Autonomous Mobile Robot Design

Topic: Inertial Measurement Unit

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Where am I?
What is my environment?

Robots use multiple sensors to understand where they are and how their environment looks like. As no single sensing modality is sufficient to have a full understanding of the robot pose and map, we employ techniques of sensor fusion.

Navigation Sensors

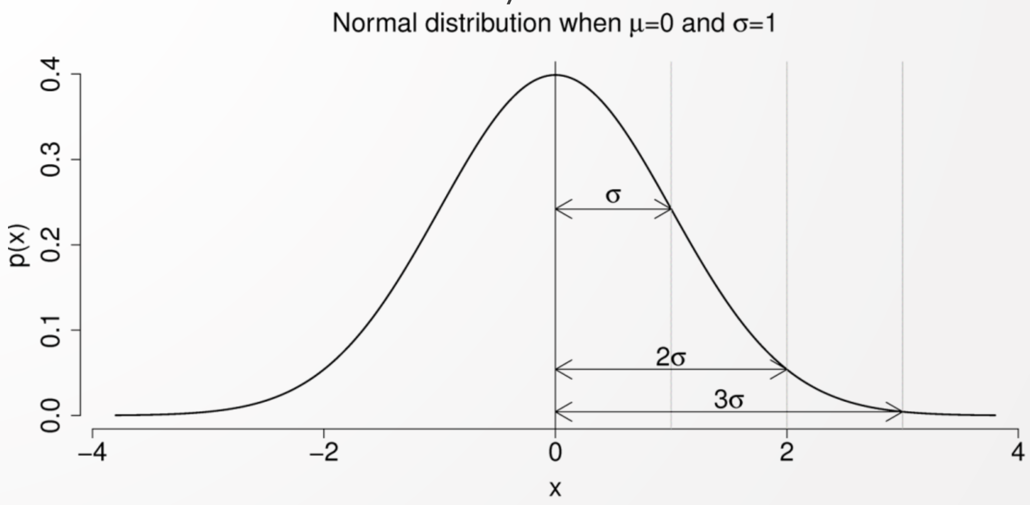
- Providing the capacity to estimate the **state** of the aerial robot
  - **Self-Localize and estimate its pose in the environment**
  - **Often this infers to also derive the map of the environment**
  - **In some cases also rely in external systems (e.g. GPS), while a lot of work is undergoing into making aerial robots completely autonomous.**

Classification of Sensors

- *What:*
  - **Proprioceptive sensors**
    - Measure values internally to the robot.
      - Angular rate, heading.
  - **Exteroceptive sensors**
    - Information from the robot environment
      - Distances to objects, extraction of features from the environment.
- *How:*
  - **Passive Sensors**
    - Measure energy coming from a signal of the environment – very much influenced from the environment.
  - **Active Sensors**
    - Emit their proper energy and measure reaction.
    - Better performance, but some influence on the environment.
    - Not always easily applicable concept.

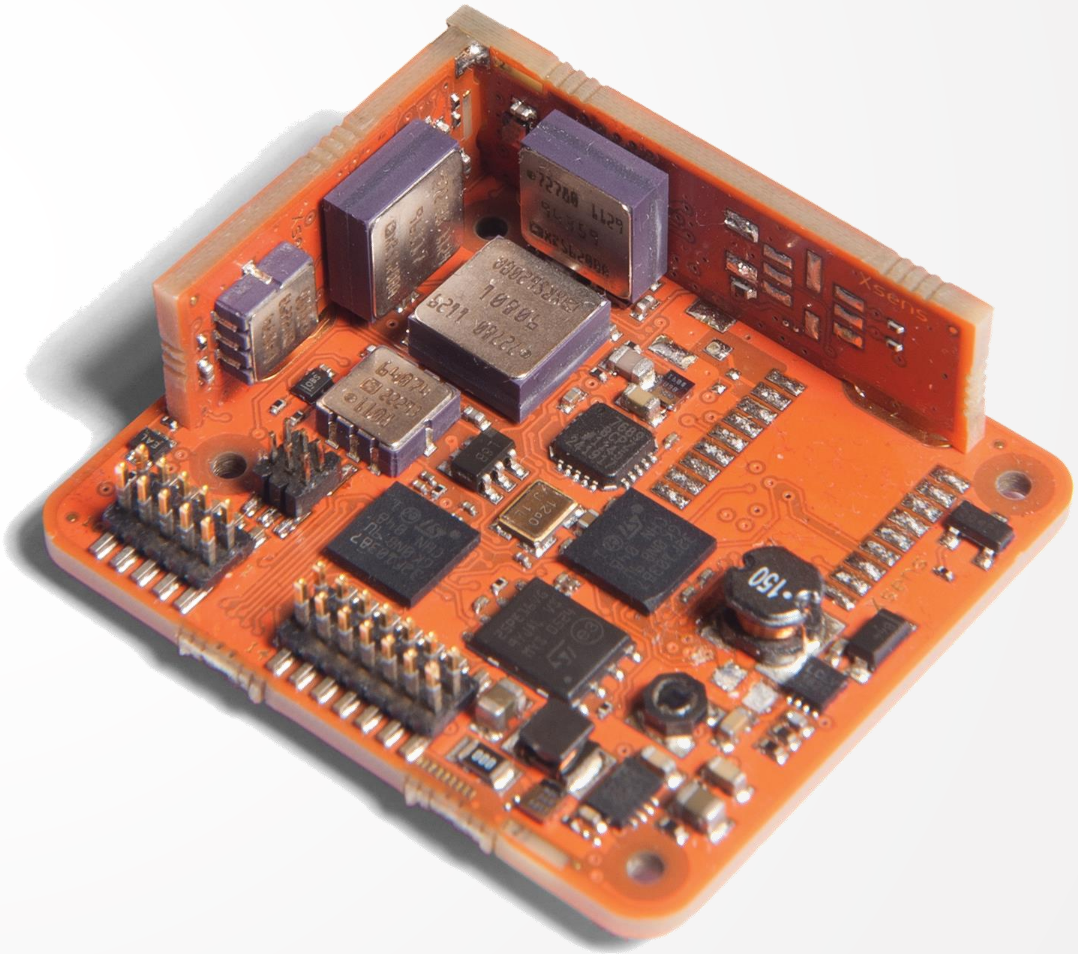
Uncertainty Representation

- **Sensing is always related to uncertainties**
  - How can uncertainty be represented or quantified?
  - How do they propagate – uncertainty of a function of uncertain values?
- **Systematic errors**
  - They are caused by factors or processes that can in theory be modeled and, thus, calibrated, (for example the misalignment of a 3-axes accelerometer)
- **Random errors**
  - They cannot be predicted using a sophisticated model but can only be described in probabilistic terms



Typical Navigation Sensors

- The following sensors are commonly used for the navigation of aerial robots:
  - **Inertial Sensors:**
    - Accelerometers
    - Gyroscopes
  - **Magnetometers (digital compass)**
  - **Pressure Sensors**
    - Barometric pressure for altitude sensing
    - Airspeed measurements
  - **GPS**
  - **Camera based systems**
  - **Time-of-Flight sensors**



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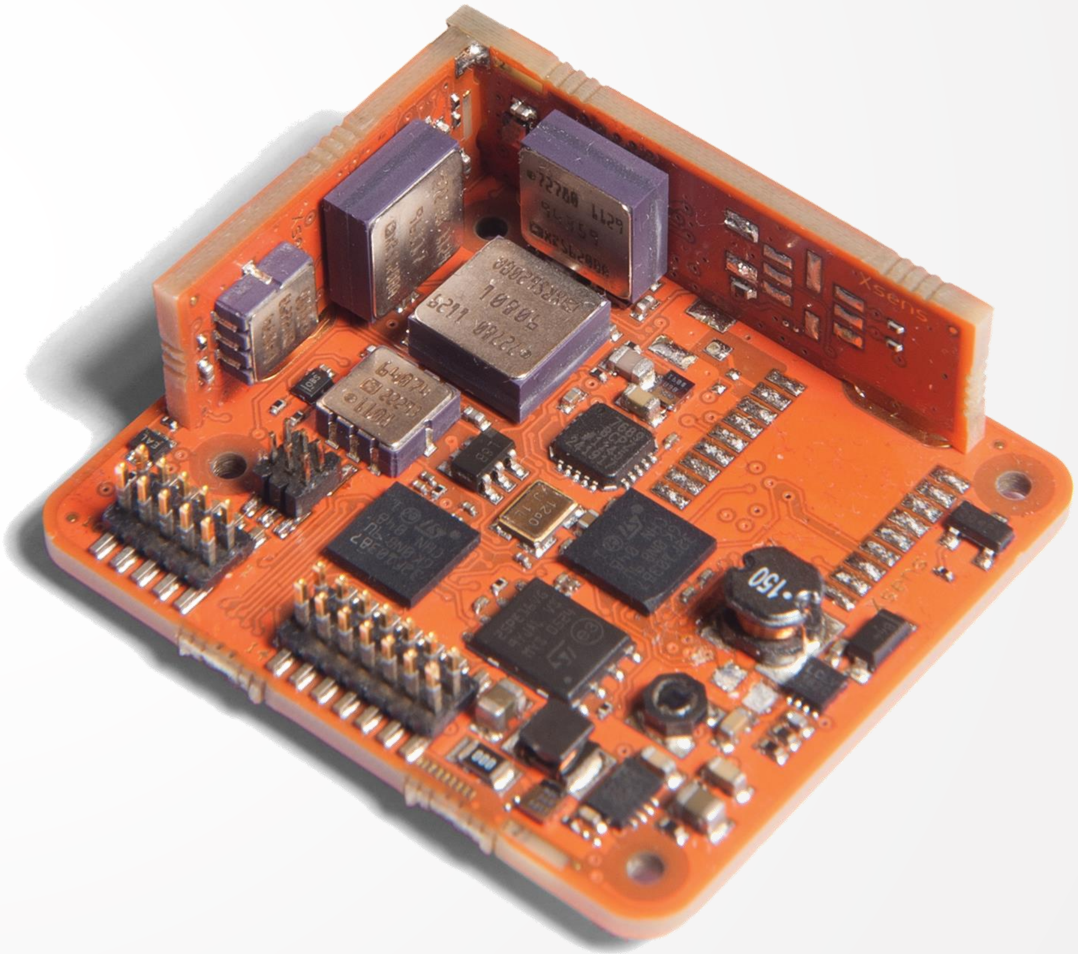
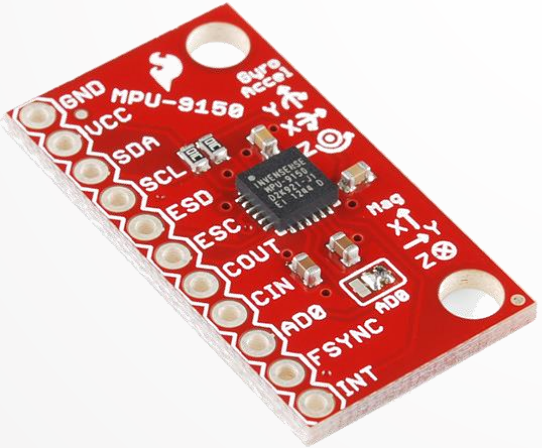
  - **Time-of-Flight sensors**

