Koç University
College of Engineering
Department of Electrical & Electronics Engineering

ELEC 390 - Independent Study
Meeting – 2: Measuring Spatial & Mechanical Variables

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1: Introduction

Spatial awareness is an integral part of any design that interacts with external objects. Therefore, measuring the spatial variables of objects is a common area of sensing technologies. Throught the years engineers have came up with not only general methods of measurement but also application specific measurement devices to measure everything from physical attributes to movement. This week will focus mainly on these mehods and devices such as.

- Displacement Measurement
- Thickness Measurement
- Proximity Measurement
- Position Measurement

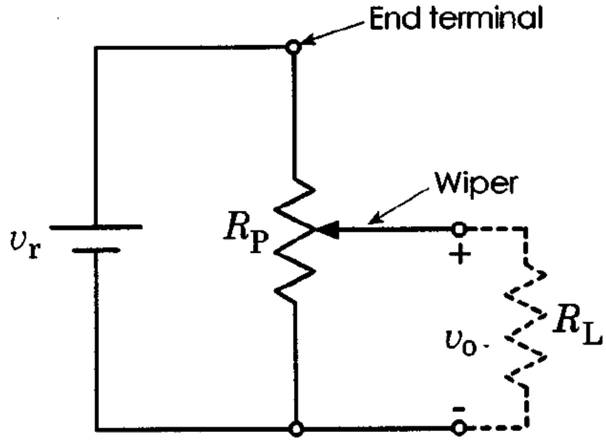
2: Spatial Variables

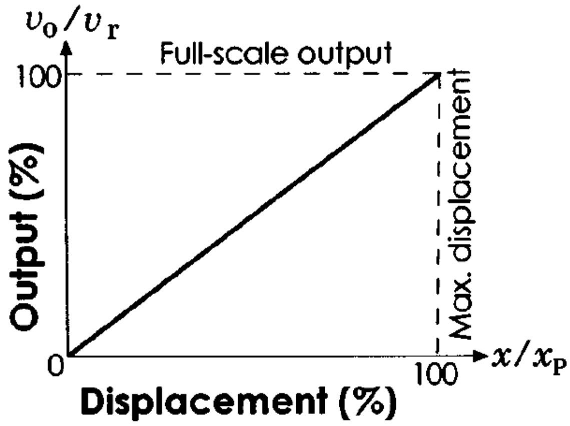
2.1: Displacement Measurement

When making designs that involve moving parts it is vital to keep track of all the moving parts, sometimes down to nanometers of accuracy in the pursuit of tracking objects engineers have created numerous ways to track the linear and rotational movement of objects.

2.1.1: Resistive Sensors

Resistive Displacement Sensors otherwise known as potentiometers consists of a resistive element and a conductive wiper and works by moving the wiper along the resistor vary the resistance of the component. When measuring displacement potentiometers are wired in a voltage divider configuration to transduce position to a voltage signal.





While potentiometers are proven and cheap devices thanks to their long history of use, they posess a wide variety of electrical characteristics that engineers need to design around to ensure accurate measurements these are:

Electrical Travel: Although the potentiometers are limited in their movement mechanically there exists a small region before the mechanical stop at both ends where the resistance of the device remains constant, engineers need to take into consideration that movement is limited to the electrical travel instead of mechanical to prevent errors.

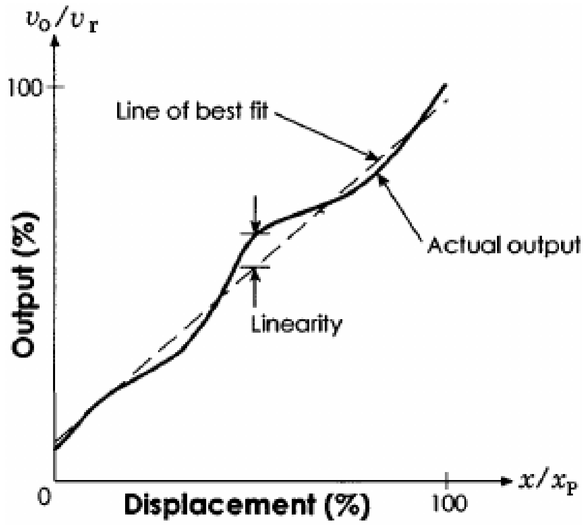


Figure 1: A Linearity Graph for a Potentiometer

Linearity: Where ideally a potentiometer would have a linear response to movement, in reality there exists a deviation from the expected output which is called linearity. It is commonly specified by the manufacturer and often range within 0.1% to 1%.

