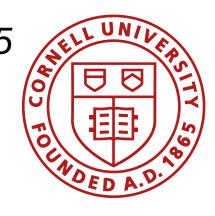
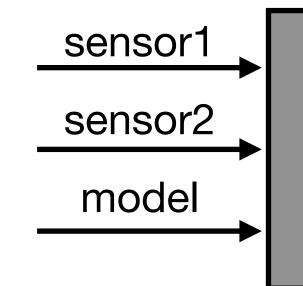
Sensors II Fast Robots, ECE4160/5160, MAE 4190/5190

E. Farrell Helbling, 1/29/25

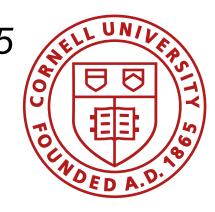


- Combine two or more data sources in a way that generates "better" understanding of the system
 - More consistent, accurate, and dependable signal over time

Data source



Fast Robots 2025

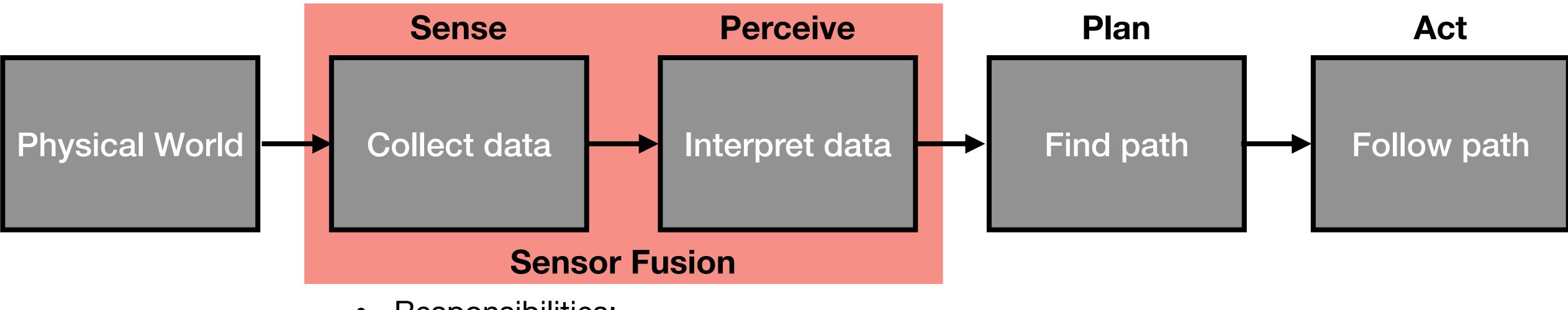


System state



acceleration, position, orientation, etc.

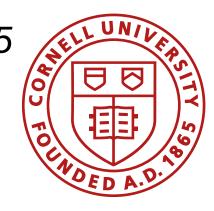
- Combine two or more data sources in a way that generates "better" understanding of the system
 - More consistent, accurate, and dependable signal over time



- **Responsibilities:**

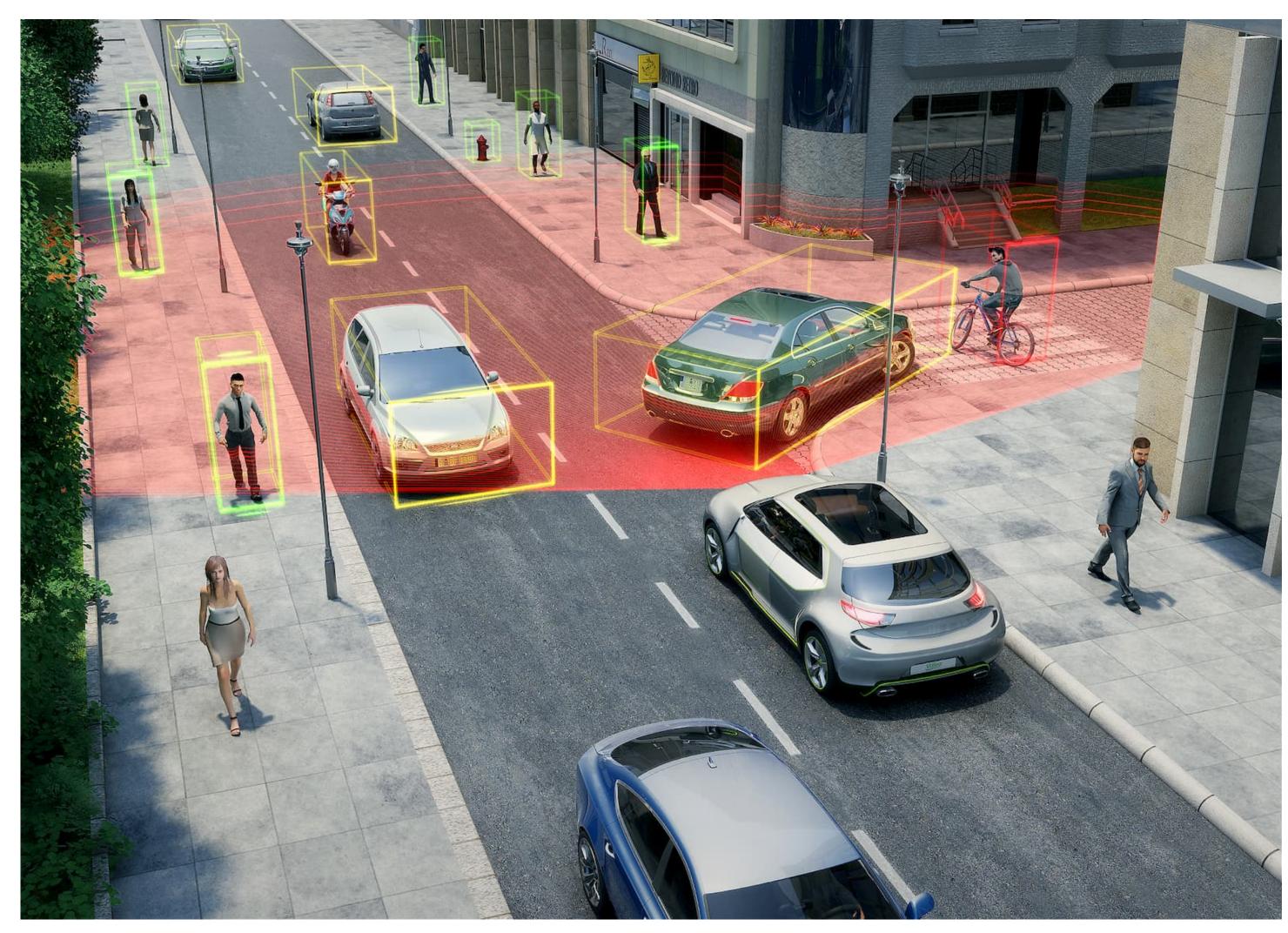
 - Situational awareness (detection/tracking)

Fast Robots 2025

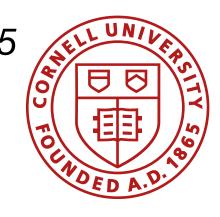


Self-awareness (where am I? what am I doing? what is my current state?

Situational awareness

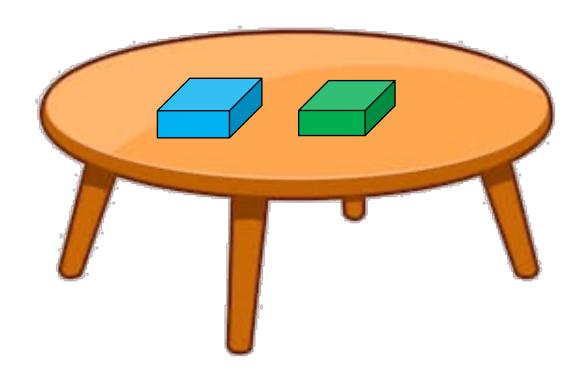


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Valeo's LIDAR

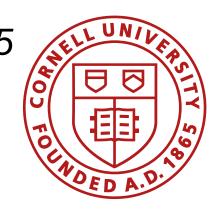
Increase the quality of the data: less noise, uncertainty, deviation \bullet

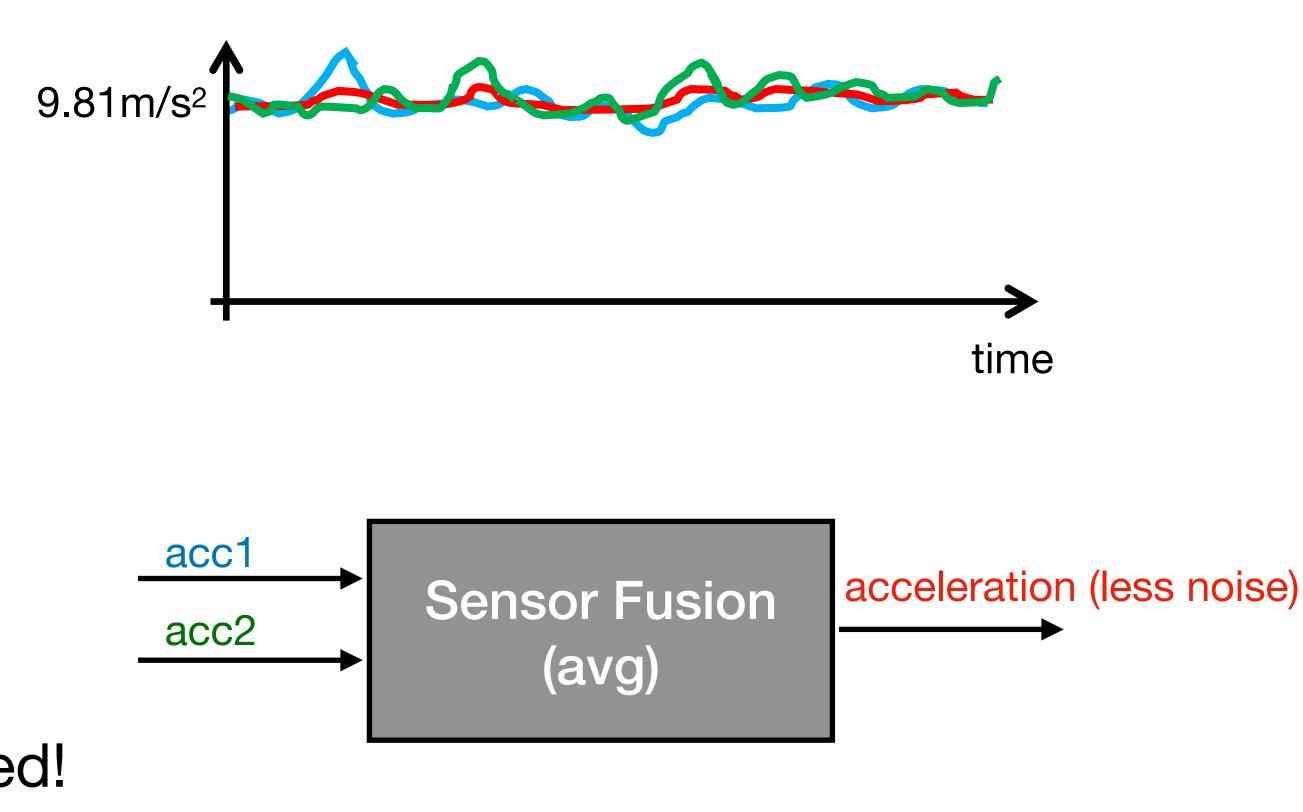


Adding sensors lowers noise: •

•
$$n = 1/\sqrt{N}$$

• Only true if the noise is not correlated!



