# Smart Health – CSE 40816

University of Notre Dame

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UNIVERSITY OF NOTRE DAME



## Sensors & Sensing

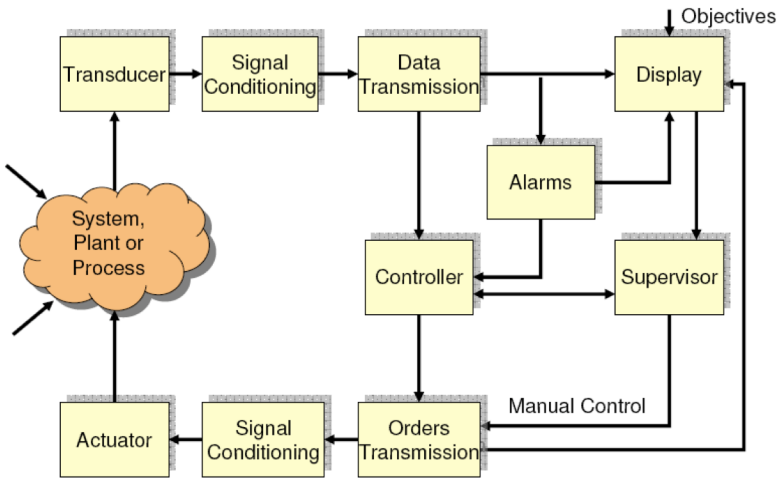
- **Transducer:** a device which converts one form of energy to another
- A **sensor** is a converter that measures a physical quantity and converts it into a signal which can be read by an instrument (i.e., a physical phenomenon is turned into an **electrical signal**)

Visual Sensor

Ultrasound Sensor

Infrared Sensor

## Sensor/Actuator System




## Sensor-to-Signal Interface

- Action of environment on a sensor causes it to **generate** an electrical signal directly
  - voltage source (V), current (I), or charge (Q) source
- Action of environment on sensor **changes** an electrical parameter that we can measure
  - Resistance changes: $V = I * R$ (R = resistance)
  - Capacitance changes: $C = \varepsilon * A / d$ (A = area, d = distance, $\varepsilon$ = permittivity)
  - Inductance changes: $V \sim dI/dt$, $I \sim \int V\,dt$

## Signal Conditioning

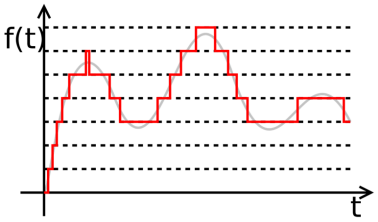
- Filter for expected frequency regime
- Subtract DC offset (“zeroing”)
- Amplify or attenuate signal (“scaling”)
- Linearize relationship between measured and observed electrical parameter
- ...

## Analog-to-Digital Converter (ADC)

- Many different principles
- All involve trade-offs of speed (conversion time), resolution (number of bits), and cost
- “Flash converter” is the fastest, has the lowest resolution, and the highest cost
- Successive approximation ADC: binary search through all possible quantization levels

# Successive Approximation ADC

$$Q = \frac{E_{FSR}}{2^M} = \frac{E_{FSR}}{N}$$

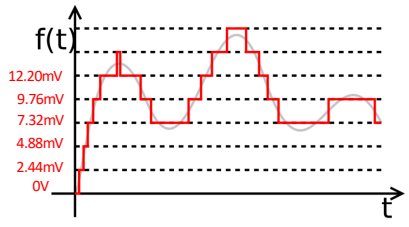



- Q = resolution in volts per step
- M = resolution in bits
- N = Number of intervals (steps)
- $E_{FSR}$ = Full scale voltage range

