Mobile Sensing

Hua Huang

In this lecture

- We will introduce fundamentals of sensors.

- We will discuss the major sensor types

- We will talk about orientation estimation

What is a sensor?

- A converter that measures a physical quantity and converts it into a signal which can be read by an instrument ...
- What are some sensors we use every day?
  - Thermometers
  - Motion sensors on a game console
  - Radar guns, red light cameras
  - Automatic door openers
  - Cameras

Why are we talking about sensors?

- Sensors have been used in cellphones since they were invented ...
    - Microphone, number keys
- What about smartphones?
    - accelerometers, gyroscopes, GPS, cameras, etc ...
- Allowed cellphones explode into different markets
    - replace: Navigator (Garmin, Tomtom)
- Instead of carrying around 10 separate devices, now you just need 1

Sensors chracteristics

Sensors can be characterised according to:

- Passive (use the signal from objects) vs. active (sensor emits signal)
  - E.g. Passive infrared vs active infrared
- Single sensors vs sensor arrays
  - E.g. microphone vs microphone array
- Read-only program vs. re-programmable

Sensor Types

Distance and Ranging

Distance and Ranging: Infrared Sensors

- Contain an infrared emitter, and an infrared detector
- Works by emitting a certain amount of infrared light, and seeing how much it gets back
- Why infrared?
  - There are not many other infrared sources in everyday life that would interfere with this sensor
  - If visible light were used, light bulbs, computer screens, cellphone screens, etc, would all interfere with the depth reading

Distance and Ranging: Infrared Sensors

- Great at measuring shorter distances (2” –30”)
- Where do you see these?
  - Touchless Switches (toilets, faucets, etc)
  - Roomba vacuums
  - Kinect
- Related: Passive Infrared (PIR) Sensors
  - No IR emitter, just detects ambient IR.
  - Detects some normal state (like a wall’s IR emissions) and when something moves in front, it detects a change
  - Great for detecting motion (motion sensors for security systems)

Distance and Ranging: Speed Detector

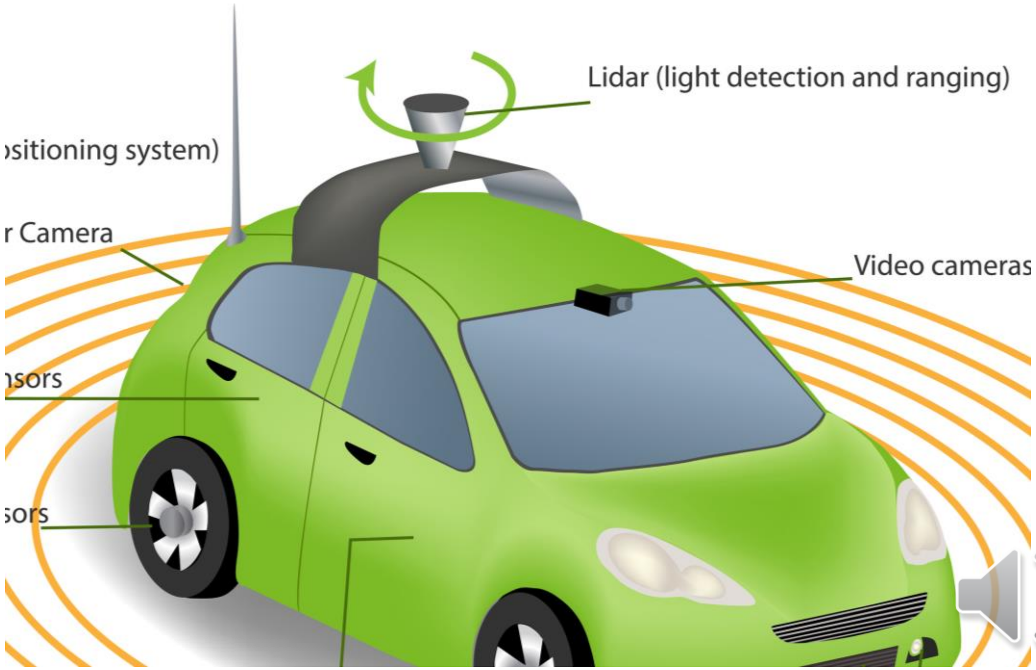
- e.g. police radar guns
  - Microwave radars use the Doppler effect (the return echo from a moving object will be frequency shifted).
  - The greater the target speed, the greater the frequency (Doppler) shift

Distance and Ranging: Ultrasonic Sensors

- Contain a high frequency speaker, and a microphone
- Works just like a sonar, emitting a sound, and listening for the echo to determine range
- Why is it called ultrasonic?
  - Very high frequency sound, it is outside of what humans can hear.
  - This is nice since it is not as annoying to use
- Pros: More accurate than IR sensors at slightly longer distance (typically up to several feet)
- Cons: twice more expensive