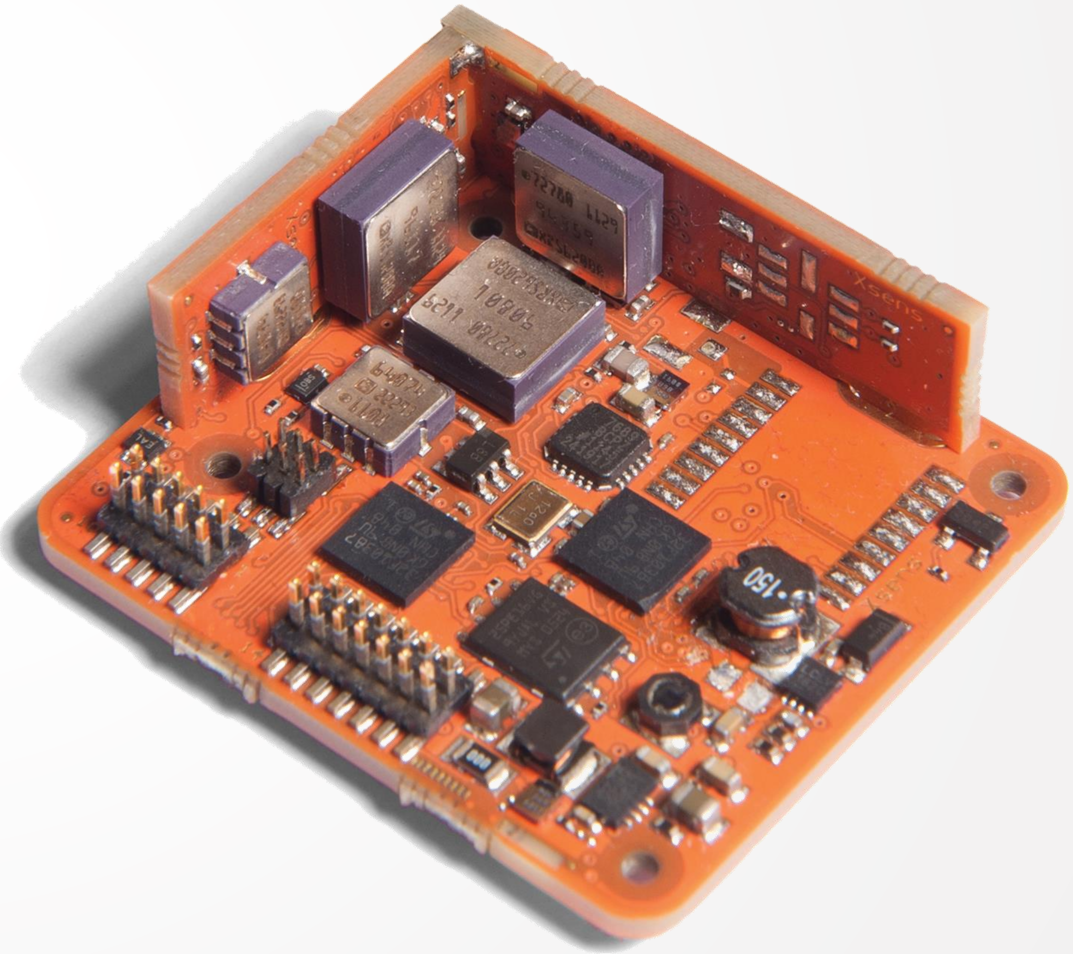
Topic of this presentation



Inertial Measurement Unit

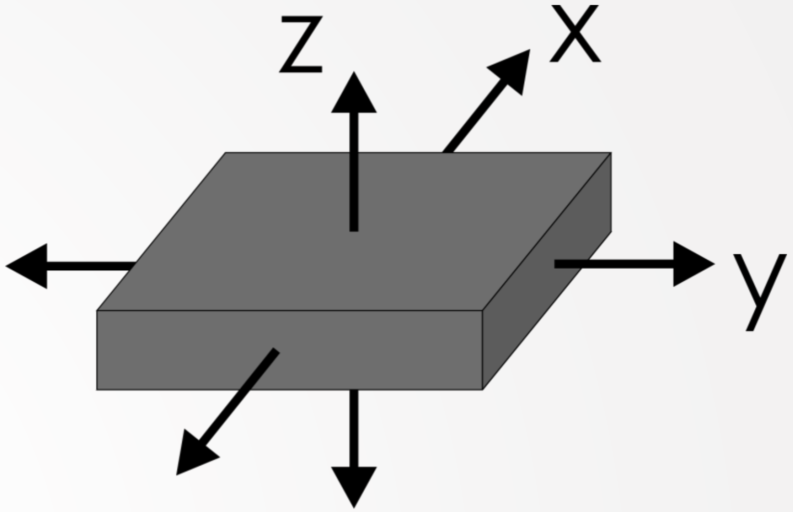
- An Inertial Measurement Unit typically integrates:
  - **3-axes Accelerometers**
  - **3-axes Gyroscopes**
  - **3-axes Magnetometer**
  - **Absolute Pressure Sensor**

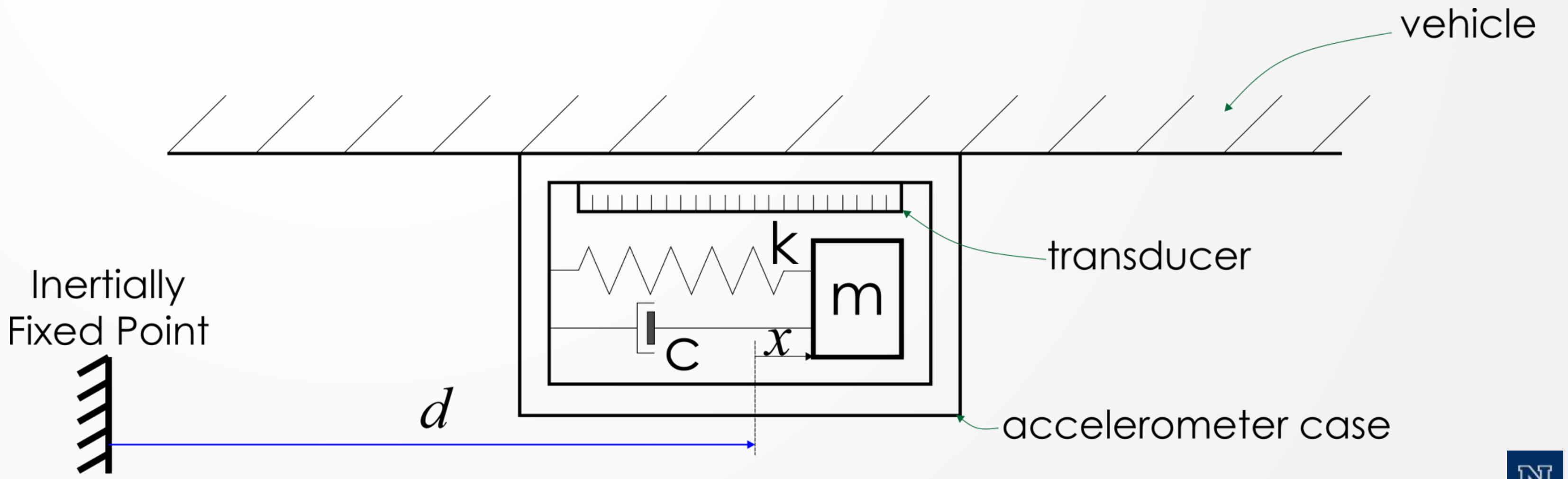




Accelerometer

- Accelerometers are devices that **measure proper acceleration** ("g-force"). Proper acceleration is not the same as coordinate acceleration (rate of change of velocity). For example, an accelerometer at rest on the surface of the Earth will measure an acceleration g= 9.81 m/s^2 straight upwards.
- Accelerometers are electromechanical devices that are able of measuring static and/or dynamic forces of acceleration. Static forces include gravity, while dynamic forces can include vibrations and movement. Accelerometers can measure acceleration on 1, 2 or 3 axes.