# Example

- Voltage range 0 – 10V; M = 12 bits
- What is N (intervals, steps)?
  - N = $2^M$ = 2^12 = 4096
- What is Q?
  - Q = 10V/4096 = 2.44mV

$$Q = \frac{E_{FSR}}{2^M} = \frac{E_{FSR}}{N}$$



## Sensor Types

| Criterion | Classes | Example |
|---|---|---|
| Power supply | Modulating | Thermistor* |
| | Generating | Thermocouple** |
| Output signal | Analog | Potentiometer |
| | Digital | Position encoder |
| Operating mode | Deflection | Deflection accelerometer |
| | Null | Servo-accelerometer |

**Thermistor*: a resistor whose resistance changes with temperature.
***Thermocouple*: a temperature-sensing element which converts thermal energy directly into electrical energy

## Sensor Types: Power Supply

- Modulating
  - Also known as Active Sensors
  - They need auxiliary power to perform functionality
- Self-Generating
  - Also known as Passive Sensors
  - They derive the power from the input

## Sensor Types: Operating Mode

- Deflection
  - The measured quantity produces a physical effect
  - Generates an apposing effect which can be measured
  - Faster
- Null
  - Applies the counter force
  - To balance the deflection from the null point (balance condition)
  - Can be more accurate but slow

## Sensor Types: Physical Property

- Temperature
- Pressure
- Humidity
- Light
- Microphone (sound)
- Motion detector
- Chemical detector
- Image Sensor
- Flow and level sensor
- …

## Sensor Types: HW & SW

- **Hardware**-based sensors
  - Physical components built into a device
  - They derive their data by directly measuring specific environmental properties
- **Software**-based sensors
  - Not physical devices, although they mimic hardware-based sensors
  - They derive their data from one or more hardware-based sensors

## Sensor Types: Function Type

- Motion sensors
  - Measure acceleration forces and rotational forces along three axes, e.g., accelerometer, gyroscope, etc.
- Position sensors
  - Measure the physical position of a device, e.g., GPS, proximity sensor, etc.
- Environmental sensors
  - Measure various environmental parameters, e.g., light sensor, thermometer, etc.

# Sensor List

| Sensor | Function Type | Software-based or Hardware-based |
|---|---|---|
| Accelerometer | Motion Sensor | Hardware-based |
| Gyroscope | Motion Sensor | Hardware-based |
| Gravity | Motion Sensor | Software-based |
| Rotation Vector | Motion Sensor | Software-based |
| Magnetic Field | Position Sensor | Hardware-based |
| Proximity | Position Sensor | Hardware-based |
| GPS | Position Sensor | Hardware-based |
| Orientation | Position Sensor | Software-based |
| Light | Environmental Sensor | Hardware-based |
| Thermometer | Environmental Sensor | Hardware-based |
| Barometer | Environmental Sensor | Hardware-based |
| Humidity | Environmental Sensor | Hardware-based |

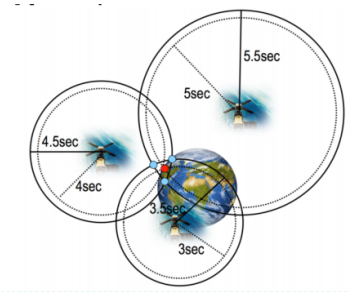
# Smartphone and Wearable Sensing

- Light
- Proximity
- Cameras (multiple)
- Microphones (multiple)
- Touch
- Position
  - GPS, Wi-Fi, cell, NFC, Bluetooth
- Accelerometer
- Gyroscope
- Magnetometer
- Pressure
- Temperature
- Humidity
- Fingerprint sensor

- Accelerometer
- Gyroscope
- Microphone
- Position
- Infrared thermopile
- Photoplethysmography (PPG)
- Electrodermal activity (EDA)
- Electrocardiogram (ECG)

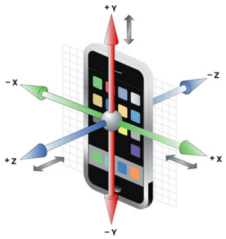
## Sensor: GPS

- Need connection to 3 satellites for 2D positioning, 4 satellites for 3D positioning (theoretically)
- More visible satellites increase precision
- Based on concept of trilateration