Electrical Loading: As with all voltage divider designs the ratio between the two resistances needs to be configured to minimize linearity. Manufacturers often include a maximum current limits for potentiometers to minimize electrical loading. The output to displacement relation can be found with the calculation.

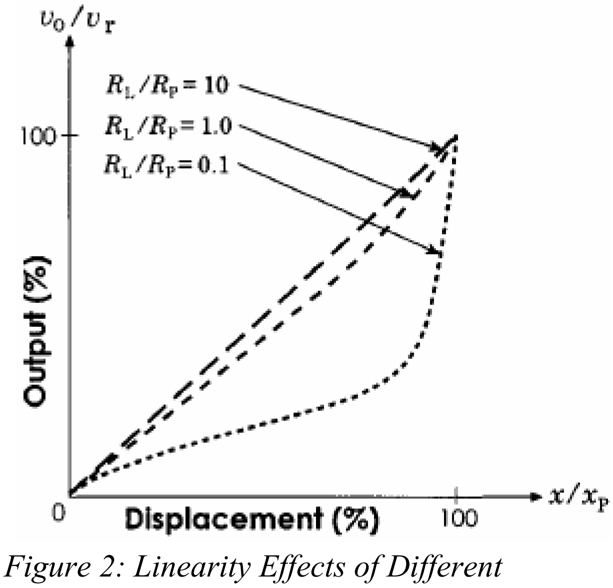


Figure 2: Linearity Effects of Different Resistance Configurations.

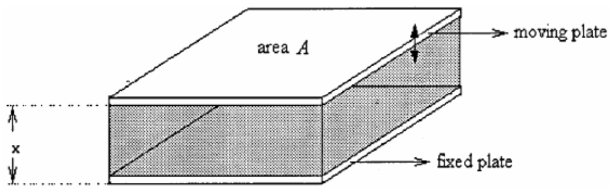
$$\frac{v_o}{v_i} = \frac{(x/x_p)(R_L/R_P)}{(R_L/R_P)+(x/x_p)-(x/x_p)^2}$$

2.1.2: Capacitive Sensors

The capacitance between two simple electrodes is a function of three things; the distance between the electrodes d, the surface area of the electrodes A and the dielectric constant of the medium between the two conductors ϵ, all three of which can be manipulated to change the capacitance of the system which can be measured in a highly sensitive and accurate manner.

$$C = f(d, A, \epsilon)$$

By varying the distance between the two electrodes we can create a change in the capacitance of the system with the transfer function.



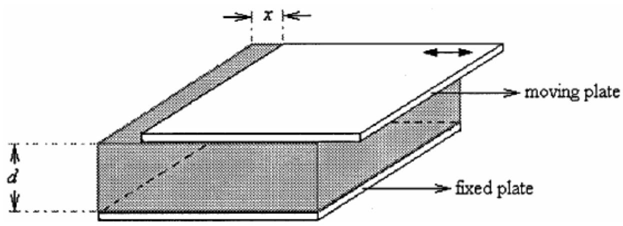
$$C(x) = \epsilon A/x$$

If we calculate the sensitivity of this device we see that the device has a nonlinear response and that the sensitivity increases as the distance between the plates decrease.

$$dC/dx = -\epsilon A/x^2$$

This characteristic makes varying distance capacitive displacement sensors excel at measuring nanometer changes and commonly found in Micro-Electro Mechanical devices. However, due to nonlinear nature some signal processing is required to achieve a readout.

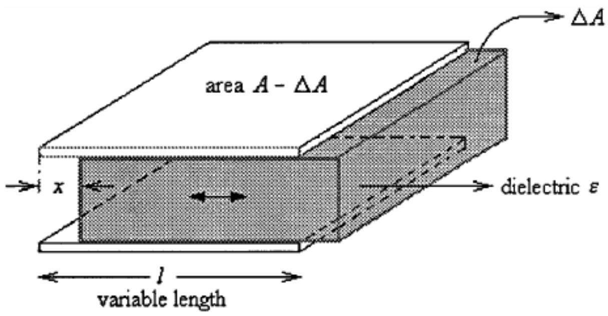
While changing the surface area of the electrodes is impractical we can still vary the effective surface area of the system by shifting electrodes out of alignment.



$$C(x) = \epsilon(A - wx)/d$$

With this configuration the capacitive change is linear with the displacement. This type of capacitive sensing is often done with rotating capacitors making it a favorable choice when measuring angular displacement.