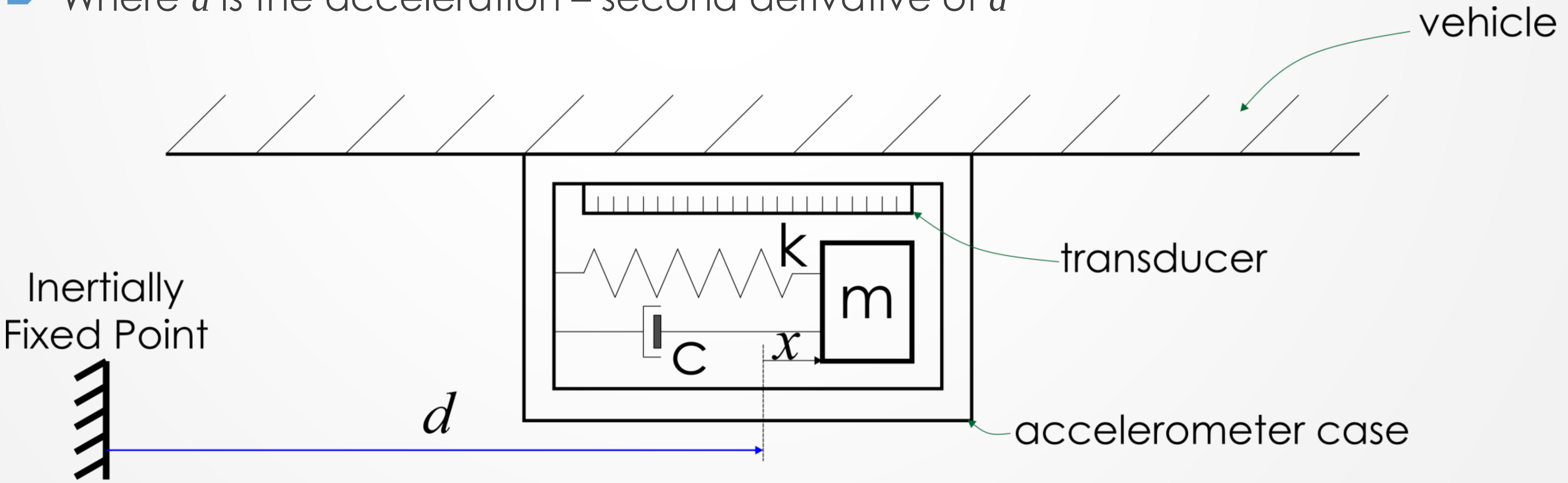


Accelerometer

- **Simplified Accelerometer Model:**

$$m(\frac{d^2}{dt}(d+x)) = F_x \Rightarrow m(\frac{d^2}{dt}(d+x)) = -c\frac{dx}{dt} - kx \Rightarrow$$
$$m(\ddot{d}+\ddot{x}) + c\dot{x} + kx = 0 \Rightarrow m\ddot{x} + c\dot{x} + kx = -ma$$

- Where a is the acceleration – second derivative of d

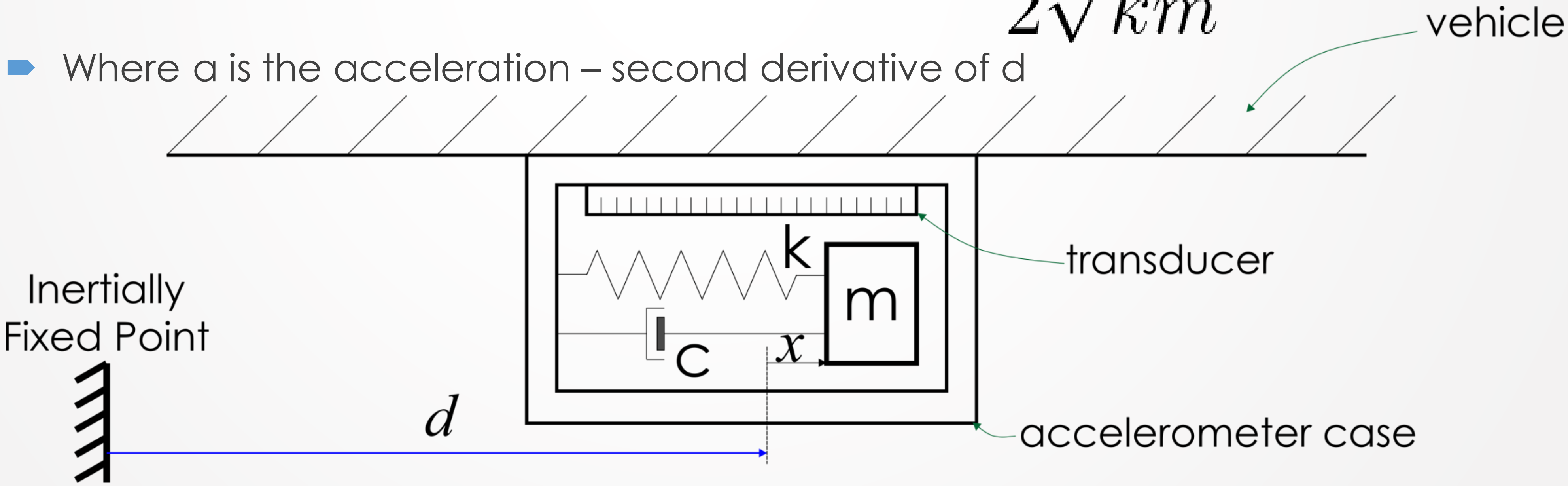


Accelerometer

- For the cases within which, the vehicle acceleration is constant, then the steady state output of the accelerometer is also constant, therefore indicating the existence and value of the acceleration.
- The **undamped natural frequency** and the **damping ratio** of the accelerometer are:

$$\omega_n = \sqrt{k/m}, \quad \zeta = \frac{c}{2\sqrt{km}}$$

- Where a is the acceleration – second derivative of d

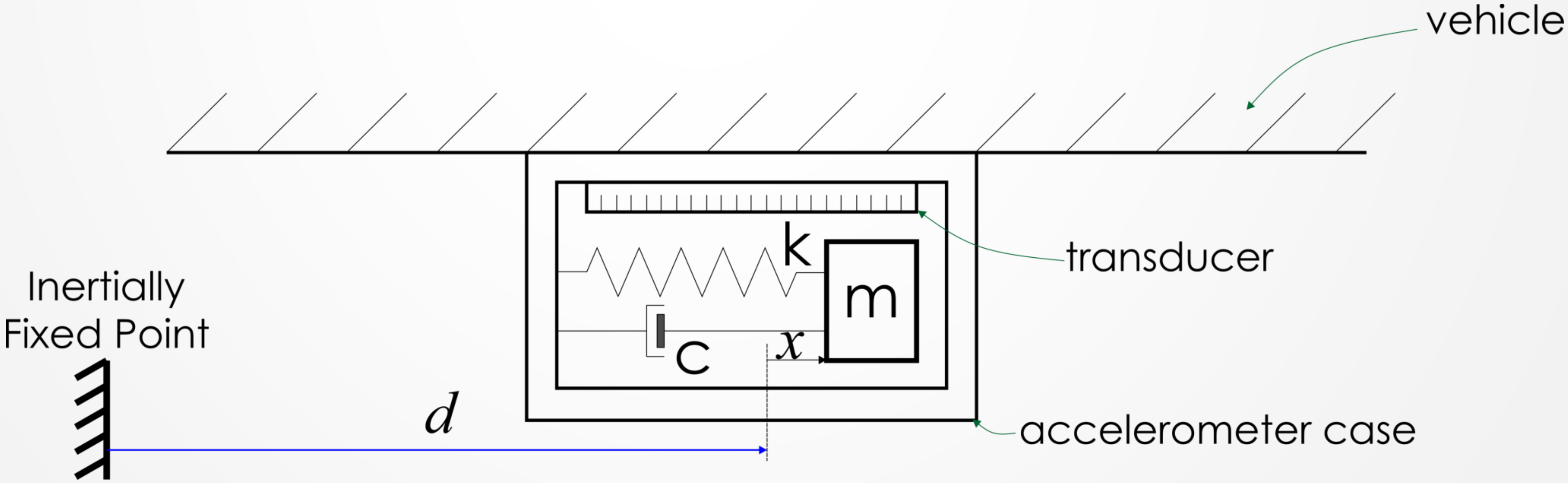


Accelerometer

- **Bias effects on accelerometers:** accelerometer measurements are degraded by scale errors and bias effects. A typical error model takes the form:

$$\mathbf{a}_{3D} = \mathbf{M}_{acc}\mathbf{a}_{3D}^{m} - \mathbf{a}_{bias} + \mathbf{a}_{n}$$

- Where a_{3D} stands for the 3-axes acceleration, M_{acc} for combined scale factor and misalignment compensation, $a_{3D}{}^{m}$ for the measurement, a_{bias} for bias signal and a^{n} for zero mean noise.

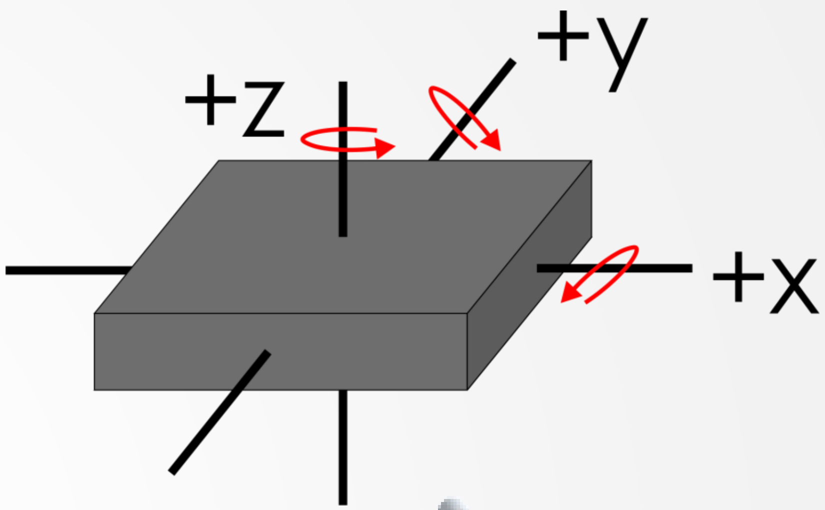


Accelerometer

- MEMS Accelerometers are widely used in UAVs. But they are not the only working principle.
- **Types of accelerometers:**
  - Bulk micromachined capacitive
  - Bulk micromachined piezoelectric resistive
  - Capacitive spring mass base
  - DC response
  - Electromechanical servo (Servo Force Balance)
  - High gravity
  - High temperature
  - Laser accelerometer
  - Low frequency
  - Magnetic induction
  - Modally tuned impact hammers
  - Null-balance
  - Optical
  - Pendulous integrating gyroscopic accelerometer (PIGA)
  - Piezoelectric accelerometer
  - Quantum (Rubidium atom cloud, laser cooled)
  - Resonance
  - Seat pad accelerometers
  - Shear mode accelerometer
  - Strain gauge
  - Surface acoustic wave (SAW)
  - Surface micromachined capacitive (MEMS)
  - Thermal (submicrometre CMOS process)
  - Triaxial
  - Vacuum diode with flexible anode[38]
  - potentiometric type
  - LVDT type accelerometer