Distance and Ranging: Lidar

- LIDAR — Light Detection and Ranging
- How it works?
  - Calculate how long it takes for the light to hit an object and reflect back to the sensor.
- Pro: longer range (10m – 200 m)
- Con: expensive why?
- Application:
  - iphone
  - automobile
  - Indoor dimension measuring



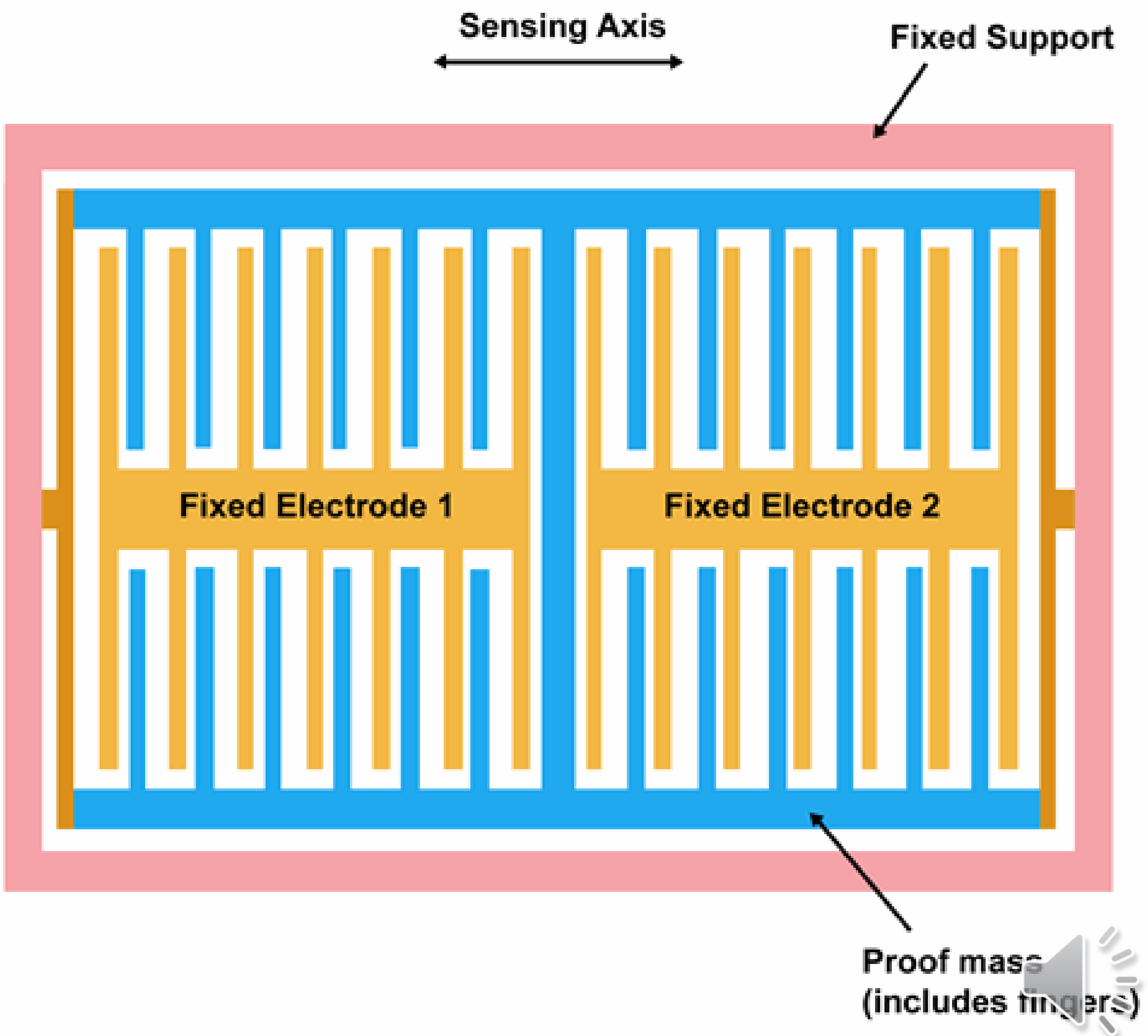
Micro Electro-Mechanical Systems (MEMS)

Meaning of MEMS

- Microsystems that constitute the technology of **microscopic** devices, particularly those with **moving parts**

MEMS: Accelerometer

- Accelerometers:
  - Measures change in velocity in x y z axes
- How does it work?
  - The “proof mass” shown above is allowed to move in a plane.
  - The attached fingers form a capacitor with the two plates around it.
  - The rate of change of the capacitance is measured and translated into an acceleration

