydraulic, pneumatic, or strain-gage based
- Strain gage load cells come in a variety of designs
  - Output voltage signal based on applied load

Various Load Cell Designs



(a) Compression
(b) Tension/Compression
(c) S-Beam
(d) Universal Mount
(e) Rectangular Beam

- Depending on design, load cells can be very sensitive to off-center loads (and provide erroneous readings)
- Universal mount load cell is best at handling off-center loads
- Load cells usually use multiple strain gages to increase sensitivity of design
- Load cells are sensitive to thermal errors arising from thermal expansion/contraction of internal elastic element

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- Load cells use strain gages and Wheatstone bridge circuit internally
    - Voltage output is specified in mV/V, meaning output voltage range is dependent on input excitation voltage
    - Example: If sensor produces 2 mV/V, if supply voltage of $10V$ is used then full-scale output of sensor is $20mV$
    - External amplifier (op-amp circuit) used to amplify outputs before being read by MCU

Futek LCF300 Universal Load Cell

* TENSION RESULTS ACHIEVE BETTER THAN 0.15% IN NONLINEARITY AND HYSTERESIS.

SPECIFICATIONS:

RATED OUTPUT	1 mV/V nom. (25, 50 lb, and 250 lb), 2 mV/V nom. (100 and 500 lb)
SAFE OVERLOAD	150% of R.O.
ZERO BALANCE	±2% of R.O.(25, 50 lb, and 250 lb) ,±1% of R.O.(100 and 500 lb)
EXCITATION (VDC OR VAC)	20 MAX
BRIDGE RESISTANCE	700 Ω nom.
NONLINEARITY	±0.25% of R.O. *
HYSTERESIS	±0.25% of R.O. *
NONREPEATABILITY	±0.05% of R.O.
TEMP. SHIFT ZERO	±0.02% of R.O./°F [0.036% of R.O./°C] (25, 50 lb, and 250 lb)
TEMP. SHIFT ZERO	±0.01% of R.O./°F [0.018% of R.O./°C] (100 and 500 lb)
TEMP. SHIFT SPAN	±0.01% of LOAD/°F [0.018% of LOAD/°C]
COMPENSATED TEMP.	60 to 160°F [15 to 72°C]
OPERATING TEMP.	-60 to 200°F [-50 to 93°C]
WEIGHT	5 oz [142 g] (2024 ALUMINUM), 10 oz [284 g] (17-4PH S.S.)
CONNECTOR: LEMO Receptacle (EGG.OB.304.CLL)	
ACCESSORIES AND RELATED INSTRUMENTS AVAILABLE	
CALIBRATION (STD)	5 pt TENSION; 100K Ω SHUNT CAL. VALUE (200K Ω for 25, 50 lb and 250 lb)
CALIBRATION (AVAILABLE)	COMPRESSION
CALIBRATION TEST EXCITATION	10 VDC
MATERIAL(Cover)	ALUMINUM. RED ANODIZE AFTER S/N:397409

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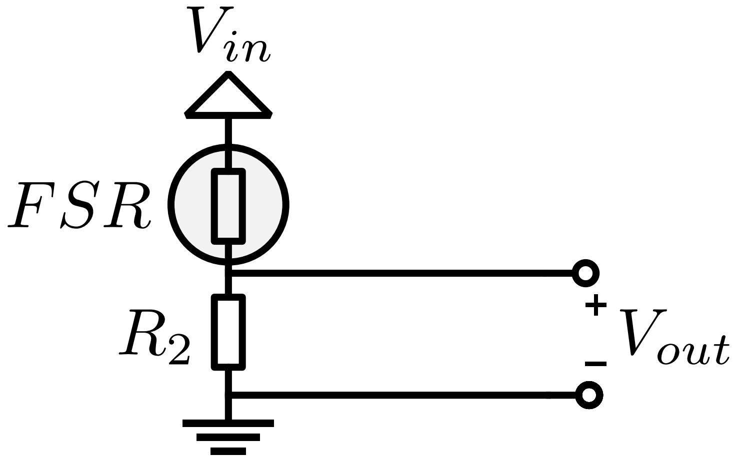
- Force sensing resistor (FSR) is low-cost alternative to load cells
  - Uses electrical resistance to measure force applied
  - Constructed from a polymer film

