ECE 4960

Prof. Kirstin Hagelskjær Petersen
kirstin@cornell.edu

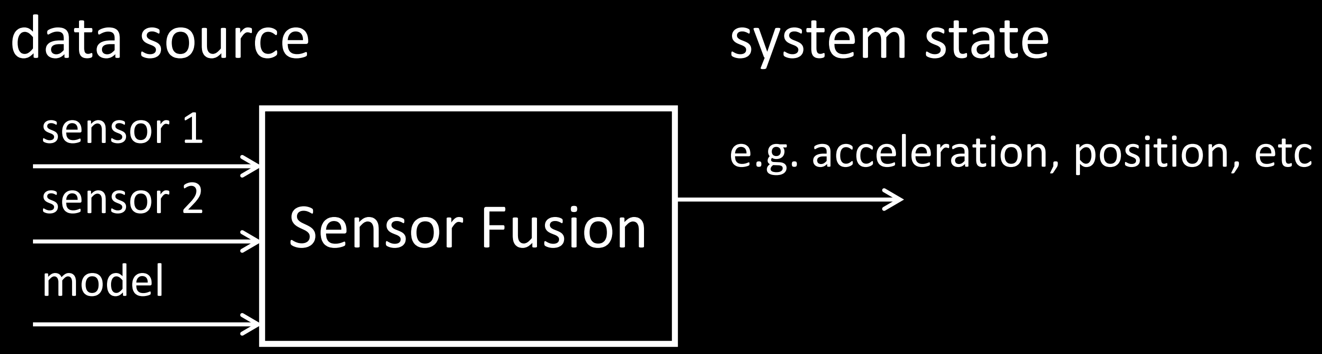
Fast Robots

Prof. Kirstin Hagelskjær Petersen
kirstin@cornell.edu

WHY SENSOR FUSION?

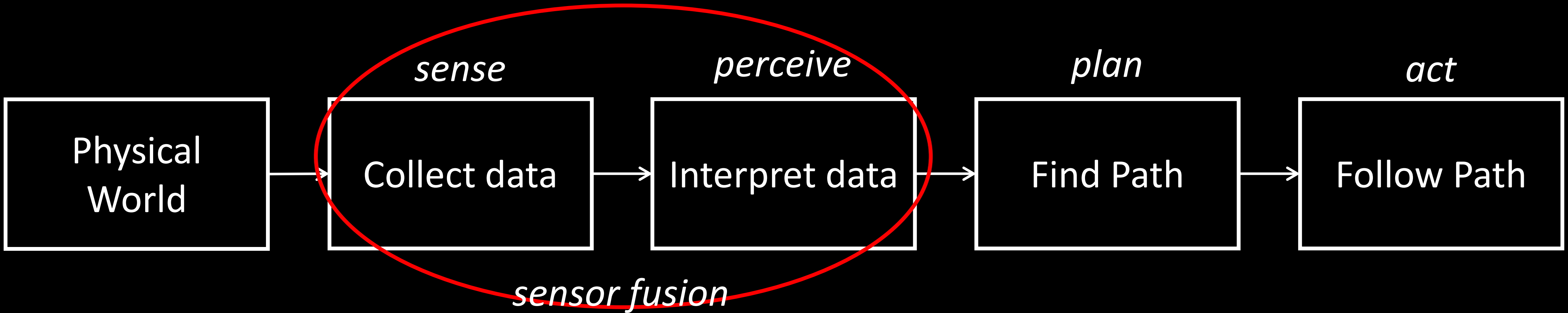
Intro to Sensor Fusion

- Combine two or more data sources in a way that generates a "better" understanding of the system
  - More consistent signal over time
  - More accurate signal over time
  - More dependable



Intro to Sensor Fusion

- Combine two or more data sources in a way that generates a “better” understanding of the system
  - More consistent signal over time
  - More accurate signal over time
  - More dependable

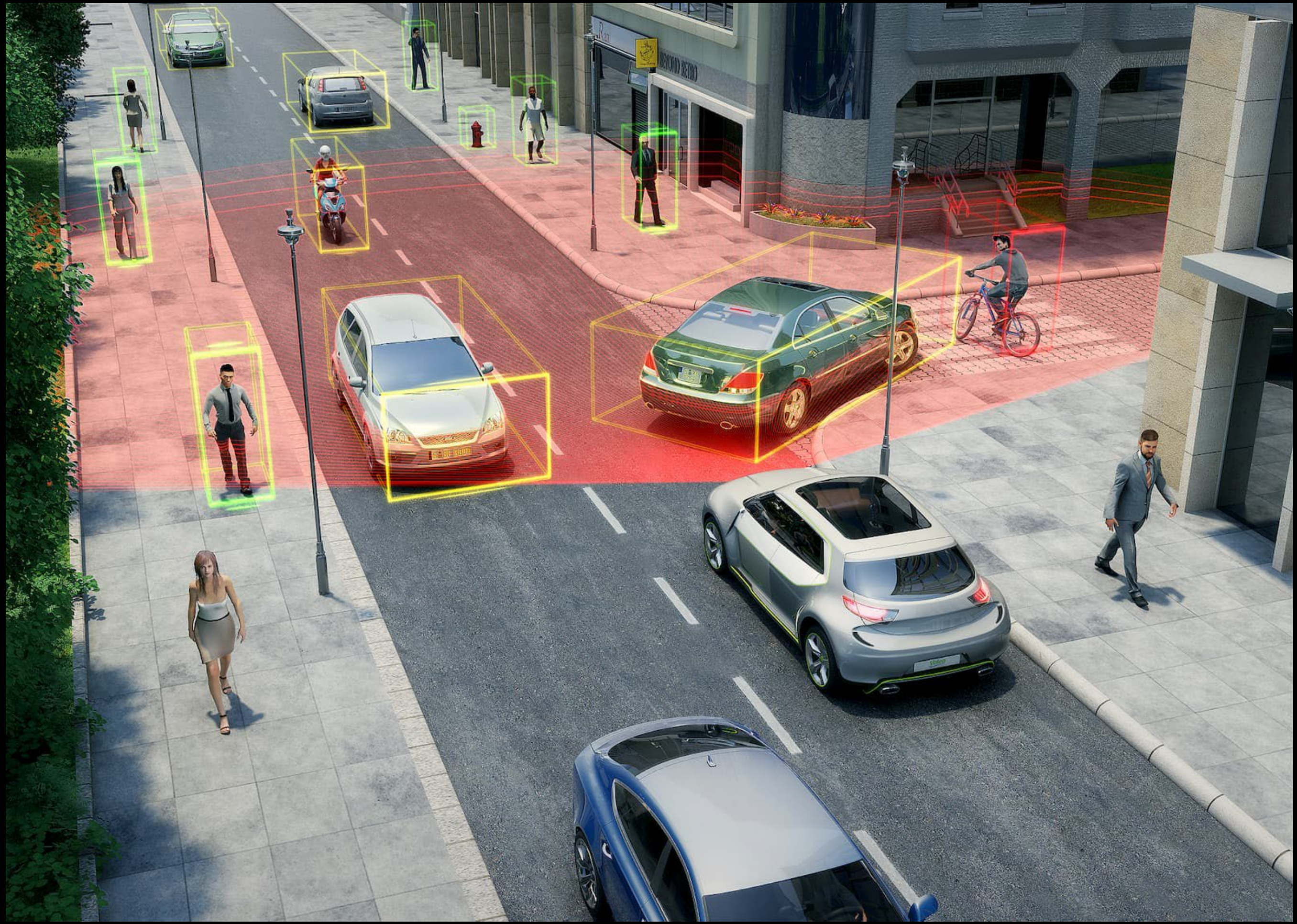


Responsibility:

- Self-awareness (where am I? what am I doing? what is my state?)
- Situational awareness (detection/tracking)

Intro to Sensor Fusion

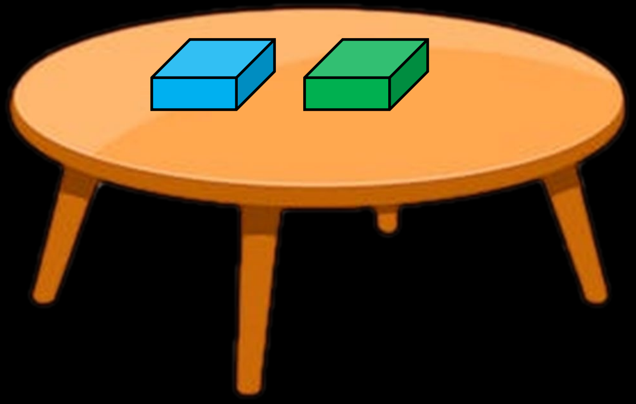
- Example of situational awareness:

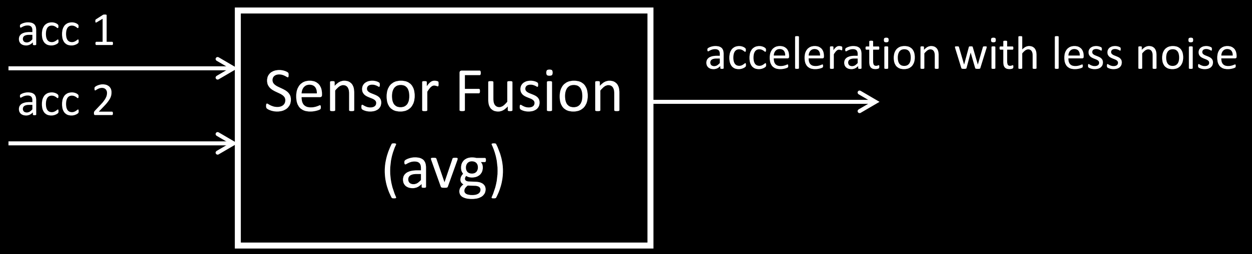


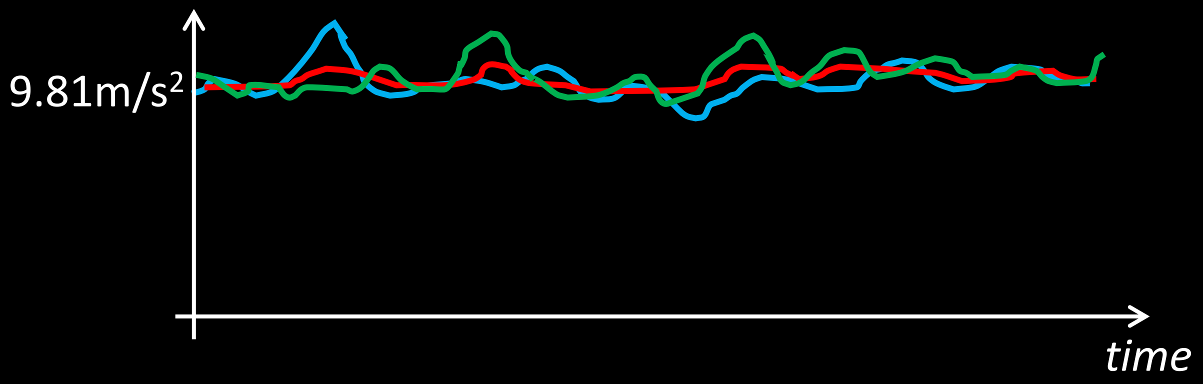
Valeo's LIDAR

Intro to Sensor Fusion

1. Increase the quality of the data
   - Less noise, uncertainty, deviations



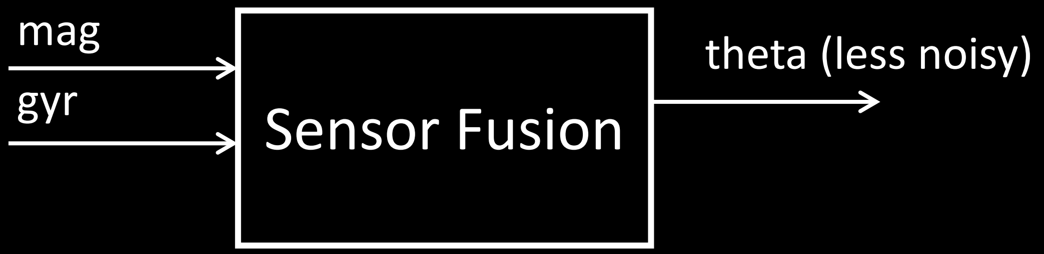


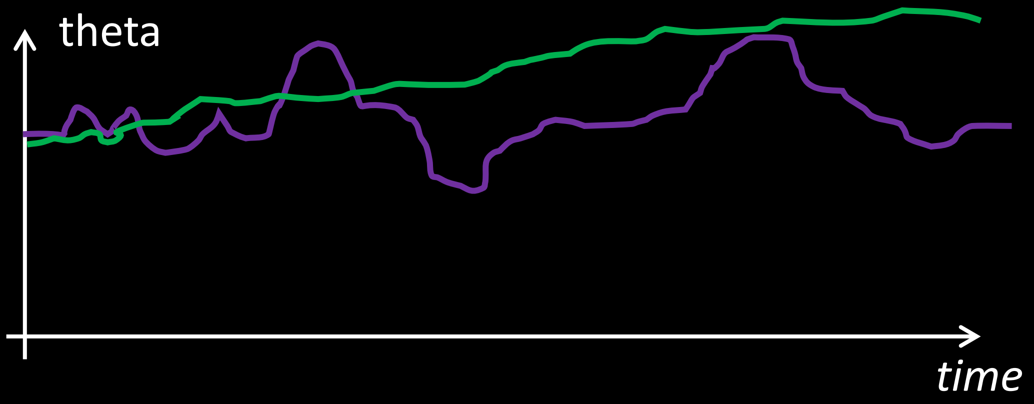


- Adding sensors lowers noise: $n = 1/(\sqrt{N})$
  - 4 identical sensors = ½ noise
    - (Only if the noise is not correlated!)

Intro to Sensor Fusion

1. Increase the quality of the data
   - Less noise, uncertainty, deviations

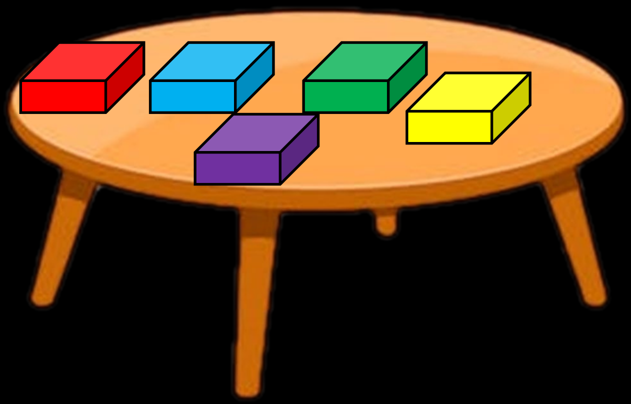


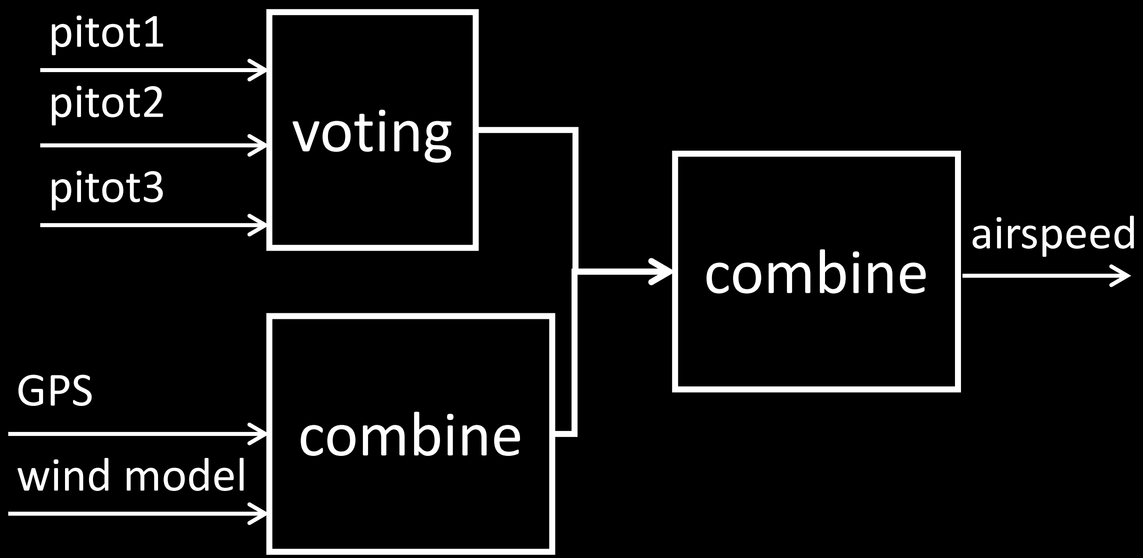


- You can add a 2nd magnetometer to decrease noise
- But some of the noise is correlated
  - Magnetic fields
- Sol 1: Move the sensor away from the magnetic field
- Sol 2: Low pass filter (introduces lag)
- Sol 3: Fuse the mag data with gyr data