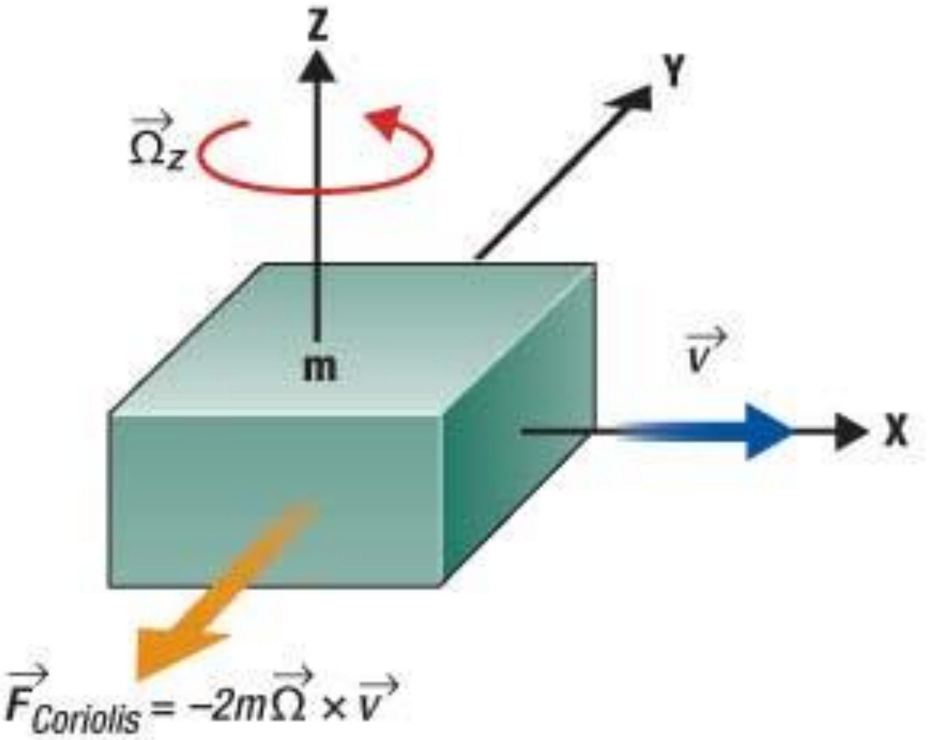


MEMS: Gyroscope

- Measures rotation speed

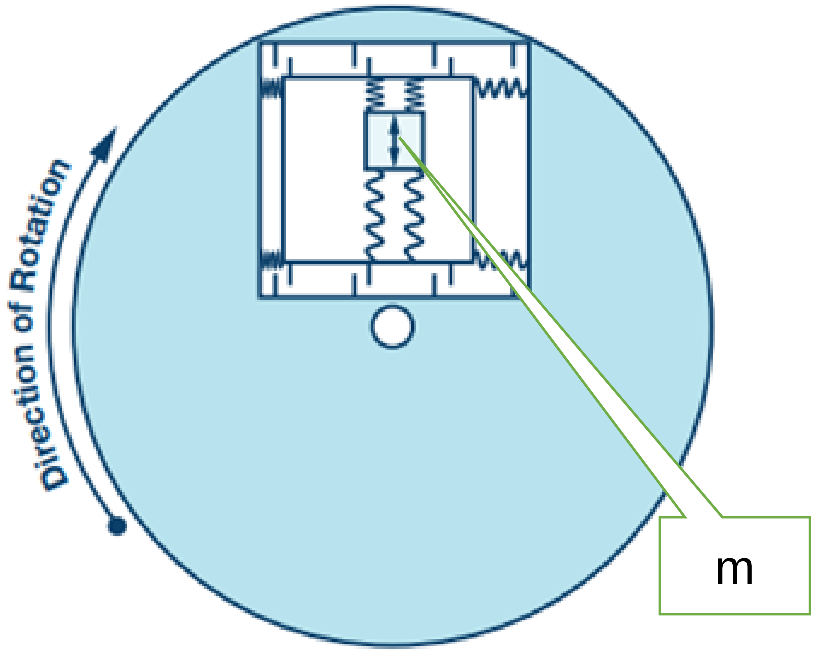
How MEMS Gyroscope works?