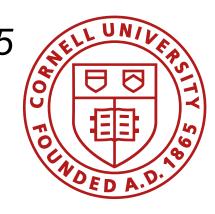


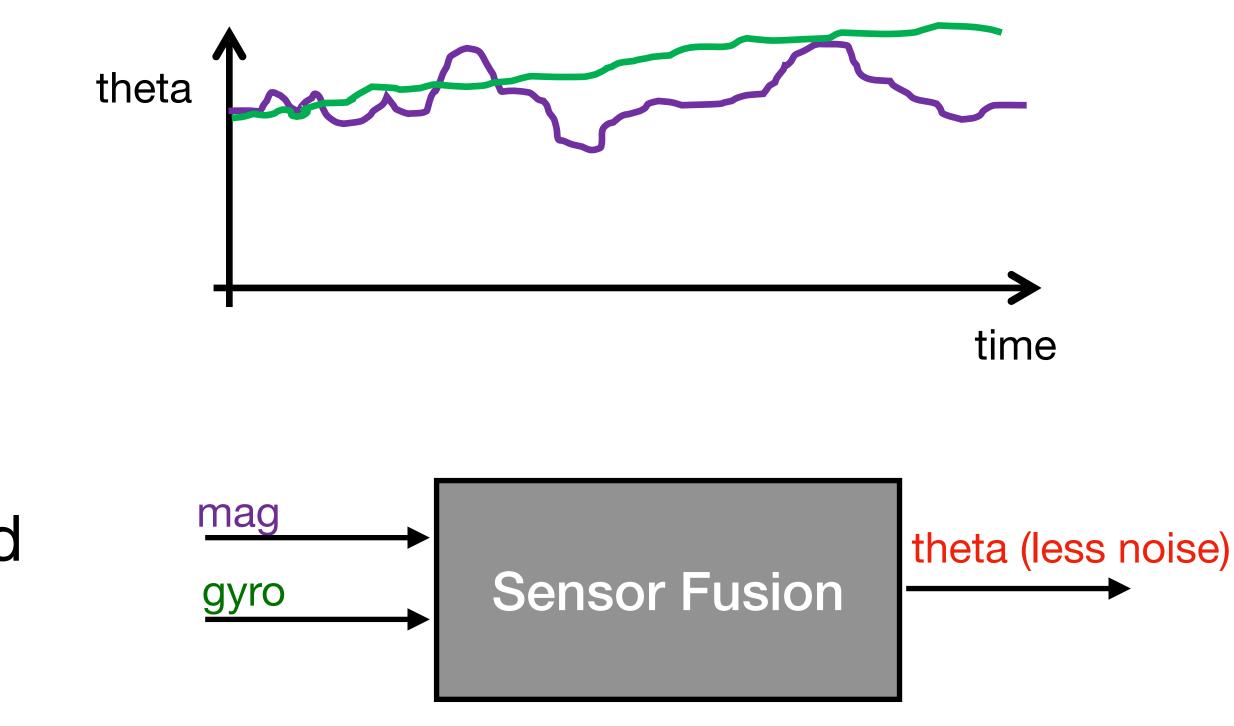


Increase the quality of the data: less noise, uncertainty, deviation



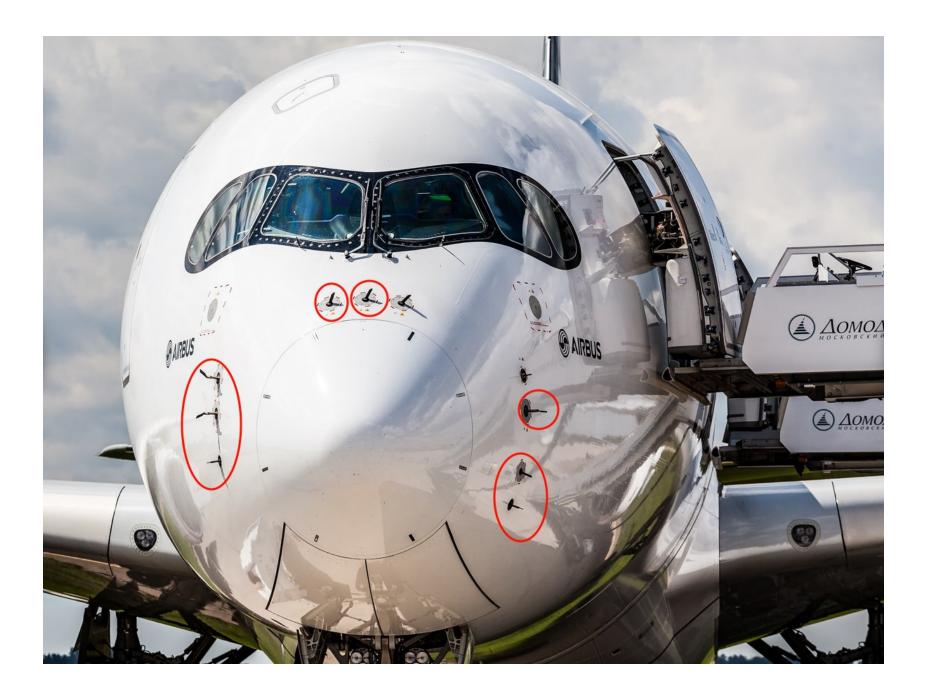
- Add a second mag?
- Move the sensor away from the field
- Low pass filter
- Fuse the mag data with the gyroscope data

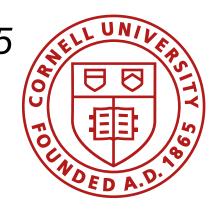


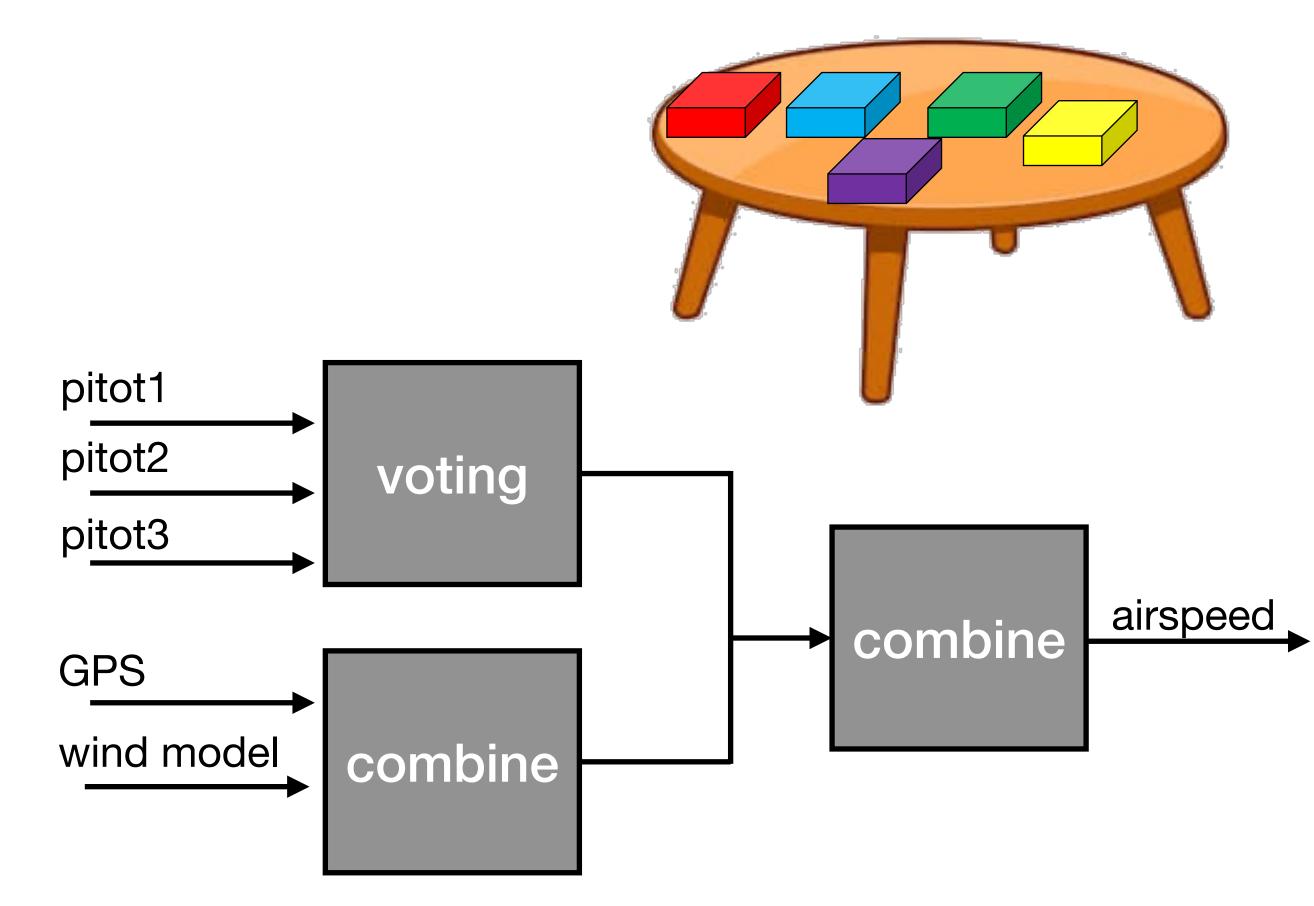




- Increase the quality of the data: less noise, uncertainty, deviation \bullet
- Increase data reliability \bullet

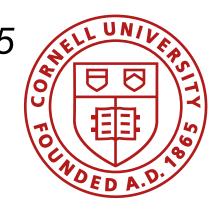


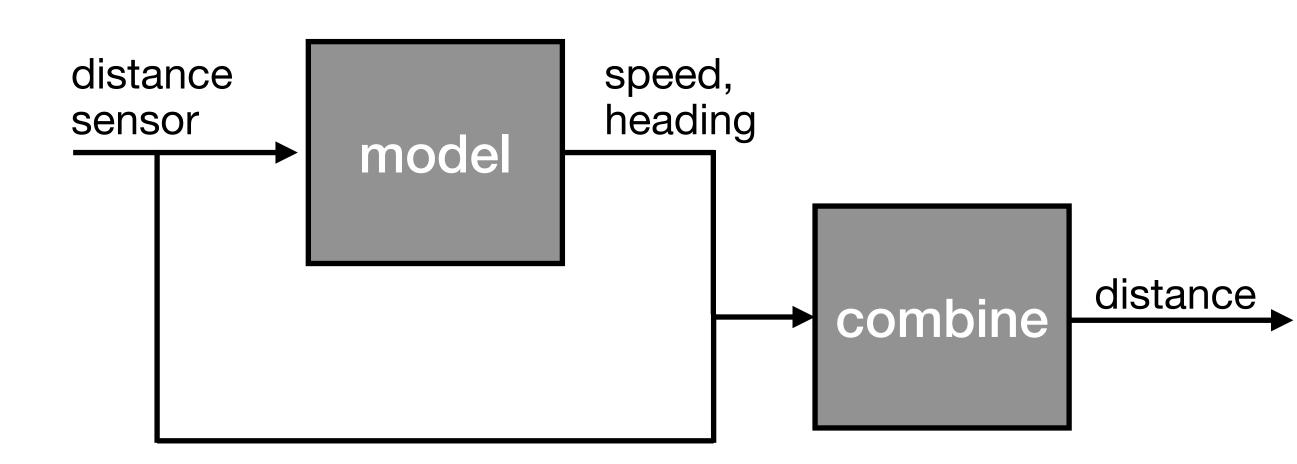




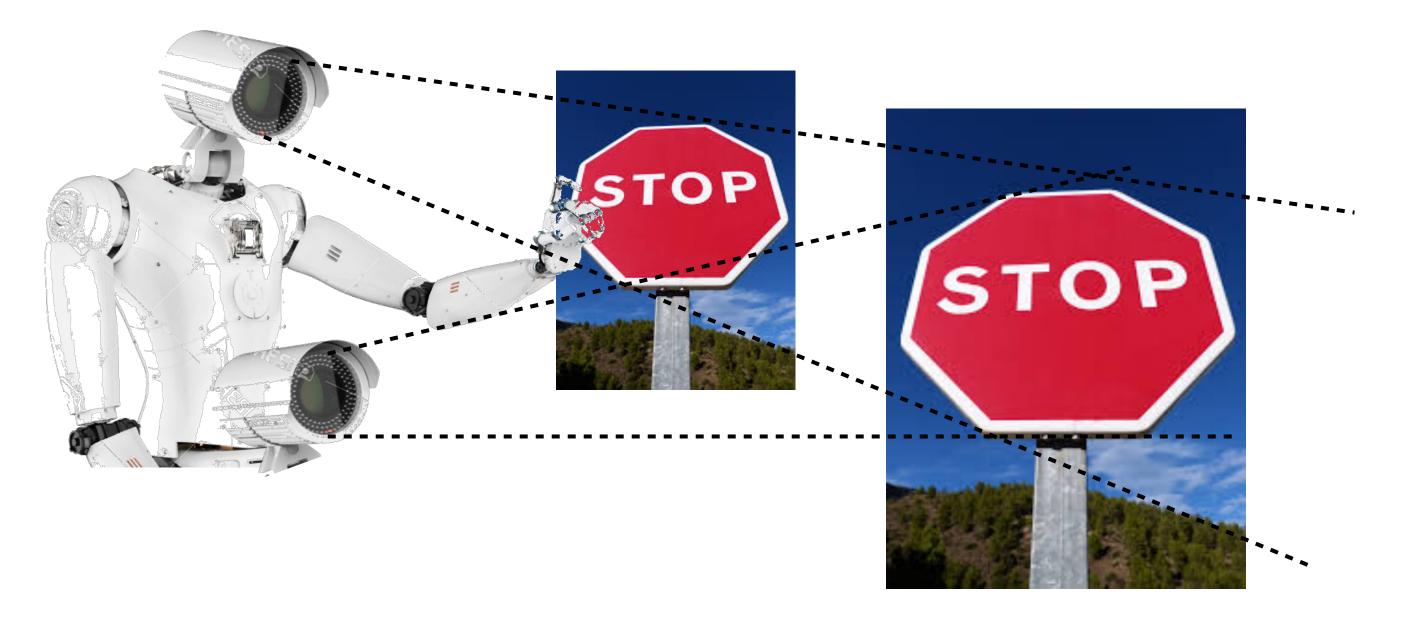
- Increase the quality of the data: less noise, uncertainty, deviation
- Increase data reliability \bullet

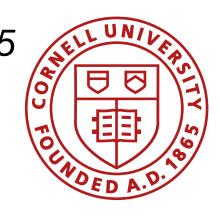


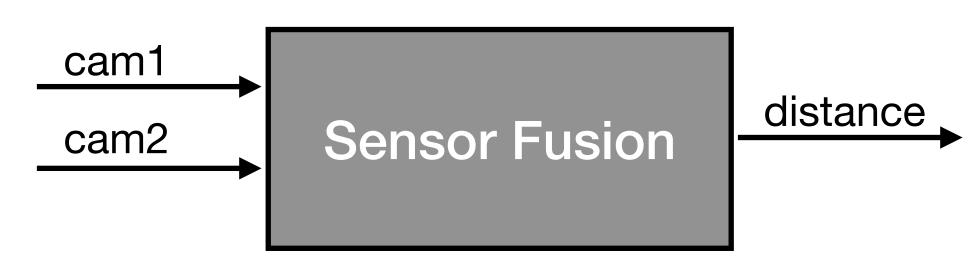




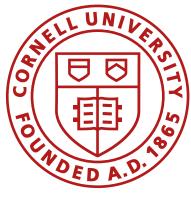
- Increase the quality of the data: less noise, uncertainty, deviation
- Increase data reliability
- Measure unmeasured states