Intro to Sensor Fusion

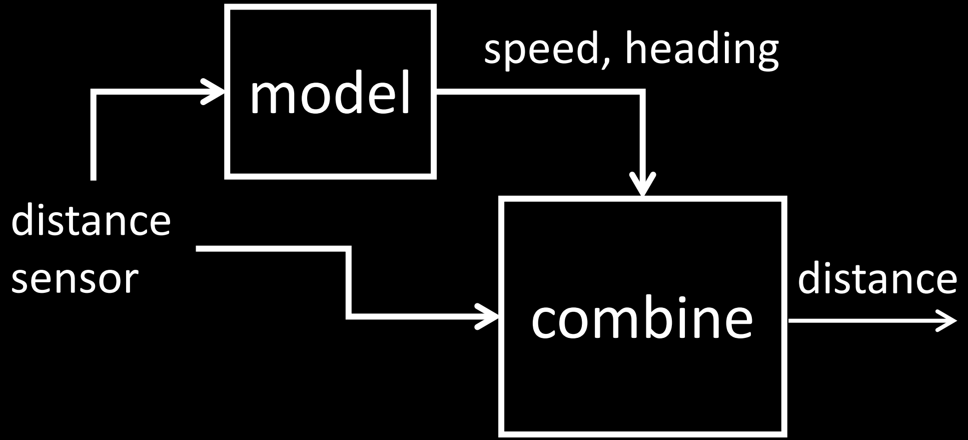
1. Increase the quality of the data
   - Less noise, uncertainty, deviations
2. Increase data reliability





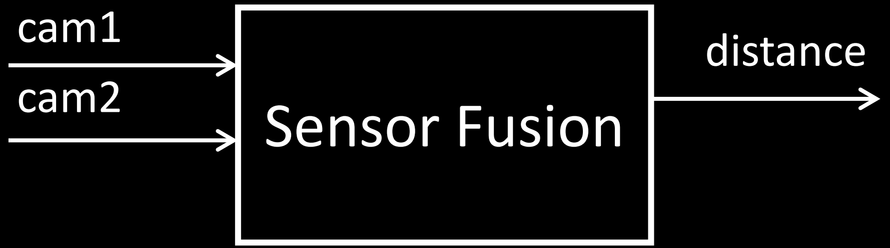
Intro to Sensor Fusion

1. Increase the quality of the data
    - Less noise, uncertainty, deviations
2. Increase data reliability



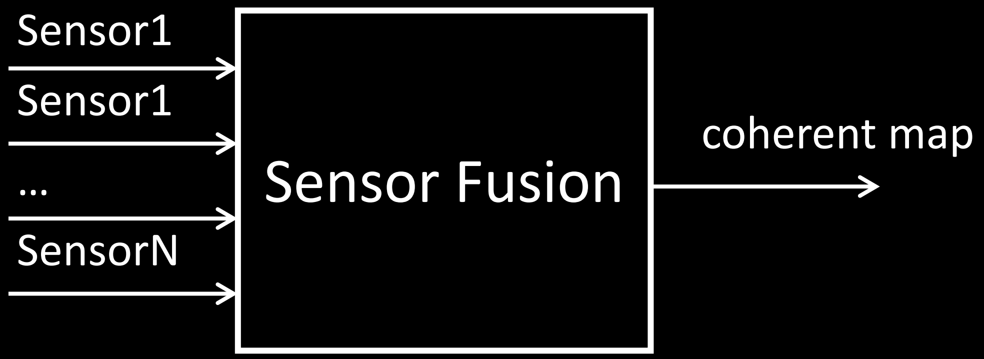
Intro to Sensor Fusion

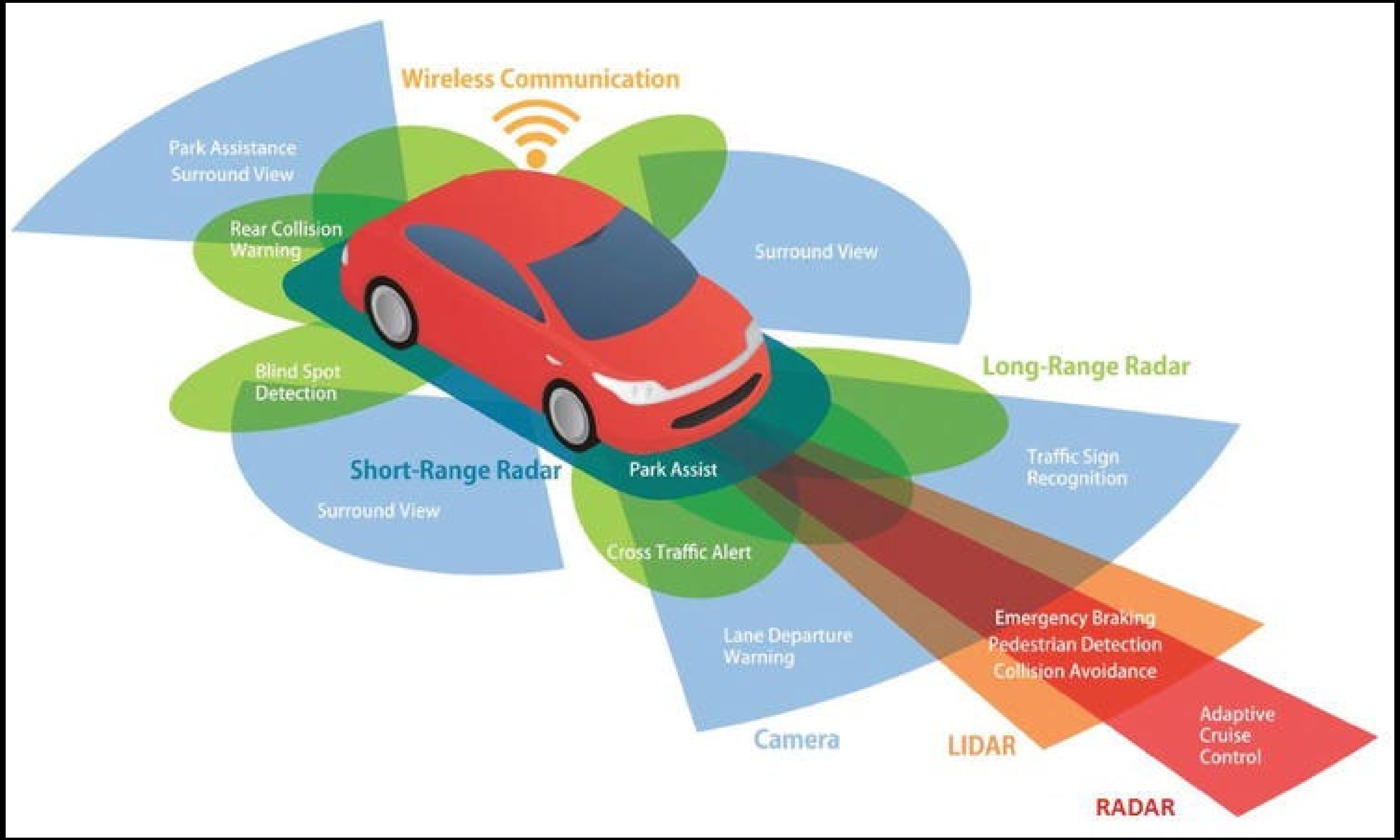
1. Increase the quality of the data
   - Less noise, uncertainty, deviations
2. Increase data reliability
3. You can measure unmeasured states



Intro to Sensor Fusion

1. Increase the quality of the data
   - Less noise, uncertainty, deviations
2. Increase data reliability
3. You can measure unmeasured states
4. Increase the coverage area



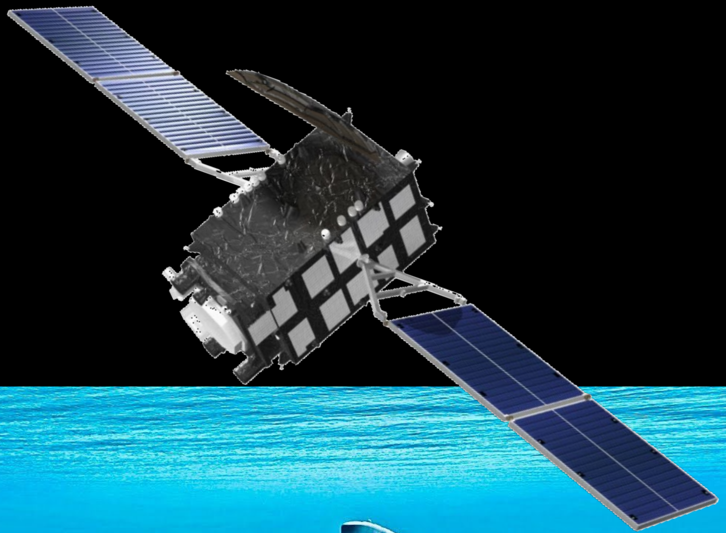


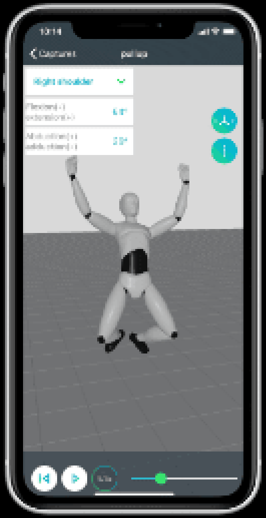
Sources and References

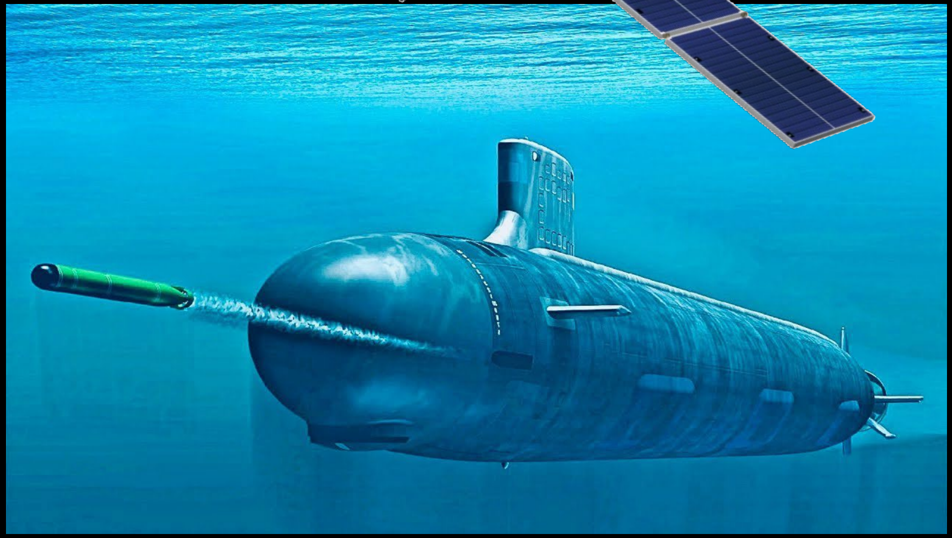
- http://www.cs.cmu.edu/~rasc/Download/AMRobots4.pdf
- https://www.ti.com/lit/ug/sbau305b/sbau305b.pdf?ts=1599417595209&ref_url=https%253A%252F%252Fwww.google.com%252F
- https://hmc.edu/lair/ARW/ARW-Lecture01-Odometry.pdf
- Matlab Tech Talks on Sensor Fusion (https://www.youtube.com/watch?v=6qV3YjFppuc)

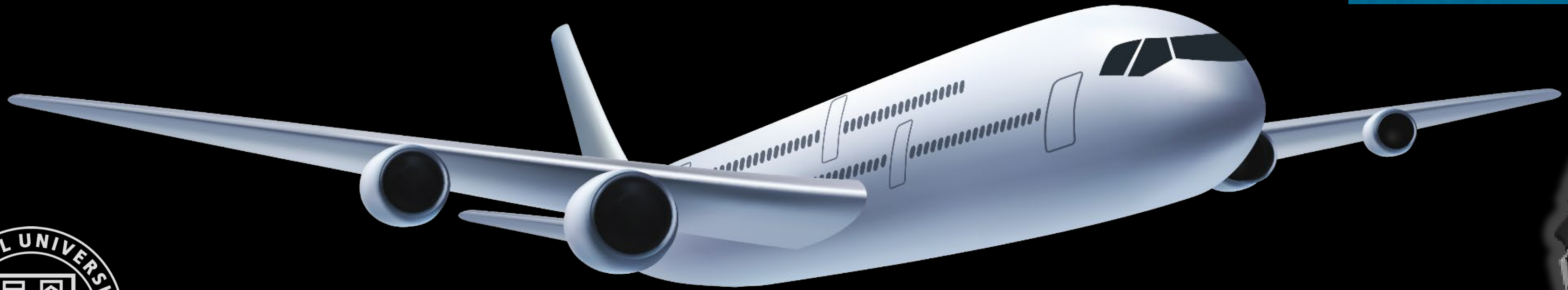
IMU

- Inertial Measurement Unit
  - Data related to orientation, velocity, and gravity









IMU

- Inertial Measurement Unit
- *Accelerometer*
  - Linear acceleration, $a = \dot{v}$ [m/s^2]
- *Gyroscope*
  - Angular velocity, $\omega = \frac{\Delta\theta}{\Delta t}$ [deg/sec]
- *Magnetometer*
  - Magnetic field strength, [uT] or [Gauss], (1 Gauss = 100uT)

→ Track orientation (position)

→ Track orientation

} Dead reckoning

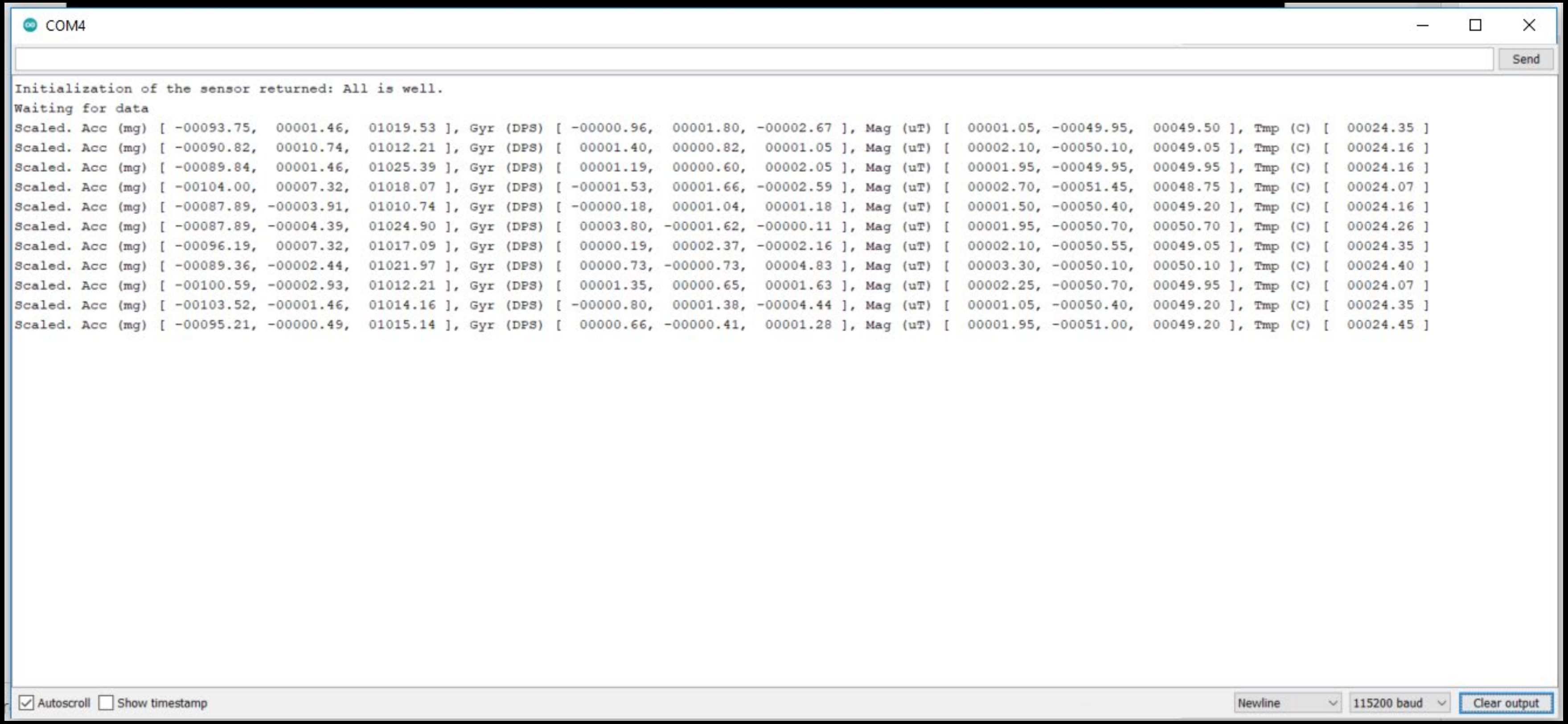
→ Get absolute orientation

- *NB: Gravity, magnetic fields, accelerations affect these sensors in many ways!*