## Sensor: Motion and Orientation

- Most of the sensors use the same **coordinate system**
- When a device's screen is facing the user
  - The X axis is horizontal and points to the right
  - The Y axis is vertical and points up
  - The Z axis pints toward outside of the screen face



## Sensor: Accelerometer

- Measure proper acceleration (acceleration it experiences relative to freefall)
- Units: g

| Example | G Force |
|---|---|
| Standing on earth at sea level | 1g |
| Bugatti Veyron from 0 to 100 km/h (2.4s) | 1.55g |
| Space Shuttle, maximum during launch and reentry | 3g |
| Formula 1 car, peak lateral in turns | 5-6g |
| Death or serious injury | 50g |
| Shock capability of mechanical Omega watches | 5000g |

## Sensor: Accelerometer

- Acceleration is measured on 3 axes
- Note that the force of gravity is always included in the measured acceleration
  - When the device is sitting on the table stationary, the accelerometer reads a magnitude of 1g
  - When the device is in free fall, the accelerometer reads a magnitude of 0g
- To measure the real acceleration of the device, the contribution of the force of gravity must be removed from the reading, for example, by calibration

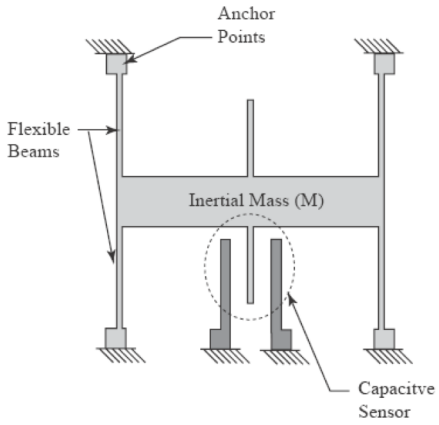
# Sensor: Accelerometer

- When the device is lying flat
  - gives +1g (gravitational force) reading on Z axis
- Stationary device, after 45 degree rotation
  - Same magnitude, but rotated


$a_x = a_y = 0$
$a_z = g$

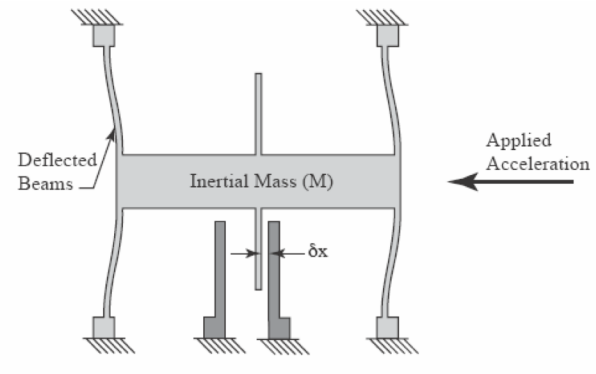
$a_y = 0$
$a_z = -a_x = g/\sqrt{2}$

# Accelerometer: Inner Working (1 of 2)




It consists of beams and a capacitive sensor with some anchor points

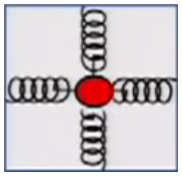
# Accelerometer: Inner Working (2 of 2)

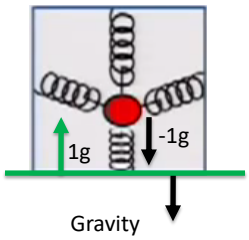



On applying the acceleration, the beams deflect and cause the change in capacitance.