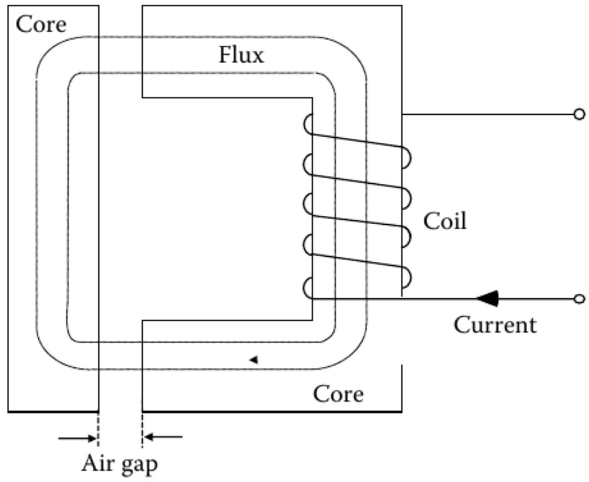
Dielectic displacement sensors are often used for measuring the fluid level in tanks where the capacitance of the sensor changes as the fluid displaces the air between the two electrodes to induce the capacitive change.



$$C(x) = w\left[\epsilon_2 l - (\epsilon_2 - \epsilon_1)x\right]$$

2.1.3: Inductive Sensors

Inductive sensors are based on the principle of induction where a conductor moving through a magnetic field induces a measureable voltage or a varying magnetic field induces voltage on a conductor that is inside it. Since this phenomenon involves only a magnet and an inductor these sensors are much more resilient to envinromental effects than their capacitive counterparts.



Inductive sensors work by driving a magnetomotive force through the core by passing current over a coil wrapped around the core. Moving the core will cause change of the magnetomotive force therefore the coil current which is then converted to the readout of the sensor.

2.1.4: Rotary Encoders

Rotary encorders are devices that are mainly used with the purpose of tracking angular motion such as the angular position of a gear. This is achieved by reading a pattern inside the encoder that changes position over the readout circuit as the encoder turns. This pattern can be made in multiple styles to achieve either an absolute or an incremental encoder.

Absolute Encoders: This type of encoders posess a pattern type that is made to track the angular position of the measured object, since the pattern is non-repeating the device retains the position information when powered off. However, they can not track the angular change infinitely.

Incremental Encoders: Unlike absolute encoders, incremental encoders posess a repeating pattern that often outputs a 2 shifted square waves, this shifted square pattern creates a 2-bit counter when converted to digital domain which allows the encoder to differentiate between clockwise and counter-clockwise turns, since the pattern is repeating the incremental encoders can track angular change infinitely, however, they do not retain position information.

2.2: Thickness Measurement

From an outside perspective measuring the thicknesses of materials may seem straightforward and in common cases where it would involve measuring the object from opposite ends, they would be right. However there are many instances where this approach is not possible from massive galaxies to objects so small that they are not visible under light. Where the object is impossible to touch due to being too hot, cold, fragile or simply far away. These are some of the conditions where engineers develop sensors and techniques to measure the thickness of materials.

2.2.1: Capacitive Measurement

Capacitive measurement for thickness is done in a similar fashion to dielectric displacement measurement of capacitors, where with the knowledge of the materials dielectric constant and the surface area of the measurement device we can calculate the thickness of the material by measuring the capacitive change as the material passes through the device. Due to the sensitivity of capacitive devices accuracy levels down to micrometers can be achieved. However this method assumes that the material is uniformly shaped.

2.2.2: Magnetic Measurement

While there are various methods of magnetic measurement all of them involve sensing the distance of a ferromagnetic object placed on the opposite end of the measured object to measure the thickness the methods mostly differ on the range and the accuracy that can be measured. While this method can measure non uniform materials they can not measure the thickness of ferromagnetic materials.