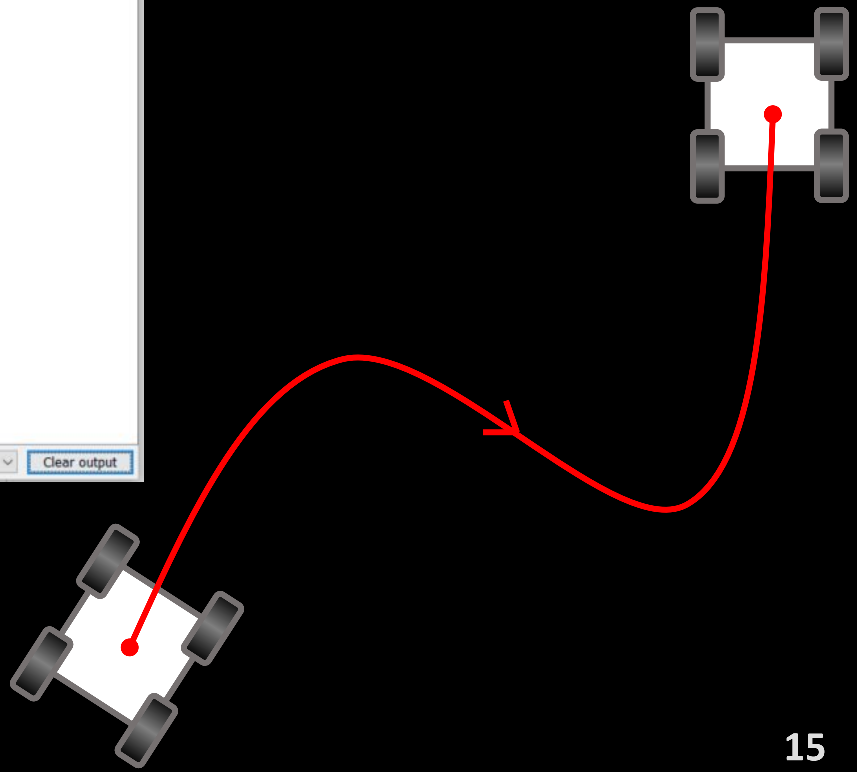
ICM-20948
Lowest power 9-axis IMU
$16

IMU - Demo

- ..\SparkFun_ICM-20948_ArduinoLibrary-master\examples\Arduino\Example1_Basics



```
Initialization of the sensor returned: All is well.
Waiting for data
Scaled. Acc (mg) [ -00093.75,  00001.46,  01019.53 ], Gyr (DPS) [ -00000.96,  00001.80, -00002.67 ], Mag (uT) [  00001.05, -00049.95,  00049.50 ], Tmp (C) [  00024.35 ]
Scaled. Acc (mg) [ -00090.82,  00010.74,  01012.21 ], Gyr (DPS) [  00001.40,  00000.82,  00001.05 ], Mag (uT) [  00002.10, -00050.10,  00049.05 ], Tmp (C) [  00024.16 ]
Scaled. Acc (mg) [ -00089.84,  00001.46,  01025.39 ], Gyr (DPS) [  00001.19,  00000.60,  00002.05 ], Mag (uT) [  00001.95, -00049.95,  00049.95 ], Tmp (C) [  00024.16 ]
Scaled. Acc (mg) [ -00104.00,  00007.32,  01018.07 ], Gyr (DPS) [ -00001.53,  00001.66, -00002.59 ], Mag (uT) [  00002.70, -00051.45,  00048.75 ], Tmp (C) [  00024.07 ]
Scaled. Acc (mg) [ -00087.89, -00003.91,  01010.74 ], Gyr (DPS) [ -00000.18,  00001.04,  00001.18 ], Mag (uT) [  00001.50, -00050.40,  00049.20 ], Tmp (C) [  00024.16 ]
Scaled. Acc (mg) [ -00087.89, -00004.39,  01024.90 ], Gyr (DPS) [  00003.80, -00001.62, -00000.11 ], Mag (uT) [  00001.95, -00050.70,  00050.70 ], Tmp (C) [  00024.26 ]
Scaled. Acc (mg) [ -00096.19,  00007.32,  01017.09 ], Gyr (DPS) [  00000.19,  00002.37, -00002.16 ], Mag (uT) [  00002.10, -00050.55,  00049.05 ], Tmp (C) [  00024.35 ]
Scaled. Acc (mg) [ -00089.36, -00002.44,  01021.97 ], Gyr (DPS) [  00000.73, -00000.73,  00004.83 ], Mag (uT) [  00003.30, -00050.10,  00050.10 ], Tmp (C) [  00024.40 ]
Scaled. Acc (mg) [ -00100.59, -00002.93,  01012.21 ], Gyr (DPS) [  00001.35,  00000.65,  00001.63 ], Mag (uT) [  00002.25, -00050.70,  00049.95 ], Tmp (C) [  00024.07 ]
Scaled. Acc (mg) [ -00103.52, -00001.46,  01014.16 ], Gyr (DPS) [ -00000.80,  00001.38, -00004.44 ], Mag (uT) [  00001.05, -00050.40,  00049.20 ], Tmp (C) [  00024.35 ]
Scaled. Acc (mg) [ -00095.21, -00000.49,  01015.14 ], Gyr (DPS) [  00000.66, -00000.41,  00001.28 ], Mag (uT) [  00001.95, -00051.00,  00049.20 ], Tmp (C) [  00024.45 ]
```