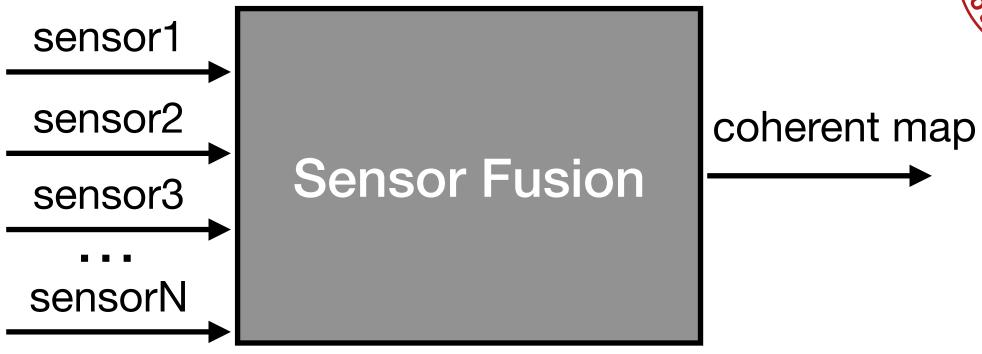


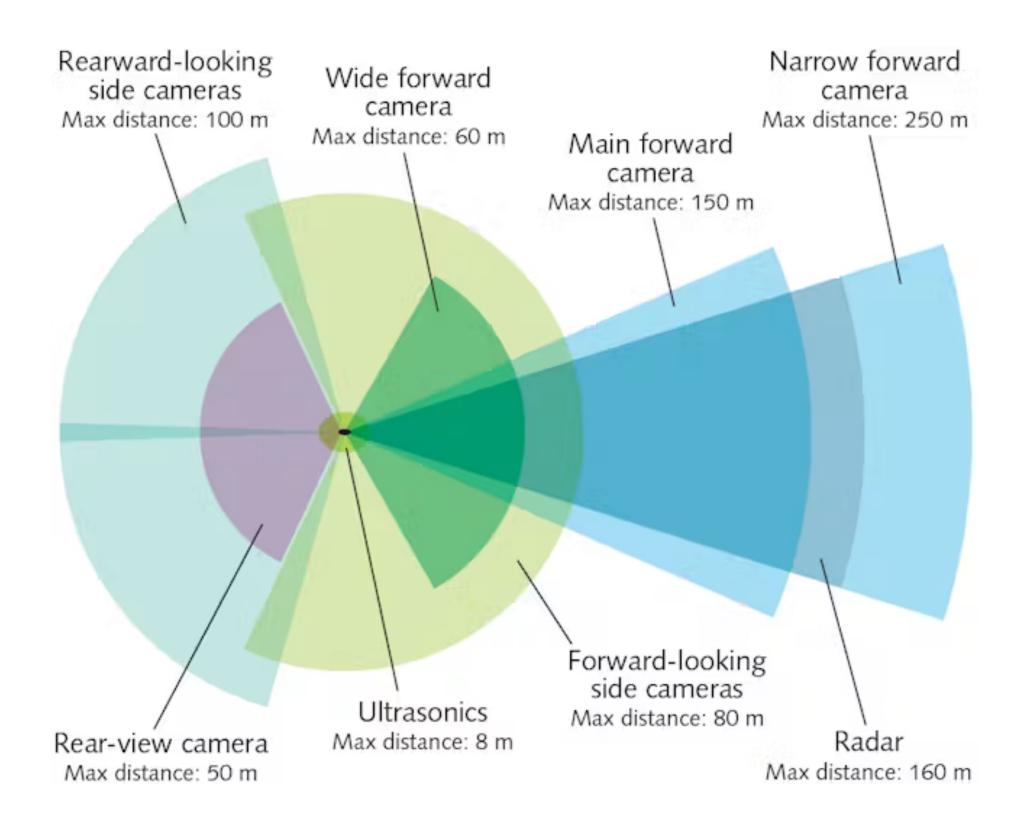




- Increase the quality of the data:
 - less noise, uncertainty, deviation
- Increase data reliability
- Measure unmeasured states
- Increase coverage area



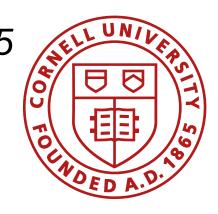




Sources and references

- http://www.cs.cmu.edu/~rasc/Download/AMRobots4.pdf
- https://www.ti.com/lit/ug/sbau305b/sbau305b.pdf? 2**F**
- https://hmc.edu/lair/ARW/ARW-Lecture01-Odometry.pdf
- Matlab Tech Talks on Sensor Fusion (https://www.youtube.com/watch?) v=6qV3YjFppuc)
- Prof. Kirstin Petersen

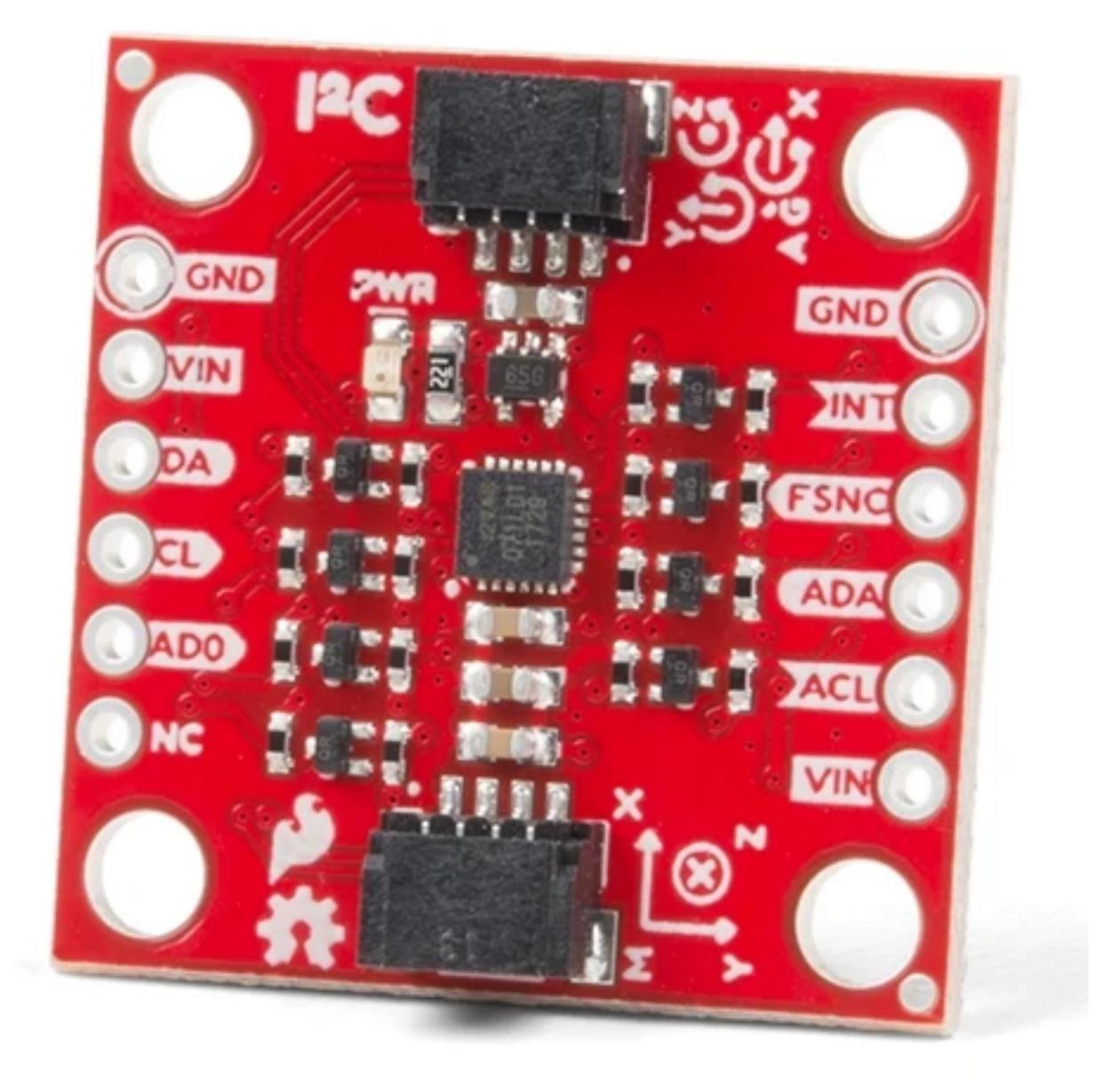
Fast Robots 2025

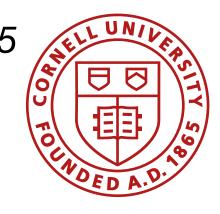




ts=1599417595209&ref_url=https%253A%252F%252Fwww.google.com%25

IMU

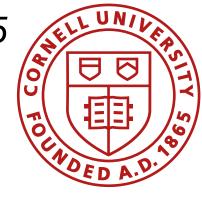




IMU

• Data related to orientation, velocity, and gravity





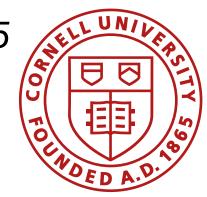


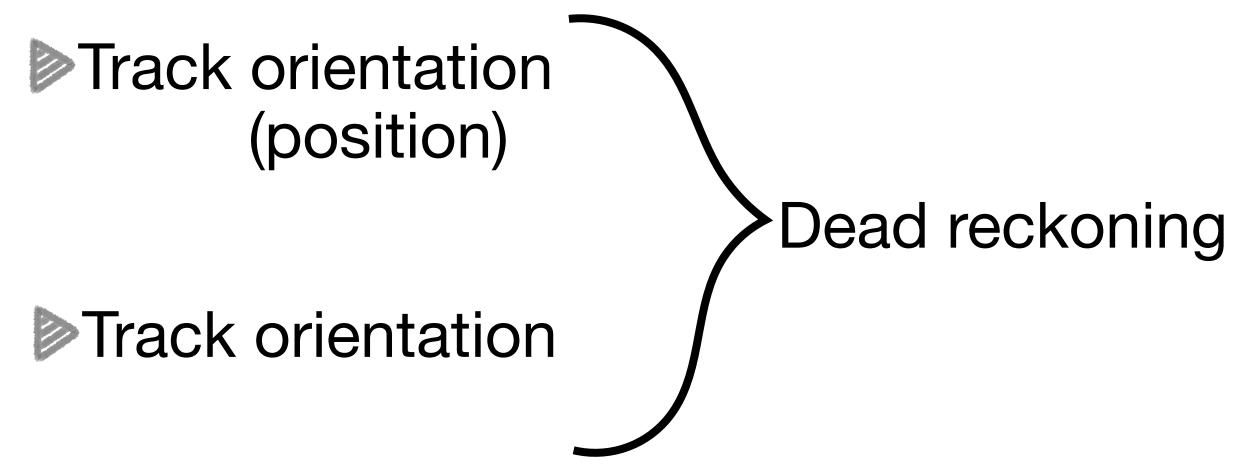


IMU

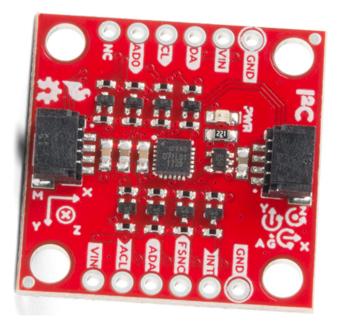
- Accelerometer
 - Linear acceleration, $a = \dot{v} [m/s^2]$
- Gyroscope
 - Angular velocity, $\omega = \frac{\Delta \theta}{\Delta t}$ [°/s]
- Magnetometer
 - Magnetic field strength, [uT] or [Gauss]
- NB: Gravity, magnetic fields, accelerations affect these sensors in many ways!

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➢Get absolute orientation



ICM-20948

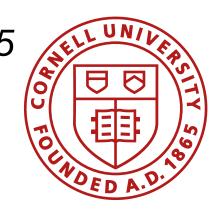
- \$16
- Low power
- 9-axis

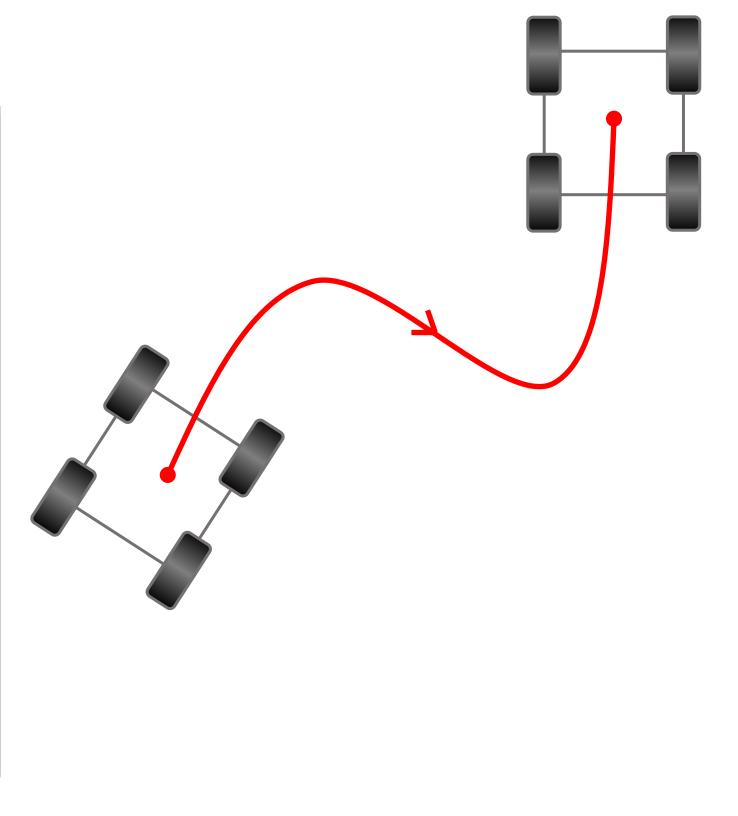
IMU Demo

- Install Sparkfun 9DOF IMU ICM 20948 library
- Follow the basics example

© COM4	×
	Send
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]	