- At zero force, sensor has infinite resistance
- As force increases, resistance increases nonlinearly
- At maximum force, resistance approaches several hundred ohms



FSR's typically wired with fixed resistor in a voltage divider

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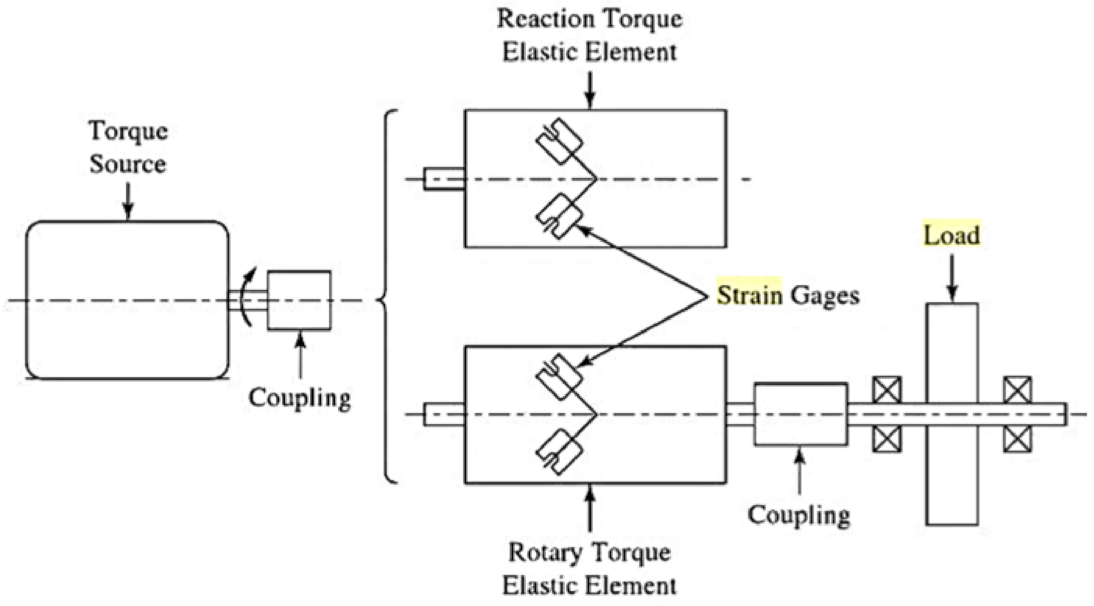
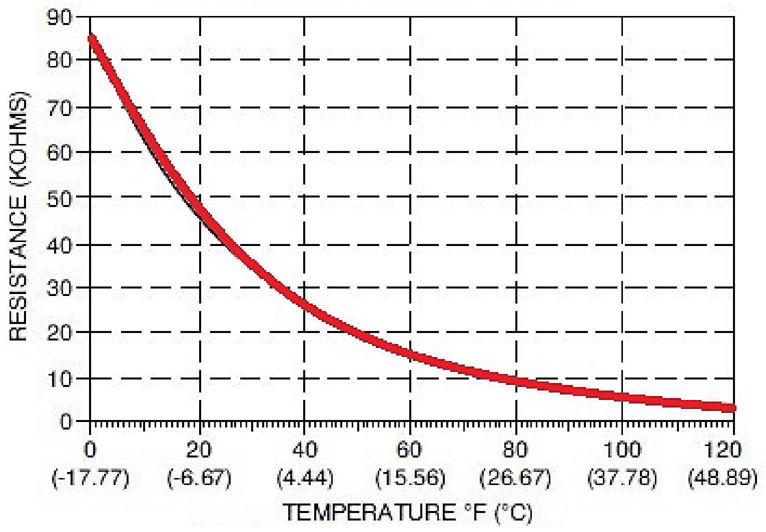
Torque Measurement