2.2.3: Time of Flight Measurement

Time of Flight measurements usually involve propogation of waves through a material such as electromagnetic or sound to determine the thickness of the material. While this method can measure multi-layered materials with individual layer thicknesses, it usually requires contact with the material and the beforehand knowledge of the propogation properties of the materials measured.

2.3: Proximity Sensing

While most sensor packages focus on measuring physical variables of objects while they're in motion, proximity sensing devices are often used when the sensor package itself is in motion. Although commonly used to measure the position of a surface from the device it is not uncommon to find proximity sensors that also measure the orientation of an object.

2.3.1: Capacitive Measurement

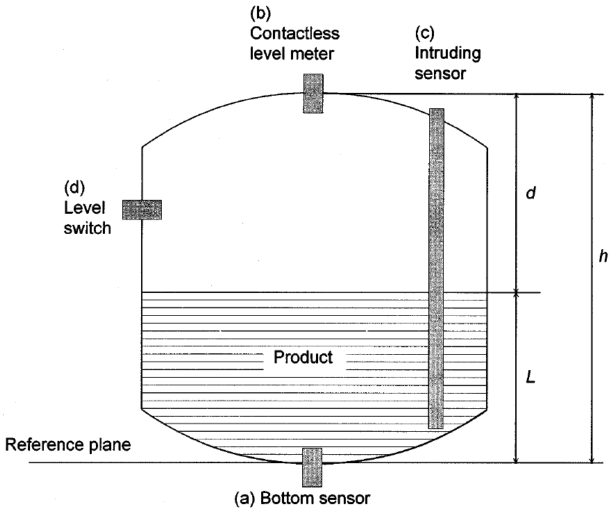
Sensing proximity with capacitive sensors involve detecting the changes to the electric field of the capacitor as an object passes through the said electric field. The measured changes to the electrical field is not limited to the space between the plates however, the changes within short distances beyond the plates where the electrical field fringes can also be measured. This means that, one can sense the objects moving through the fringing fields given that the dielectric between the plates do not change. However, as this is a dielectric displacement type measurement, the sensor has to be calibrated for the target object specifically.

2.3.2: Time of Flight Measurement

Time of flight sensors work on the principle of timing the waves travelling through the air and bouncing back from the measured object to sense proximity usually done with ultrasonic or LASER emitters, by placing multiple ToF sensors one can determine the orientation of the measured object. However, ToF sensors often suffer from size constraints.

2.4: Level Measurement

When working with large amounts of liquid or other types of material that are stored in tanks it is crucial to keep track of the height of the filled material, otherwise known as the level, primarily to avoid overfilling the containers. Measuring level is commonly done in two methods, either by a Level Switch which is activated when the fill level reaches the switch is mounted at or as Level Indicators which continuously measure the fill height.



Bottom Sensors: Bottom sensors usually involve measuring the force of the mass or the pressure exerted by the material to the bottom of the container. While measuring pressure the Level can be found with the equation.

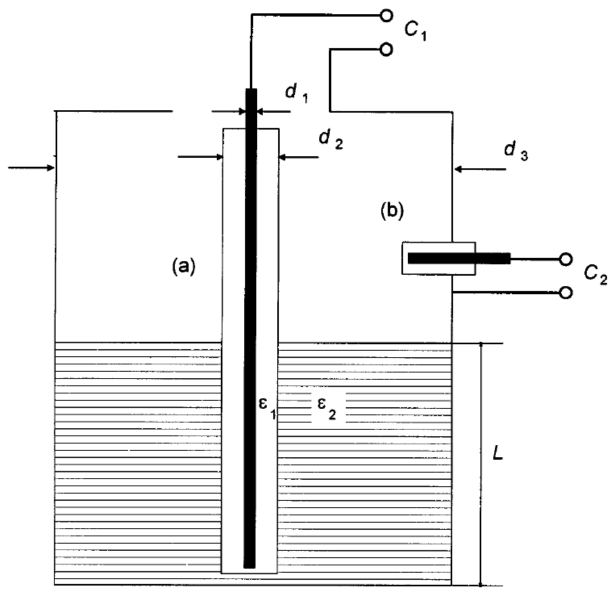
$$p = p_{Atmo} + g\,\rho_{Material}\,L \Leftrightarrow L = \frac{p - p_{Atmo}}{g\,\rho_{Material}}$$