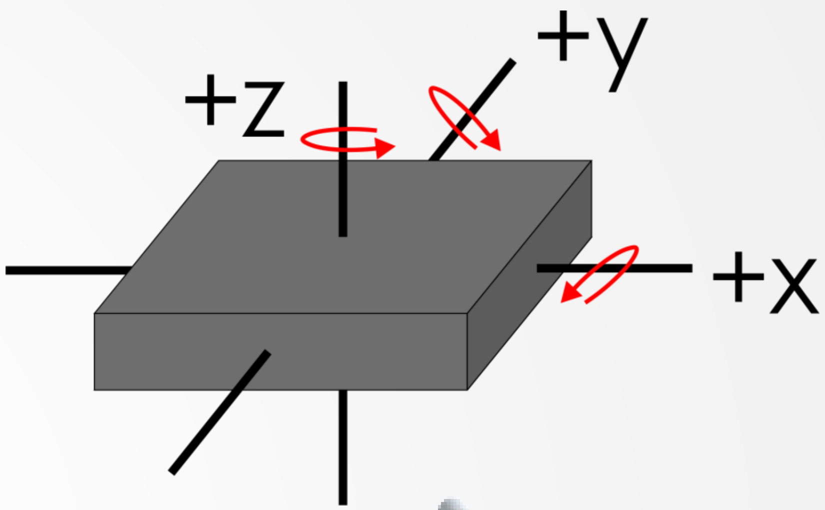
Gyroscope

- **A gyroscope is - conceptually - a spinning wheel in which the axis of rotation is free to assume any possible orientation.** When rotating, the orientation of this axis remains unaffected by tilting or rotation of the mounting, according to the conservation of angular momentum. Due to this principle, a gyroscope can lead to the measurement of orientation and its rate of change. The word comes from the Greek "γύρος" and σκοπεύω which mean "circle" and "to look" correspondingly.
- Nowadays, we are mostly using gyroscopes that are based on different operating principles. In aviation we especially focus on MEMS gyroscopes or solid-state ring lasers, and fibre optic gyroscopes. In small-scale aerial robotics, we mostly care for MEMS gyroscopes.



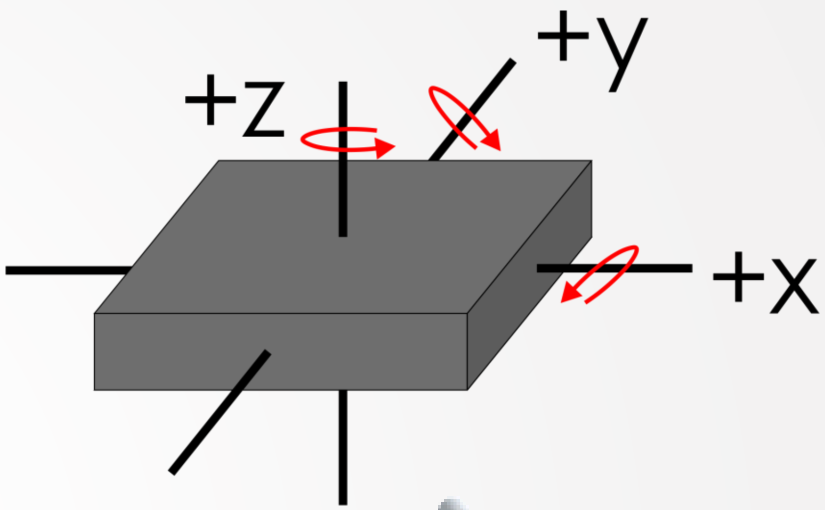
Gyroscope

- A classical rotary gyroscope relies on the **law of conversation of angular momentum**.
  - ***The total angular momentum of a system remains constant in both magnitude and direction of the resultant external torque acting upon the system is zero.***
- Gyroscopes exploiting this principle, typically consist of a spinning disk or mass on an axle, which is then mounted on a series of gimbals. Each of these gimbals provides the spinning disk an additional degree of freedom.



Gyroscope

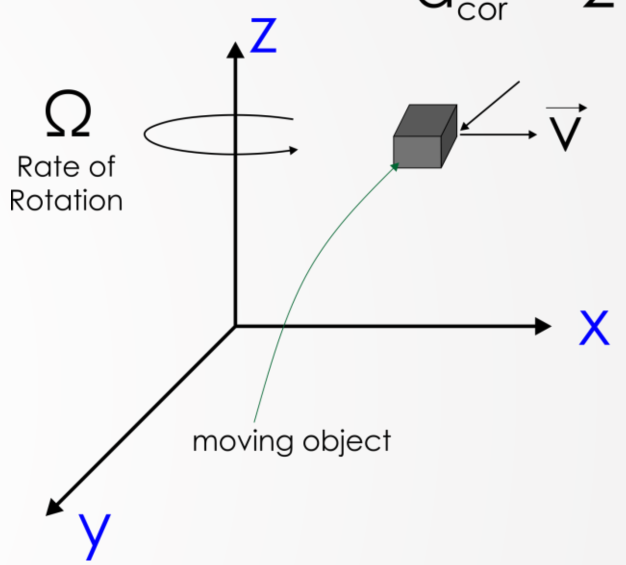
- As long as the gyroscope is spinning, it will maintain a constant orientation. In the case that external torques or rotations about a given axis are present in these devices, orientation can be maintained, and measurement of angular velocity can take place - due to precession.
    - **The phenomenon of precession takes place when an object that is spinning about some axis (its "spin axis") has an external torque applied in a direction perpendicular to the spin axis (the input axis).** In a rotational system, when net external torques are present, the angular momentum vector (along the spin axis) will move in the direction of the applied external torque vector. Consequently, the spin axis rotates about an axis that is perpendicular to both the input axis and the spin axis (this is now the output axis).
- This rotation about the output axis is then sensed and fed back to the input axis where a motor-like device applies torque in the opposite direction therefore canceling the precession of the gyroscope and maintaining its orientation.
    - To measure rotation rate, counteracting torque is pulsed at periodic time intervals. Each pulse represents a fixed step of angular rotataion, and the pulse count in a fixed time interval will be proportional to the angle change θ over that time period.

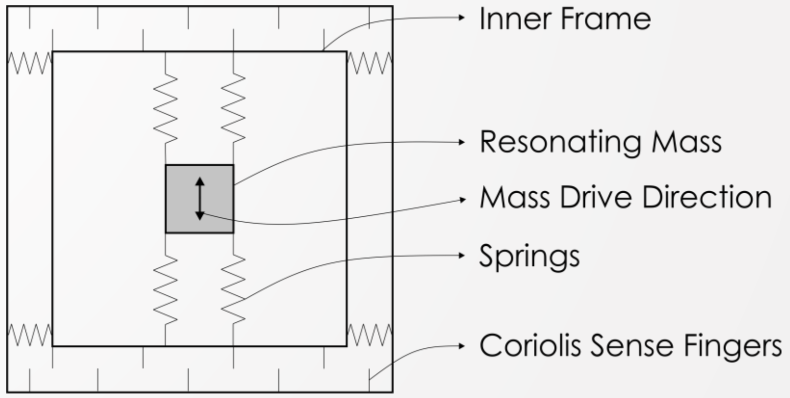


Gyroscope

- MEMS gyroscopes are micro vibrating structures that base their operation the phenomenon of **Coriolis force**.
- In a rotating system, every point rotates with the same rotational speed. As one approaches the axis of rotation of this system, the rotational speed remains the same, but the speed in the direction perpendicular to the rotation axis decreases.
  - In order to travel along a straight line towards or away from the axis of rotation, lateral speed must be adjusted in order to maintain the same relative angular position on the body.
  - The Coriolis force corresponds to the product of the object mass (whose longitude is to be maintained) times the acceleration that leads to the required slowing down or speeding up.
  - **The Coriolis force is proportional to both the angular velocity of the rotating object, as well as to the velocity of the object moving towards or away from the axis of rotation**.