- Reaction torque sensors attached to rotating shaft (but measure stationary torque)
- Rotary torque sensors attached between torque source (engine, motor, etc) and load



- When used in rotary configuration, need to provide power to and extract measurements from rotating torque sensor
- Slip rings or rotary transformers usually used for this purpose

- Thermistors are commonly used for temperature measurement
  - Resistor whose resistance value decreases with temperature
  - Response is highly nonlinear – can be approximated by exponential function



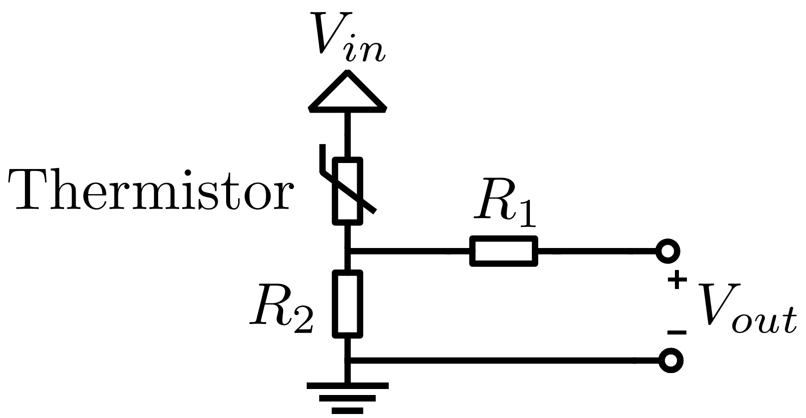
Thermistor Response Equation

$$R = R_o e^{\beta\left(\frac{1}{T} - \frac{1}{T_o}\right)}$$

R_0 = resistance at temp T_0

T_0 = reference temperature

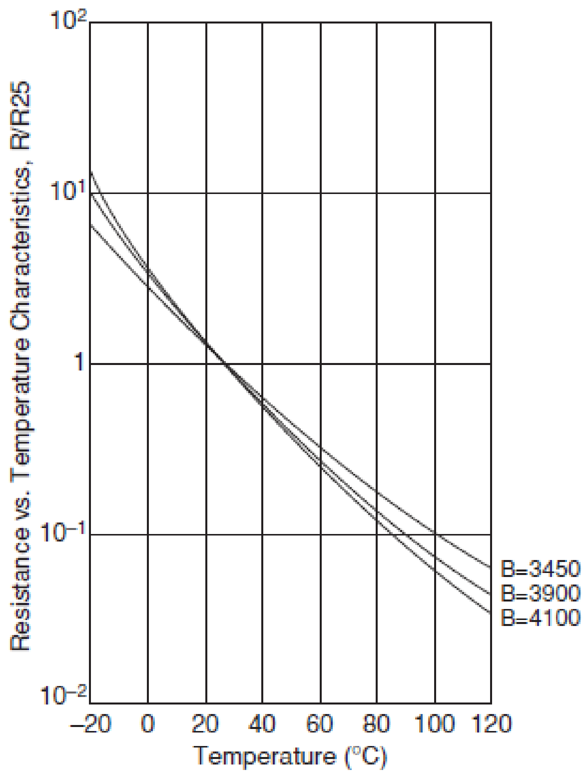
β = constant that depends on thermistor material



Thermistor can be wired with fixed resistor in a voltage divider to extract temperature measurement.