Contactless Meters: This measurement type often relies on the Time of Flight method used by radar, laser or ultrasonic sensors where a modulated signal is sent towards the material and the reflection is timed to find the distance from the top of the material to the top of the container which is subtracted by the total height to find the level, this type of measurements are often favored in non-intrusive or hazardous applications. The basic formula involving *ToF* Level measurement is.

$$d = \frac{t \times v}{2} \qquad L = h - d \Rightarrow L = h - \frac{t \times v}{2}$$

Intruding Sensors: Intruding sensors involve circuits placed throught the height of the container to track the Level changes. A common practice is to insert a electrode to the container and measure the capacitange change between the electrode and the container wall as the level increases with the formula.

$$C = \frac{2\pi\epsilon_0 L}{\frac{1}{\epsilon_1}\ln\frac{d_2}{d_1} + \frac{1}{\epsilon_2}\ln\frac{d_3}{d_2}} \Leftrightarrow L = \frac{C\left(\frac{1}{\epsilon_1}\ln\frac{d_2}{d_1} + \frac{1}{\epsilon_2}\ln\frac{d_3}{d_2}\right)}{2\pi\epsilon_0}$$



Level Switches: These switches are mounted at various heights on the containter to signal that the material has reached that level and can be done in variety of methods such as capacitive, optical, viscous and thermal switches. This method can also be used in an intruding fashion to create a stepped level indicator.

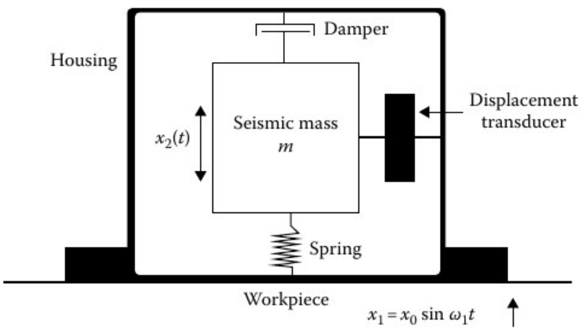
2.5: Angle & Tilt Measurement

Angle is referred to as the rotational distance between two intersecting lines in space. When multiple angles are pointed towards a point of reference, usually the direction of gravity, it becomes tilt, tilt of objects refer to the rotational orientation of objects in 3 dimensional space and an important part of spatial awareness.

3: Mechanical Variables

3.1 : Acceleration Measurements

Acceleration is a potent metric when concerning motion measurements as velocity and distance can easily be extrapolated by integrating acceleration measurements. As motion is an integral component our lives so are the accelerometers that measure its magnitude, as such one can find an abundance of accelerometers that meet the demands of wide variety of appliations employing numerous methods that have been developed over the times for measurement such as piezo-effect or capacitive sensors. Most accelerometers work with the principle of tracking the displacement of a mass inside the sensor.



Calibration of accelerometers are crucial and often times necessary for applications that involve shock and vibration detection, numerous methods for calibrating accelerometers exist which can be generalized as either static or dynamic calibration.

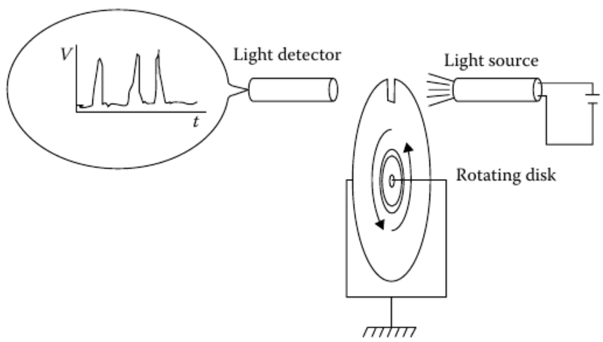
Static Calibration: This method involves recording the accelerometer output at various levels of constant acceleration such as a tilt table where a entirety of a portion of the gravitational acceleration is applied to the sensor as a function of the tilt or in a centrifuge where a constant acceleration can be achieved as a function of the rotational velocity.