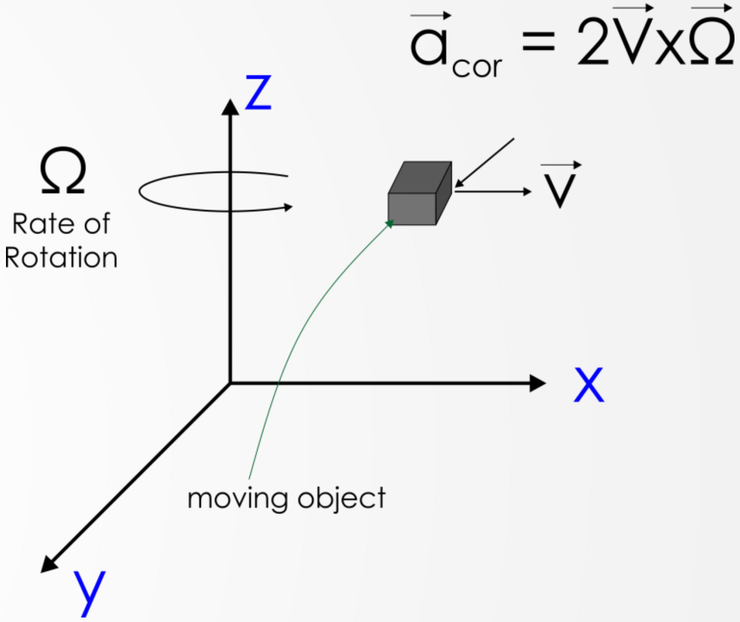
$$\vec{a}_{cor} = 2\vec{V} \times \vec{\Omega}$$

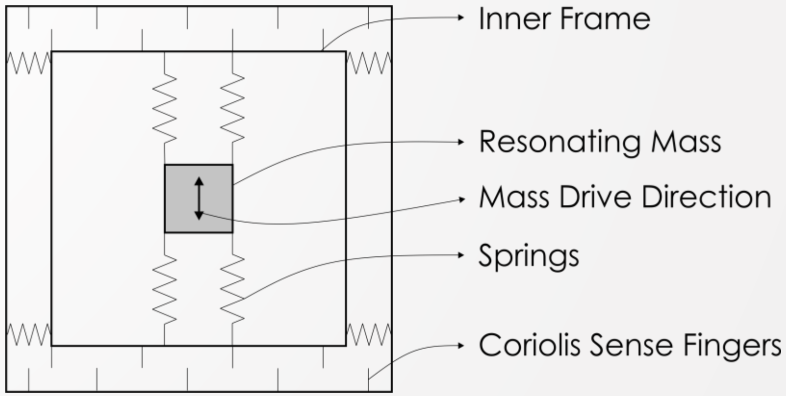




Gyroscope

- **Fabrication:** a micro-machined mass which is connected to an outer housing by a pair of springs. This outer housing is then connected to the fixed circuit board using a second set of orthogonal springs.
  - The test mass is continuously driven sinusoidally along the first set of springs. As any rotation of the system will induce Coriolis acceleration in the mass, it will subsequently push it in the direction of the second set of springs.
  - As the mass is driven away from the axis of rotation, the mass will be pushed perpendicularly in one direction, and as it is driven back toward the axis of rotation, it will be pushed in the opposite direction, due to the Coriolis force acting on the mass.
- **Coriolis force sensing:** Coriolis force is sensed and detected by capacitive sense fingers that are integrated along the test mass housing and the rigid structure.
  - **As the test mass is pushed by the Coriolis force, a differential capacitance will develop and will be detected as the sensing fingers are brought closer together.** When the mass is pushed in the opposite direction, different sets of sense fingers are brought closer together.
  - The sensor can detect both the magnitude as well as the direction of the angular velocity of the system.

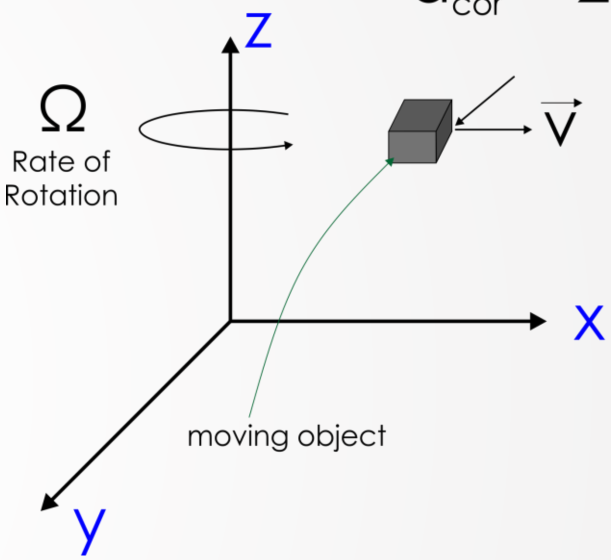


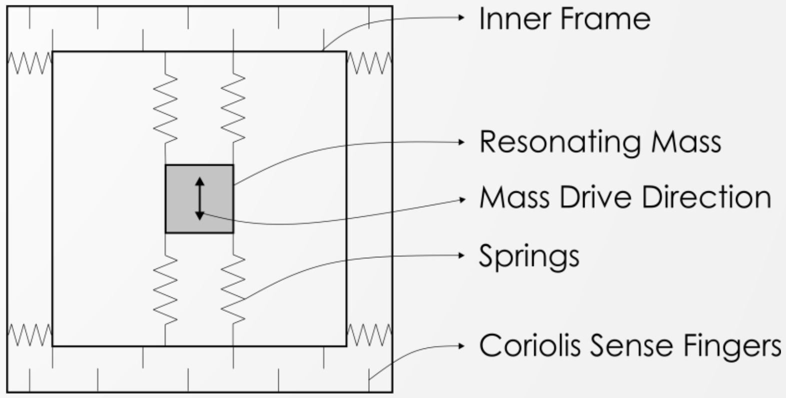


Gyroscope

- **Bias effects on Gyros:** The biggest problem with gyros (and what essentially constraints us from simply performing integrating actions on their measurements), is the existence of bias effects. Bias are mostly caused by:
  - Drive excitation feedthrough
  - Output electronics offsets
  - Bearing torques
- **Biases are present in three forms** - as far as their expression and time evolution is concerned - namely:
  - Fixed bias ("const")
  - Bias variation from one turn-on to another (thermal), called bias stability ("BS")
  - Bias drift, usually modeled as a random walk ("BD")

$$\vec{a}_{cor} = 2\vec{V} \times \vec{\Omega}$$





Gyroscope

- **As the bias effect are additive, we may write:**

$$\delta\omega_{bias} = \delta\omega_{const} + \delta\omega_{BS} + \delta\omega_{BD}$$
$$\frac{d}{dt}\omega_{BD} = \omega(t); \omega \sim N(O, Q)$$

- Where Q is known
- **Error model a single-axis gyroscope:**

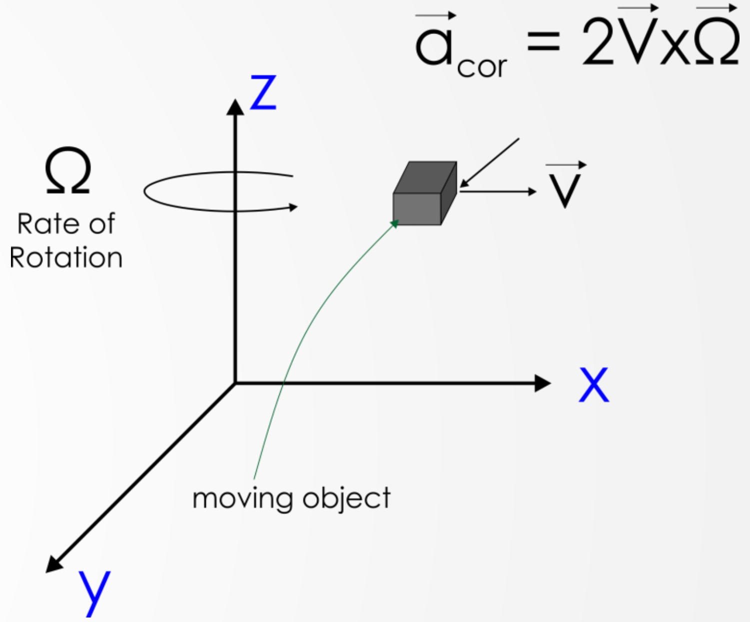
$$\omega_{1D} = k_g \omega_{1D}^m - \omega_{bias} + \omega_n$$

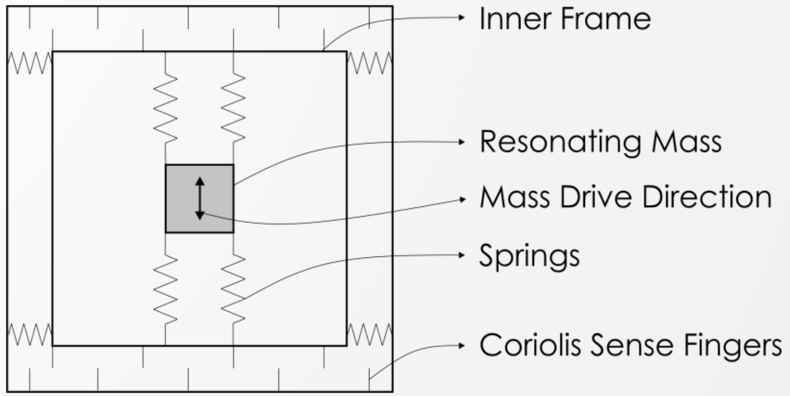
  - ω_{bias} : bias model

$$\dot{\omega}_{bias} = n_\omega, E[n_\omega] = 0, E[n_\omega(t) n_\omega^T(t)] = n(t - t'), E[n_\omega(t) n_\omega^T](t')] = 0$$

  - ω_n : noise model

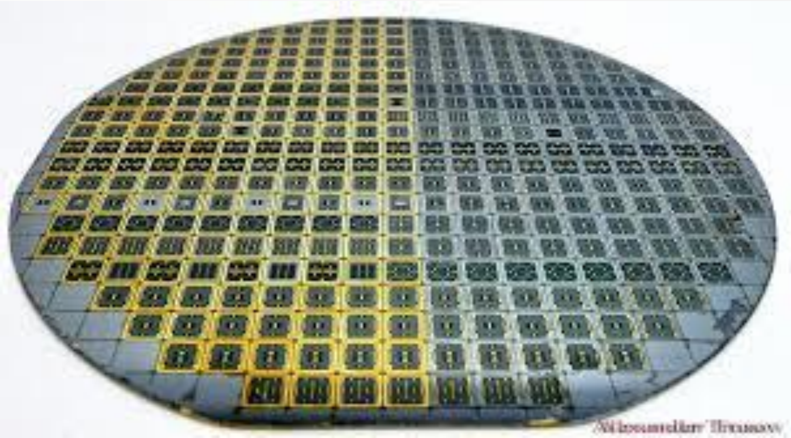
$$\omega_n : \quad E[\omega_n] = 0, E[\omega_n(t)\omega'(t')] = N_r \delta(t - t')$$