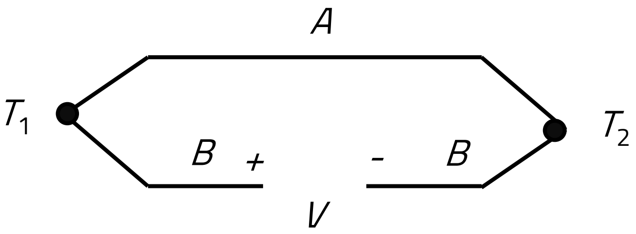
- Remember that because sensor response is nonlinear, you will need to store entire response function (or exponential approximation) on MCU to convert voltage to temperature
  - Cannot just use sensitivity since this sensor does not have linear response

Example 2-lead thermistor



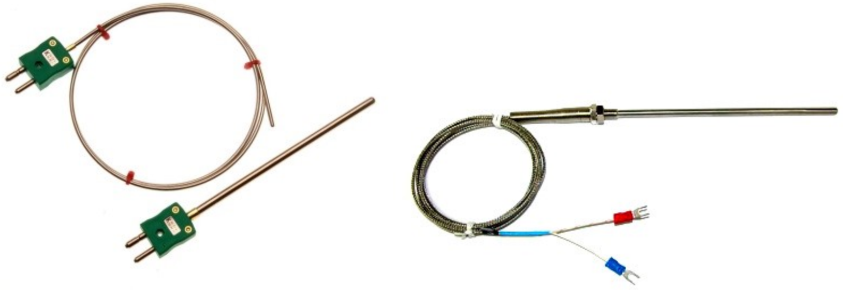
Murata NCP21XW223J03RA surface mount thermistor

- Thermocouples are another type of temperature sensor that uses so-called Seebeck effect
  - EMF (voltage) created across two junctions of different metals when junctions are at different temperatures
  - If one junction is at a known temperature, temperature of the other junction can be determined by measuring voltage



- Thermocouple outputs are usually in millivolts and must be amplified appropriately
- Filtering is also oftentimes needed to mitigate noise since thermocouple leads act as antennas

- Two different metals, *A* and *B* are connected at two different points
- Two junctions have different temperatures → generates voltage



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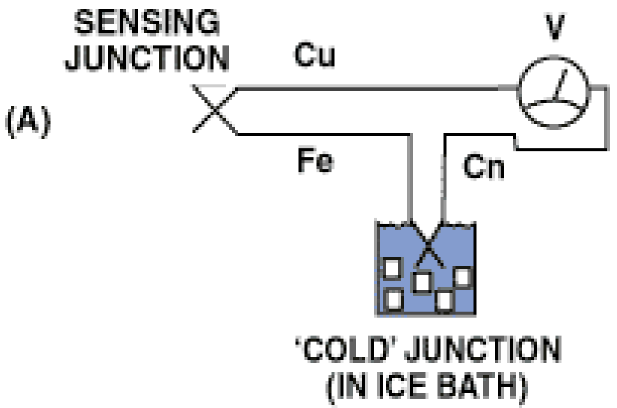
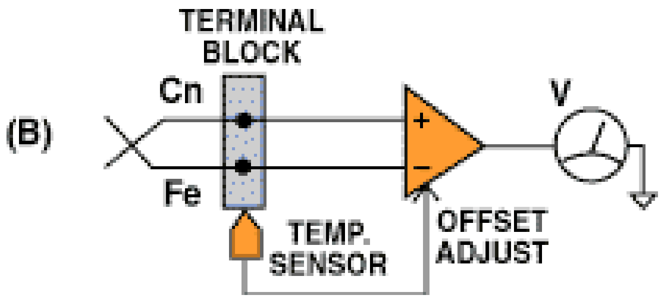
- Thermocouples need one junction to be placed at known temperature in order to detect absolute temperature at other junction
- Two methods to do this:

Insert one junction into ice bath



Use solid-state sensor or thermistor to measure temperature of reference junction



Thermocouple temperature to voltage response is usually nonlinear and described by polynomial curve.