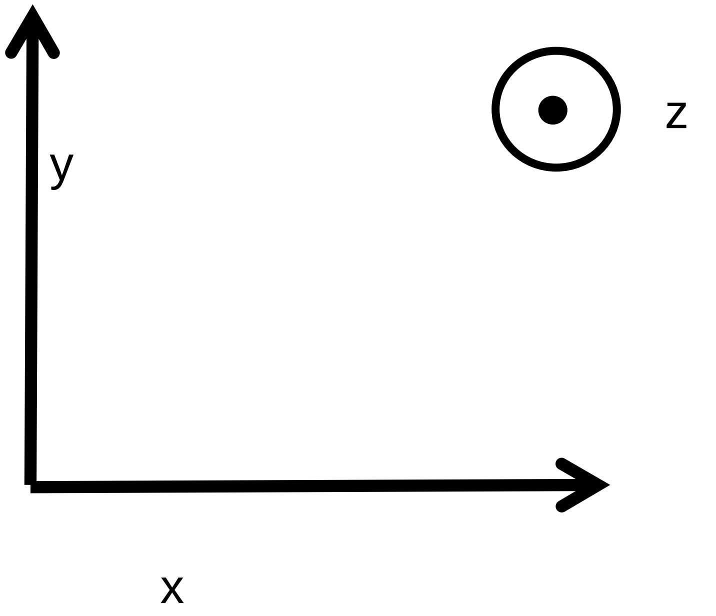
- The Coriolis force
  - If an object is moving along one axis, and it is rotated above another, it will feel a Coriolis force in the third axial direction



Inside an MEMS gyroscope

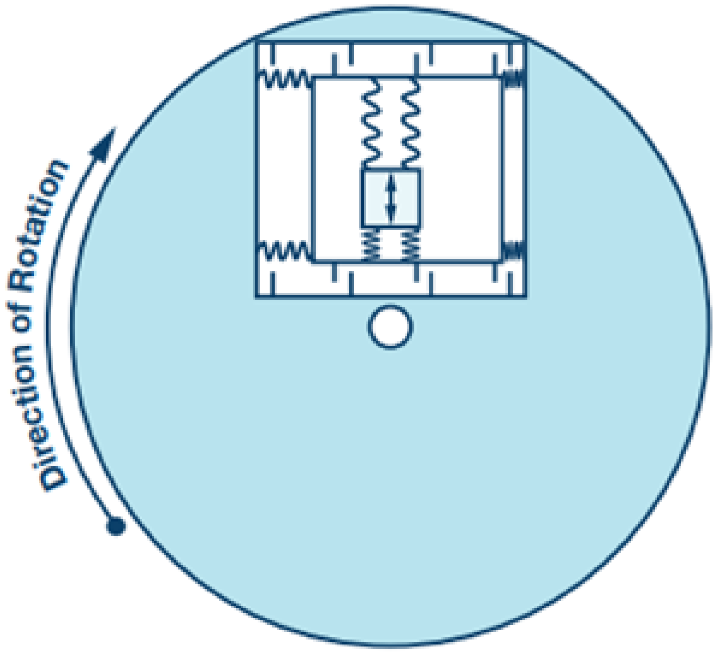
- A mass,m, vibrating along y axis
- When y moves +y direction, rotating along z clockwise
  - What is Coriolis force direction? -x
  - Force proportional to capacitance

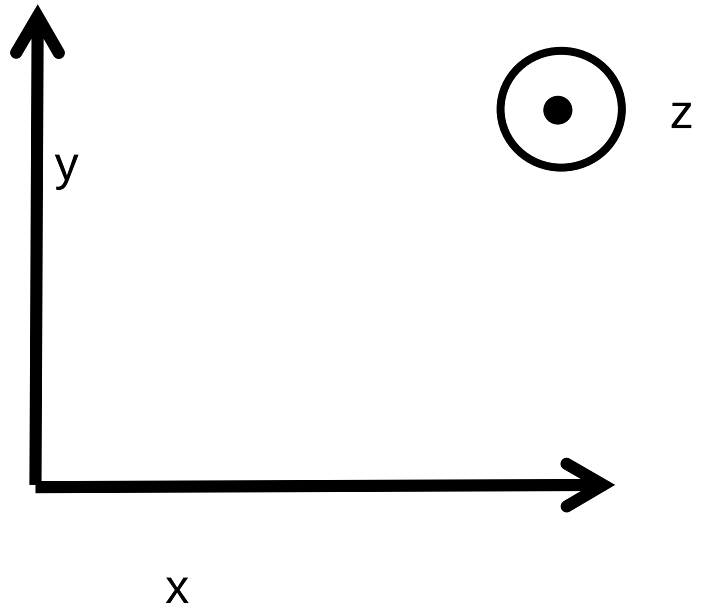




Exercise

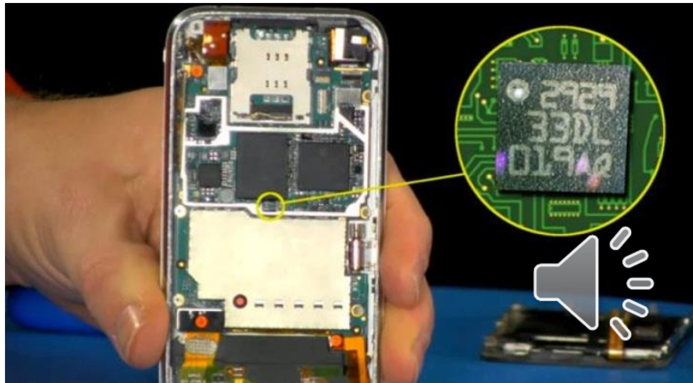
- Explain the direction of Coriolis force