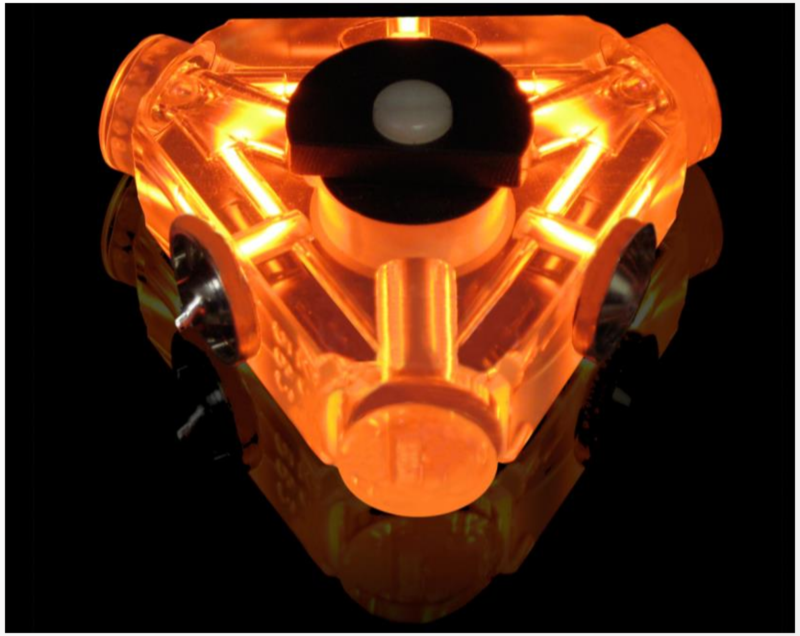




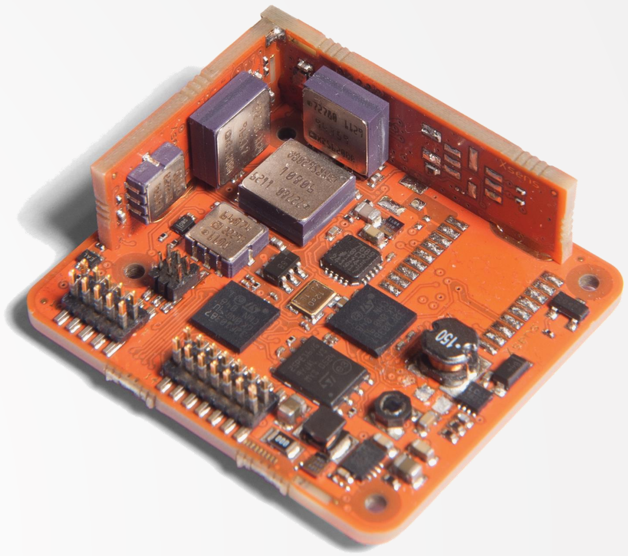
Gyroscope

- **Types of gyroscopes:**
  - Gyrostat
  - Micro ElectroMechanical Systems (MEMS)
  - Fibre Optic Gyroscope (FOG)
  - Hemispherical Resonator Gyroscope (HRG)
  - Vibrating Structure Gyroscope (VSG)
  - Dynamically Tuned Gyroscope (DTG)
  - Ring Laser Gyroscope (RLG)
  - London moment gyroscope

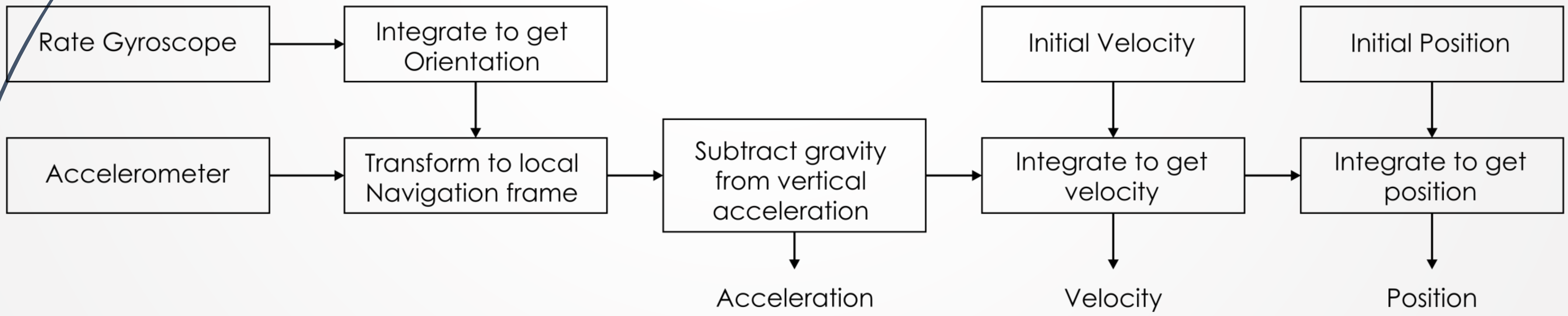




Simplified IMU

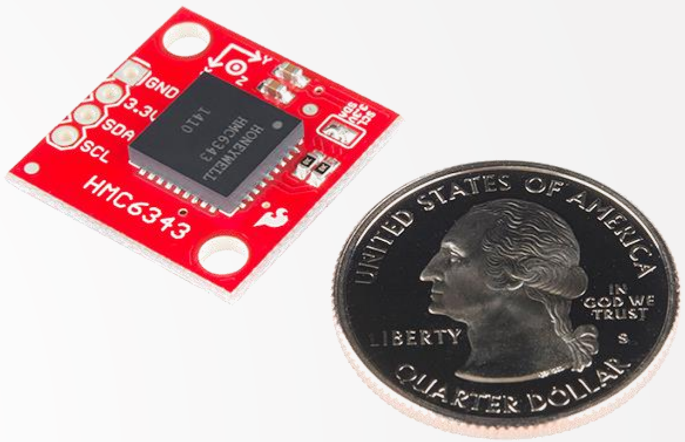


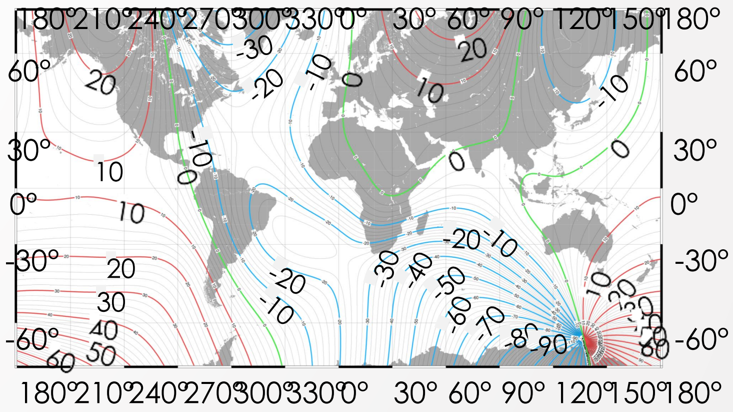
- It uses gyroscopes and accelerometers to estimate the relative pose (position and orientation), velocity and acceleration of a moving vehicle with respect to an inertial frame.
- In order to estimate the motion, the gravity vector must be subtracted and the initial velocity has to be known.
- After long periods of operation, drifts occur: need external reference to cancel it.



Magnetometer

- A magnetometer is a type of sensor that measures the strength and direction of the local magnetic field. The magnetic field measured will be a combination of both the earth's magnetic field and any magnetic field created by nearby objects. The magnetic field is measured in the sensor reference frame.
- The earth's magnetic field is a self sustaining magnetic field that resembles a magnetic dipole with one end near the Earth's geographic North Pole and the other near the earth's geographic South Pole. The strength of this magnetic field varies across the Earth with strengths as low as 0.3 Gauss in South America to over 0.6 Gauss in northern Canada.





Magnetometer

- Heading is the sum of the magnetic declination angle and the magnetic heading:

$$\psi = \delta + \psi_m$$

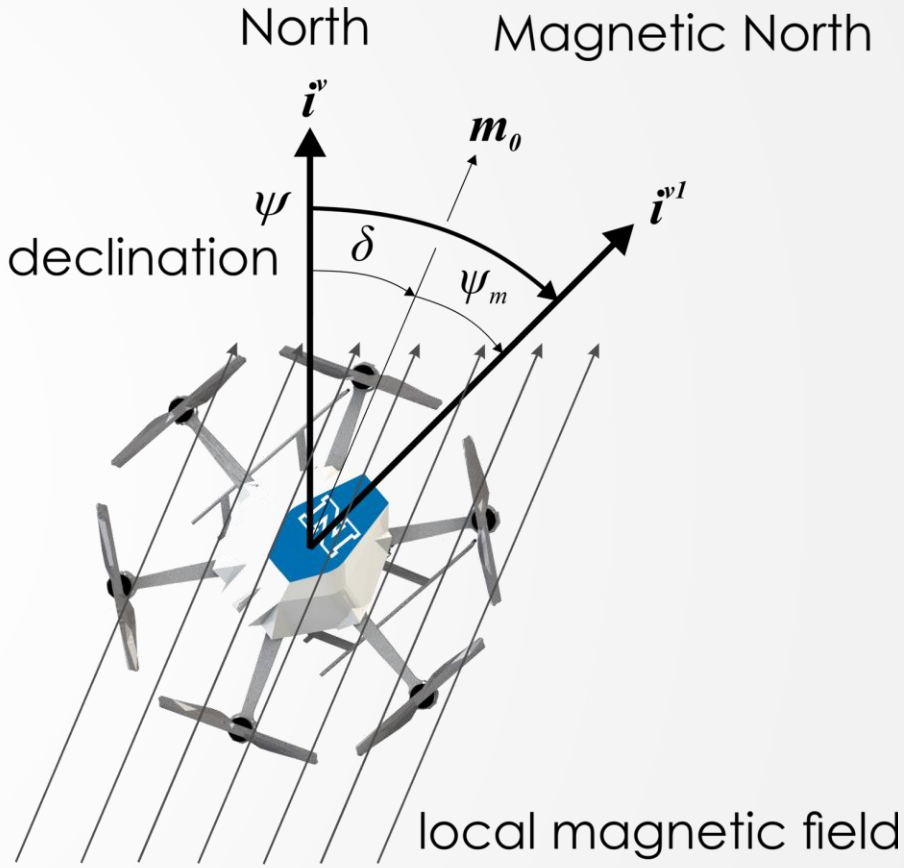
- Magnetic heading determined from measurements of body-frame components of magnetic field projected onto the horizontal plane:

$$\mathbf{m}_0^{v1} = \begin{bmatrix} m_{0x}^{v1} \\ m_{0y}^{v1} \\ m_{0z}^{v1} \end{bmatrix} = \mathcal{R}_b^{v1}(\phi,\theta)\mathbf{m}_0^b = \mathcal{R}_{v2}^{v1}(\theta)\mathcal{R}_b^{v2}(\phi)\mathbf{m}_0^b \Rightarrow$$