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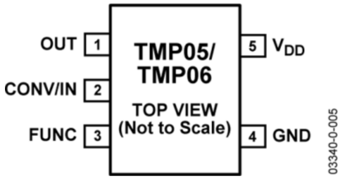
Temperature Measurement – IC Temperature Sensors

- IC temperature sensors use fact that difference in forward voltage of silicon PN junction in transistor is directly proportional to temperature
  - Provides cheap, very accurate solution to temperature sensing
  - Have smaller temperature sensing range than thermocouples
  - Come in either analog or digital versions

TI LM34 Analog Temperature Sensor

Analog Devices TMP05 Digital Temperature Sensor (PWM output)



- Digital sensors have ADC built in
- Provide output in either PWM, I^2C, SPI format

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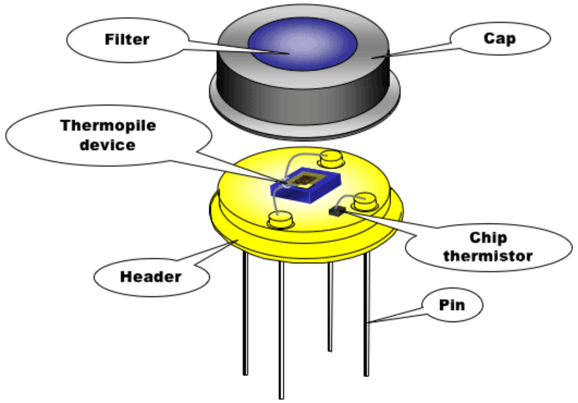
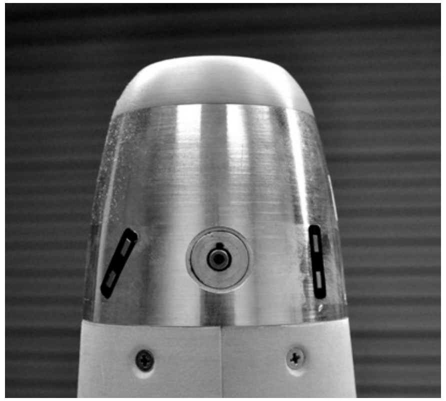
- Remote temperature sensors measures infrared energy emitted by object which is hot
  - Objects emit certain "blackbody" radiation which is dependent on temperature
  - Measuring this IR energy can provide measurement of remote object's temperature
  - IR cameras can be used in this manner to detect objects that are hot compared to surrounding environment

Temperature Measurement – Remote Temperature Sensors

- Thermopiles are remote temperature sensors
  - Used in digital (ear) thermometers, remote thermometers, satellite orientation sensors, etc.
  - Consist of multiple thermocouples put together in series
  - Wide field of view, provide voltage signal corresponding to temperature
    - Rugged, cheap, small

Heimann HMS J11F5.5 Thermopile





Thermopiles can be used to detect whether an object is facing toward ground (warm) or sky (cold). Above is a picture of a thermopile embedded in a projectile for this purpose.

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Temperature Sensor Tradeoffs

Property	Thermistor	Thermocouple	IC
Resolution	**Very high**	Average	High
Temperature Range	Small	**Very broad**	Limited
Output	Highly nonlinear	Nonlinear	**Linear**
Accuracy	**Very high**	Limited	Limited
Ruggedness	Fragile	**Very rugged**	Fragile