Fast Robots 2025

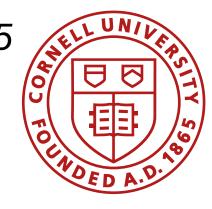




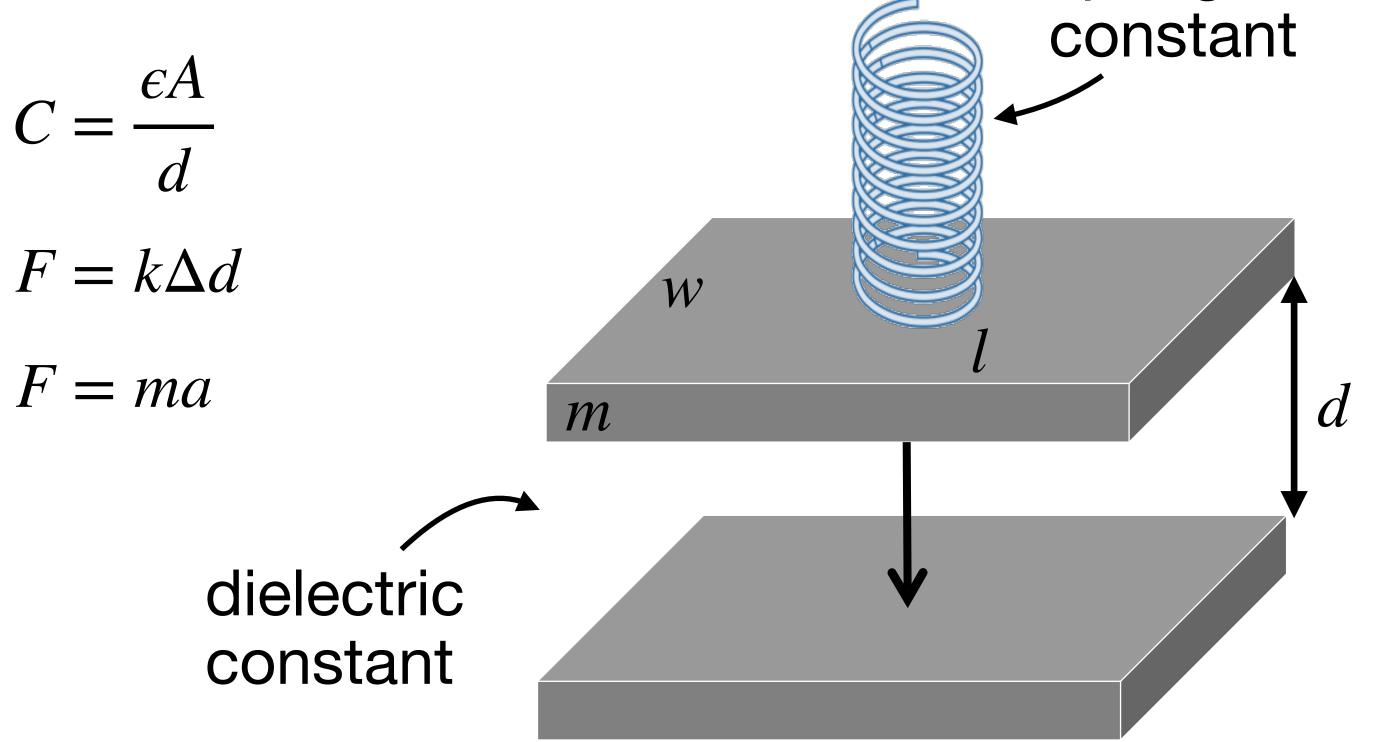
Newline

115200 baud ~ Clear output

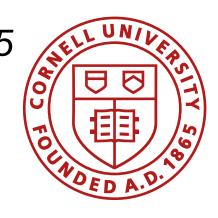
Accelerometer



Accelerometer **Measure acceleration**

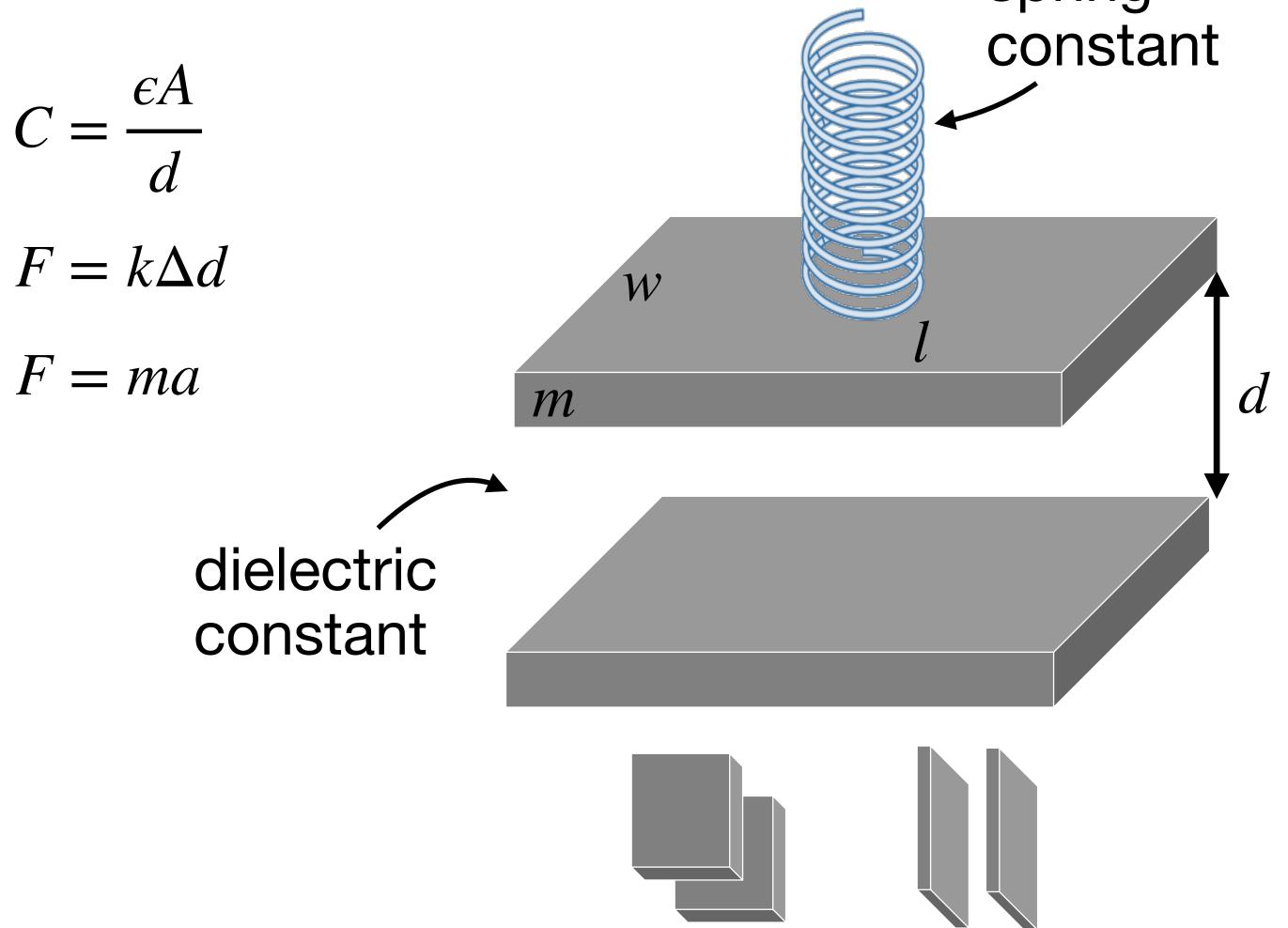


Fast Robots 2025

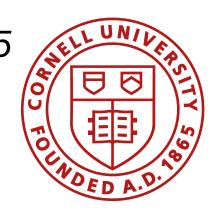


spring

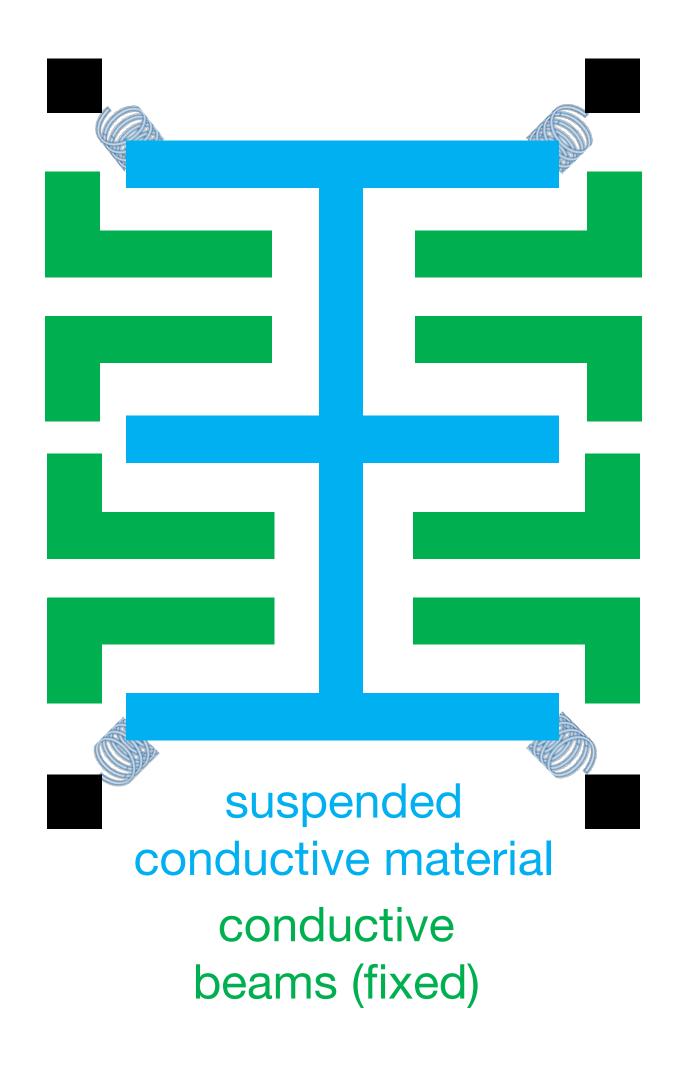
Accelerometer **Measure acceleration in 3D**