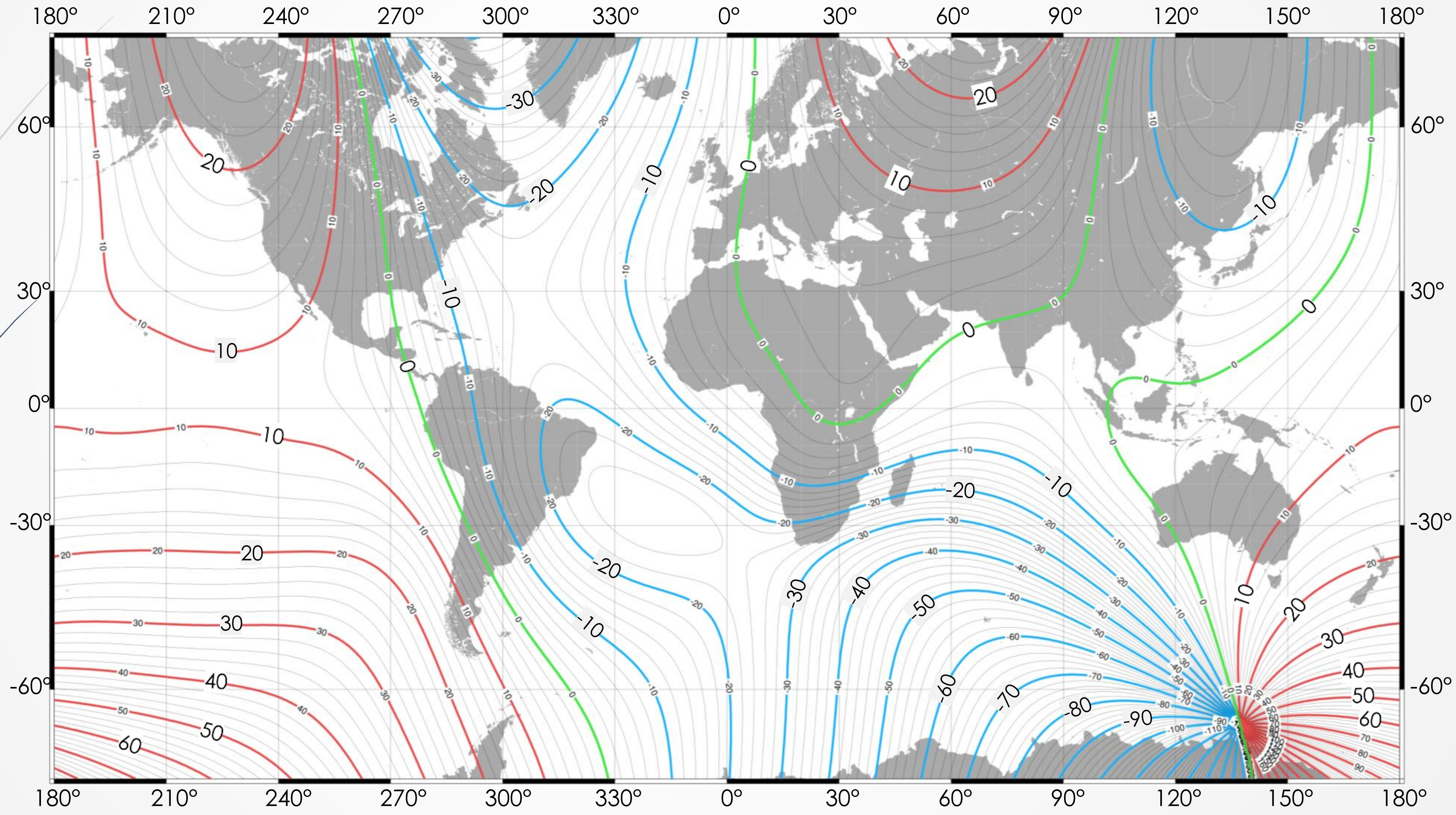
$$\begin{bmatrix} m_{0x}^{v1} \\ m_{0y}^{v1} \\ m_{0z}^{v1} \end{bmatrix} = \begin{bmatrix} c_\theta & s_\theta s_\phi & s_\theta c_\phi \\ 0 & c_\phi & -s_\phi \\ -s_\theta & c_\theta s_\phi & c_\theta c_\phi \end{bmatrix} \mathbf{m}_0^b$$

- Solving for heading:

$$\psi = -\arctan 2(m_{0y}^{v1}, m_{0x}^{v1})$$



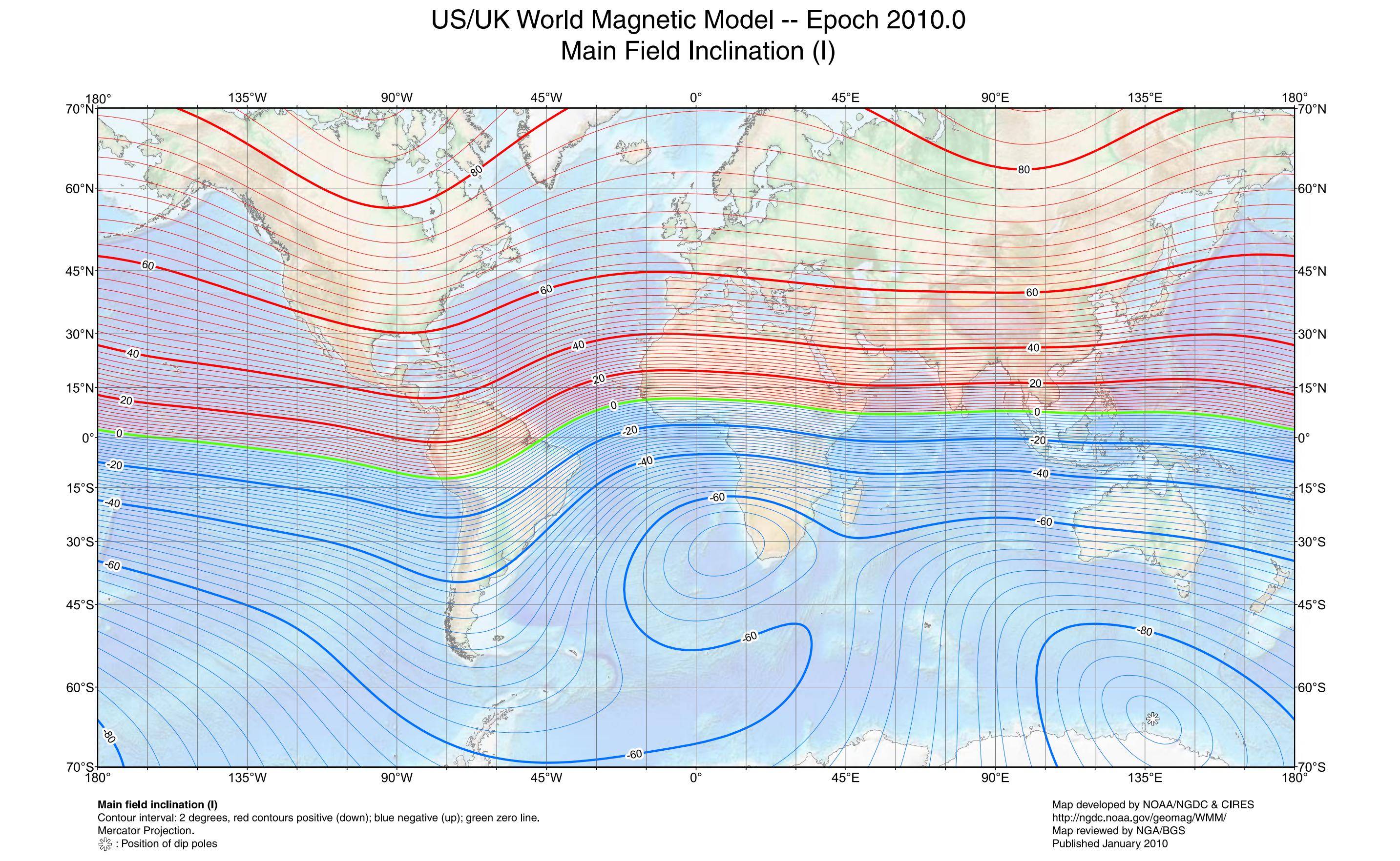
Magnetic Declination Variation



World Magnetic Model, National Geophysical Data Center

Magnetic Inclination

Magnetic dip or magnetic inclination is the angle made by a compass needle with the horizontal at any point on the Earth's surface. Positive values of inclination indicate that the field is pointing downward, into the Earth, at the point of measurement.



Pressure Measurements

- A pressure sensor measures pressure, typically of gases or liquids. Pressure is an expression of the force required to stop a fluid from expanding, and is usually stated in terms of force per unit area. A pressure sensor usually acts as a transducer; it generates a signal as a function of the pressure imposed.

- **Pressure sensing:**
  - This is where the measurement of interest is pressure, expressed as a force per unit area. This is useful in weather instrumentation, aircraft, automobiles, and any other machinery that has pressure functionality implemented.

- **Altitude sensing:**
  - This is useful in aircraft, rockets, satellites, weather balloons, and many other applications. All these applications make use of the relationship between changes in pressure relative to the altitude.