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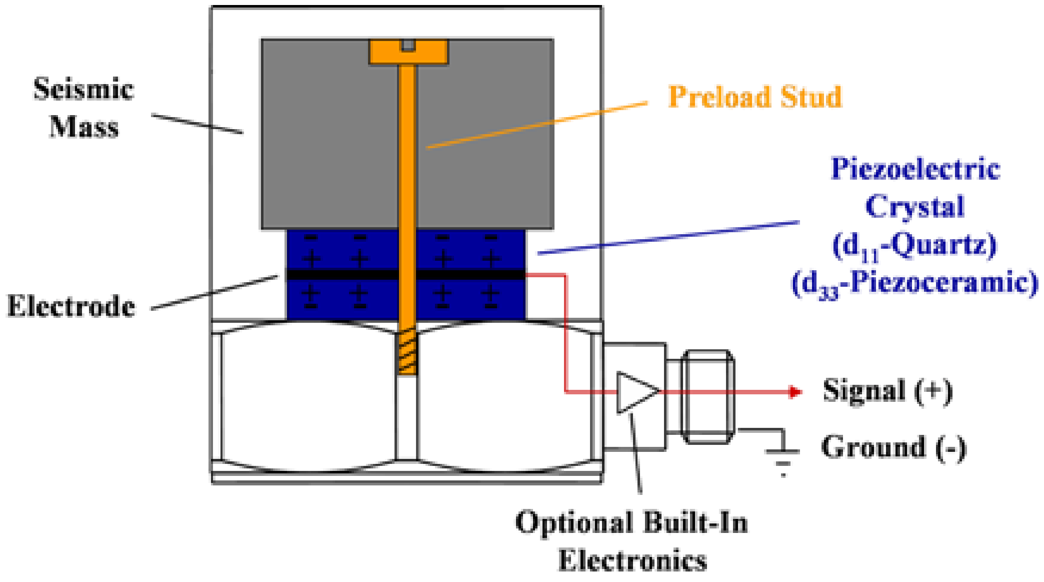
- Piezoelectric accelerometers use direct piezoelectric effect – they emit charge proportional to applied force
  - Piezoelectric accelerometers are built by placing a known mass on top of piezoelectric crystal

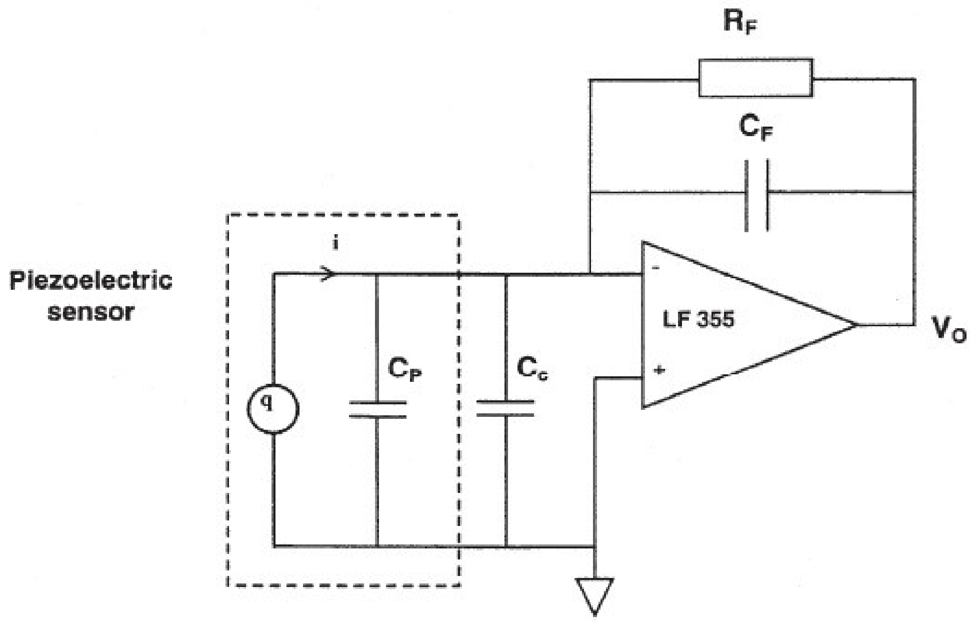
- Preloaded stud (spring) used to apply continuous pressure to crystal
- Base of accelerometer attached to device whose acceleration is to be measured



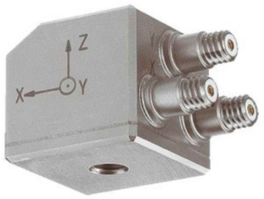
- Motion of structure causes motion of seismic mass, which pushes against crystal producing charge signal
- Seismic mass is known and thus force on crystal is proportional to acceleration

- Piezoelectric accelerometers actually produce charge rather than voltage
  - Additional electronics, called a charge amplifier, is used to convert charge output to usable voltage signal
  - Piezoelectric accelerometers can be purchased with this amplifier attached, or it can be built separately