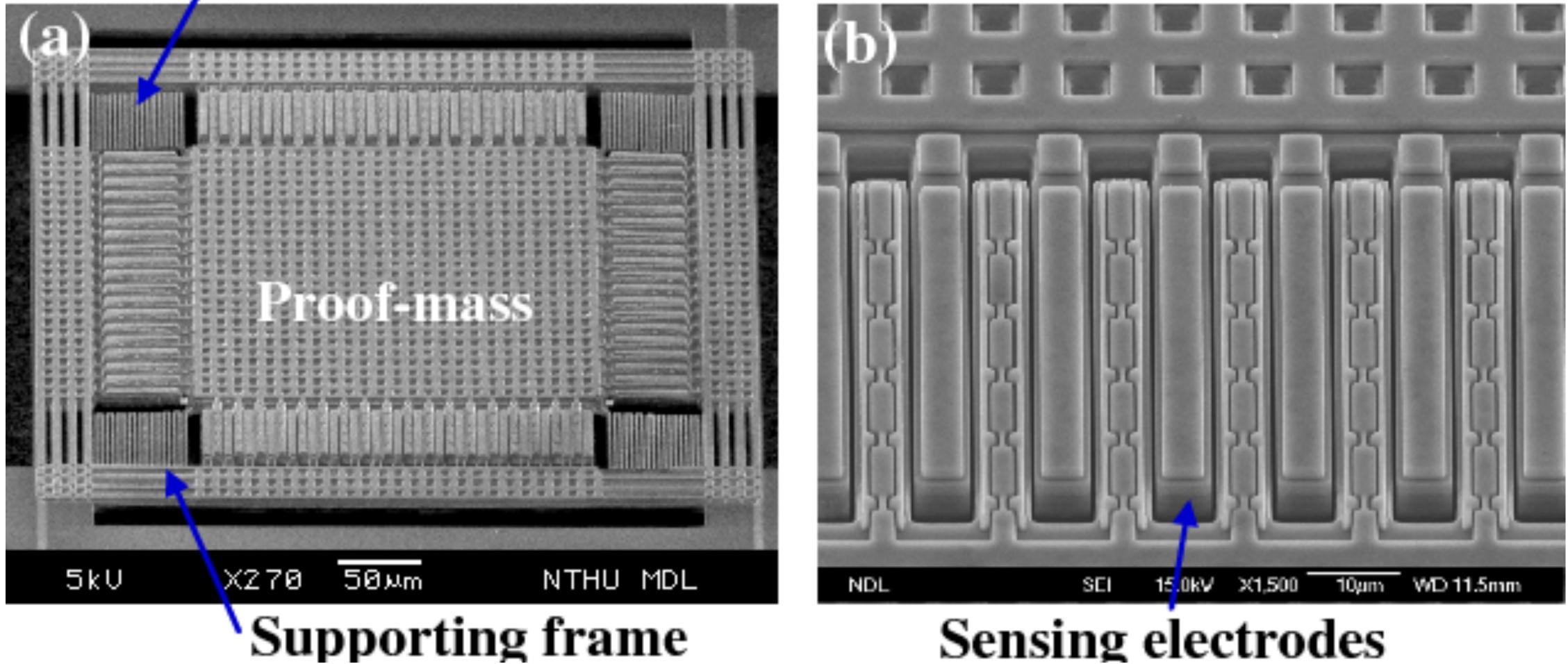
Fast Robots 2025



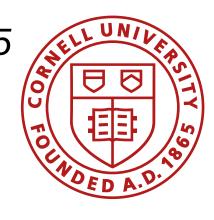
spring



Accelerometer Measure acceleration in 3D Spring

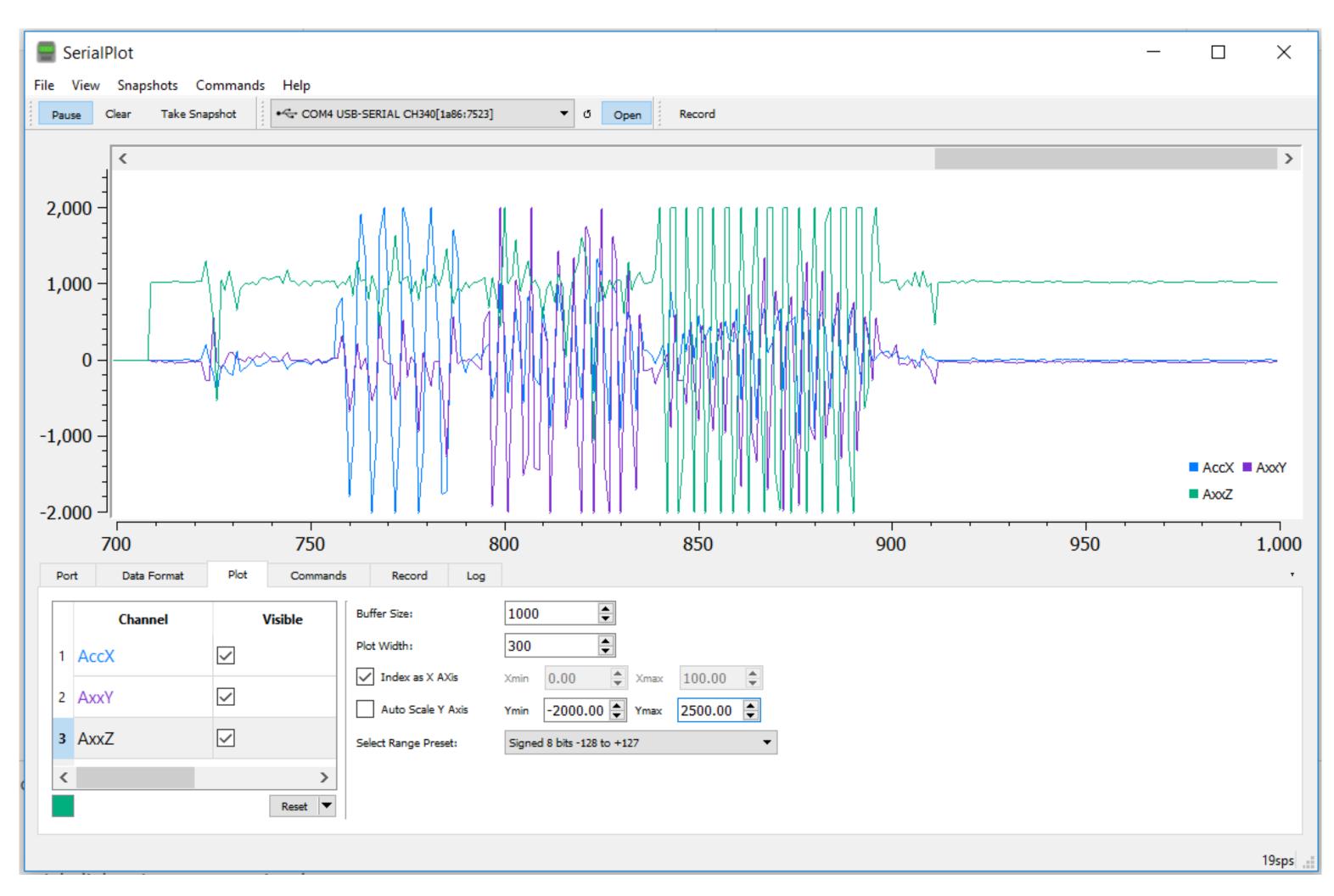


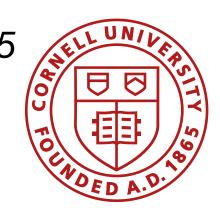
Fast Robots 2025



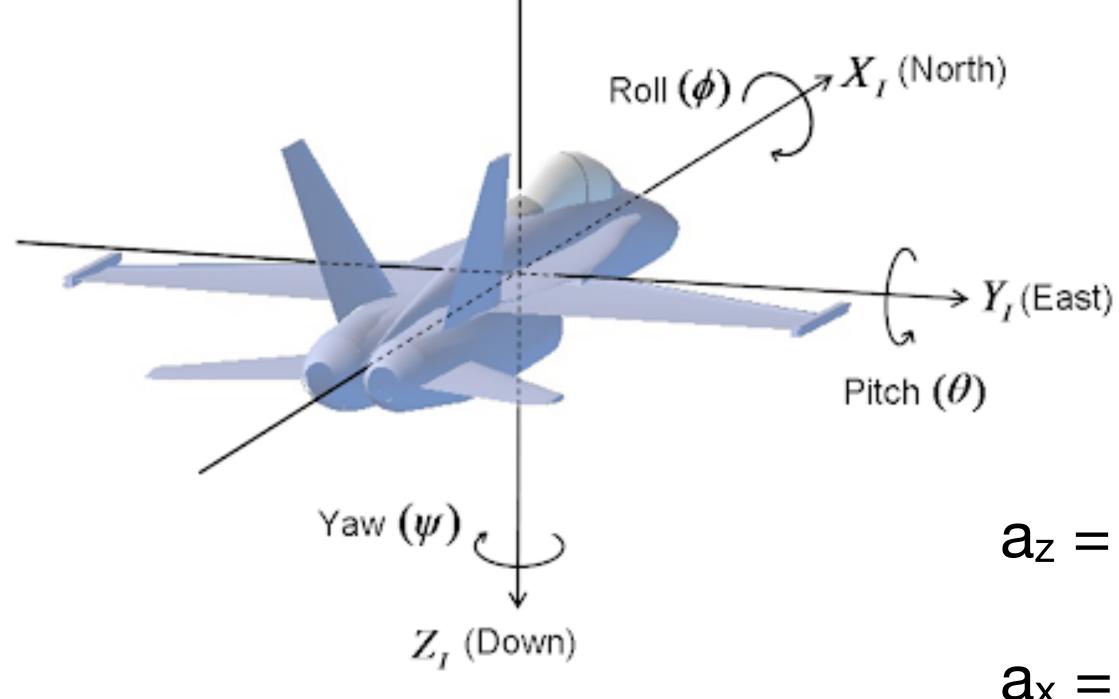
Fang, 2011

Accelerometer Use Serial Monitor or Serial Plot

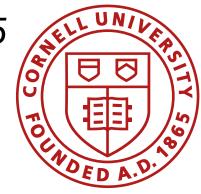


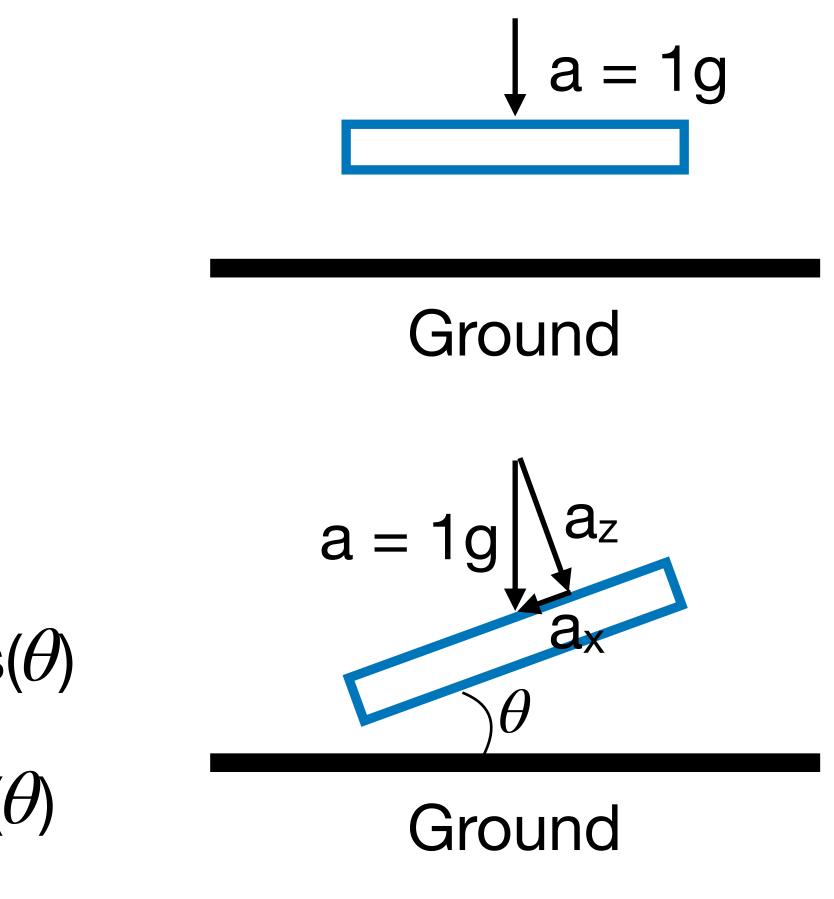


Accelerometer Roll, Pitch, Yaw





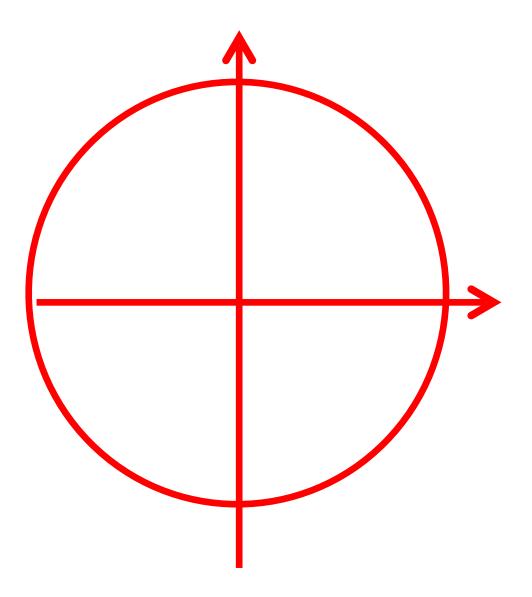




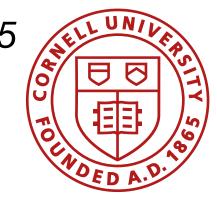
- $a_z = 1g \cos(\theta)$
- $a_x = 1g sin(\theta)$

atan vs. atan2

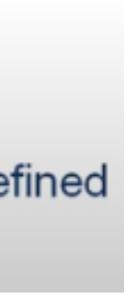
- $atan(a_x, a_z)$ returns $[-\pi/2, \pi/2]$
- Instead use atan2(a_x , a_z) which returns [- π , π]



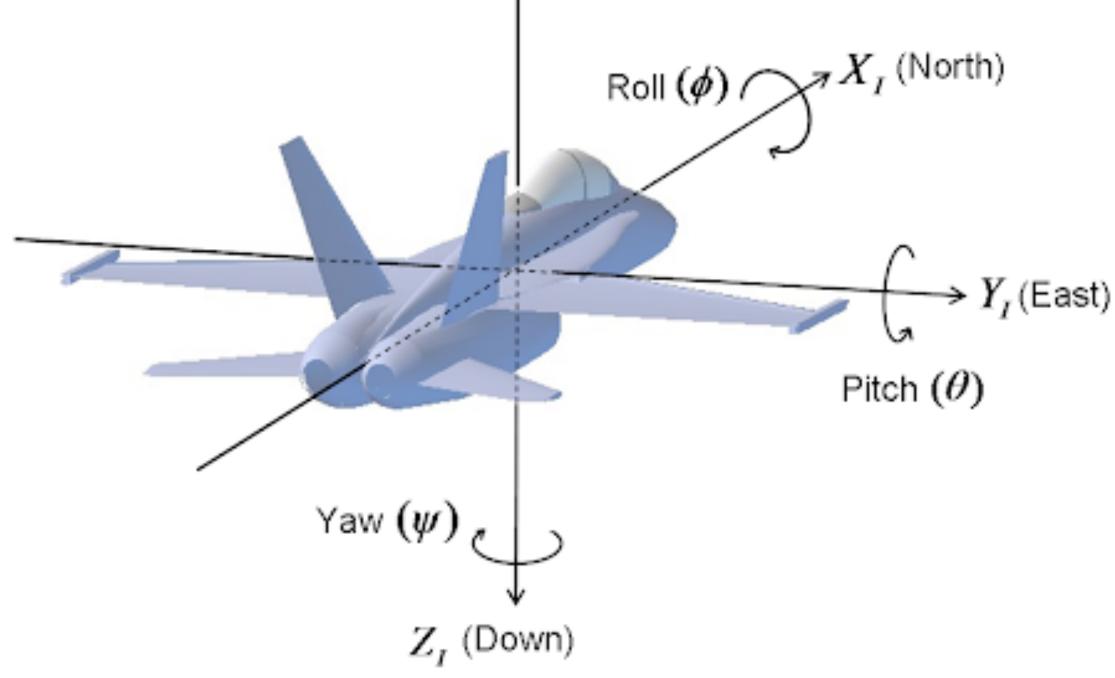
Fast Robots 2025



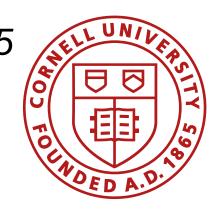
float atan2(float x, float y) { if (x > 0.0)return atan(y/x); if (x < 0.0) { if $(y \ge 0.0)$ return (PI + atan(y/x)); else return (-PI + atan(y/x)); if (y > 0.0) // x == 0return PI_ON_TWO; if (y < 0.0)return -PI ON TWO: return 0.0; // Should be undefined

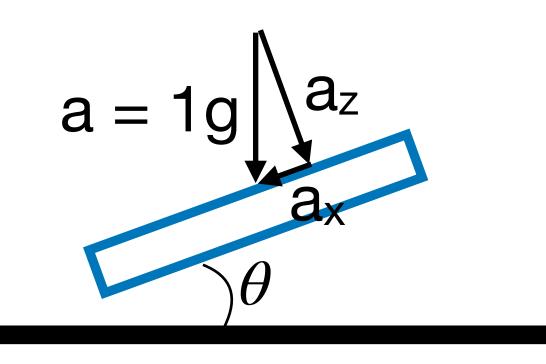


Accelerometer Roll, Pitch, Yaw



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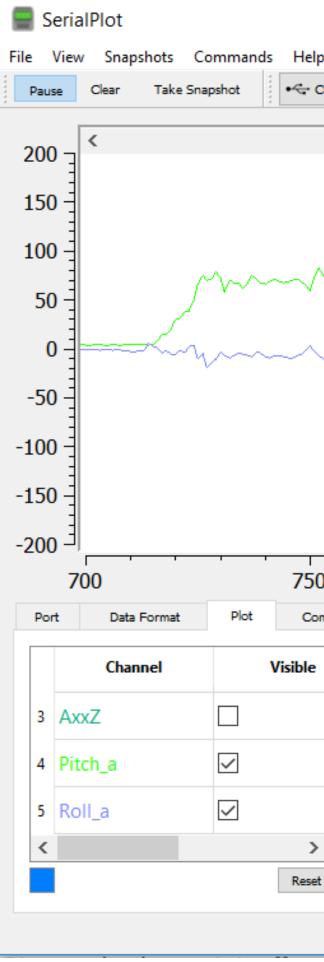
Ground

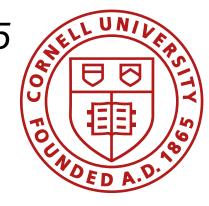
Can we estimate yaw?