Pressure Measurements

- The basic equation of hydrostatics is:

$$P_2 - P_1 = \rho g(z_2 - z_1)$$

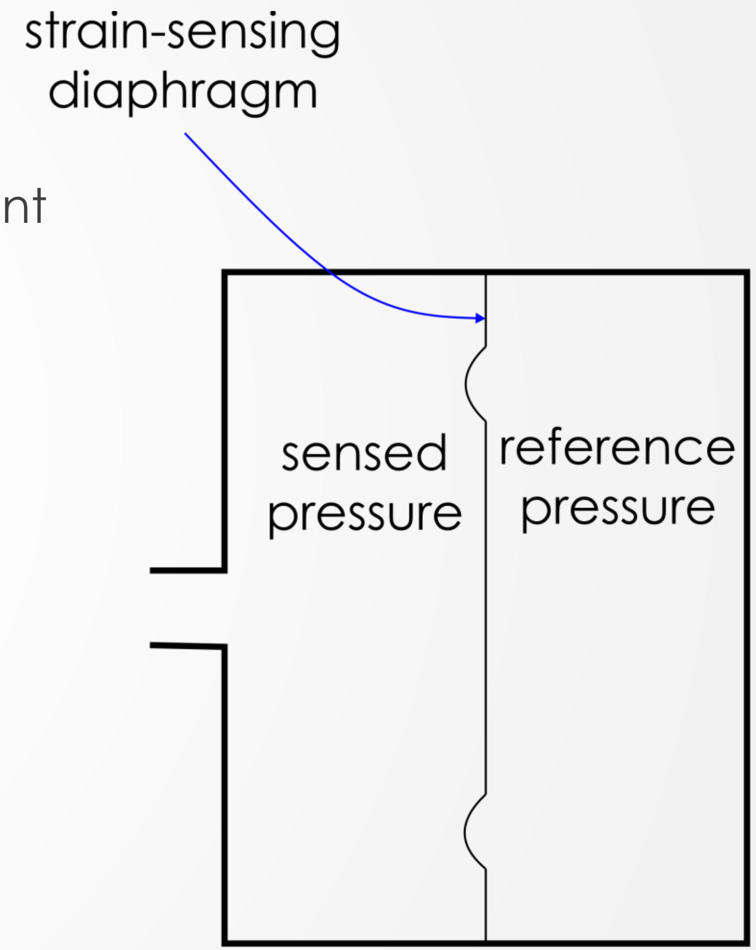
- Using the ground as reference, and assuming constant air density gives:

$$P - P_{ground} = -\rho g(h - h_{ground}) = -\rho g h_{AGL}$$

  - AGL: Above Ground Level
- Below 11,000m, the barometric formula can be used:

$$P = P_0 \left[\frac{T_0}{T_0 + L_0 h_{ASL}}\right]^{\frac{gM}{RL_0}}$$

  - Where:
    - P0 : standard pressure at sea level
    - T0 : standard temperature at sea level
    - L0 : rate of temperature decrease
    - g : gravitational constant
    - R : universal gas constant for air
    - M : standard molar mass of atmospheric air (takes into account change in density with altitude and temperature)



Pressure Measurements

- Altitude Measurement:
  - We usually assume that the density is constant (valid for small altitude variations):

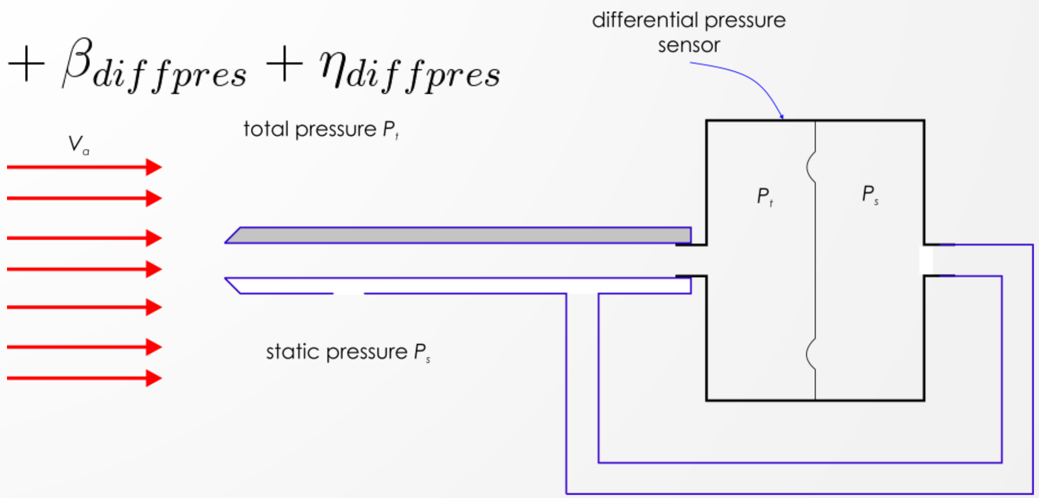
$$y_{abspres} = (P_{ground} - P) + \beta_{abspres} + \eta_{abspres} = \rho g h_{AGL} + \beta_{abspres} + \eta_{abspres}$$

- Airspeed Measurement:
  - From Bernoulli's equation:

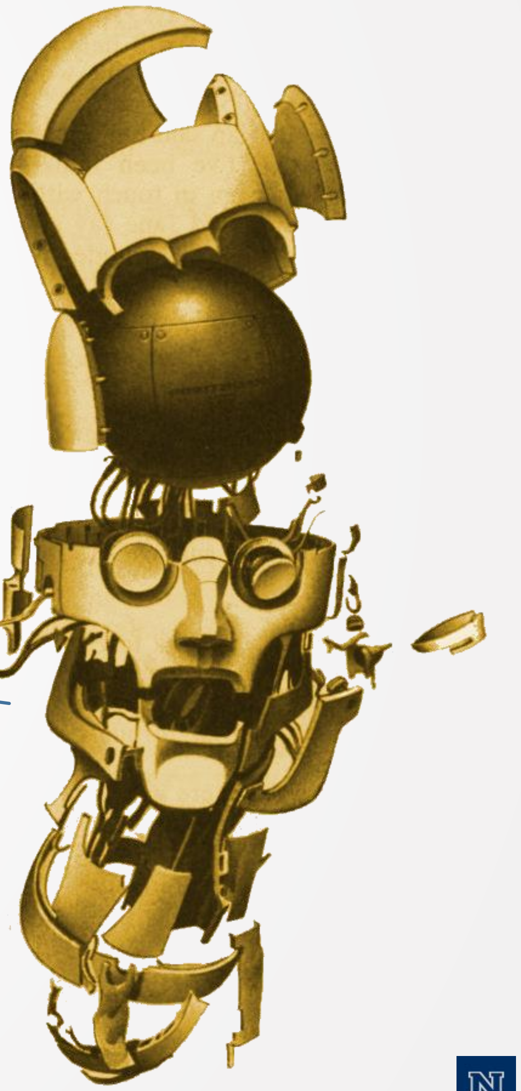
$$P_t = P_s + \frac{\rho V_a^2}{2} \Rightarrow \frac{\rho V_a^2}{2} = P_t - P_s$$

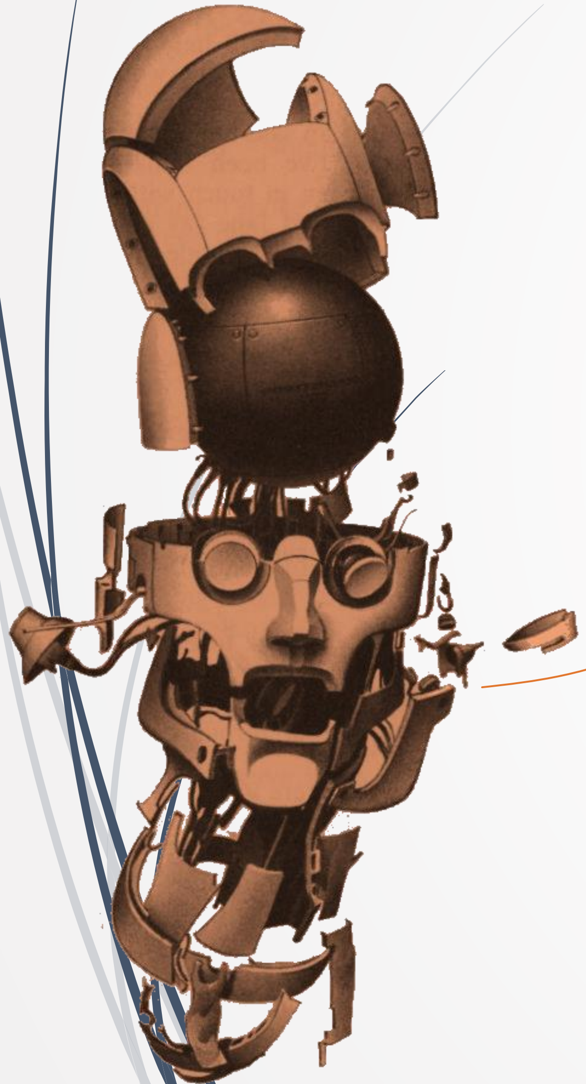
  - Pitot-static pressure sensor measures dynamic pressure

$$y_{diffpres} = \frac{\rho V_a^2}{2} + \beta_{diffpres} + \eta_{diffpres}$$



How do I fuse all these data to get attitude?





Refer to the State Estimation lecture

Code Example

- MATLAB DC Motor Control Example
  - https://github.com/unr-arl/autonomous_mobile_robot_design_course/tree/master/matlab/state-estimation
  - MATLAB 2016 Live note

How does this apply to my project?

- Inertial Measurement Units are used to derive orientation for all robots.
- Pixhawk is integrating its own IMU and runs an Extended Kalman Filter for pose estimation.
- Read the manual!

Find out more

- http://www.kostasalexis.com/inertial-sensors.html
- http://px4.io/
- http://www.vectornav.com/support/library/imu-and-ins
- http://www.sensorwiki.org/
- http://www.kostasalexis.com/literature-and-links.html

Thank you!

Please ask your question!