Prof. Kirstin Hagelskjær Petersen
kirstin@cornell.edu

ACCELEROMETER

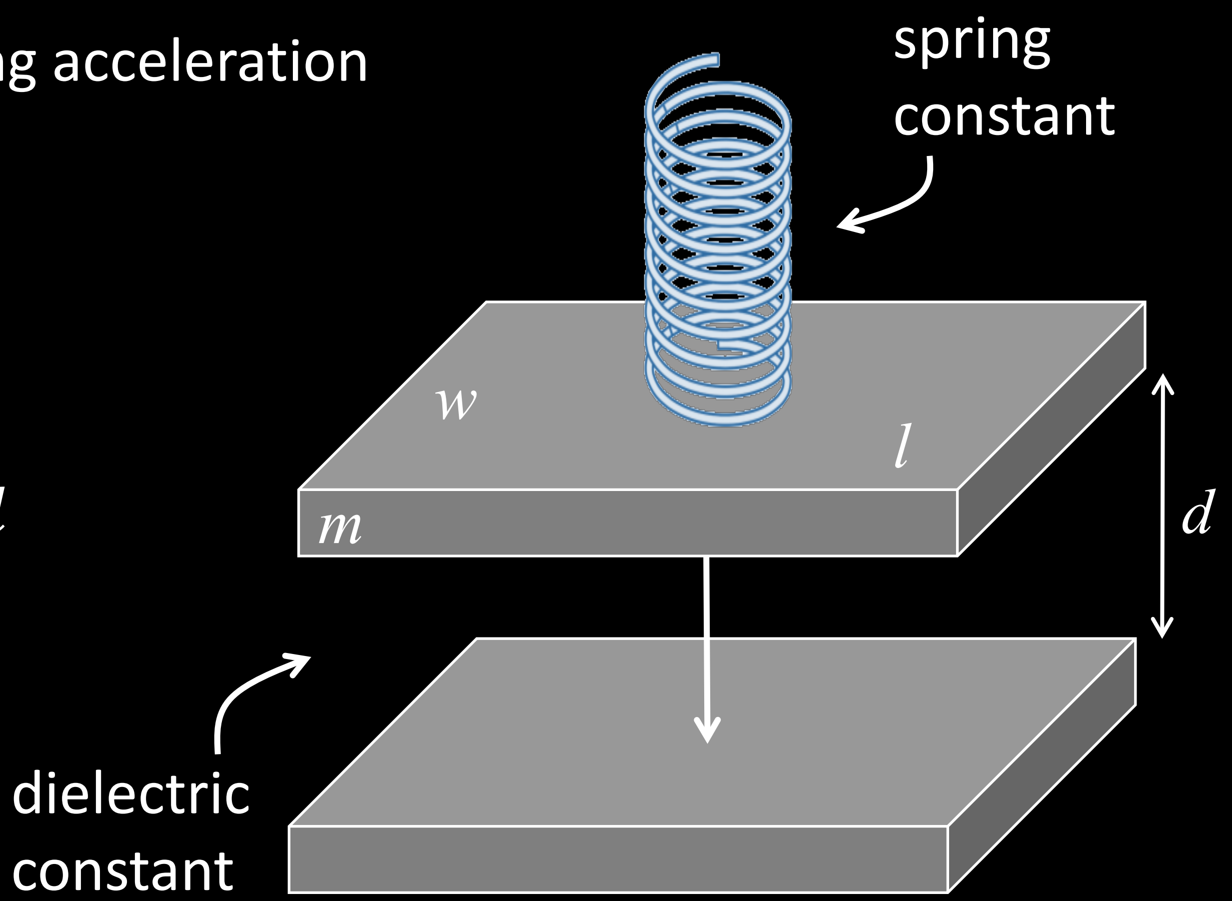
Accelerometer

- Measuring acceleration

$$C = \frac{\in A}{d}$$

$$F = k\Delta d$$

$$F = ma$$



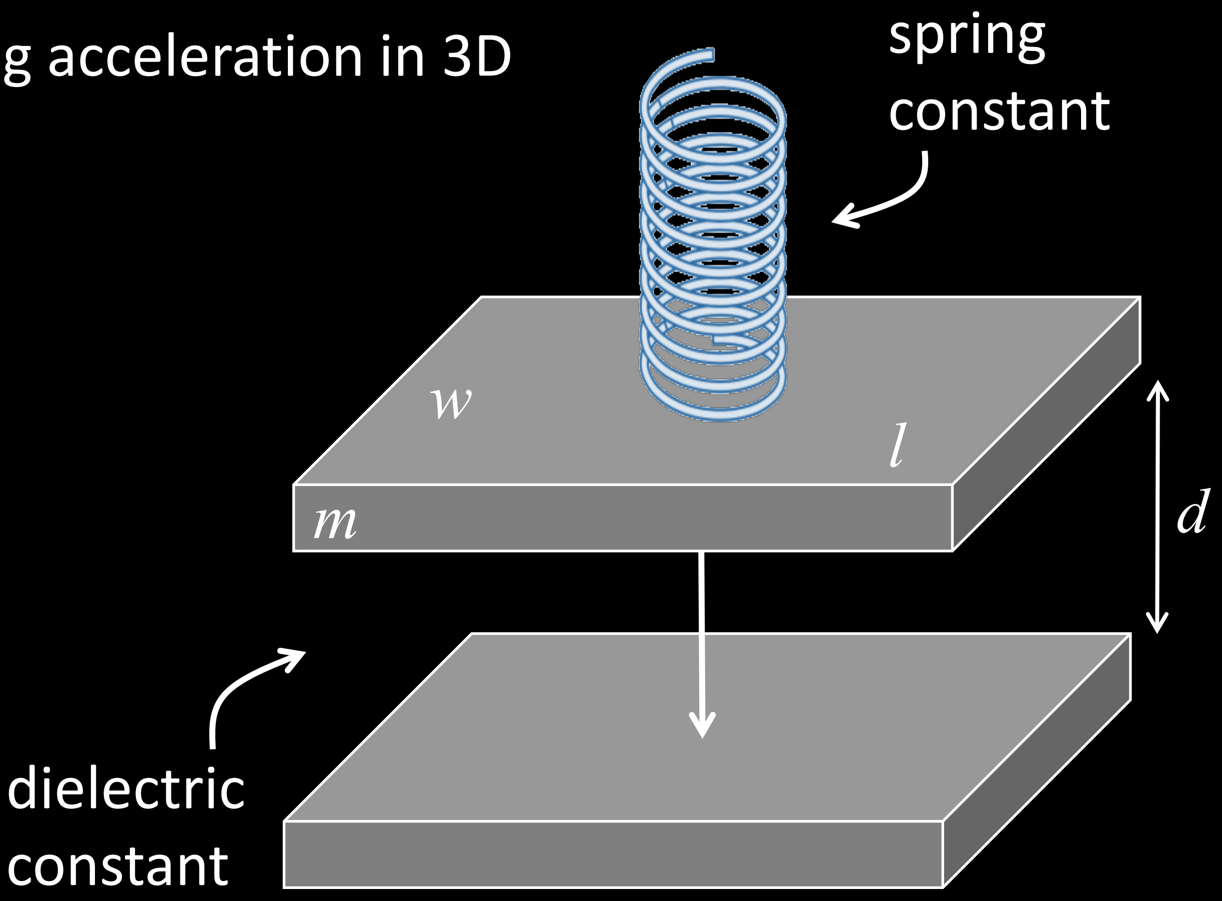
Accelerometer

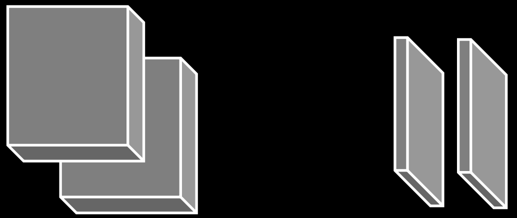
- Measuring acceleration in 3D

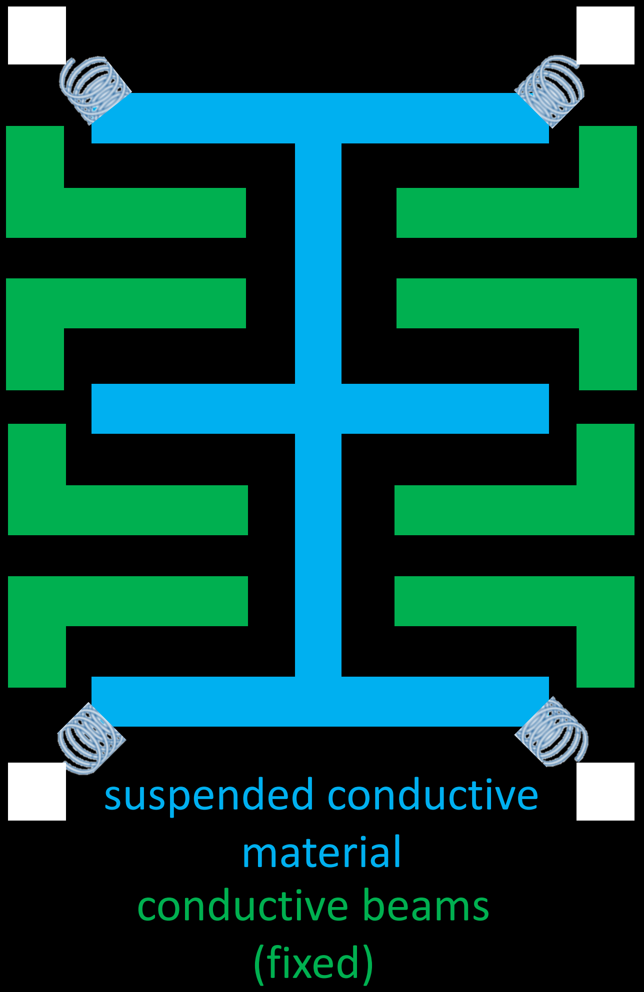
$$C = \frac{\in A}{d}$$

$$F = k\Delta d$$

$$F = ma$$

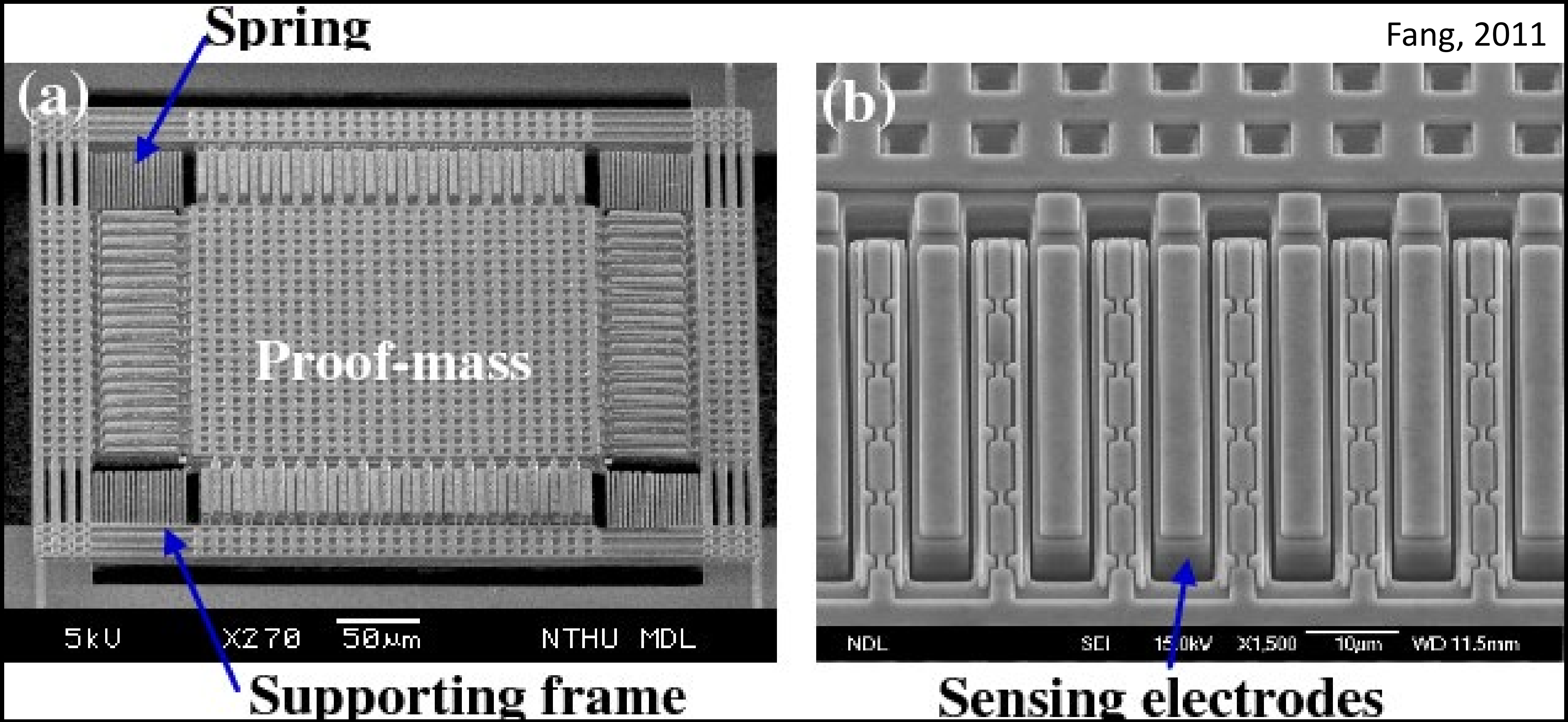






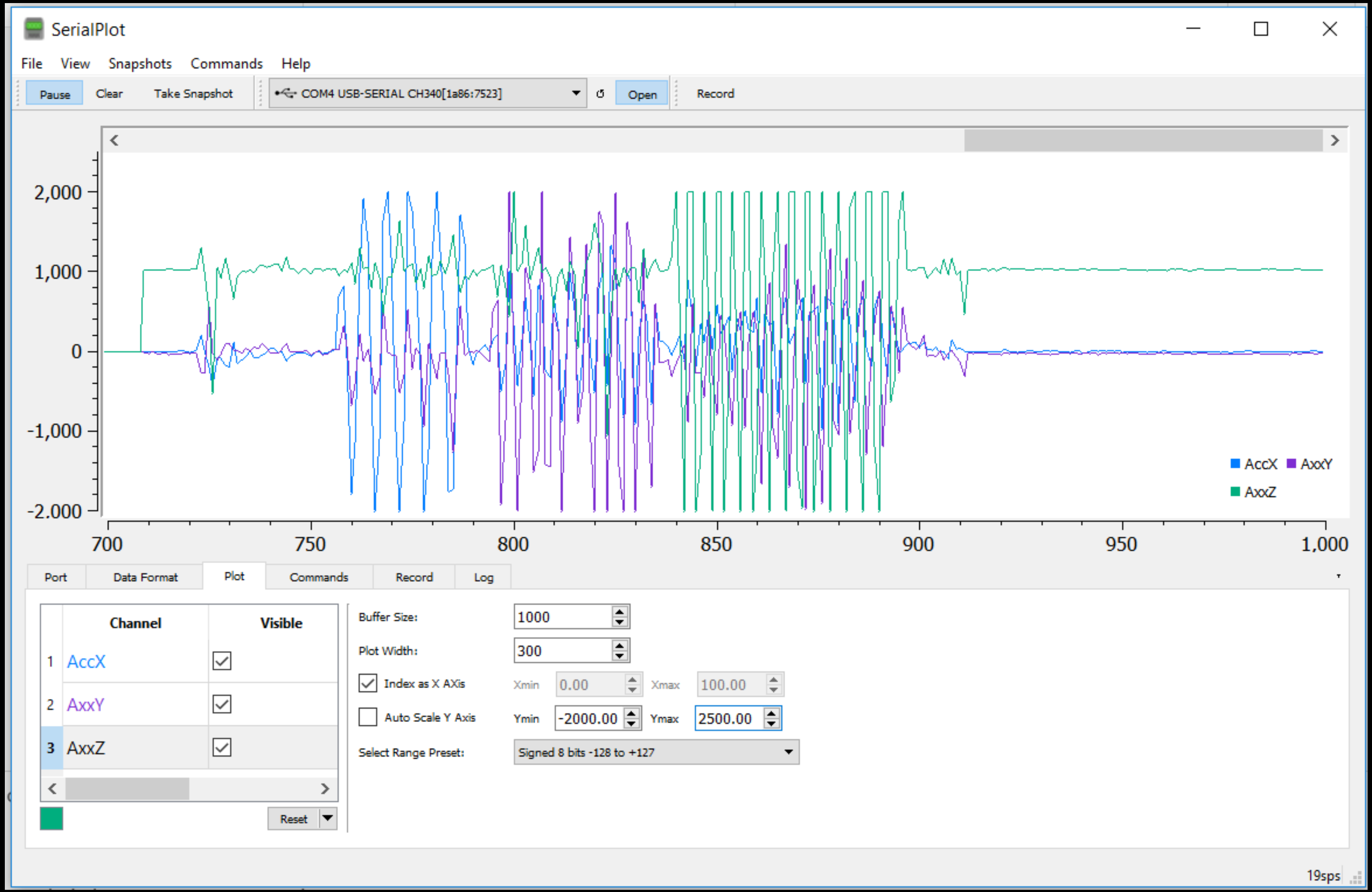
Accelerometer

- Measuring acceleration in 3D
- Micro-Electro-Mechanical Systems



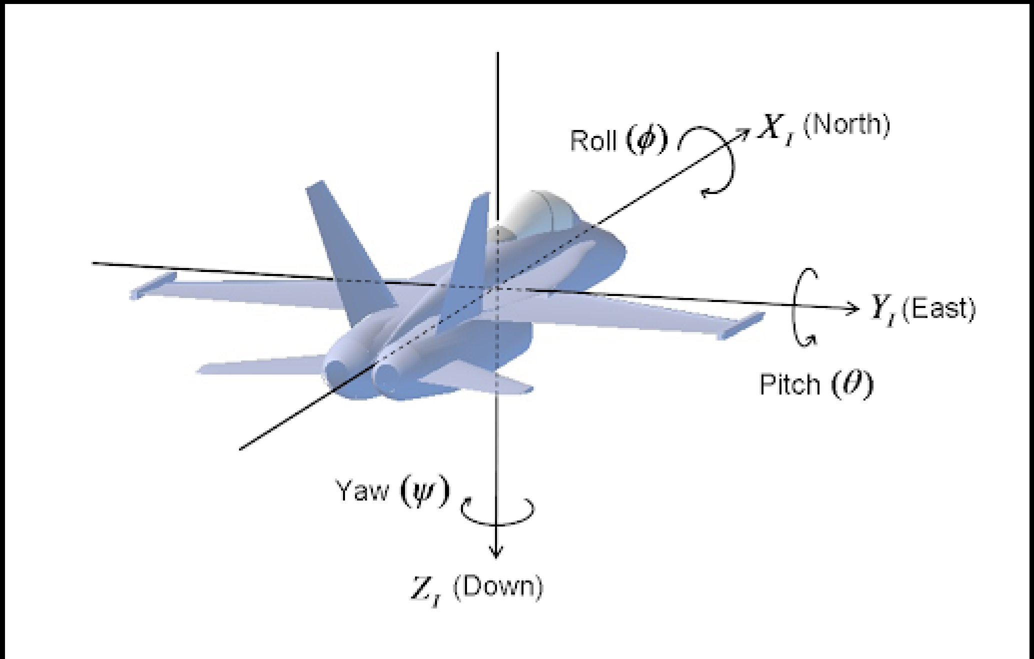
Accelerometer

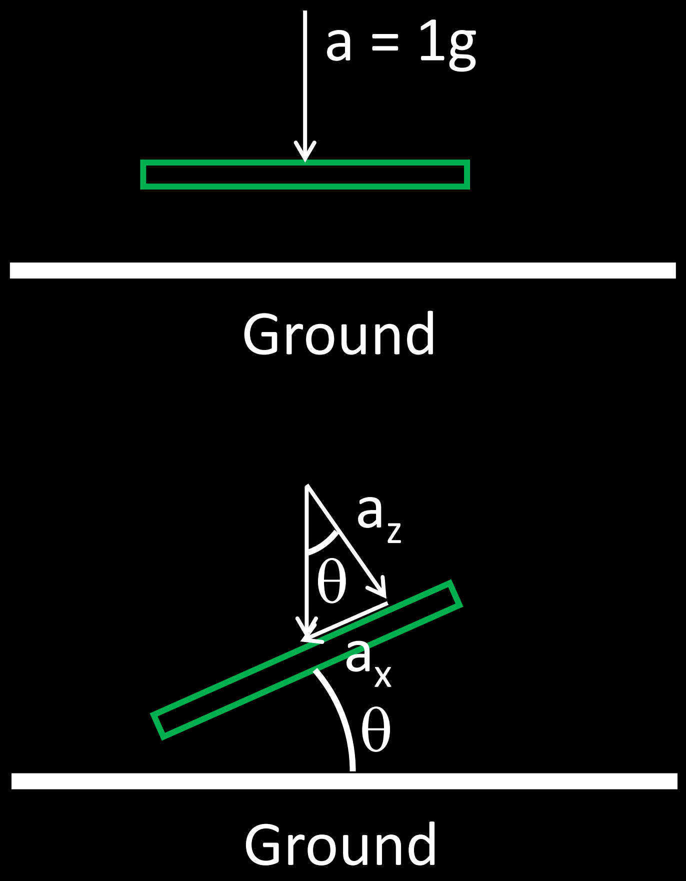
- Measuring acceleration in 3D
- Use Arduino Serial Monitor or a program like SerialPlot to visualize your data



Accelerometer

- How to use the accelerometer to determine roll, tilt, and ~~yaw~~?



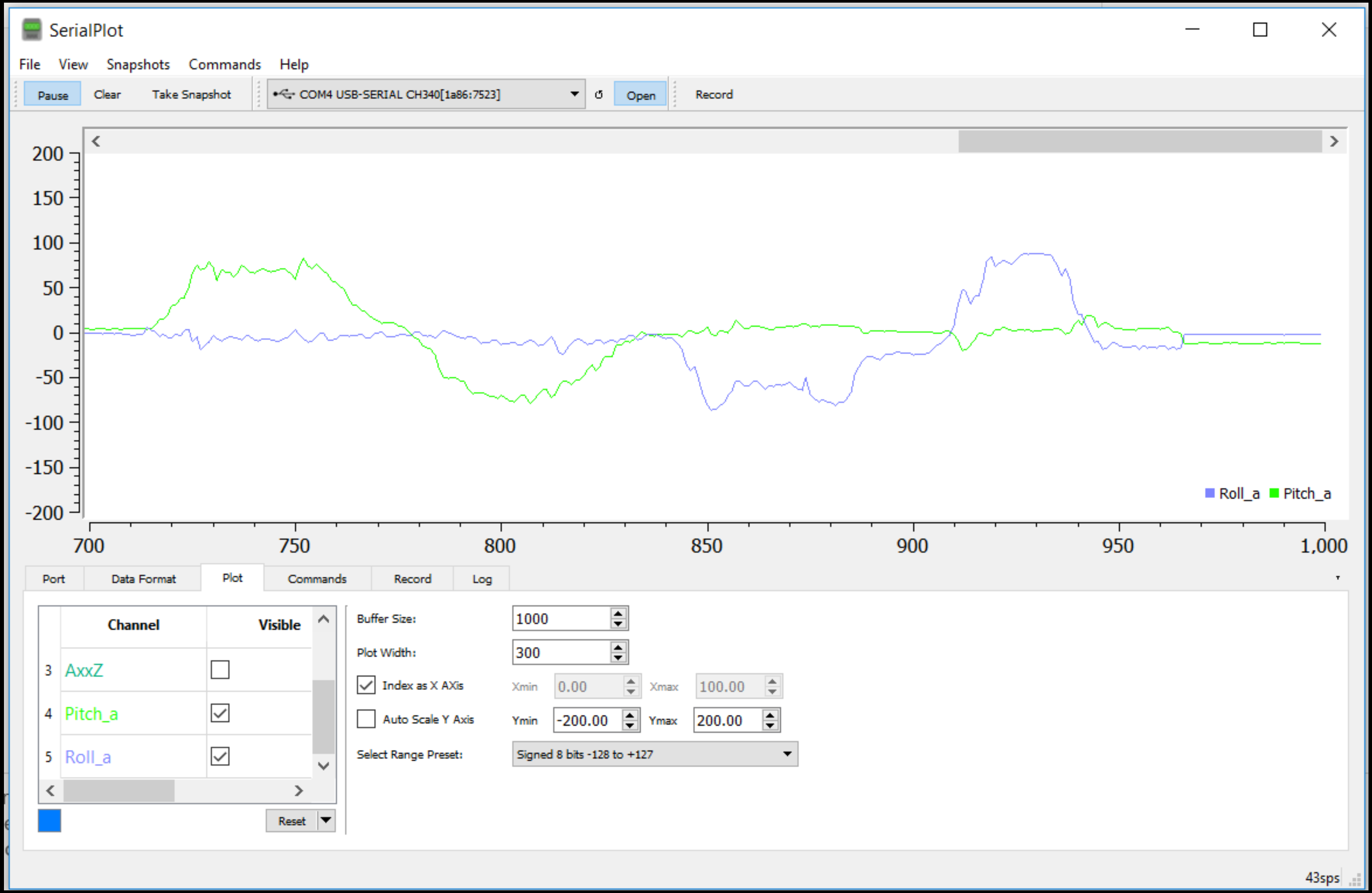


- $a_x = 1g \sin \theta$
- $a_z = 1g \cos \theta$
- $a_x / a_z = \tan \theta$
- $\theta = \text{atan}(a_x/a_z)$
  - Remember, use atan2!
- $\phi = \text{atan}(a_y/a_z)$

How do you measure yaw with the accelerometer?