# Accelerometer

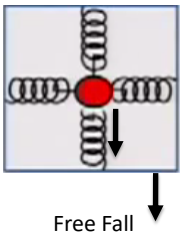
Mass on spring



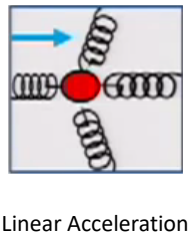



Gravity

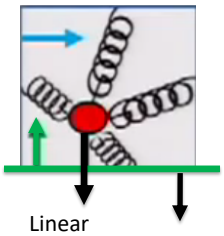
$1g = 9.8 m/s^2$



Free Fall



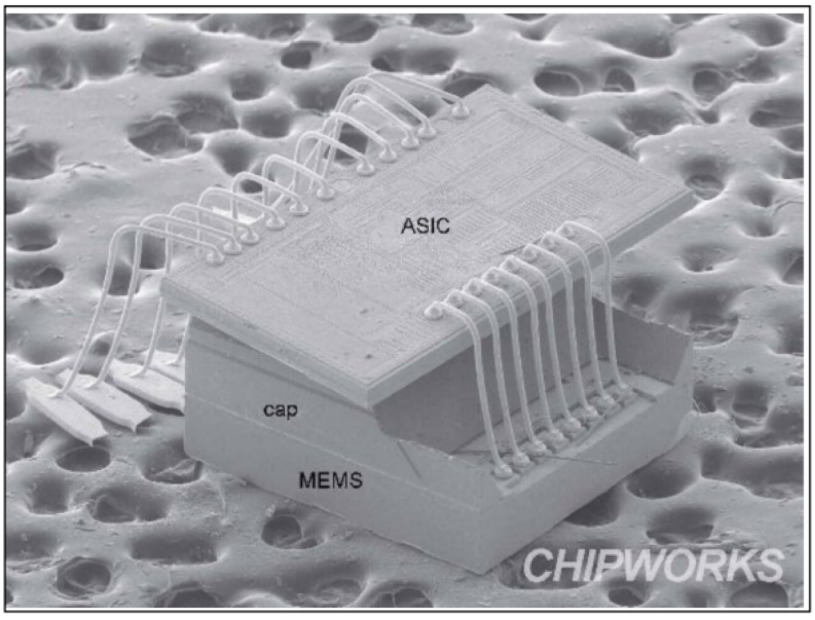
Linear Acceleration



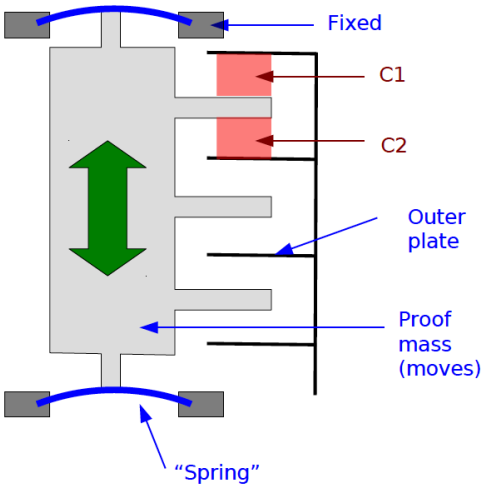
Linear Acceleration plus gravity

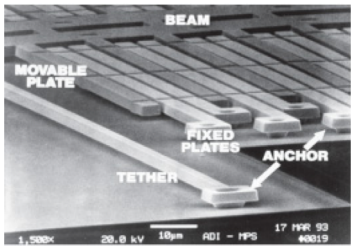
## Smartphones: MEMS Sensors

- Micro Electro-Mechanical Systems
- Term coined in 1989
- Describes creation of mechanical elements at a scale more usually reserved for microelectronics
- MEMS use cavities, channels, cantilevers, membranes, etc. to imitate traditional mechanical systems
- Small enough to be integrated with the electronics



# MEMS Accelerometer




- Have a proof mass between springs and a series of 'plates'
- Measure deflection via capacitance changes
- 1-D only