MEMS

- Accelerometer+Gyroscope=6 DoF Inertia Motion Units(IMU)
- Very small and low-cost
  - less than 6 mm × 6 mm in footprint can weigh less than a gram
  - MEMS vendors have been shipping high volumes for mobiles, tablets, and automotive applications since 1990.
- Robust to environmental changes
  - The shock specifications of today’s generation of devices are stated to 10,000 g, but in reality can tolerate much higher
  - Normal humans can withstand no more than 9 g's



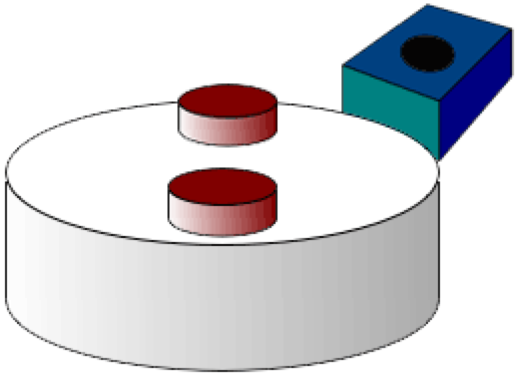
MEMS

- Where do you see these?
  - Game consoles: Wii
  - Orientation sensing in smartphones
  - Image Stabilization in cameras
  - Collision detection in cars
  - Pedometers
  - Monitoring equipment for failure (vibrations in ball bearings, etc)

Other Sensors

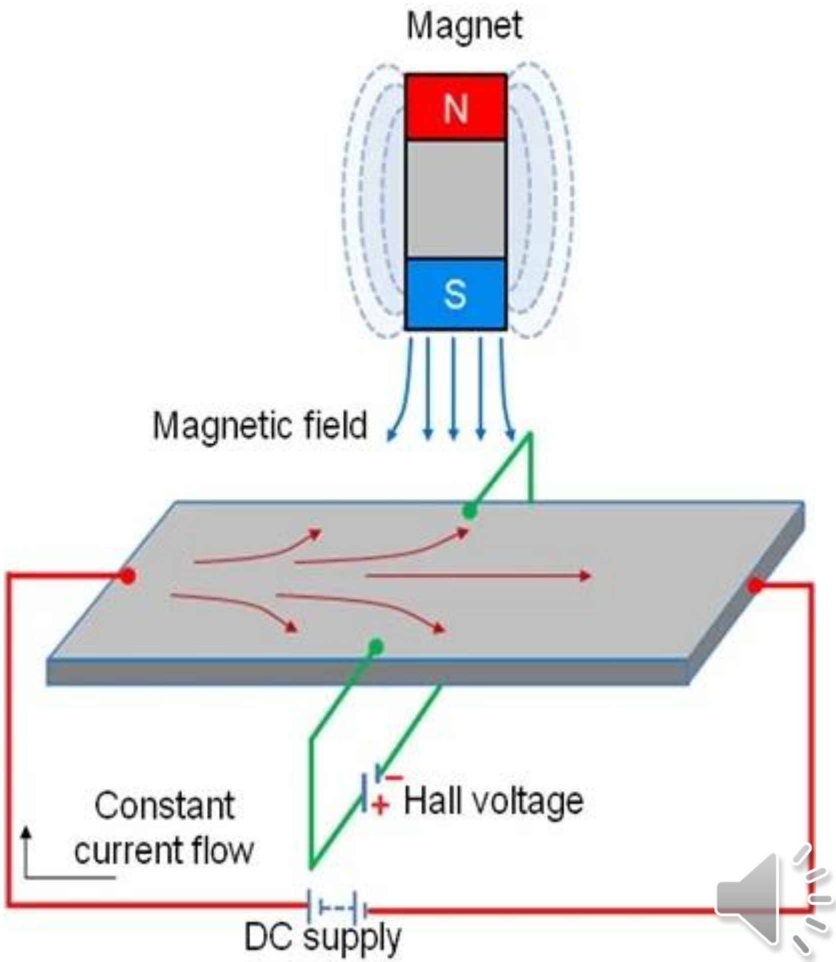
Hall-Effect Magnetic Sensors

- A Hall-effect sensor (or simply Hall sensor) is a device to measure the magnitude of a magnetic field.
  - Its output voltage is directly proportional to the magnetic field strength
- Applications
  - proximity sensing
  - positioning
  - compass
  - current sensing



How does the Hall effect sensor work?