Accelerometer

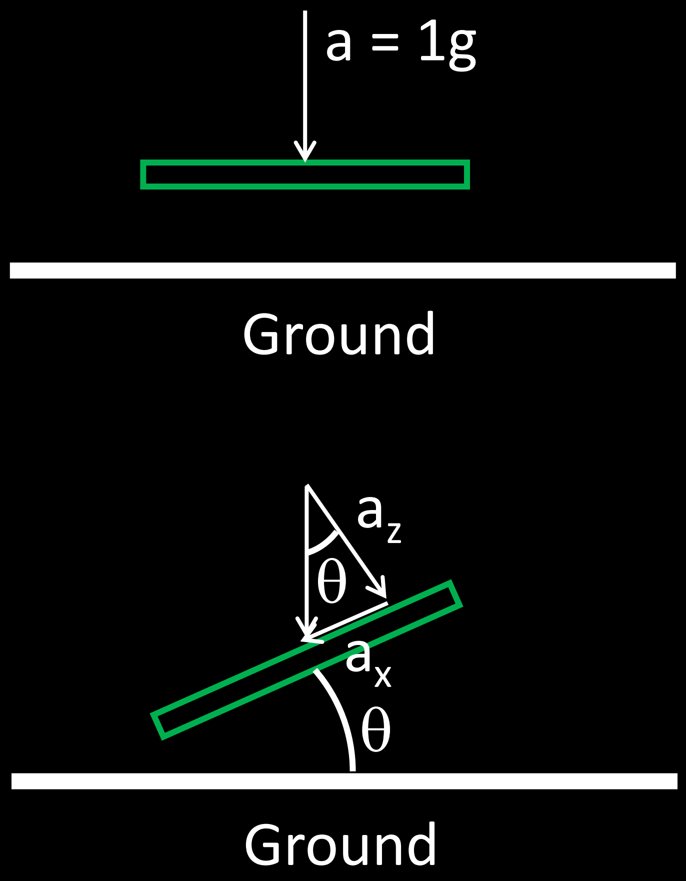
- Determining tilt and roll
- $\theta = \text{atan}(a_x/a_z)$
- $\phi = \text{atan}(a_y/a_z)$

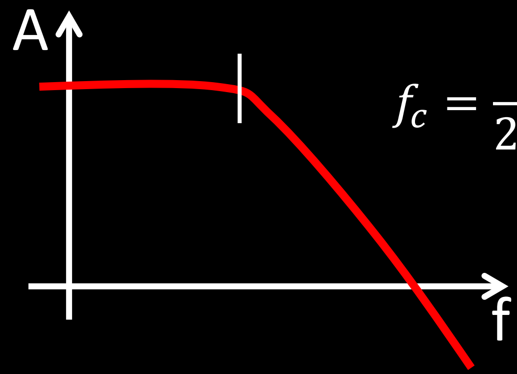


Accelerometer

- Determining tilt and roll
- Good (very accurate on average) vs Bad (noisy)
- Low pass complimentary filter

  - $\theta_{LPF}[n] = \alpha * \theta + (1 - \alpha) * \theta_{LPF}[n-1]$
  - $\theta_{LPF}[n-1] = \theta_{LPF}[n]$
  - $\alpha = \frac{T}{T+RC}$

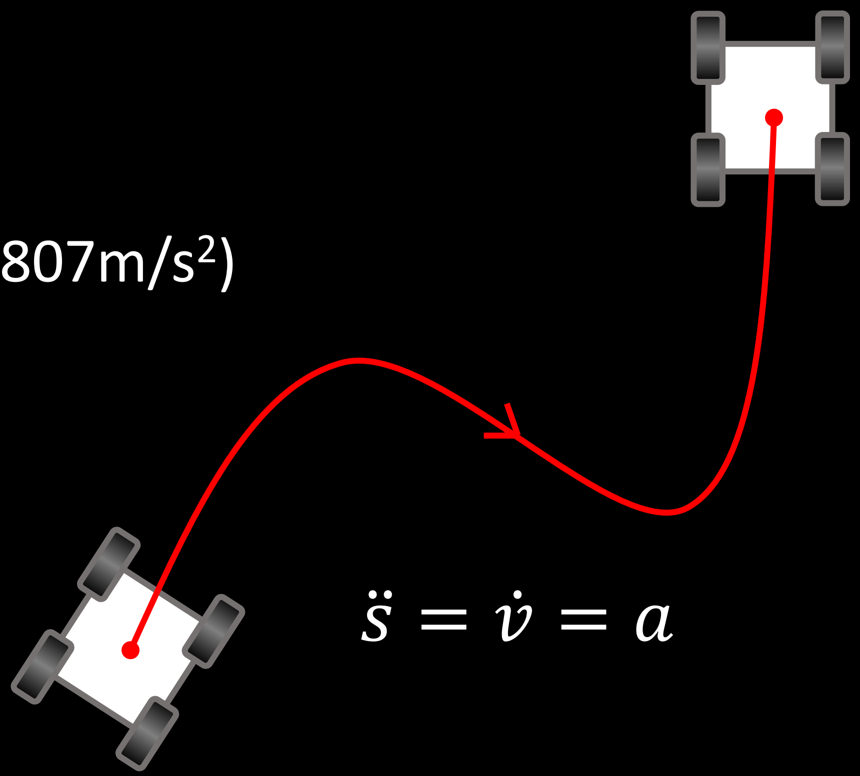




$$f_c = \frac{1}{2\pi RC}$$

Accelerometer

- Determining tilt and roll √
- How to use the accelerometer to do dead reckoning?
  - $v = \int a$
  - s= $\int \int a$
  - `v[k+1]=v[k]+a[k]*dt`
  - `s[k+1]=s[k]+v[k]*dt`
- *Remember:* The accelerometer output is in mg (1g = 9.807m/s^2)



$$\ddot{s} = \dot{v} = a$$

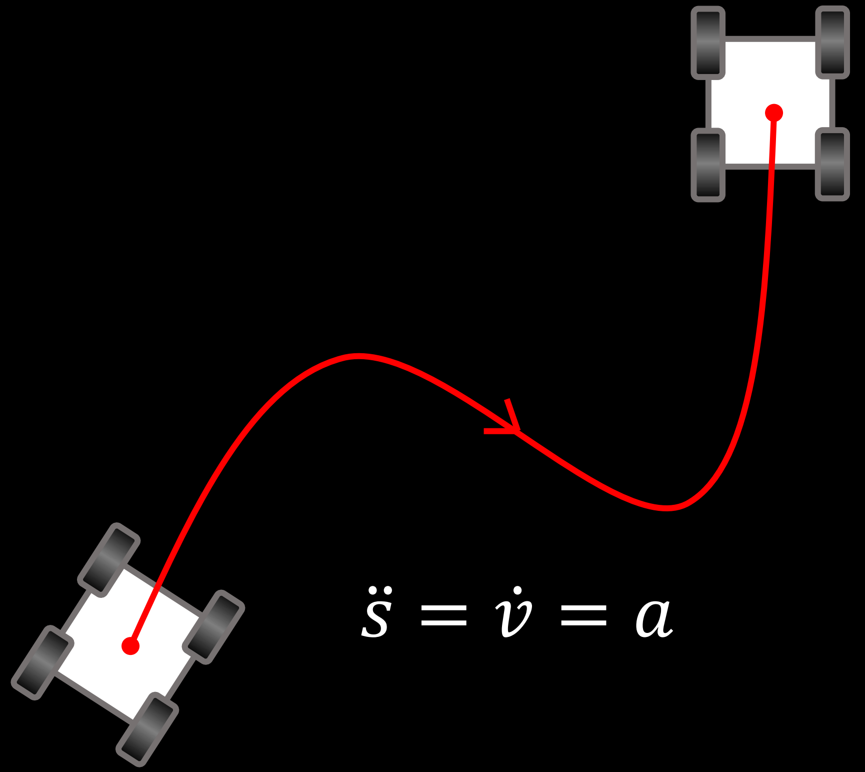
Accelerometer

- Determining tilt and roll √
- How to use the accelerometer to do dead reckoning?
  - *Issue:* Distinguishing acceleration of the sensor from gravitational acceleration

COM3

```
Waiting for data
dt= 0.01s, Acc = -0.01mg, Speed = -0.01m/s, Dis = -0.00m
dt= 0.01s, Acc = -0.04mg, Speed = -0.03m/s, Dis = -0.01m
dt= 0.01s, Acc = -0.15mg, Speed = -0.07m/s, Dis = -0.03m
dt= 0.01s, Acc = -0.15mg, Speed = -0.13m/s, Dis = -0.06m
dt= 0.01s, Acc = -0.17mg, Speed = -0.19m/s, Dis = -0.12m
dt= 0.01s, Acc = -0.17mg, Speed = -0.26m/s, Dis = -0.19m
dt= 0.01s, Acc = -0.18mg, Speed = -0.34m/s, Dis = -0.30m
dt= 0.01s, Acc = -0.21mg, Speed = -0.41m/s, Dis = -0.43m
dt= 0.01s, Acc = -0.22mg, Speed = -0.50m/s, Dis = -0.58m
dt= 0.01s, Acc = -0.25mg, Speed = -0.59m/s, Dis = -0.77m
dt= 0.01s, Acc = -0.27mg, Speed = -0.69m/s, Dis = -0.99m
dt= 0.01s, Acc = -0.28mg, Speed = -0.79m/s, Dis = -1.25m
dt= 0.01s, Acc = -0.29mg, Speed = -0.90m/s, Dis = -1.54m
dt= 0.01s, Acc = -0.31mg, Speed = -1.02m/s, Dis = -1.87m
dt= 0.01s, Acc = -0.32mg, Speed = -1.14m/s, Dis = -2.24m
dt= 0.01s, Acc = -0.34mg, Speed = -1.26m/s, Dis = -2.66m
dt= 0.01s, Acc = -0.35mg, Speed = -1.39m/s, Dis = -3.12m
dt= 0.01s, Acc = -0.36mg, Speed = -1.52m/s, Dis = -3.62m
dt= 0.01s, Acc = -0.35mg, Speed = -1.65m/s, Dis = -4.17m
dt= 0.01s, Acc = -0.36mg, Speed = -1.79m/s, Dis = -4.76m
dt= 0.01s, Acc = -0.36mg, Speed = -1.92m/s, Dis = -5.40m
dt= 0.01s, Acc = -0.34mg, Speed = -2.05m/s, Dis = -6.09m
dt= 0.01s, Acc = -0.35mg, Speed = -2.18m/s, Dis = -6.82m
dt= 0.01s, Acc = -0.37mg, Speed = -2.32m/s, Dis = -7.60m
dt= 0.01s, Acc = -0.38mg, Speed = -2.46m/s, Dis = -8.43m
```

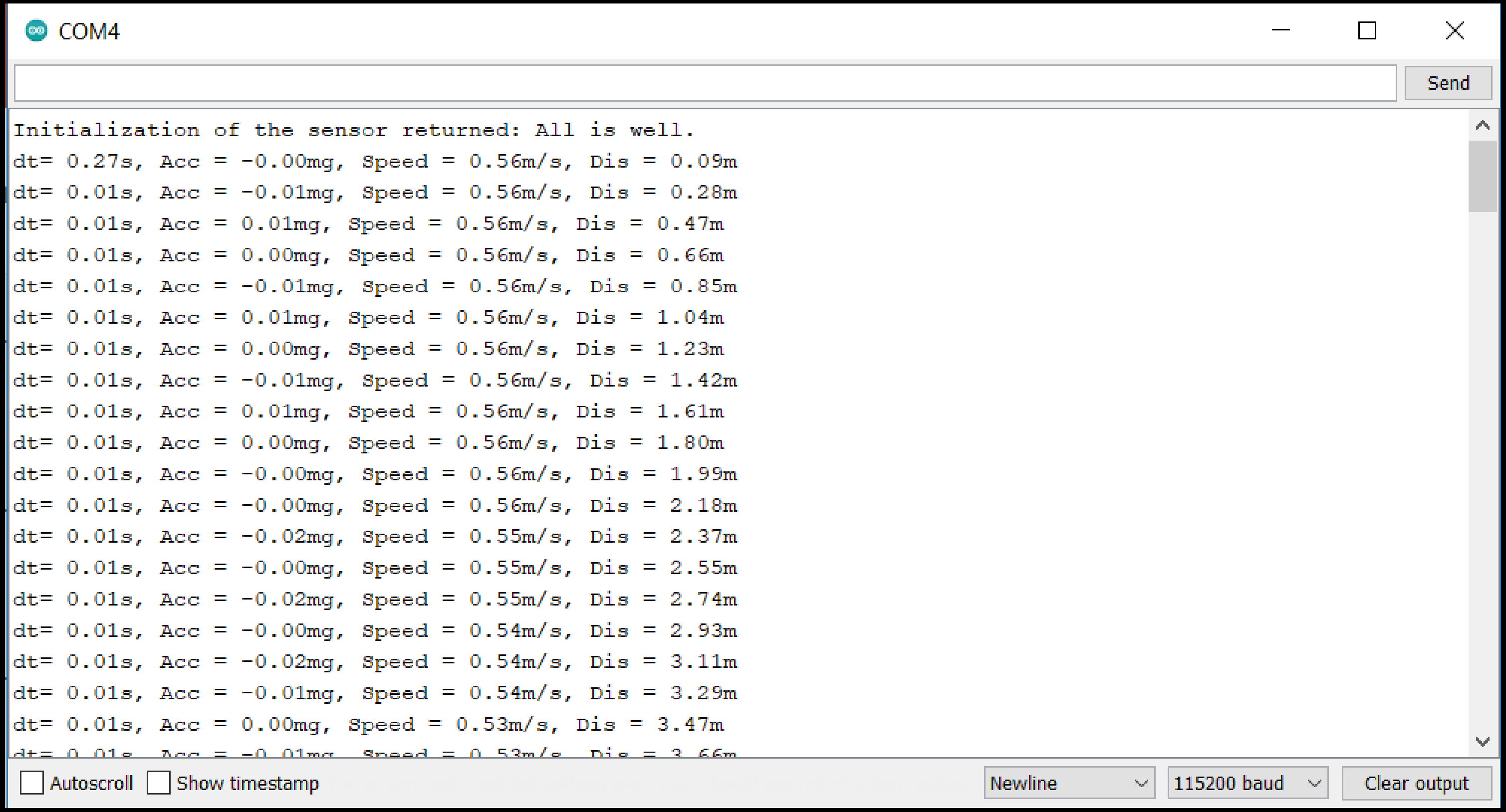
Autoscroll | Show timestamp | Newline | 115200 baud | Clear output