Charge Amplifier Circuit



- Piezoelectric accelerometers can measure of to $500g$, operate at measurement frequencies up to $25kHz$
- Sensitivities range from $10mV/g$ to $10V/g$



Kistler Triaxial Accelerometer

- $+/-1000g$ range
- $-25\ pC/g$ (needs charge amplifier)

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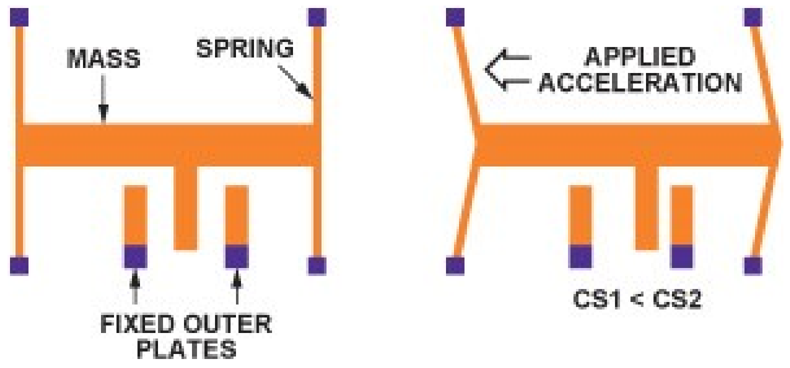
- IC accelerometers are low-cost sensors used in numerous applications
  - Air bag deployment, computer hard drive protection, etc.
- Based on silicon capacitive micromachined technology (MEMS sensor)



- Sensor uses two fixed plates, and one middle plate which is attached to spring/mass system
- During acceleration, middle plate deflects causing difference in capacitance between two sets of plates
- Difference in capacitance used as measure of acceleration

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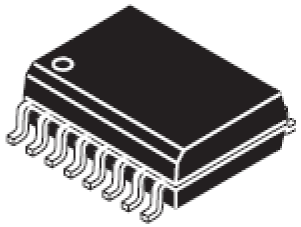
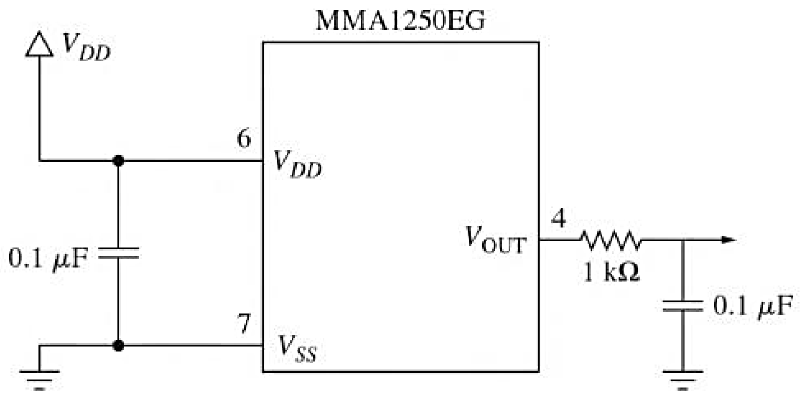
- IC accelerometers made to be mounted on circuitboards
  - Output voltage proportional to acceleration
  - Easy to integrate – output can be read directly by MCU (no charge amplifier) and powered by 5 VDC
  - More sensitive to temperature than piezoelectric accelerometers and not as rugged

Freescale Semiconductor MMA1250EG MEMS Accelerometer





- Sensitivity of 380-420 mV/g
- Range of +/- 5 g
- Outputs 2.65 V at zero g when powered by 5V

Sensor Wrap-up

- There are <u>tons</u> of different kinds of sensors available for every application you can think of
- Important things to know are:
  - How to read the spec sheet (previous class)
  - How to filter/condition sensor outputs (previous class)
  - How to choose the right sensor for your application