- When we have
  - current moving along one axis
  - a magnetic field perpendicular to the first axis
- Then a voltage is generated along the third axis
- The fundamental magnetic force:
  - $F = qvB \sin\theta$

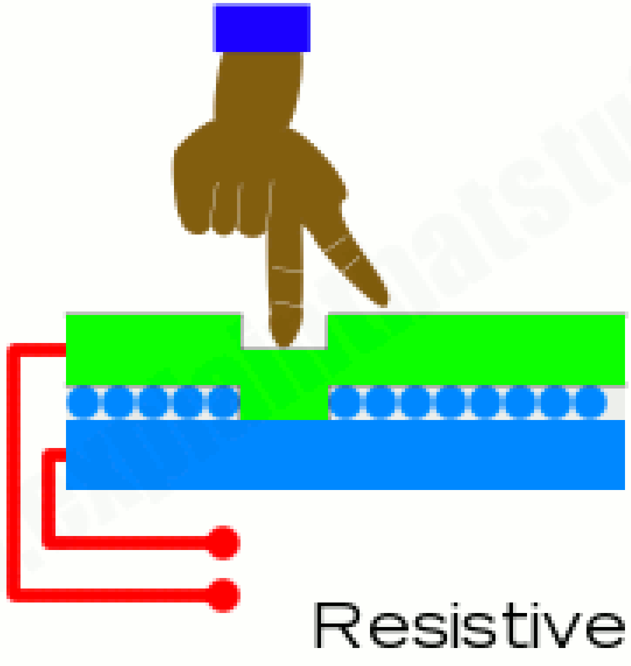


Force sensing resistor

Determines when pressure is being applied

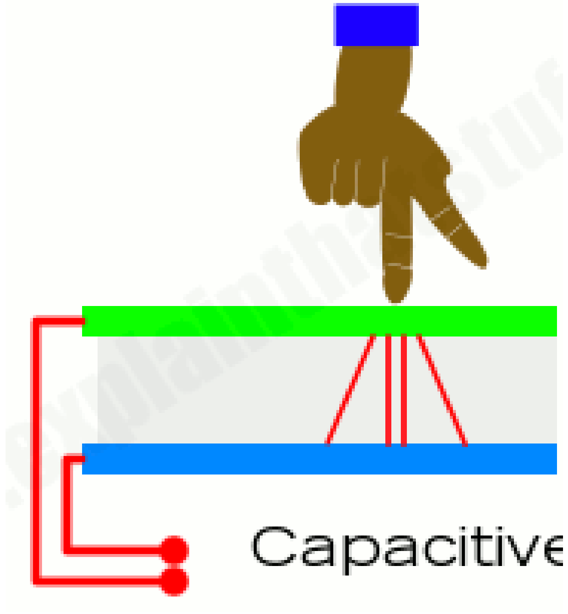
- How does it work?
  - Made of a material called Polymer Thick Film (PTF)
  - When pressure is applied to a PTF, its resistance decreases, which can be easy measured (strain gauge)
- What is it used for?
  - Robot end-effectors, load and compression sensing, contact sensing (buttons), Joysticks

Touchscreen: resistive



- How it works
  - Consists of 2 layers held apart by spacers
  - An electric current is constantly sent through the layers
  - When something touches the screen, it causes the two layers to touch, changing the electric current
  - This change can be measured and based on how much it changes, the location of touch can be computed
- Pro: very cheap, doesn't require the input to be a finger or some other conductive input
- Con: Since two layers are required, only about 75% of the screen light can get through

Touchscreen: capacitive



- How it works
  - Consists of a single capacitive layer
  - This layer stores a constant charge
  - When something conductive touches the screen, the charge on the screen decreases
  - This change can be measured and based on how much it changes, the location of touch can be computed
- Pro: Since only 1 layer is required, about 90% of the screen light can get through
- Con: More expensive than a resistive system. Requires a conductive input device

A Good Sensor

- Sensitive to only the measured property
  - Biggest worry here is temperature
- The sensor itself doesn’t influence the measured property
  - A sensor attached to an insect.
- The output should be linearly proportional to the measured value
- Sensitivity = the minimal signal strengths that can be detected

A Bad Sensor

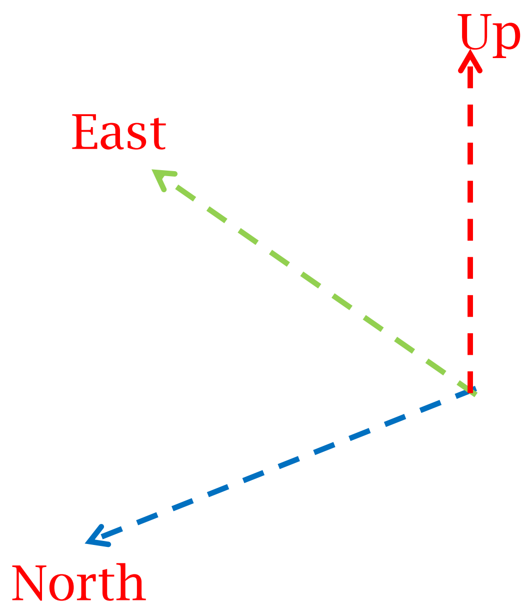
- Drift: Produce unbounded measurement error. Examples?
- Noise: Random deviation of the signal over time
- Systematic errors can often be corrected via calibration
- Random errors (noise) can be filtered out using signal processing techniques, but these are slow
- Particularly in the context of mobile devices
  - Computation and battery are valuable resources