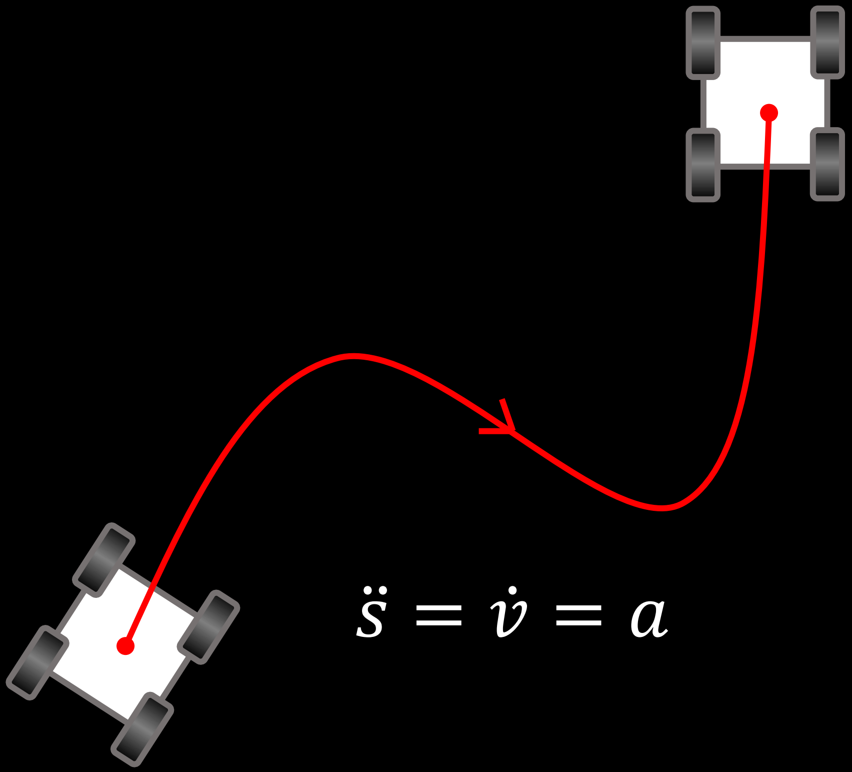


$$\ddot{s} = \dot{v} = a$$

Accelerometer

- Determining tilt and roll √
- How to use the accelerometer to do dead reckoning?
  - *Issue:* Distinguishing acceleration of the sensor from gravitational acceleration
  - *Solution 1*: Calibrate the offset

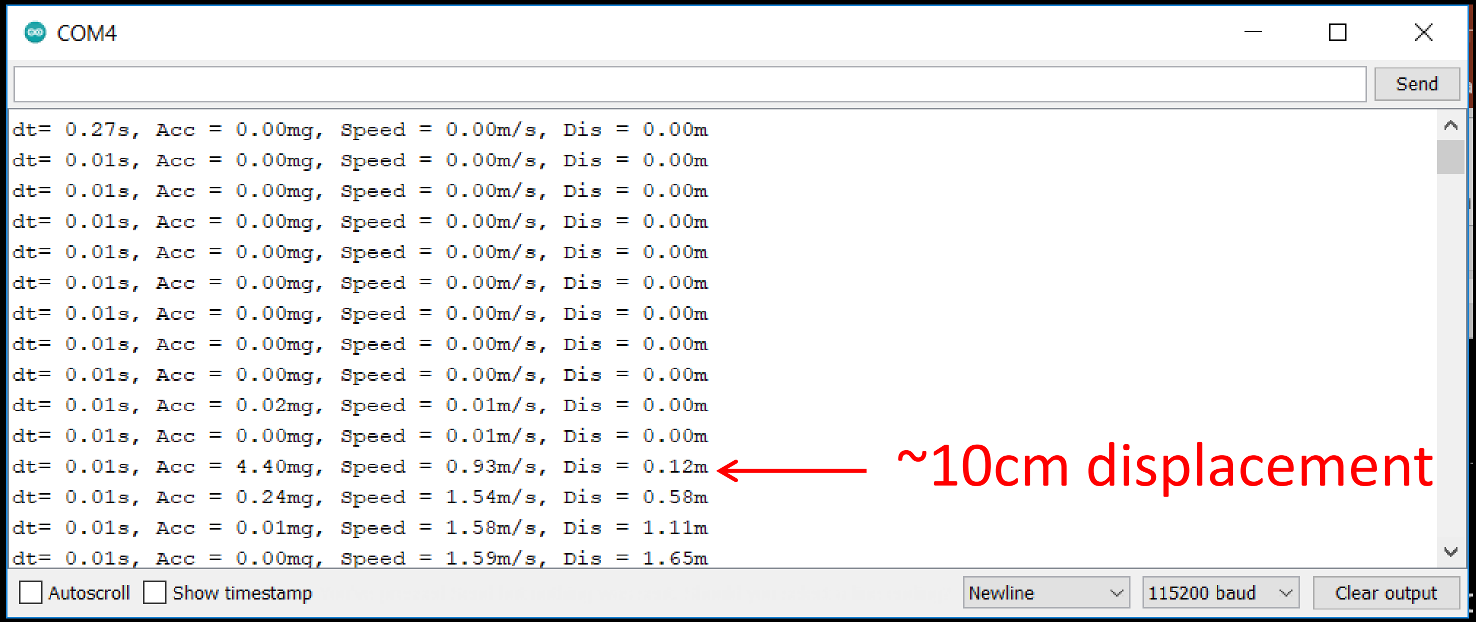


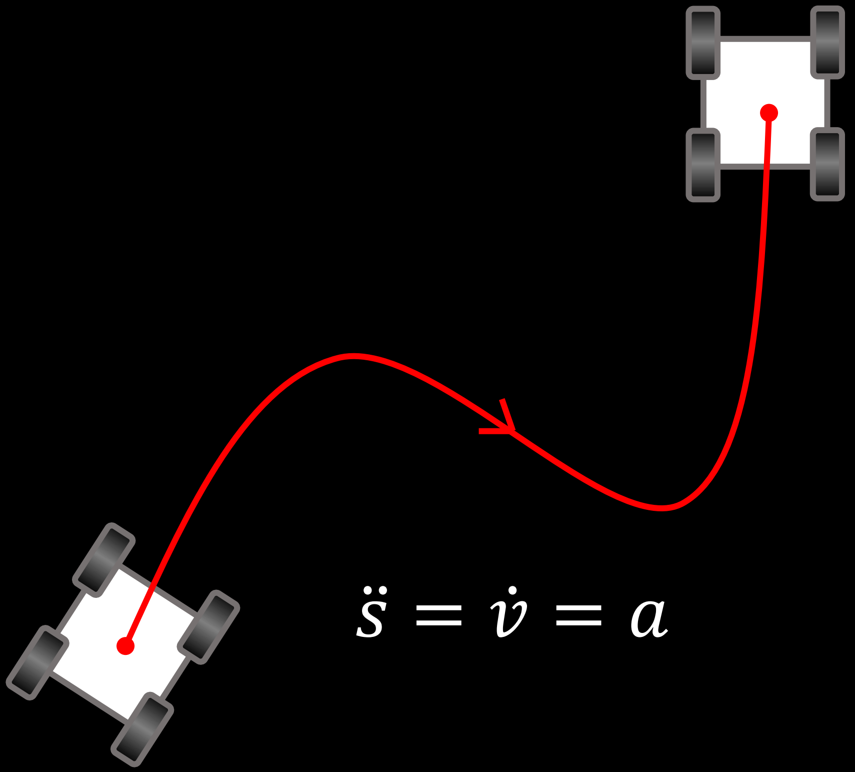


$$\ddot{s} = \dot{v} = a$$

Accelerometer

- Determining tilt and roll √
- How to use the accelerometer to do dead reckoning?
  - *Issue:* Distinguishing acceleration of the sensor from gravitational acceleration
  - *Solution 1*: Calibrate the offset
  - *Solution 2:* Low pass filter the output
  - *Solution 3:* Minimum signal cut-off

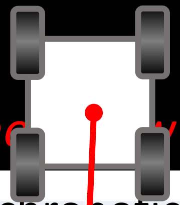




$$\ddot{s} = \dot{v} = a$$

Accelerometer

- Determining tilt and roll √
- How to use the accelerometer to do dead reckoning?
  - *Issue:* Distinguishing acceleration of the sensor from gravitational acceleration
  - *Solution 1*: Calibrate the offset
  - *Solution 2:* Low pass filter the output
  - *Solution 3:* Minimum signal cut-off



Errors only accumulate, and they grow fast!

www.chrobotics.com

Angle Error (degrees)	Acceleration Error (m/s/s)	Velocity Error (m/s) at 10 seconds	Position Error (m) at 10 seconds	Position Error (m) at 1 minute	Position Error (m) at 10 minutes	Position Error (m) at 1 hour
0.1	0.017	0.17	1.7	61.2	6120	220 e 3
0.5	0.086	[illegible]	8.6	309.6	30960	1.1 e 6
1.0	0.17	[illegible]	17	[illegible]	61200	2.2 e 6
1.5	0.256	[illegible]	25.6	921.6	92160	3.3 e 6
2.0	0.342	[illegible]	34.2	1231.2	123120	4.4 e 6
3.0	0.513	5.13	51.3	1846.8	184680	6.6 e 6
5.0	0.854	8.54	85.4	3074.4	307440	11 e 6

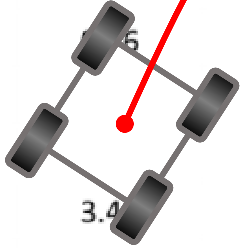
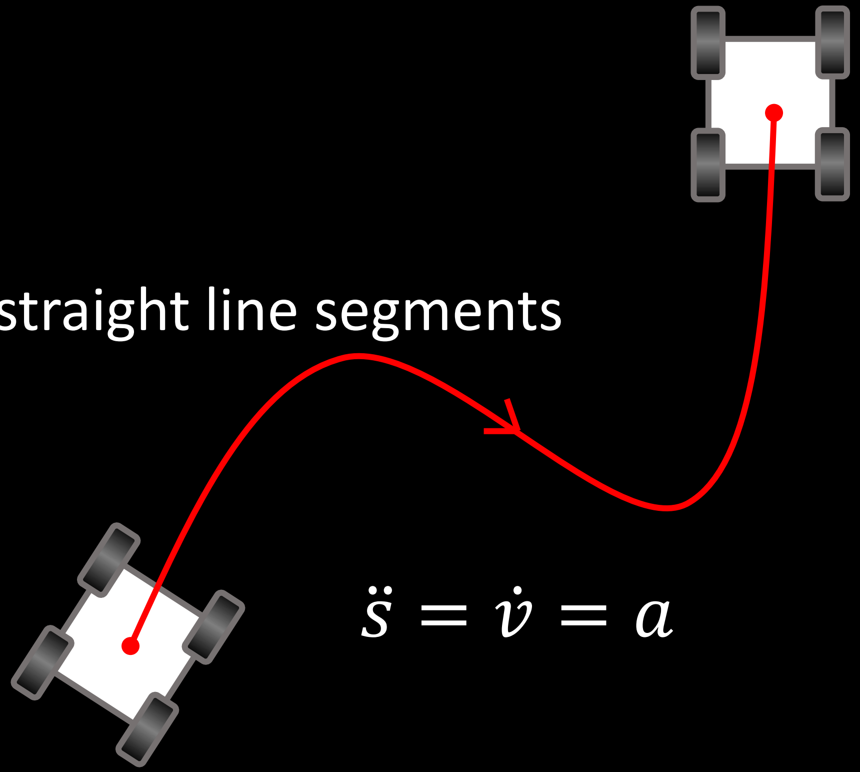


Table 1 - A summary of velocity and position errors caused by attitude estimation error.

Accelerometer

- Determining tilt and roll √
- How to use the accelerometer to do dead reckoning?
  - *Issue:* Distinguishing acceleration of the sensor from gravitational acceleration
  - *Solution 1*: Calibrate the offset
  - *Solution 2:* Low pass filter the output
  - *Solution 3:* Minimum signal cut-off
  - *Solution 4:* Stop periodically and zero the velocity
  - *Solution 5:* Use in combination with TOF sensor on straight line segments
  - *Solution 6:* Buy a more expensive IMU
  - etc…



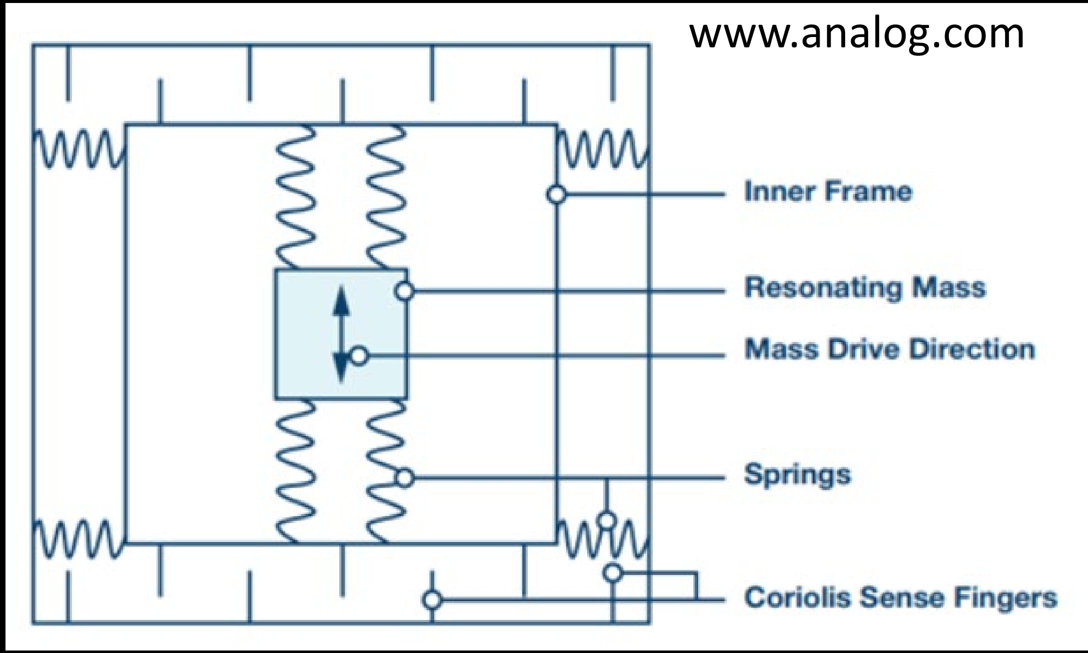
$$\ddot{s} = \dot{v} = a$$

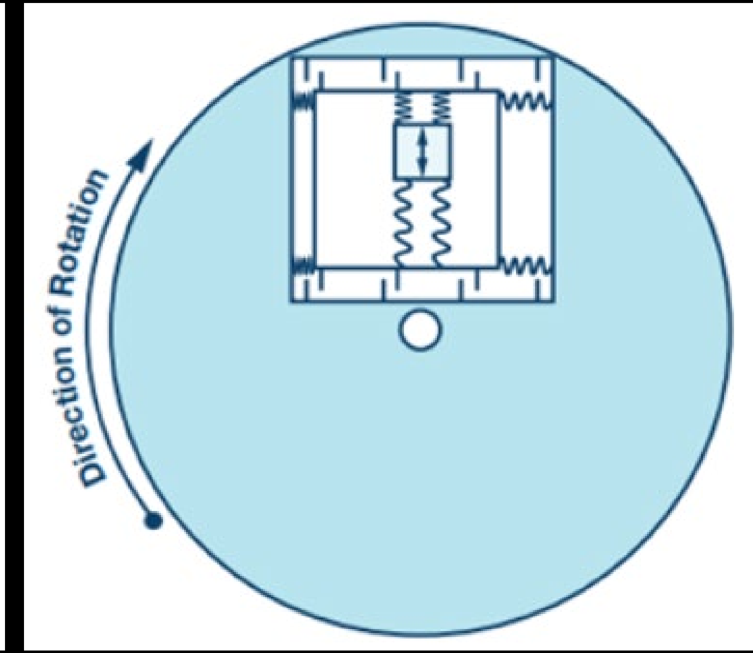
Prof. Kirstin Hagelskjær Petersen
kirstin@cornell.edu