# Sensor: Gravity

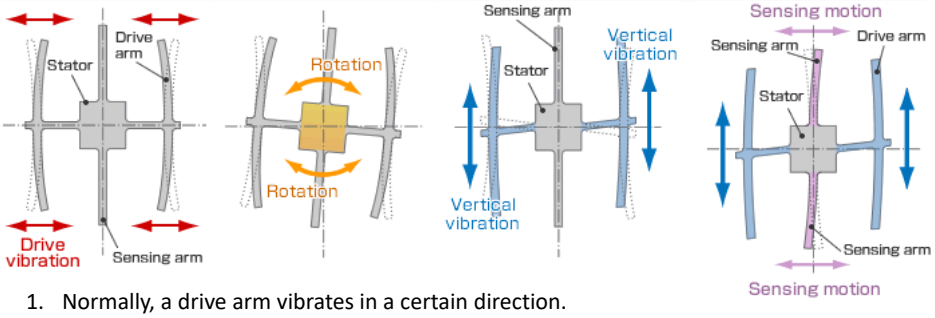
- Gravity sensor is not a separate hardware
- It is a virtual sensor based on the accelerometer
- It is the result when real acceleration component is removed from the reading

# Sensor: Gyroscope

- Measures the rate of rotation (angular speed) around an axis
- Speed is expressed in rad/s on 3 axis
- When the device is not rotating, the sensor values will be zeros
- It gives us 3 values
  - Pitch value (rotation around X axis)
  - Roll value (rotation around Y axis)
  - Yaw value (rotation around Z axis)

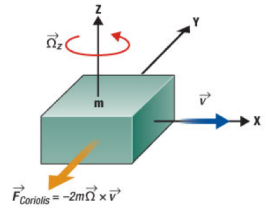

- Unfortunately, gyroscope is error prone over time.
- As time goes, gyroscope introduces drift in result
- By sensor fusion (combining accelerometer and gyroscope), results can be corrected and path of movement of device can be obtained correctly

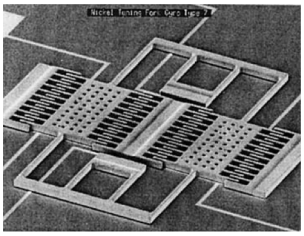
# Gyroscope

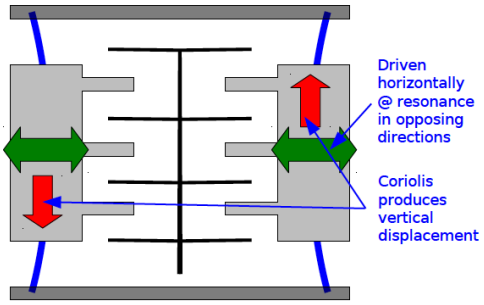



1. Normally, a drive arm vibrates in a certain direction.
2. Direction of rotation
3. When the gyro is rotated, the Coriolis force acts on the drive arms, producing vertical vibration.
4. The stationary part bends due to vertical drive arm vibration, producing a sensing motion in the sensing arms.
5. The motion of a pair of sensing arms produces a potential difference from which angular velocity is sensed. The angular velocity is converted to, and output as, an electrical signal.

# MEMS Gyroscope






- Based on measuring Coriolis force as experienced by a moving object in a rotating frame of reference
- Many implementations, but the "tuning fork" method is most common

# Accelerometer vs. Gyroscope

- Accelerometer
  - Senses linear movement: not good for rotations, good for tilt detection
  - Does not know difference between gravity and linear movement
- Gyroscope
  - Measures all types of rotations
  - Not movement
- A+G = both rotation and movement tracking possible

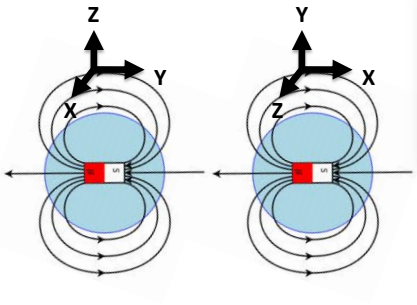
# Sensor: Magnetic Field

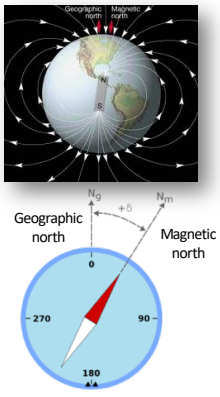
- Measures direction and strength of earth's magnetic field
- Strength is expressed in Tesla (T)

| Example | Field strength |
|---|---|
| Earth's magnetic field on the equator (0° latitude) | 31μT (0.00031T) |
| Typical fridge magnet | 5mT (0.005T) |
| Strong neodymium magnet | 1.25T |
| MRI system | 1.5T – 3T |