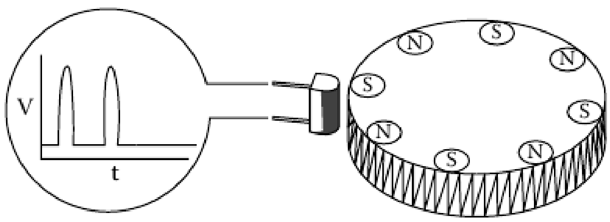
Dynamic Calibration: Dynamic Calibration is often referred to as back-to-back calibration where electrodynamic shakers are used to calibrate a working standard accelerometer with the usage of laser interferometers, this working standard is later used to calibrate more sensors on the same shaker to subject the sensor to sinusoidal motion of varying magnitude and frequency and comparing the target sensor output to the working standard.

3.2: Velocity Measurements

Measuring linear velocity is often straightforward as it can be easily derived by integrating the accelerometer output. However, same techniques often can not be applied viably to rotational bodies as the centrifugal force often causes the accelerometers to drift making the measurements unuseable.

As angular velocity is often measured in rotating applications such as engines, revolutions per minute or RPM is used to quantify the measurement, as such RPM measurements often involve generating sine waves or pulse trains that are proportional to the angular velocity of the object these signals are often generated by electrical, magnetic or optical methods.





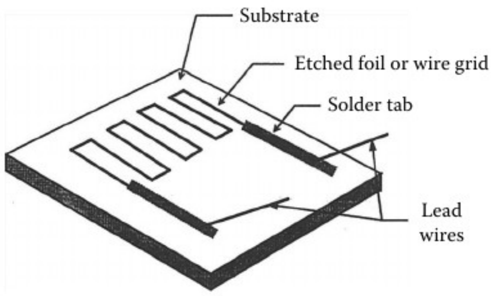
3.3: Vibration & Shock Measurements

Vibration refers to the oscillating motion of an object around a center position, vibrations often consist of multiple oscillations of varying frequency and magnitude, due to its mixed nature it is often implausible to determine its components by observing the magnitude graph alone, for this reason spectograms are used to display the vibration amplitude as a function of frequency.

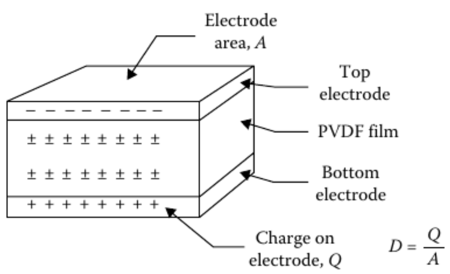
3.4: Strain Measurement

Strain refers to the various mechanical loads a solid body experiences due to the environmental effects, when the strain on a body is within the non-deformation region of the materials that compose the body, it acts as a spring expanding or compressing under the effect of the forces and returning to its normal when the force is removed, strain sensors use various methods to track these movements from the surface of the material such as.

Piezoresistive Gages: Where a piezoresistive device in a thin film form is attached to the surface and the changes of the resistance is measured as the body experiences strain.



Piezoelectric Gages: Which consists of a thin film capacitor that is attached to the surface where the changes of the capacitance, which is a result of the deformations under strain, is measured



3.4: Strain Measurement

4: Datasheet Examples

4.1: Processing Encoder Outputs

Optical encoders output the angular position by outputting a bitwise representation of the reader that is inside the encoder. However due to the size constraints it is at times impossible to fit patterns with enough bits to represent the position in a precise manner in the case of 4-bit optoencoder from grayhill the 16 possible outputs of the sensor is distributed to the 360 degrees which equals a travel of 22.5 degrees which is called the angle of throw.

Switch Position	Code Position	BCD Output*				Gray Output*			
		1	2	4	8	1	2	4	8
1	0								
2	1	●				●			
3	2		●			●	●		
4	3	●	●				●		
5	4			●			●	●	
6	5	●		●		●	●	●	
7	6		●	●		●		●	
8	7	●	●	●				●	
9	8				●			●	●
10	9	●			●	●		●	●
11	10		●		●	●	●	●	●
12	11	●	●		●		●	●	●
13	12			●	●		●		●
14	13	●		●	●	●	●		●
15	14		●	●	●	●			●
16	15	●	●	●	●				●

Therefore, when getting a readout from an optoencoder one should consider the uncertainty that the current position is within the angle of throw for the current reading and the next position of the encoder.