GYROSCOPE

Gyroscopes

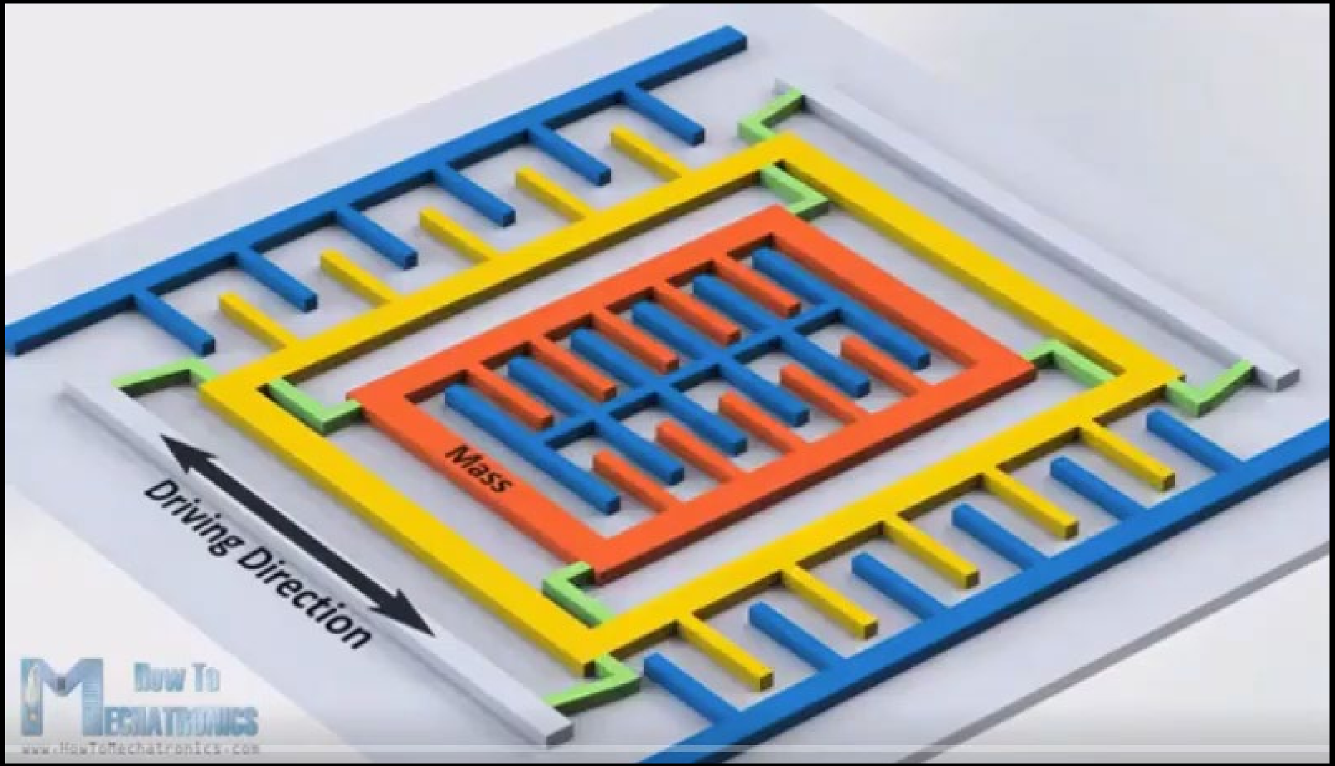
- Measures the rate of angular change [deg/s]





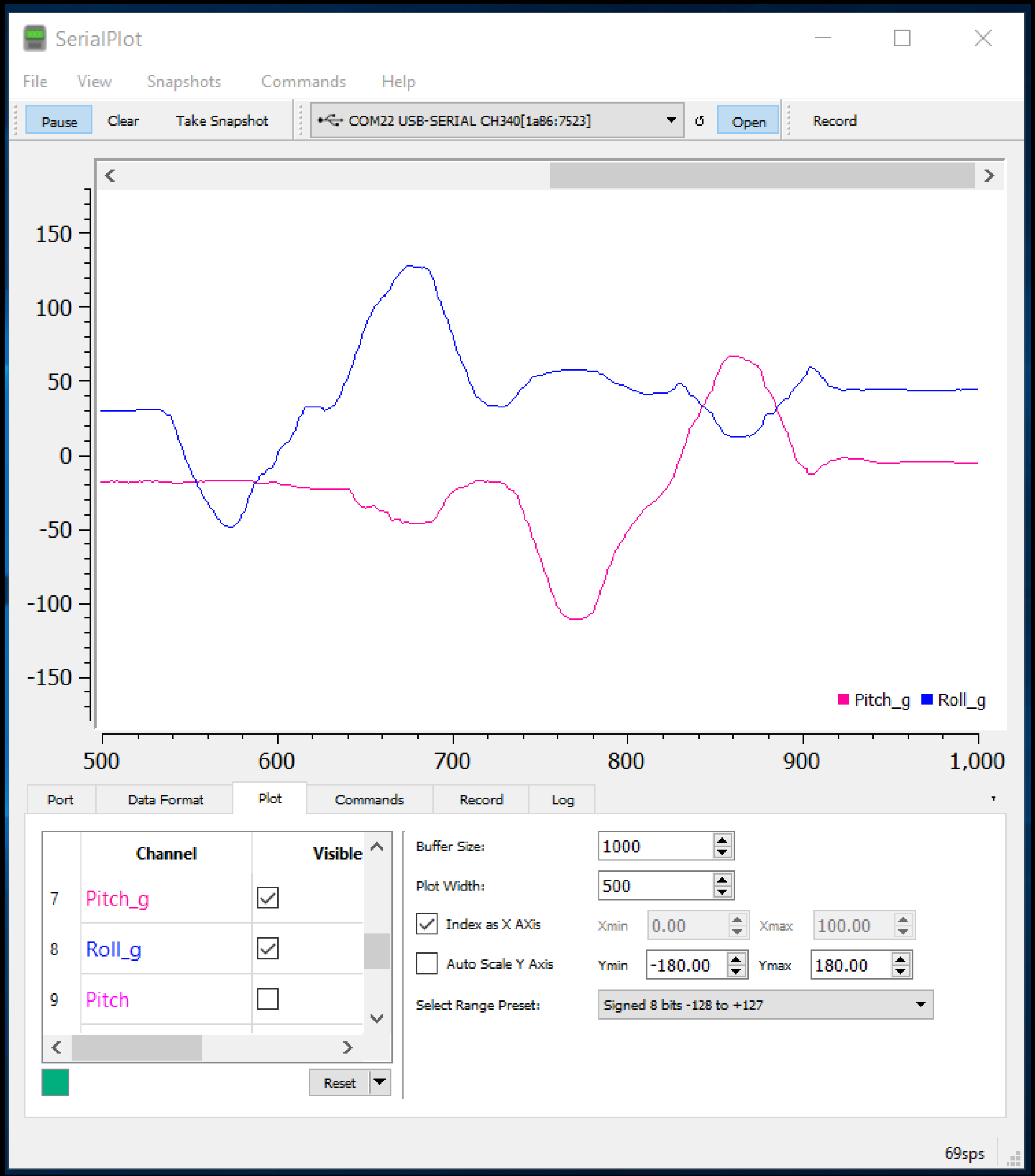
Gyroscopes

- Measures the rate of angular change [deg/s]



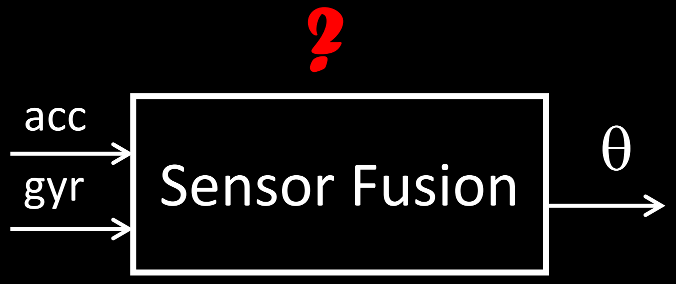
Gyroscopes

- Measures the rate of angular change [deg/s]
- How to use the gyroscope to measure angles?
  - $\theta_g = \theta_g - gyr\_reading*dt$
- *Drift, but low noise*



Gyroscopes

- Measures the rate of angular change [deg/s]
- How to use the gyroscope to measure angles?
  - $\theta_g = \theta_g - \text{gyr\_reading} * dt$
- *Drift, but low noise*
  - Complimentary to the accelerometer!
- Complimentary filter:
  - $\theta = (\theta + \theta_g * dt)(1-\alpha) + \theta_a \alpha$

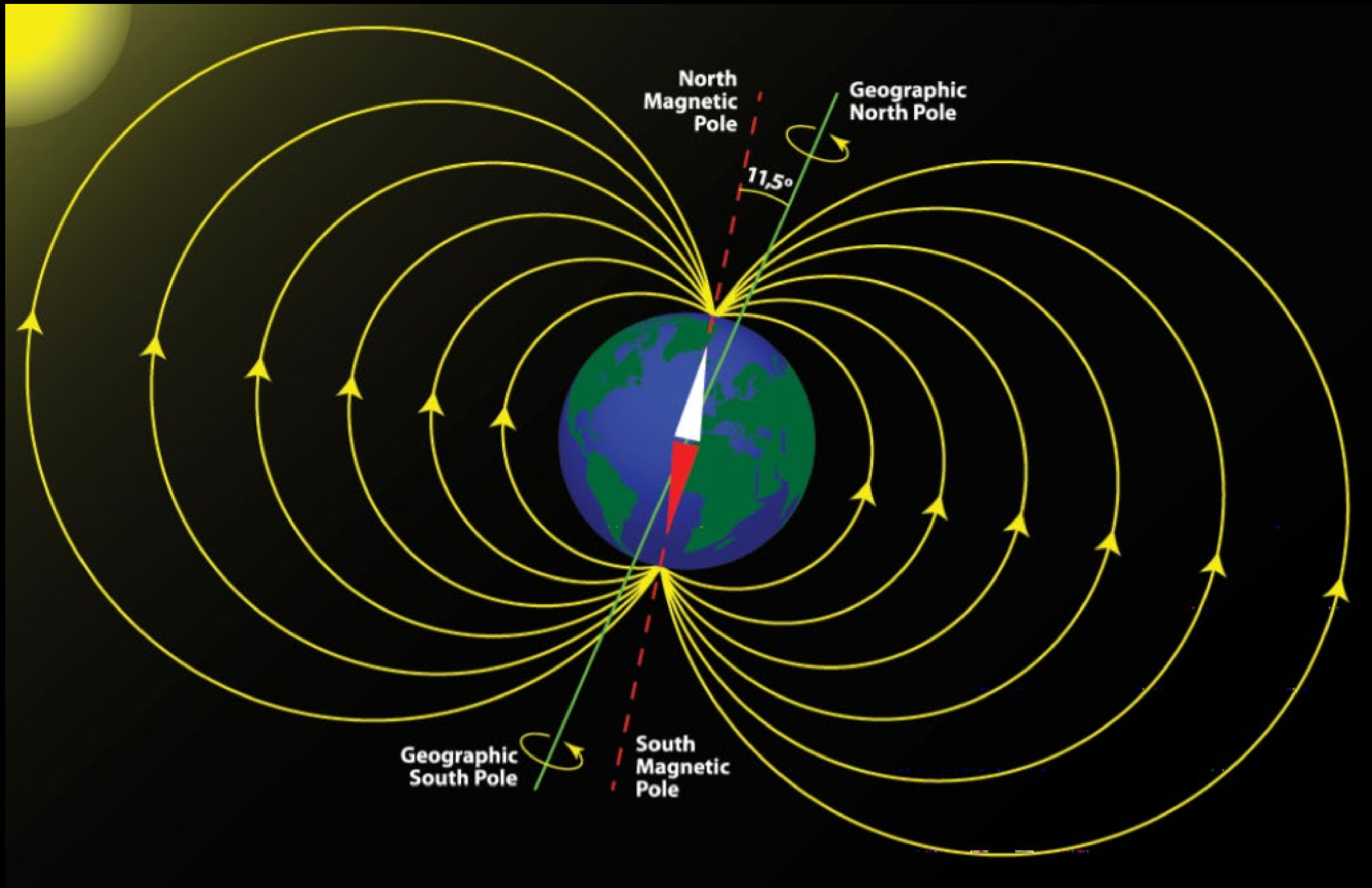


Can we also estimate yaw?

- Yes! (but there is no complementary data from the accelerometer)

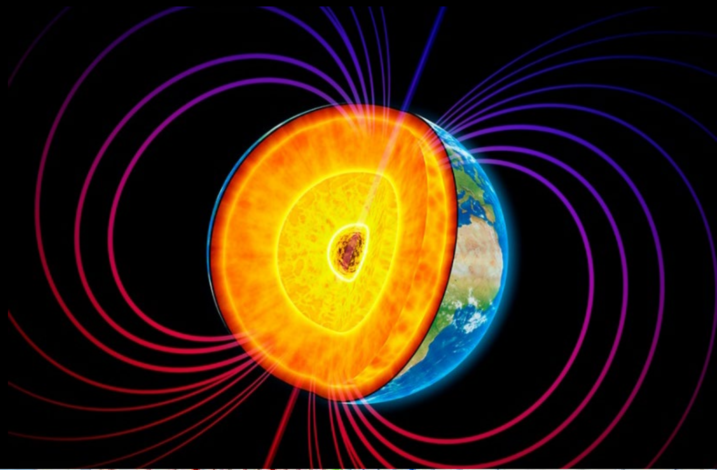
Magnetometer

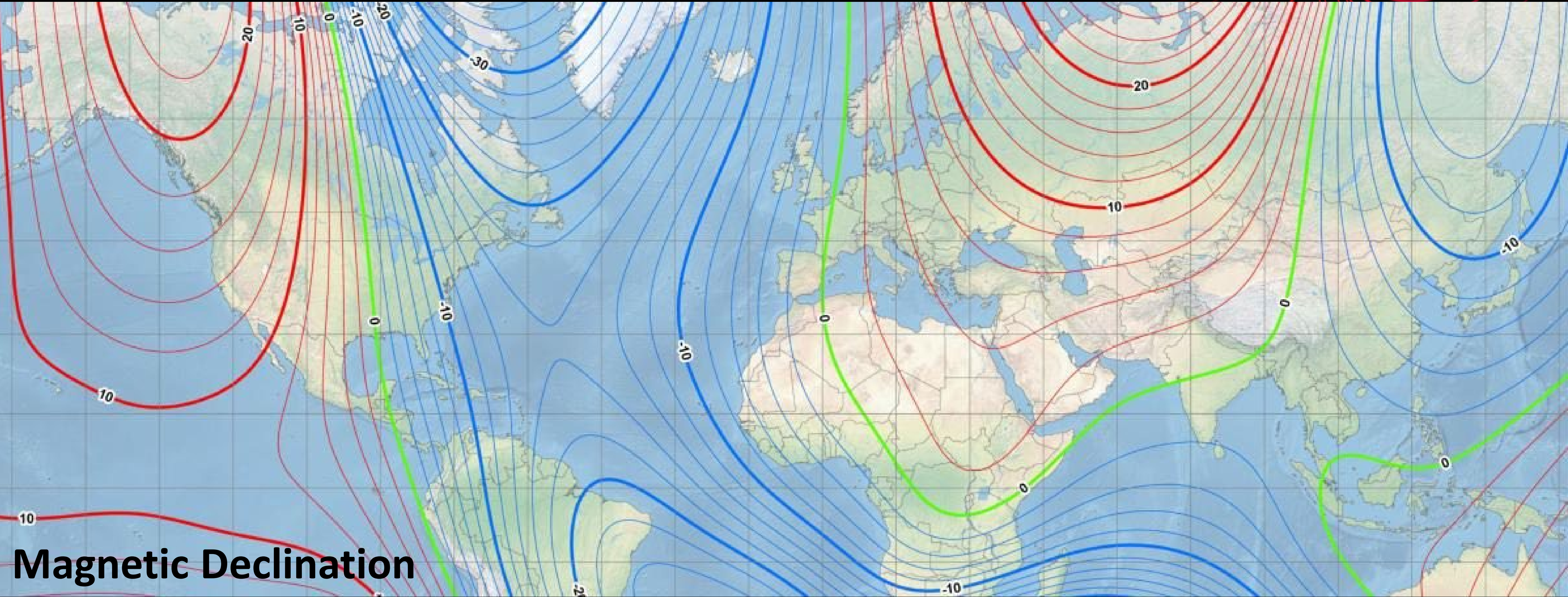
- Measure the Earth's magnetic field [Gauss] or [uT]
- The actual direction depends on latitude, longitude, and time



Magnetometer

- Measure the Earth's magnetic field [Gauss] or [uT]
- The actual direction depends on latitude, longitude, and time
- Distortions due to metal objects or nearby EM fields