- $a_z = 1g \cos(\theta)$ $a_x = 1g sin(\theta)$
- $\theta = \operatorname{atan2}(a_{x, a_z})$
- $\phi = \operatorname{atan2}(a_{y,} a_{z})$

Accelerometer Pitch and Roll

 $\theta = \operatorname{atan2}(a_{x,} a_{z})$ $\phi = \operatorname{atan2}(a_{y,} a_{z})$



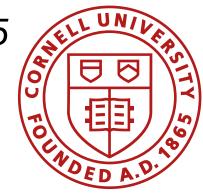


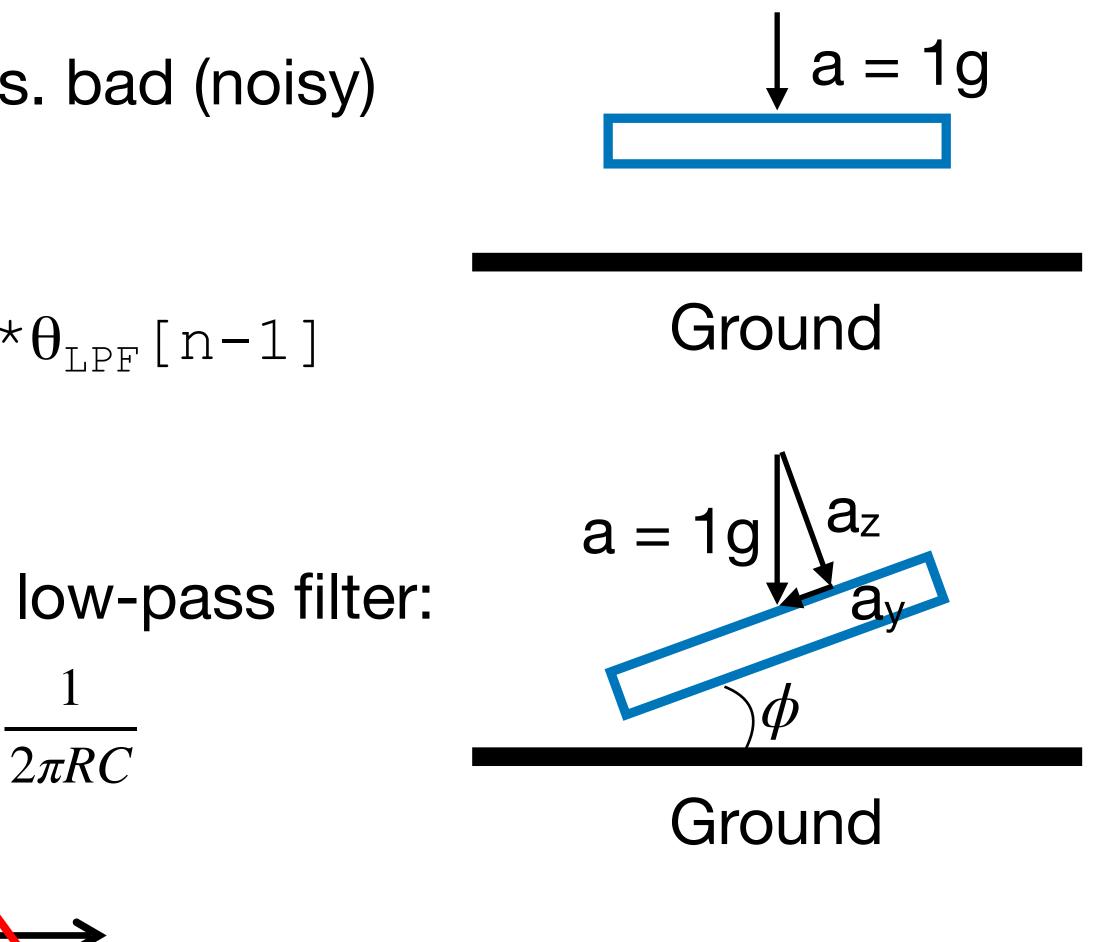
					_	
р						
COM4 U	SB-SERIAL CH340[1a86:7523]] 🔻 ර Ope	n Record			
						>
~						
					-	Roll_a 💻 Pitch_a
0	8	00	850	900	950	1,000
mmand	s Record Log					Ŧ
^	Buffer Size:	1000				
_	Plot Width:	300				
	Index as X AXis		Xmax 100.00 🚖			
	Auto Scale Y Axis		Ymax 200.00 🚖			
~	Select Range Preset:	Signed 8 bits -128 to +127				
~						
•						
t ▼						

Accelerometer Roll and Pitch

- Good (very accurate on average) vs. bad (noisy)
- Low pass filter

$$\theta_{\text{LPF}}[n] = \alpha * \theta_{\text{RAW}} + (1 - \alpha) *$$
$$\theta_{\text{LPF}}[n-1] = \theta_{\text{LPF}}[n]$$



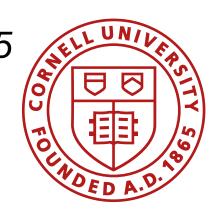


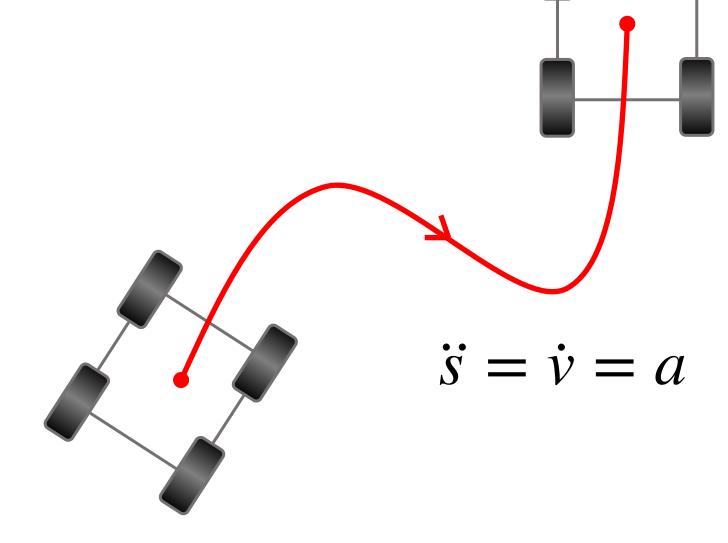
Accelerometer **Dead Reckoning**

• Use the accelerometer to do dead reckoning? v = as = ||a|

v[k+1] = v[k] + a[k]*dts[k+1] = s[k] + v[k]*dt

• If you do this at home, remember unit conversion! Accelerometer output is in mg (1g ~9.81 m/s²)

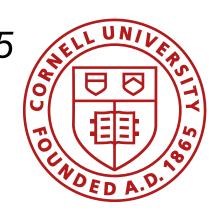




Accelerometer **Dead Reckoning**

- Issue: Distinguishing sensor acceleration from gravity
 - **Solution 1**: Calibrate the offset
 - Solution 2: Low pass filter
 - Solution 3: Minimum signal cut-off

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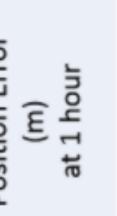


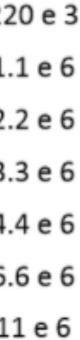
Errors only accumulate, and they grow fast!

				W	ww.chrobotics.co	m
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
0.1	0.017	0.17	1.7	61.2	6120	22
0.5	0.086	0.86	8.6	309.6	30960	1.1
1.0	0.17	1.7	17	612	61200	2.2
1.5	0.256	2.56	25.6	921.6	92160	3.3
2.0	0.342	3.42	34.2	1231.2	123120	4.4
3.0	0.513	5.13	51.3	1846.8	184680	6.6
5.0	0.854	8.54	85.4	3074.4	307440	11

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

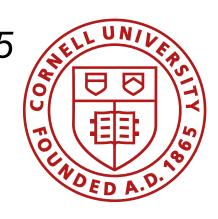


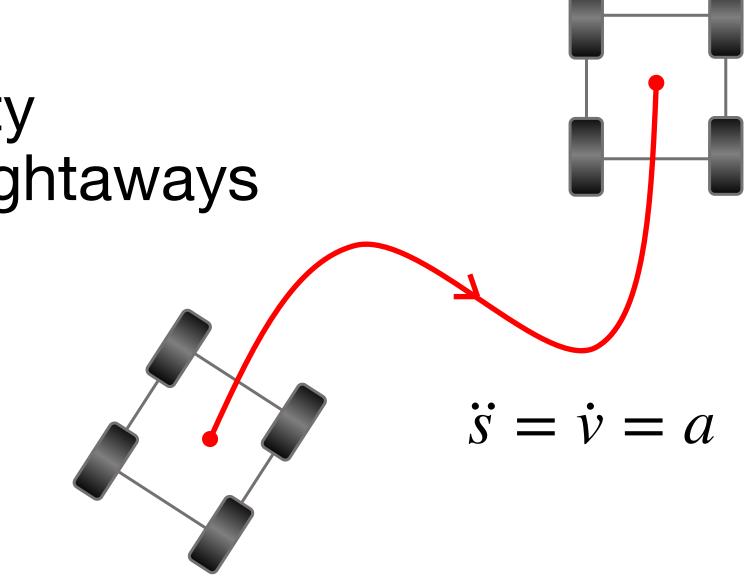




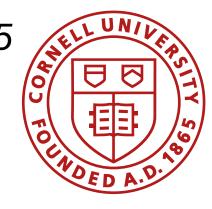
Accelerometer **Dead Reckoning**

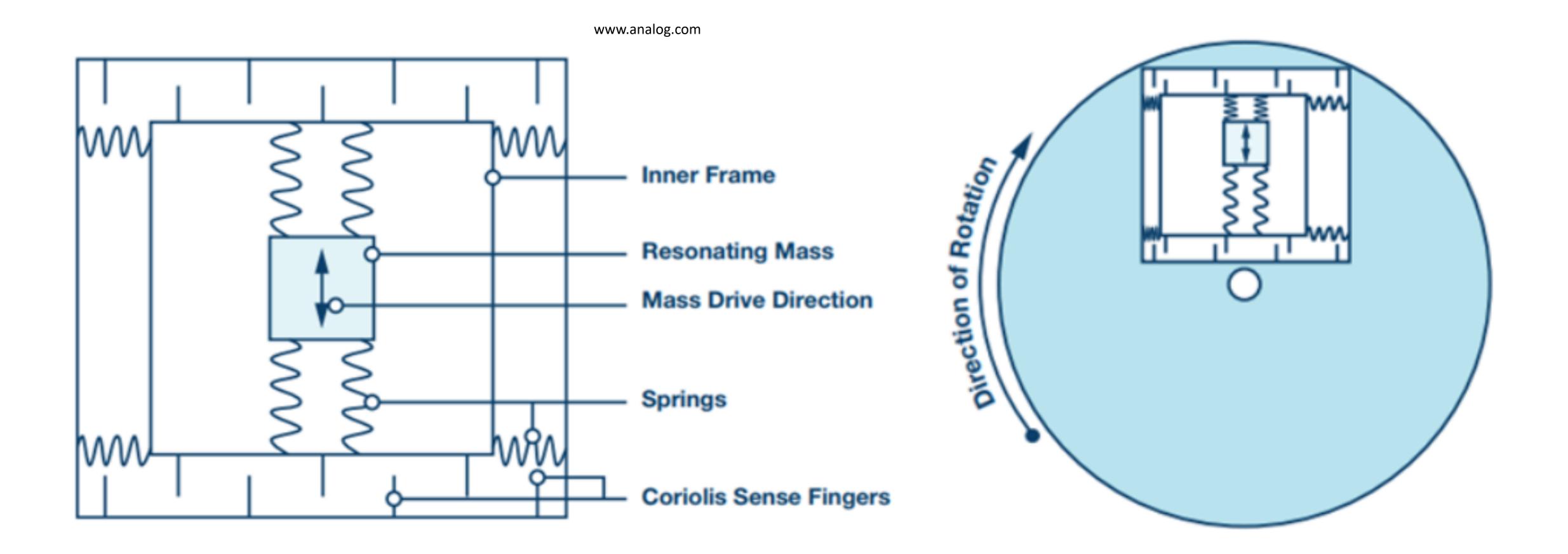
- Issue: Distinguishing sensor acceleration from gravity
 - **Solution 1**: Calibrate the offset
 - Solution 2: Low pass filter
 - Solution 3: Minimum signal cut-off
 - Solution 4: Stop periodically and zero the velocity
 - Solution 5: Use in combination with ToF on straightaways
 - Solution 6: Buy a more expensive IMU
 - etc...