3D orientation

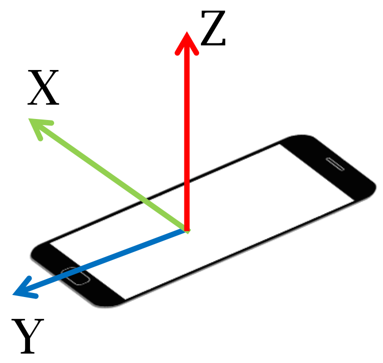
Question:

How do we know the orientation of the phone?

Coordinate frames

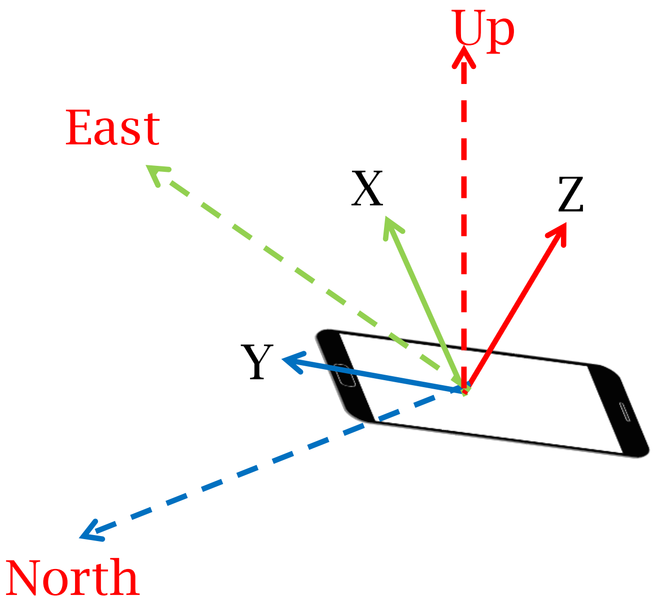


Global Frame



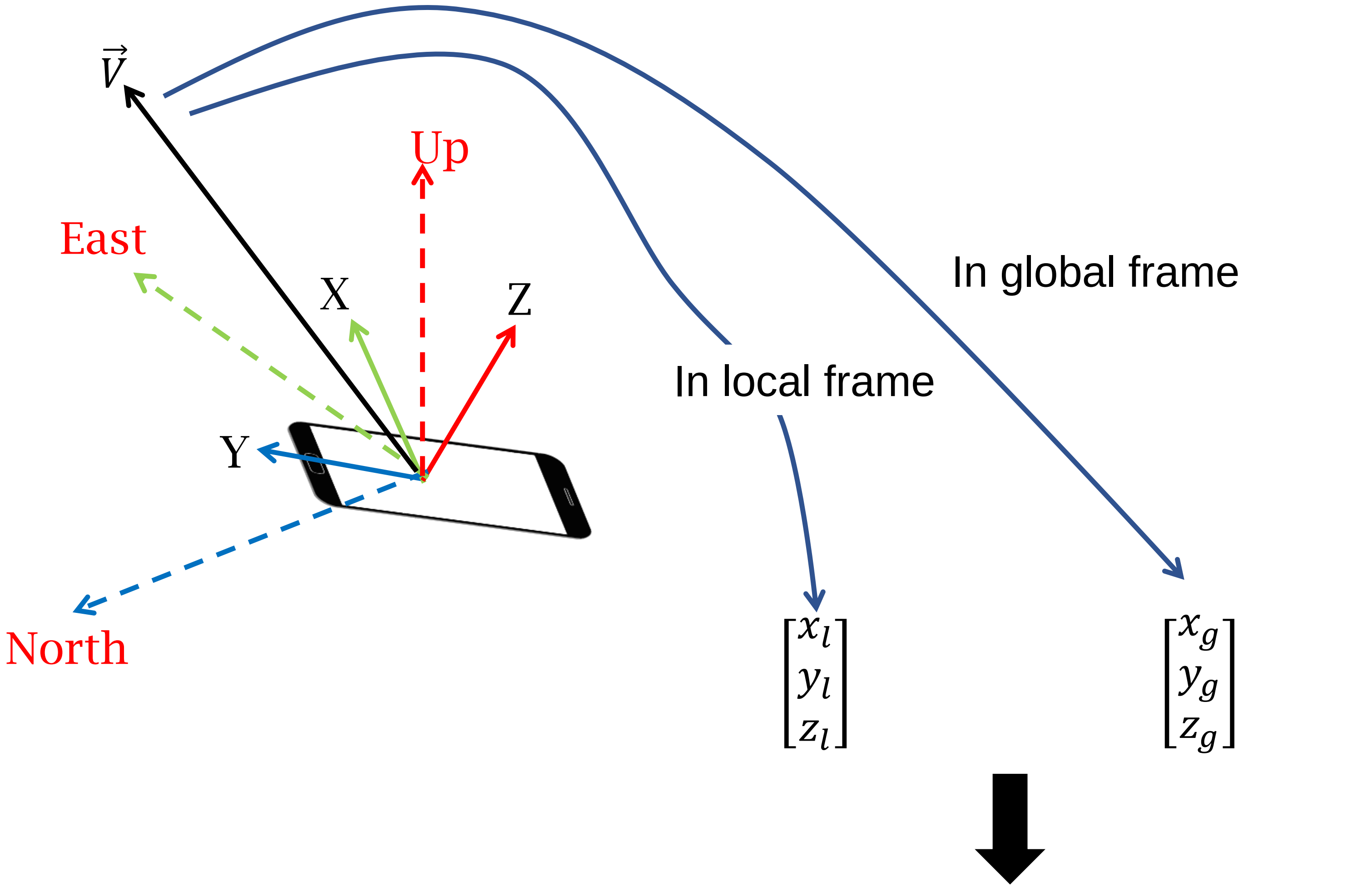
Local Frame

Consider a phone in a random orientation



3D Orientation captures the misalignment between global and local frames

Rotation Matrix



R is the 3x3 Rotation Matrix

3x3 Rotation matrix captures the full 3D orientation

How can we estimate rotation matrix?

Key idea → use globally known reference vectors

which can also be measured in the local frame of reference

- Gravity
- Magnetic North

Gravity Sensor

- A 'software sensor' and
- Calculated using accelerometer and gyroscope.
- Always points to the earth

Gravity equation

Gravity globally known, measurable in local frame with gravity sensor

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \qquad \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \qquad \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} \qquad \left|\begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}\right.$$

Magnetic north, globally known, measurable in local frame with magnetometer

6 equations and 9 unknowns (3x3 rotation matrix) can we solve ?

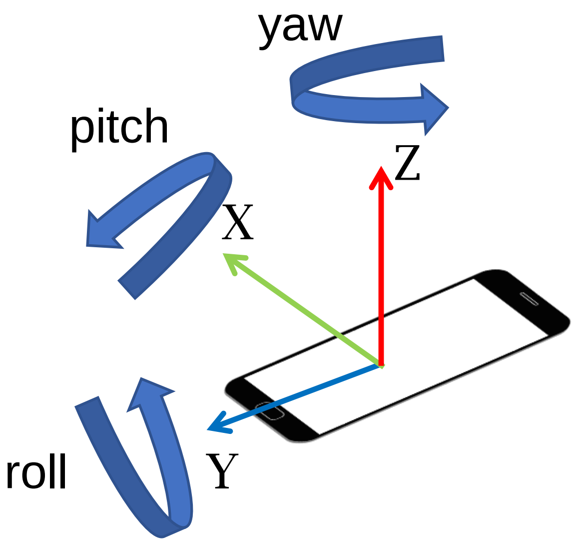
Yes, these 9 unknowns are all not independent (rotation matrix satisfies special properties)

- It does not change length of a vector
- Columns are orthogonal unit vectors

The above 6 equations are sufficient to solve the rotation matrix

Gravity Sensor and Magnetometer can be used to determine the rotation matrix (3D orientation)

Decomposing the rotation matrix



$$\begin{bmatrix} \text{3x3 Rotation Matrix R} \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Orientation can be represented as 3D yaw, pitch, roll

Estimating yaw, pitch, roll will determine the orientation

Gravity equation

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \text{Rotation Matrix R} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \boxed{\begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}}$$

Gravity equation

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \boxed{\text{Rotation Matrix R}} \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}$$

Gravity output does not depend on yaw!

Hence, yaw cannot be estimated using gravity

Accelerometer equation

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \text{Rotation Matrix R} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} -\sin(pitch)\,.\cos(roll)\,.\,g \\ -\sin(roll)\,.\,g \\ -\cos(pitch)\,.\cos(roll)\,.\,g \end{bmatrix}$$

The above equations estimate pitch and roll

Magnetometer equation

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \text{Rotation Matrix R} \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

Magnetometer equation

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \text{Rotation Matrix R} \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

Pitch, roll known from accelerometer

Unknown yaw can be determined from above equations

yaw, pitch, roll together determine the rotation matrix (3D orientation) of a system

Reference

- Android implementation

  https://developer.android.com/guide/topics/sensors/sensors_position