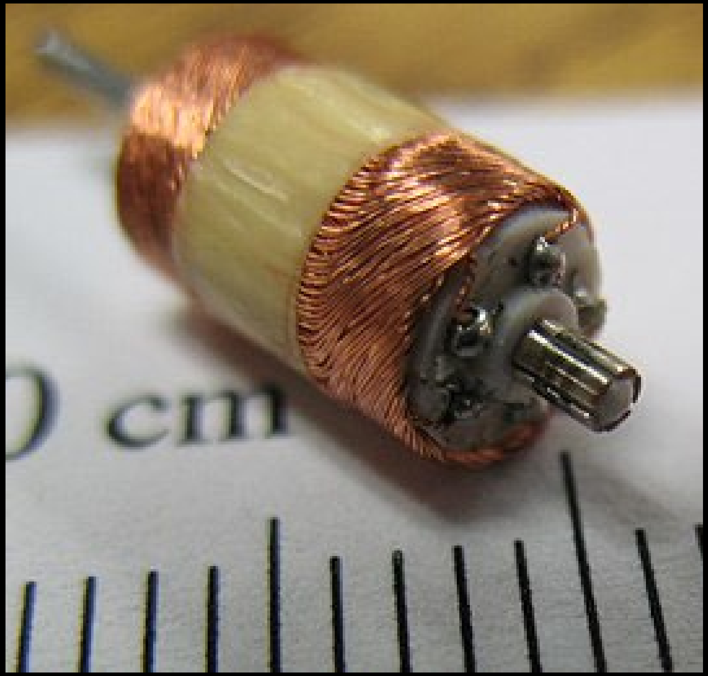




Magnetic Declination

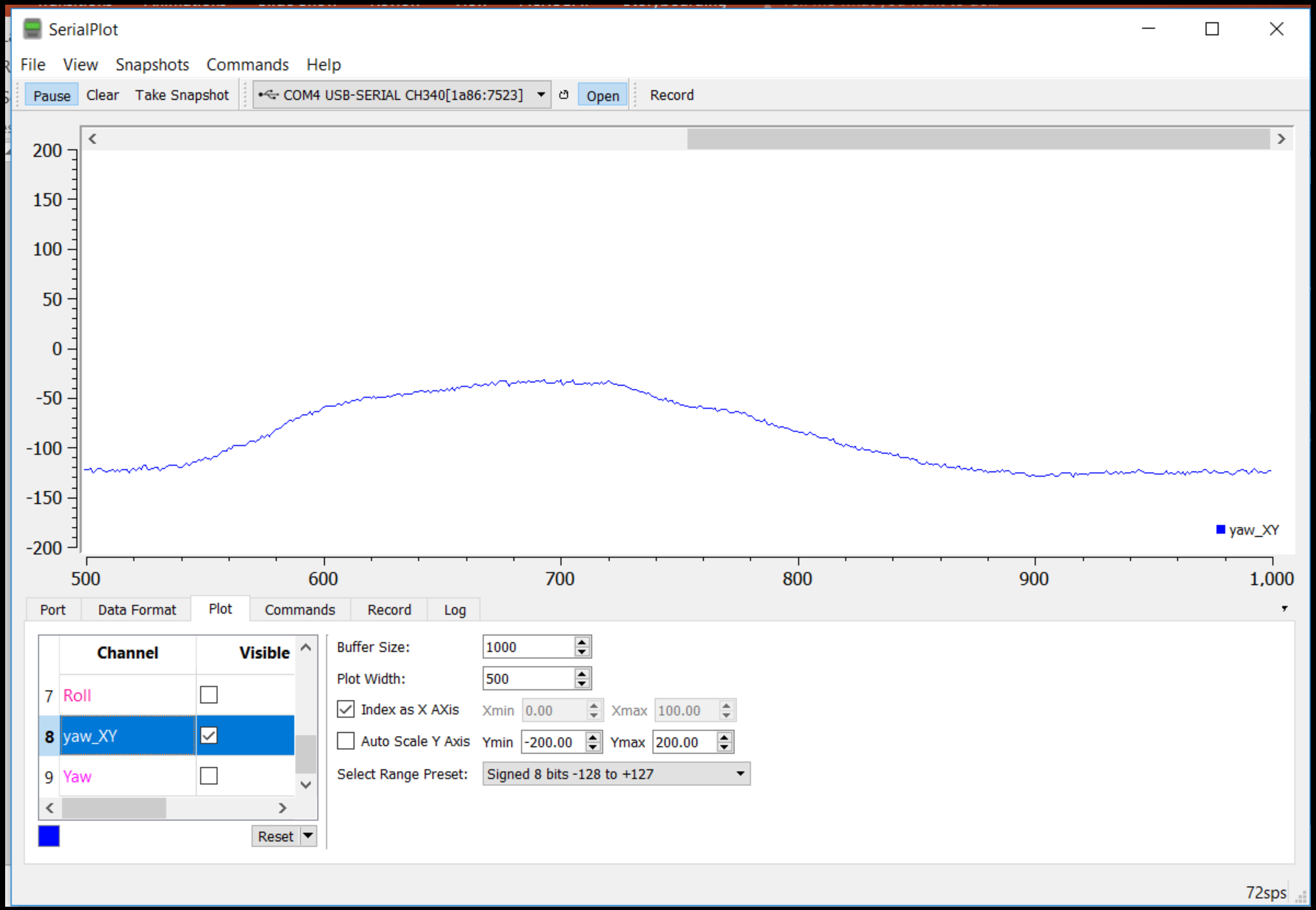
Magnetometer

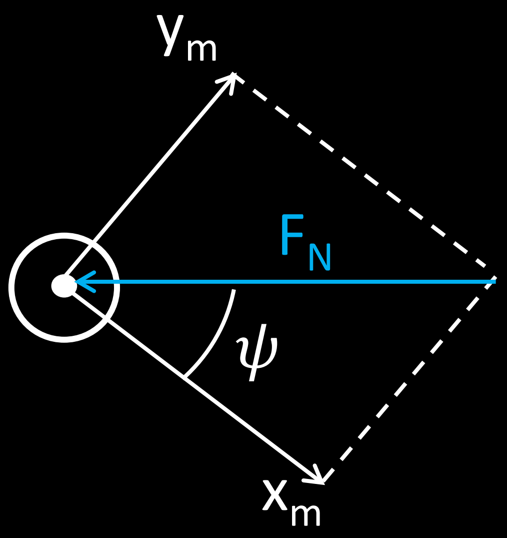
- Measure the Earth's magnetic field [Gauss] or [uT]
- The actual direction depends on latitude, longitude, and time
- Distortions due to metal objects or nearby EM fields
  - ***Examples?***



Magnetometer

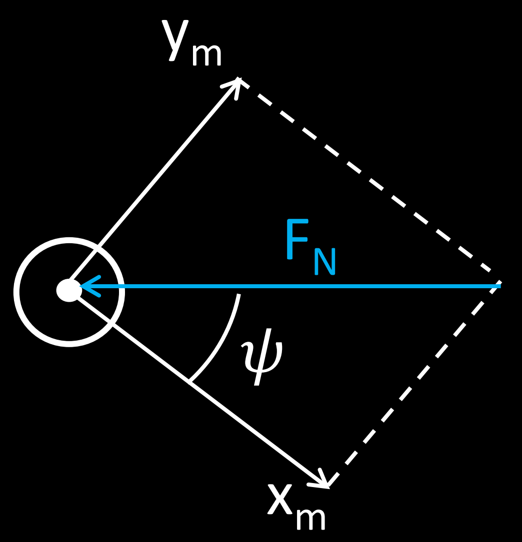
- Measure the Earth's magnetic field [Gauss] or [uT]
- $\psi = \text{atan}\left(\frac{y_m}{x_m}\right)$





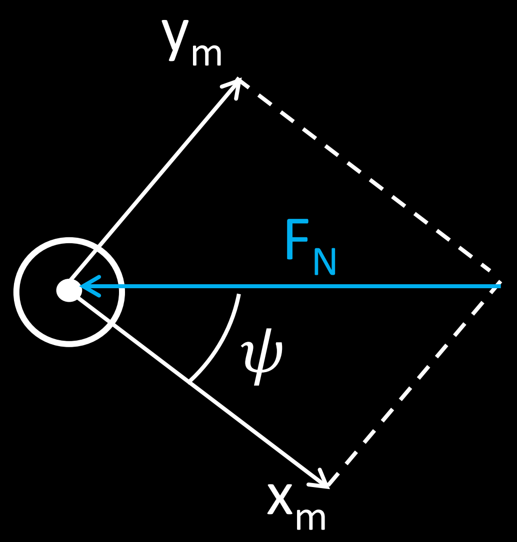
Magnetometer

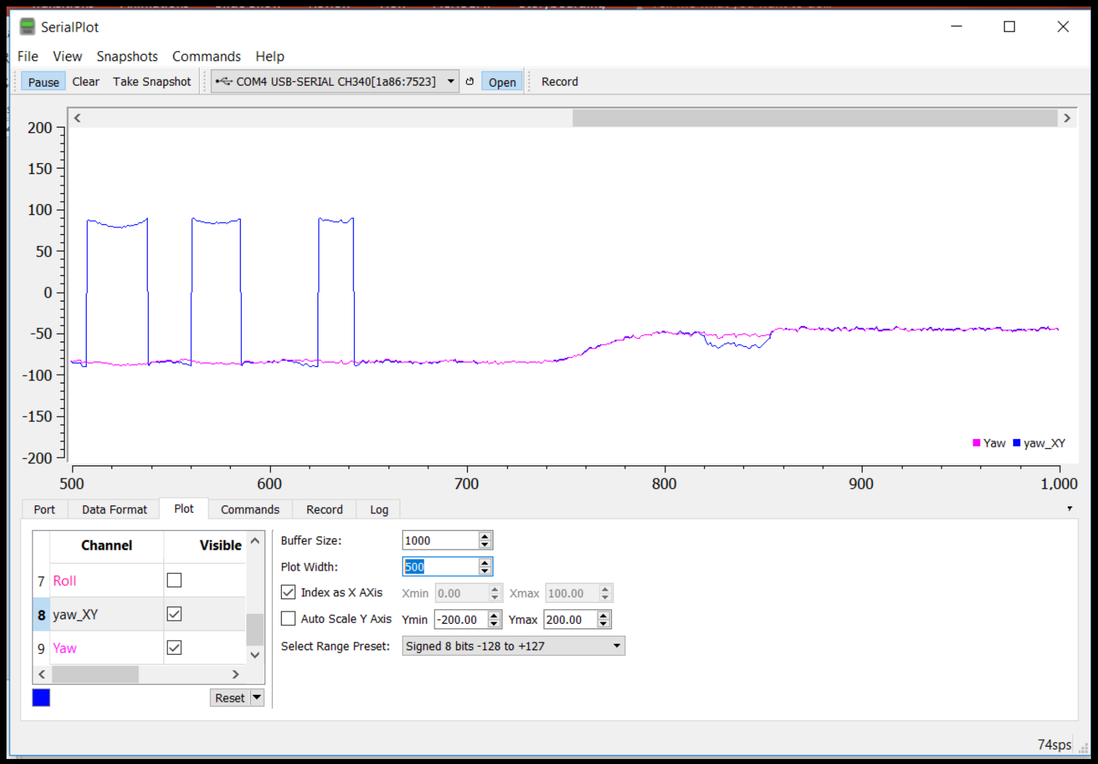
- Measure the Earth's magnetic field [Gauss] or [uT]
- $\psi = \text{atan}\left(\frac{y_m}{x_m}\right)$
- What if you are also experiencing pitch and roll?
  - Fuse accelerometer + gyroscope + magnetometer data
- Tilt-compensated compass
  - $\begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix} = R_{x,\phi} R_{y,\theta} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$
  - $\begin{bmatrix} x \\ y \\ z \end{bmatrix} = {R_{x,\phi}}^T {R_{y,\theta}}^T \begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix} = \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ \sin(\phi)\sin(\theta) & \cos(\phi) & \cos(\theta)\sin(\phi) \\ \cos(\phi)\sin(\theta) & -\sin(\phi) & \cos(\phi)\cos(\theta) \end{bmatrix} \begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix}$
  - x = y_m*cos(ϕ) - z_m*sin(ϕ);
  - y = x_m*cos(θ) + y_m*sin(ϕ)*sin(θ) + z_m*cos(ϕ)*sin(θ);
  - ψ = atan2(y,x)



Magnetometer

- Measure the Earth's magnetic field [Gauss] or [uT]
- $\psi = \operatorname{atan}\left(\frac{y_m}{x_m}\right)$
- What if you are also experiencing pitch and roll?
  - Fuse accelerometer + gyroscope + magnetometer data
- Tilt-compensated compass





Sources and References

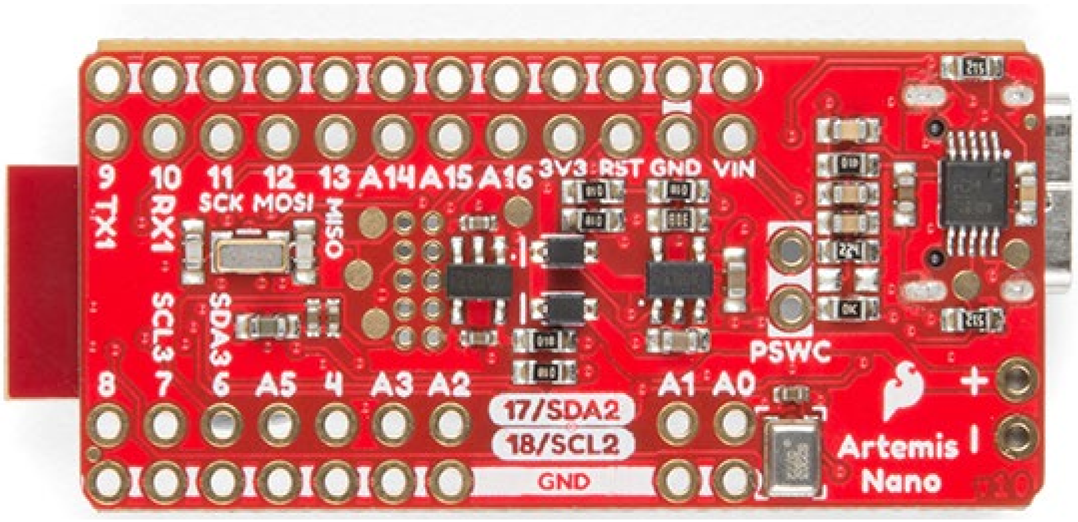
- http://www.chrobotics.com/library/accel-position-velocity
- EE 267 Virtual Reality, by Gordon Wetzstein at Stanford University
- Analog.com
- https://toptechboy.com/

Lab 3: Sensors

- Connect to TOF sensors and IMU
- Understand and process data
- Route wires and solder connections (get this done during lab!!)
  - Permanent solder joints / Detachable connections?
  - Single core or braided wires?
  - Routing of TOF sensors, IMU, motor drivers, Artemis, battery for motors and battery for the processor
- Mechanical mounting components (optional)

Lab 3: Sensors (pre-lab)

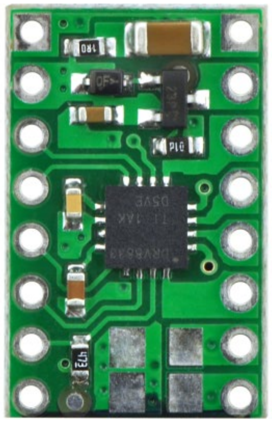
Draw the connection diagram that you intend to use



VDD (2.8V out)
VIN (2.6–5.5V)
GND
SDA
SCL
XSHUT
GPIO1

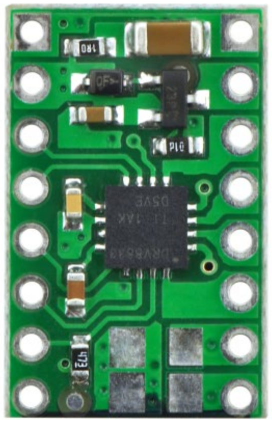
VDD (2.8V out)
VIN (2.6–5.5V)
GND
SDA
SCL
XSHUT
GPIO1

GND
VMM
BIN1
BIN2
AIN2
AIN1
nSLEEP
nFAULT



GND
VIN
BOUT1
BOUT2
AOUT2
AOUT1
AISEN
BISEN

GND
VMM
BIN1
BIN2
AIN2
AIN1
nSLEEP
nFAULT



GND
VIN
BOUT1
BOUT2
AOUT2
AOUT1
AISEN
BISEN

Lab 3: Sensors (pre-lab)

Think about the placement of components and batteries