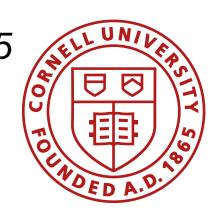


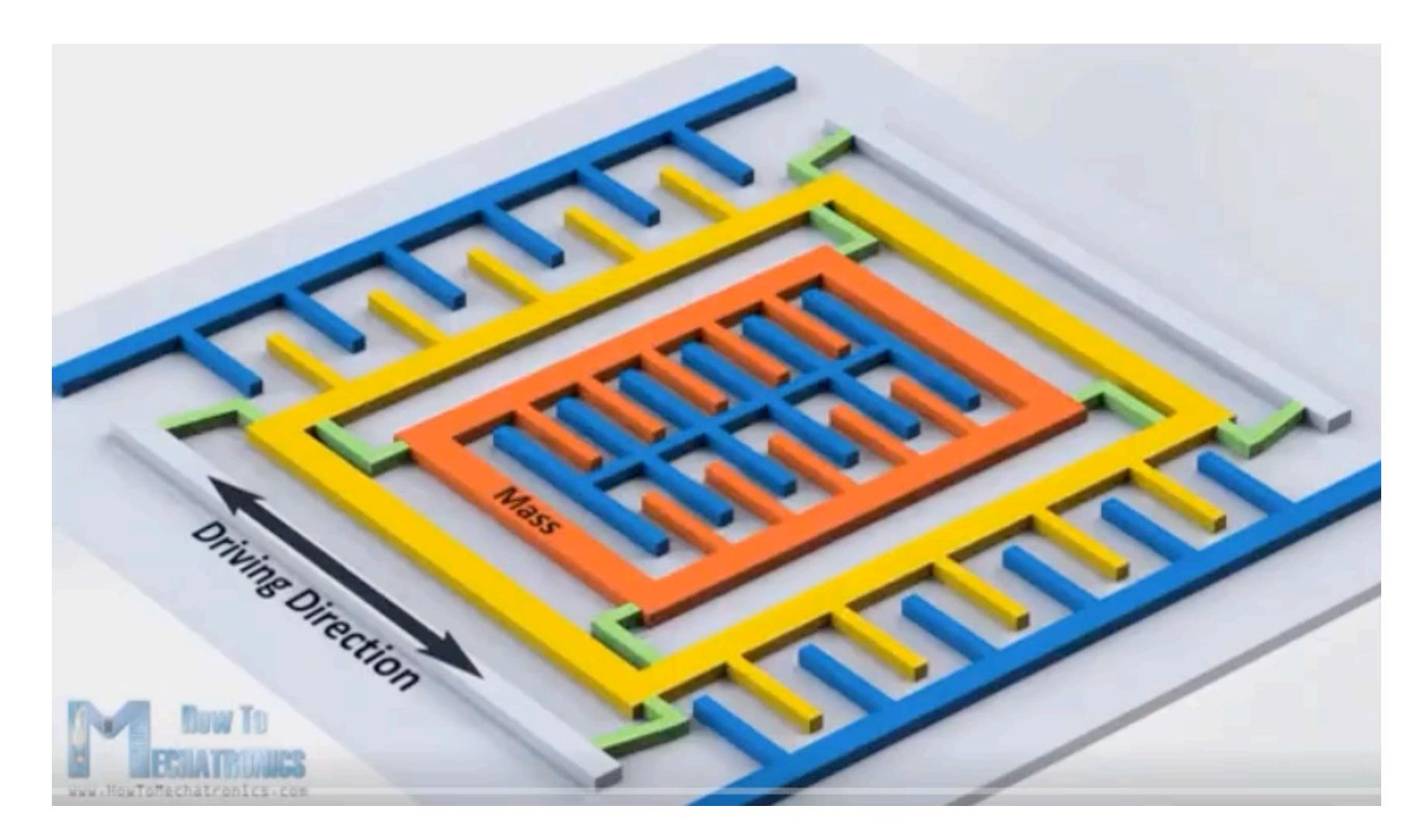


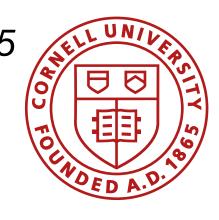
Gyroscope



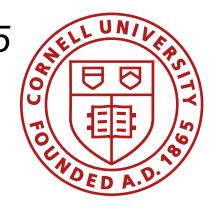


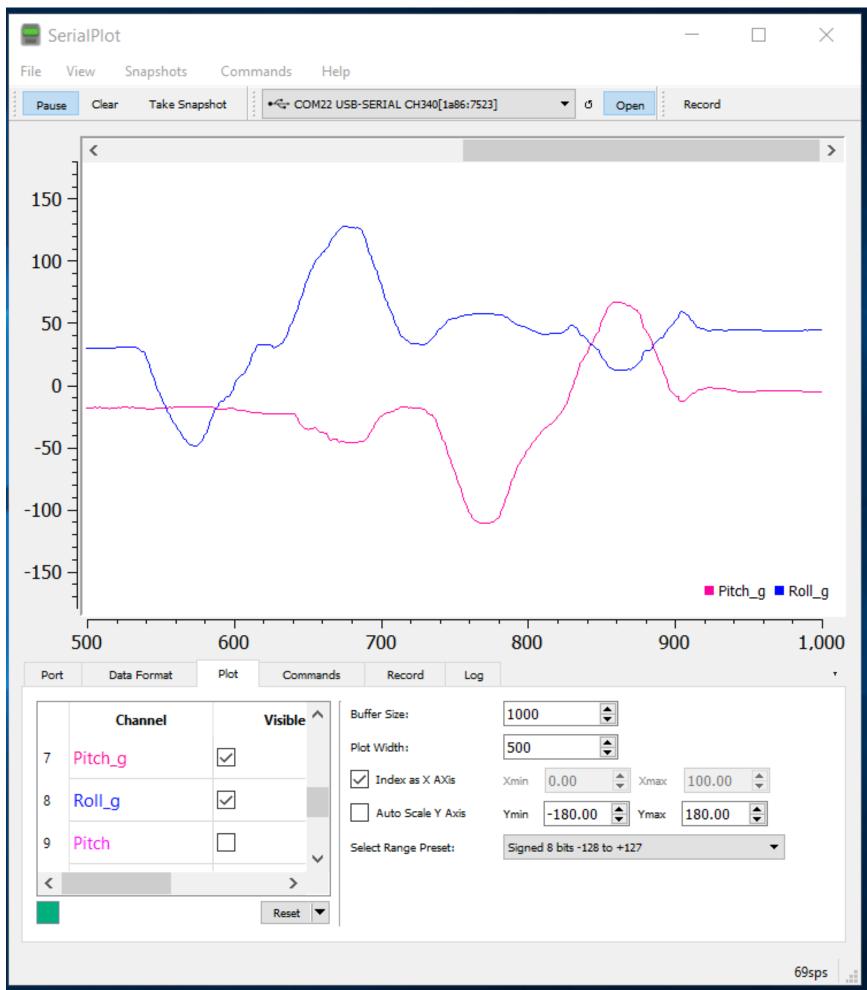






- How to measure angles?
 - $\theta_g = \theta_g + \text{gyro}_{\text{reading}} \times \text{dt}$
- Drift, but low noise

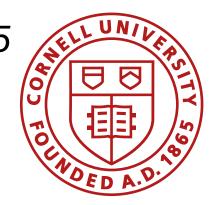


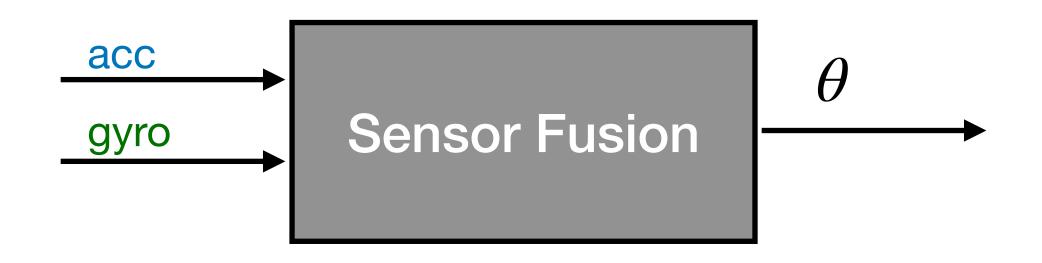


- How to measure angles?
 - $\theta_g = \theta_g + \text{gyro}_{\text{reading}} \times \text{dt}$
- Drift, but low noise
- Complementary filter:

•
$$\theta = (\theta + \theta_g)(1 - \alpha) + \theta_a \alpha$$

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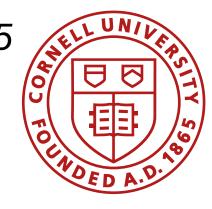




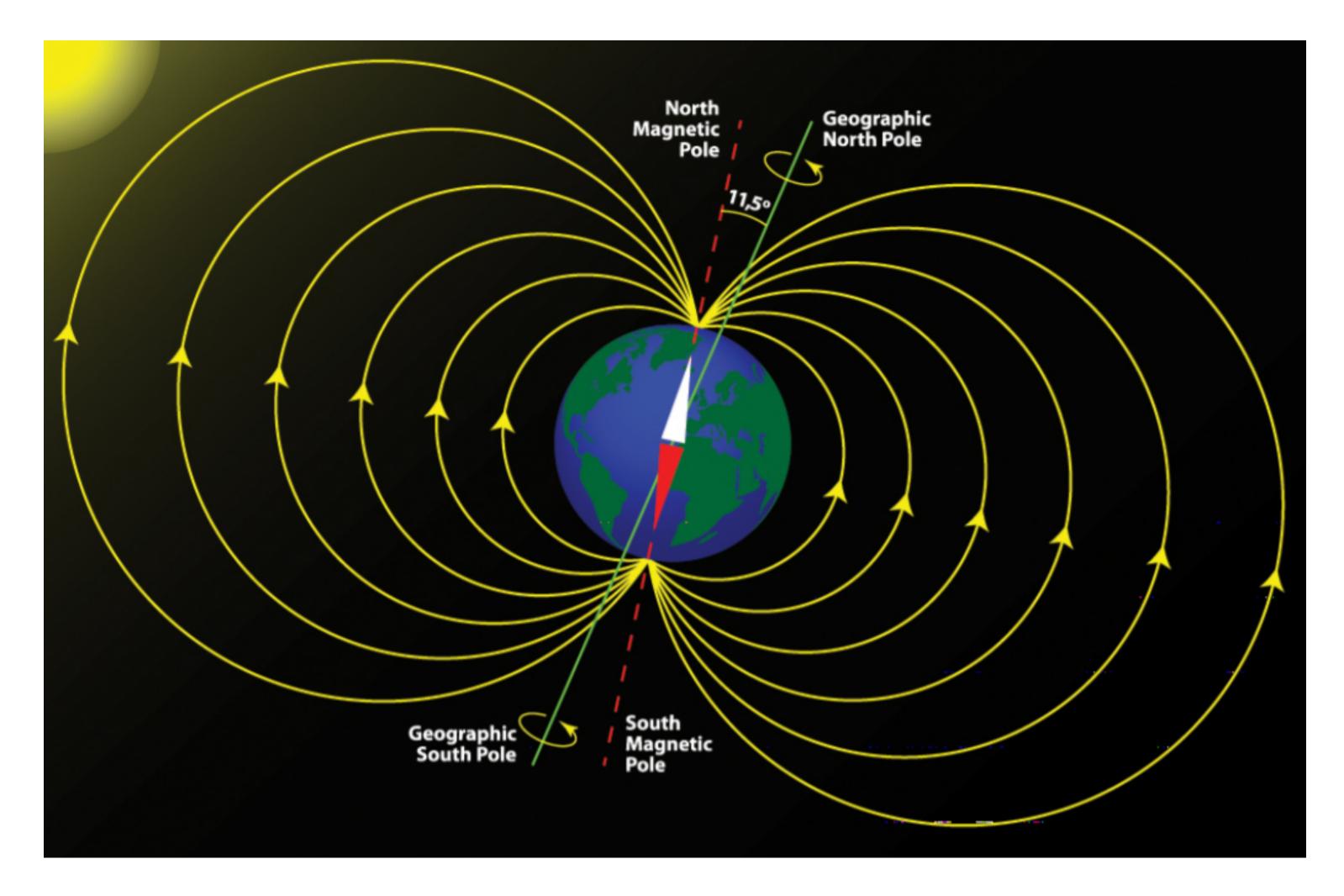
Can we estimate yaw?

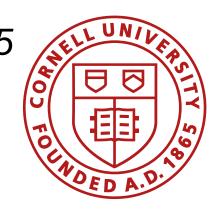
Yes, but no complementary data from the accelerometer

Magnetometer



• Depends on location, time

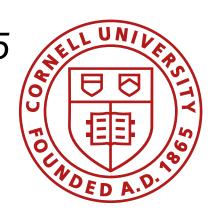


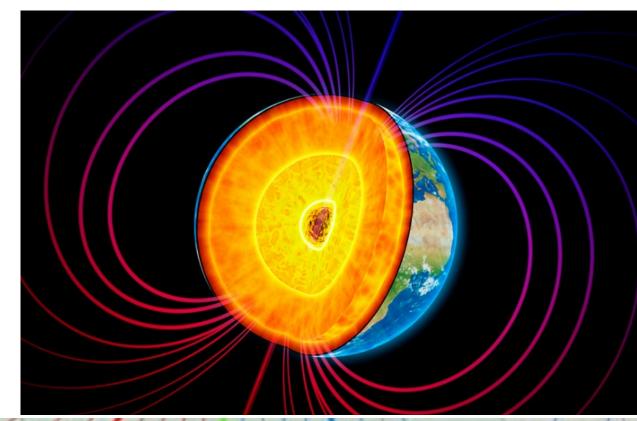


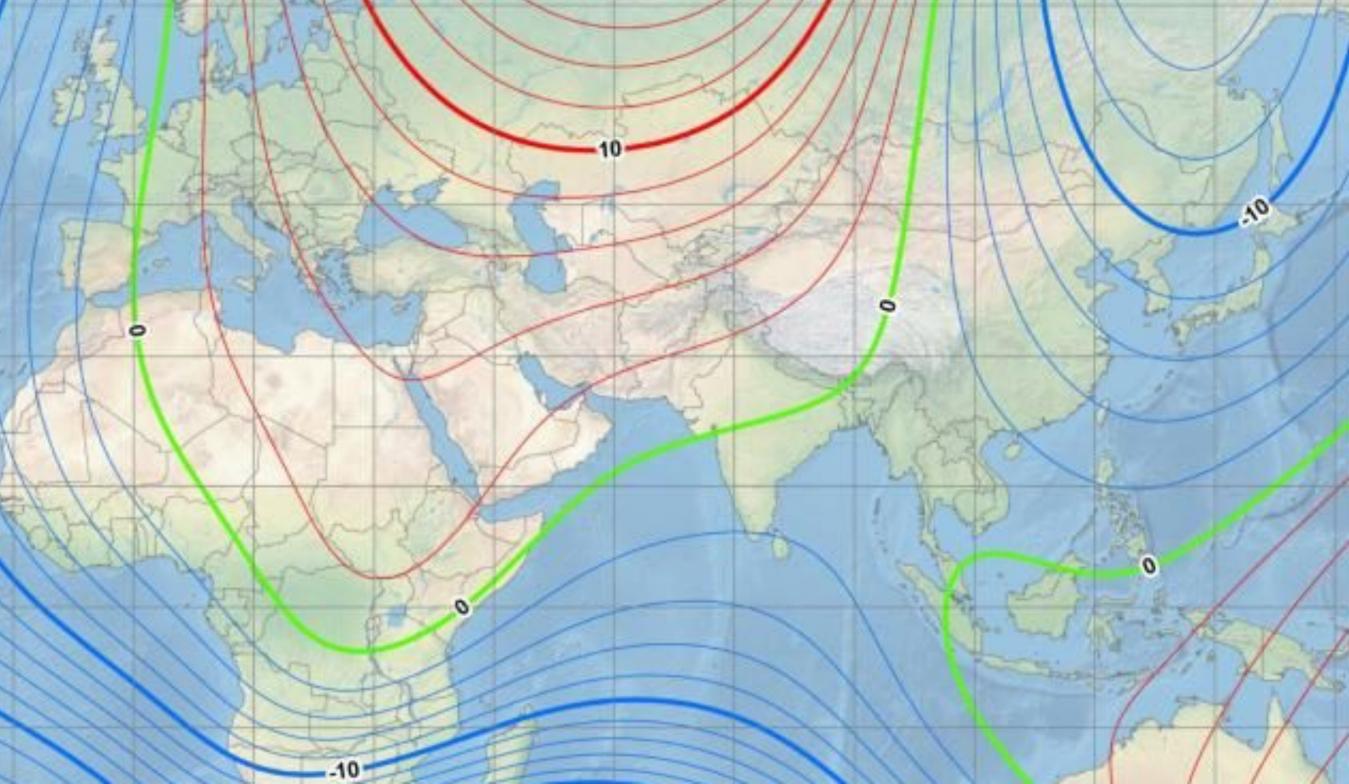
- Depends on location, time
- Distortion due to metal objects or nearby EM fields