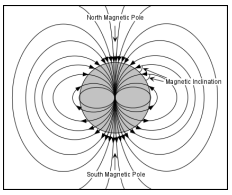
# Compass

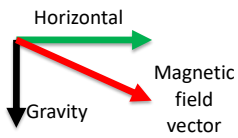
- Magnetic field sensor (magnetometer)




Magnetic declination

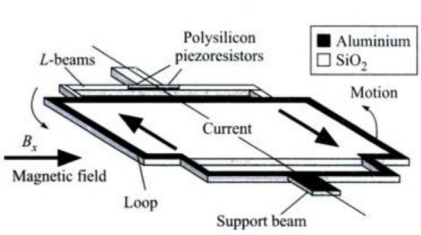


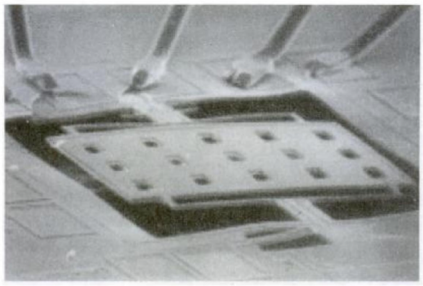




Magnetic inclination

# MEMS Compass

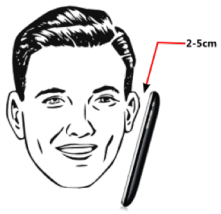
- Most use Lorentz Force
- A current-carrying wire in a magnetic field experiences a perpendicular force



# Sensor: Proximity

- A proximity sensor can detect the presence of nearby objects without physical contact
- It often emits an electromagnetic field (e.g., infrared) and looks for changes in the field or return signal
- It is usually used by mobile device to determine how far a person's head is from the face of a handset
  - E.g., a user is making a phone call




- The measured results could be different based on different devices
  - Most proximity sensors return the absolute distance in centimeters (cm)
  - Some return only a flag that represents near or far
  - Some return either 0.0 or the maximum value only

# Sensor: Light

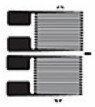
- It gives a reading of the light level detected by the light sensor of the device
- Located at front of mobile device near to front facing camera
- The units are in SI lux units
- The device uses the data to adjust the display's brightness automatically
  - When ambient light is plentiful, the screen's brightness is pumped up and when it is dark, the display is dimmed down
  - High-end Samsung galaxy phones use an advanced light sensor that can measure white, red, green, and blue light independently to fine tune image representation


# Sensor: Thermometer

- Ambient temperature outside of the device
- In fact, there's a thermometer in almost every mobile device and some handsets might have more than one of them; however, they are used to monitor the temperature inside the device and its battery to detect overheating
- A temperature sensor detects a change in a physical parameter such as resistance or output voltage that corresponds to a temperature change
- Contact (direct physical contact) vs. non-contact (radiant energy of a heat source)

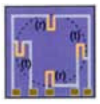
## Sensor: Pressure

- Transduces pressure into electrical quantity
- Pressure exerts force which can be converted to electrical voltage using various methods
- **Strain Gauges**
  - Based on the variation of resistance of a conductor or semiconductor when applied to mechanical stress



- **Capacitive diaphragms**
  - Diaphragm acts as one plate of capacitor
  - The stress changes the space between capacitor plates

- **Piezo-resistive**
  - Micro-machined silicon diaphragms
  - Piezo-resistive strain gauges diffused into it
  - Very sensitive to pressure



## Piezoelectric Sensors

- Device that measures changes in pressure, strain, force, etc. by converting them to an electrical charge
- Typically crystals or ceramics