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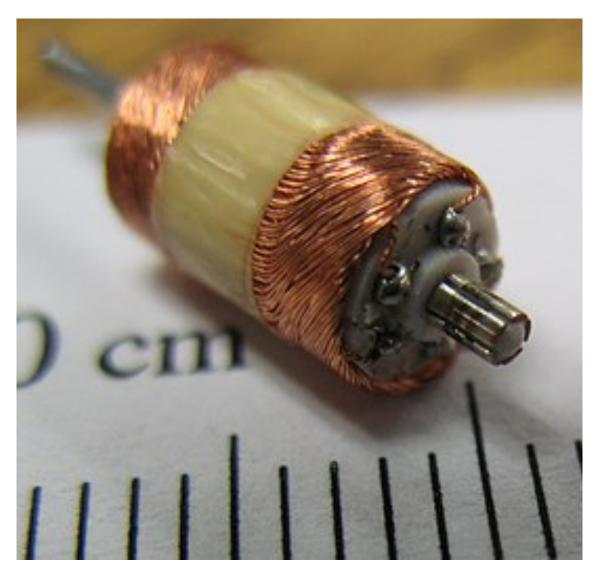




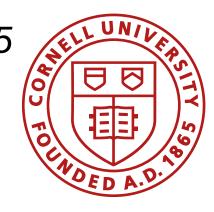




- Depends on location, time
- Distortion due to metal objects or nearby EM fields Examples





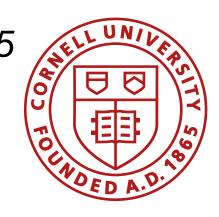


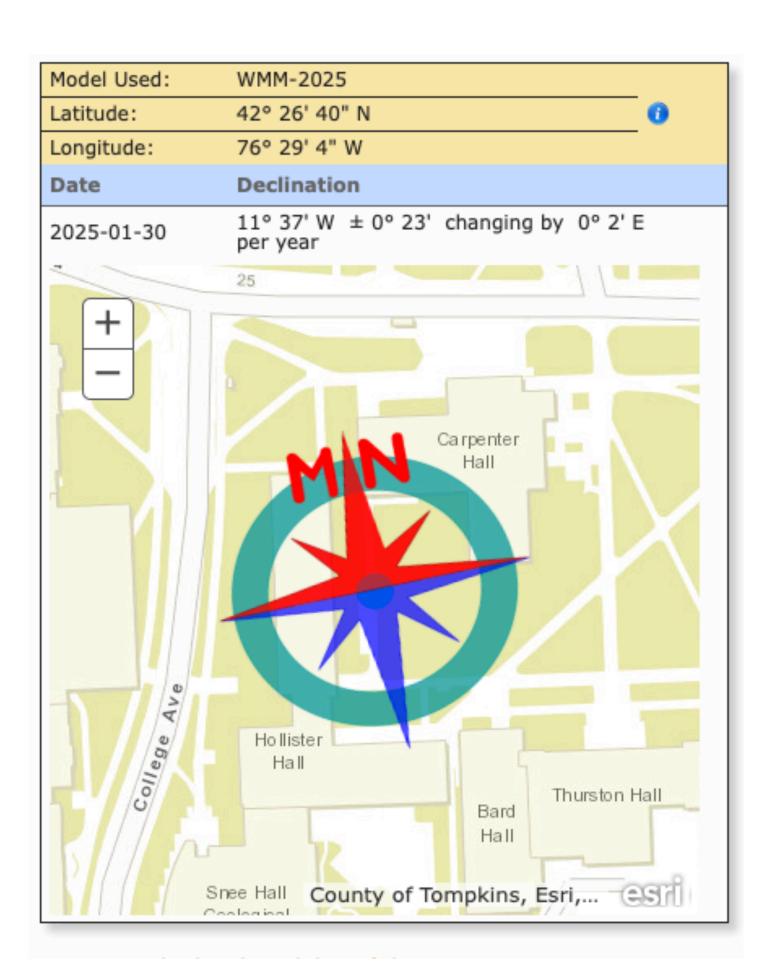




Magnetic North is along the xmax-axis

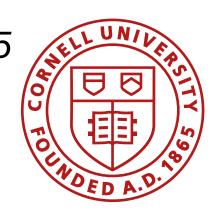
Model Used:	WMM-2025									
Latitude:	42° 26' 40" N									
Longitude:	76° 29' 4" W	6° 29' 4" W								
Elevation:	0.0 km Mean Sea l).0 km Mean Sea Level								
Date	Declination (+E -W)	Inclination (+ D - U)	Horizontal Intensity	North Comp (+ N - S)	East Comp (+ E - W)	Vertical Comp (+ D - U)	Total Field			
2025-01-29	-11° 37' 27"	67° 33' 22"	19,914.2 nT	19,505.8 nT	-4,012.5 nT	48,210.8 nT	52,161.8 nT			
Change/year	0° 2' 18"/yr	-0° 5' 56"/yr	41.5 nT/yr	43.4 nT/yr	4.7 nT/yr	-135.1 nT/yr	-109.0 nT/yr			
Uncertainty	0° 23'	0° 12'	133 nT	137 nT	89 nT	141 nT	138 nT			

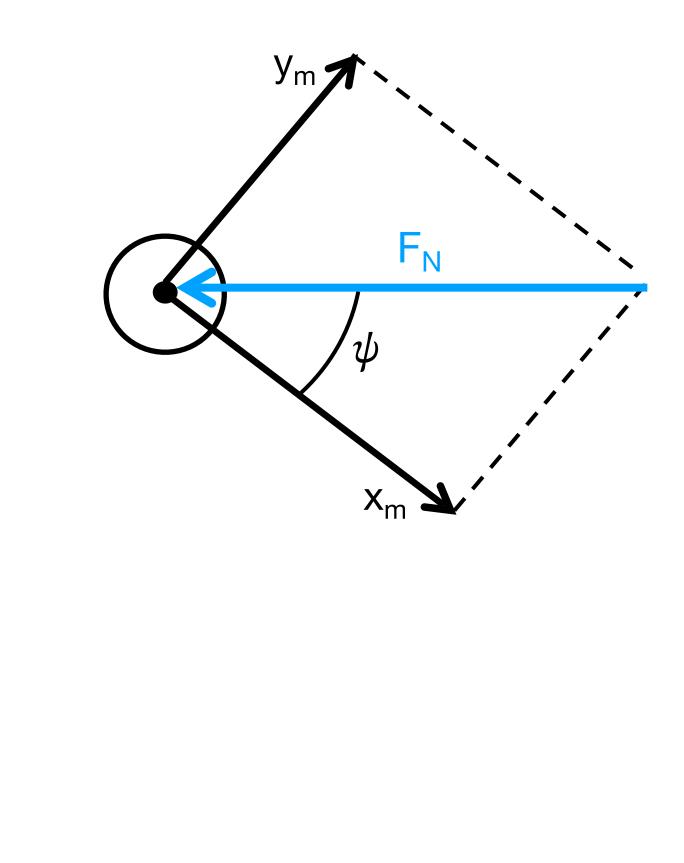


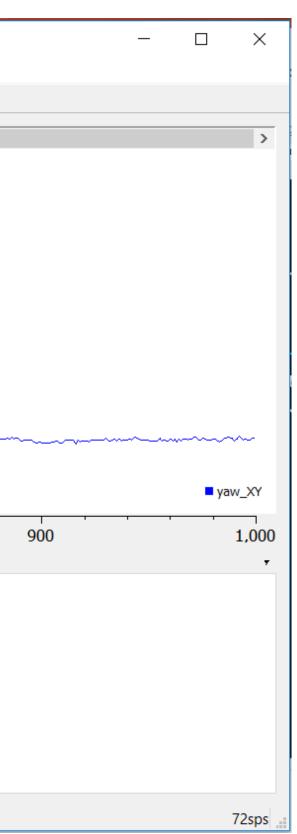


• $\psi = \operatorname{atan2}(x_m, y_m)$

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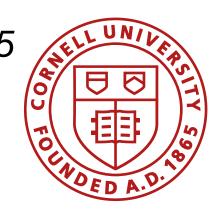


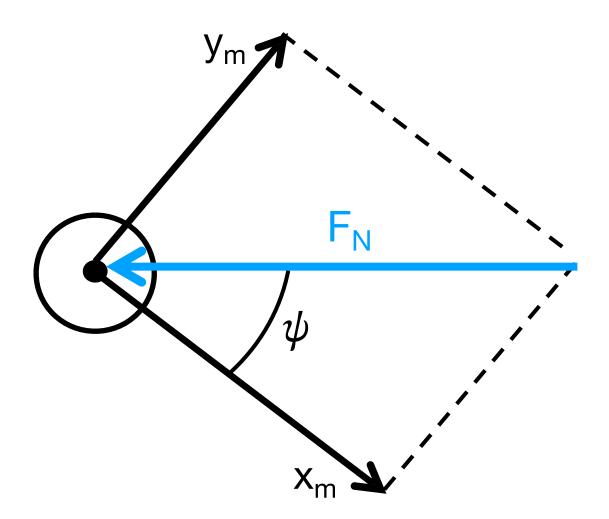


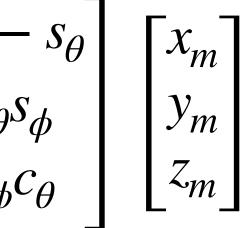
•
$$\psi = \operatorname{atan2}(x_m, y_m)$$

• How to compensate for tilt? — Fuse data

$$\begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix} = R_{x,\phi} R_{y,\theta} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$
$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R_{x,\phi}^T R_{y,\theta}^T \begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix} = \begin{bmatrix} c_\theta & 0 & c_\phi - c_\phi \\ s_\phi s_\theta & c_\phi & c_\theta \\ c_\phi s_\theta & -s_\phi & c_\phi \end{bmatrix}$$







$$x = y_m \cos(\phi) - z_m \sin(\phi)$$

$$y = x_m \cos(\theta) + y_m \sin(\phi) \sin(\theta)$$

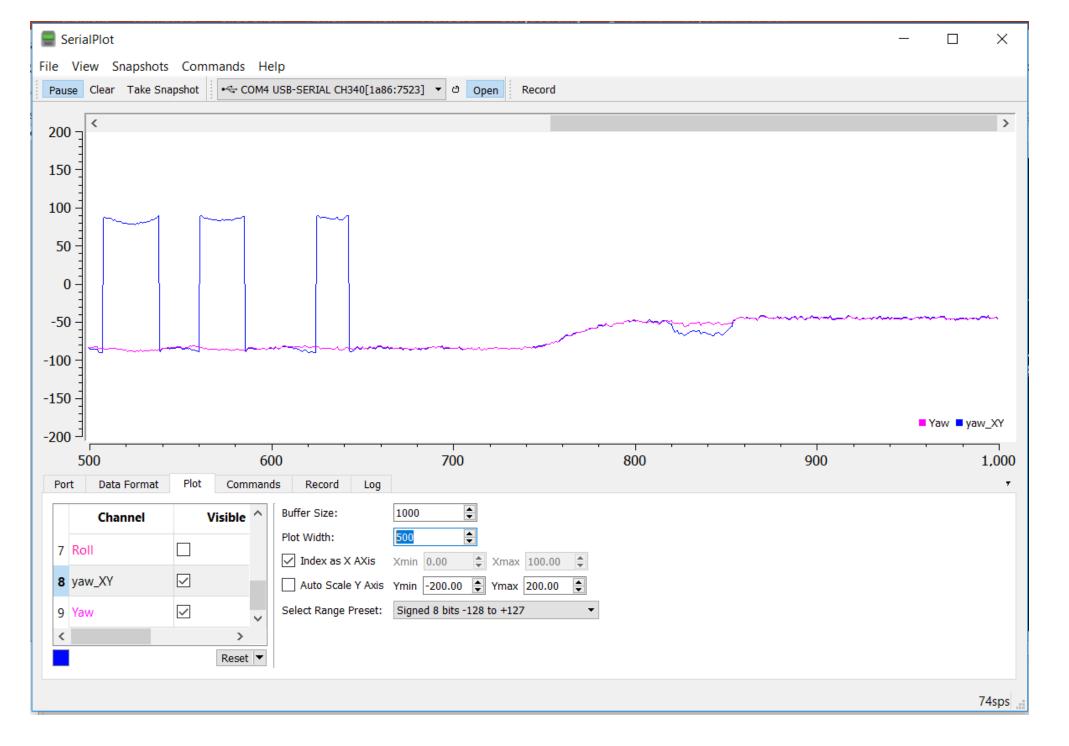
$$+ z_m \cos(\phi) \sin(\theta)$$

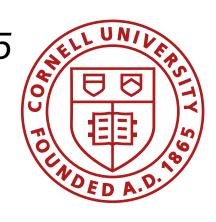
$$\psi = \operatorname{atan2}(x, y)$$

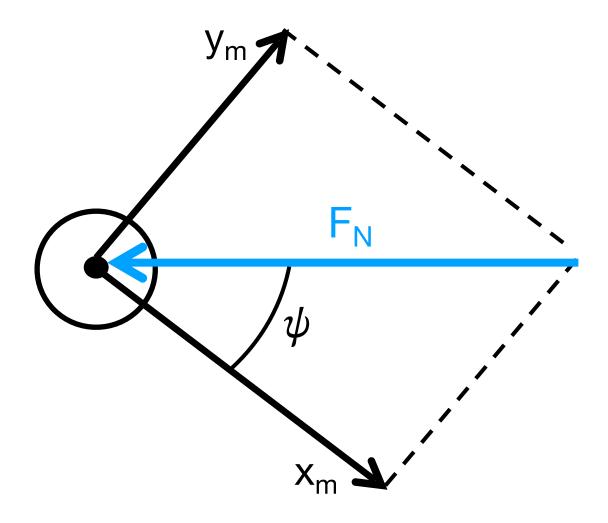


• $\psi = \operatorname{atan2}(x_m, y_m)$

• How to compensate for tilt? — Fuse data

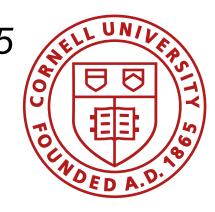






Sources and references

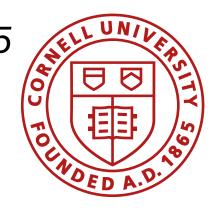
- http://www.chrobotics.com/library/accel-position-velocity
- EE 267 Virtual Reality, by Gordon Wetzstein at Stanford University
- Analog.com
- https://toptechboy.com/
- Prof. Kirstin Petersen



Class Action Items

- kits!
- January 31st, midnight: Make a GitHub repository and build your Github page
 - Include: name, photo, a small introduction, and the class number
 - Share the page link in the canvas assignment
- February 4th (8am) for Lab 401, and February 5th (8am) for Labs 402 & 403: Lab 1A and Lab 1B write-ups are due!

Fast Robots 2025



• If you want to drop the class, please let me know **ASAP** and return your lab