This lecture uses Socrative…

- Access via the app (Socrative Student) or via the webpage (https://b.socrative.com/login/student/) – It's free!
- ROOM NAME: **BIOM1010SENSORS**

Before the lecture starts

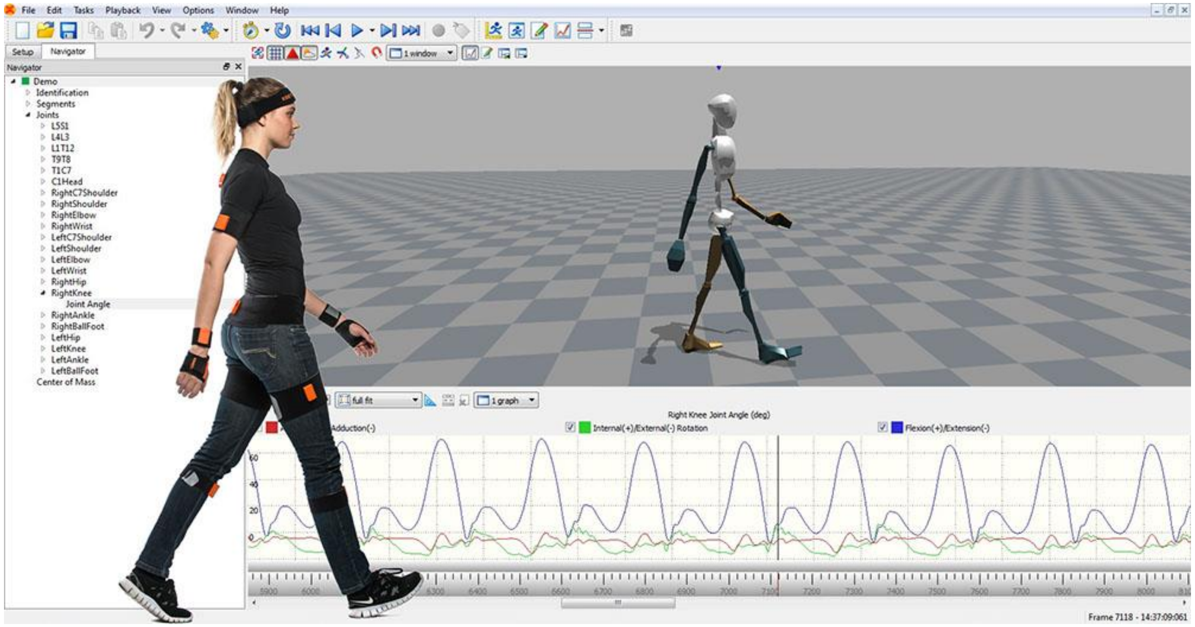
- Download Physics Toolbox Suite
  - Android: http://tinyurl.com/yc2qsutc
  - Apple: http://tinyurl.com/y8a5l2gd

Graduate School of Biomedical Engineering

Up, down, turn around:

Monitoring human movement using wearable sensors

Dr Michael Stevens michael.stevens@unsw.edu.au



With thanks to A/Prof Stephen Redmond

Learning outcomes of this lecture and tutorial

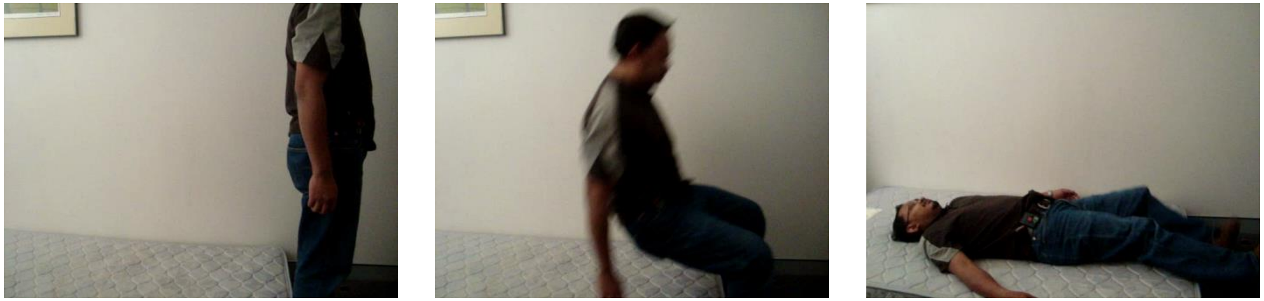
- To compare the functions of the components of an inertial measurement unit (IMU) and identify what aspects of movement that each are measuring
- To outline the basic physics of how each of these sensors work
- To measure motion of your own bodies with your smartphone
- To experiment with applying sensor fusion techniques to correct attitude measurements from an IMU

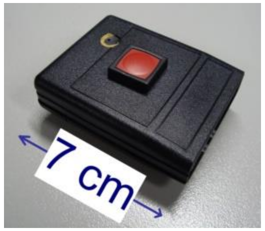
Wearable sensors

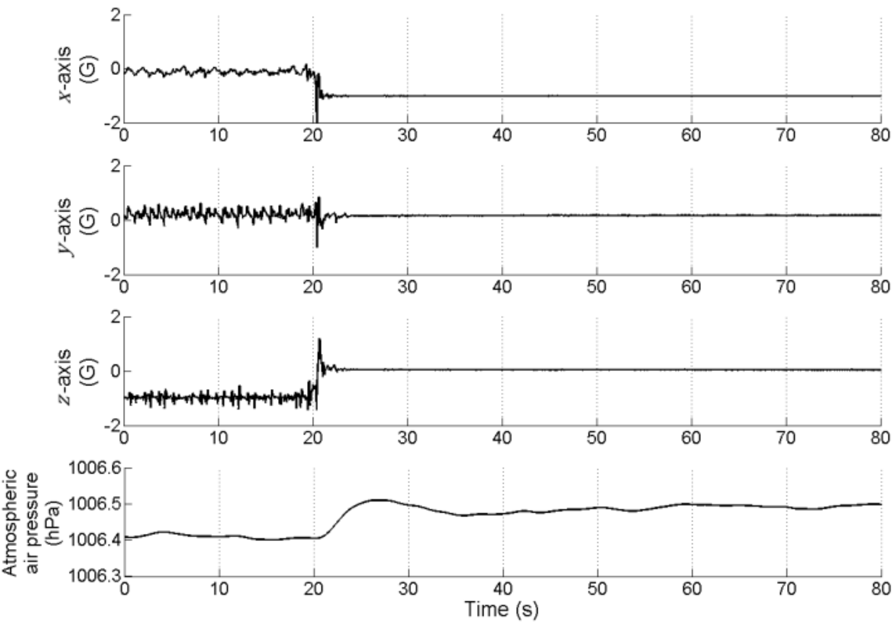
Fitness & health

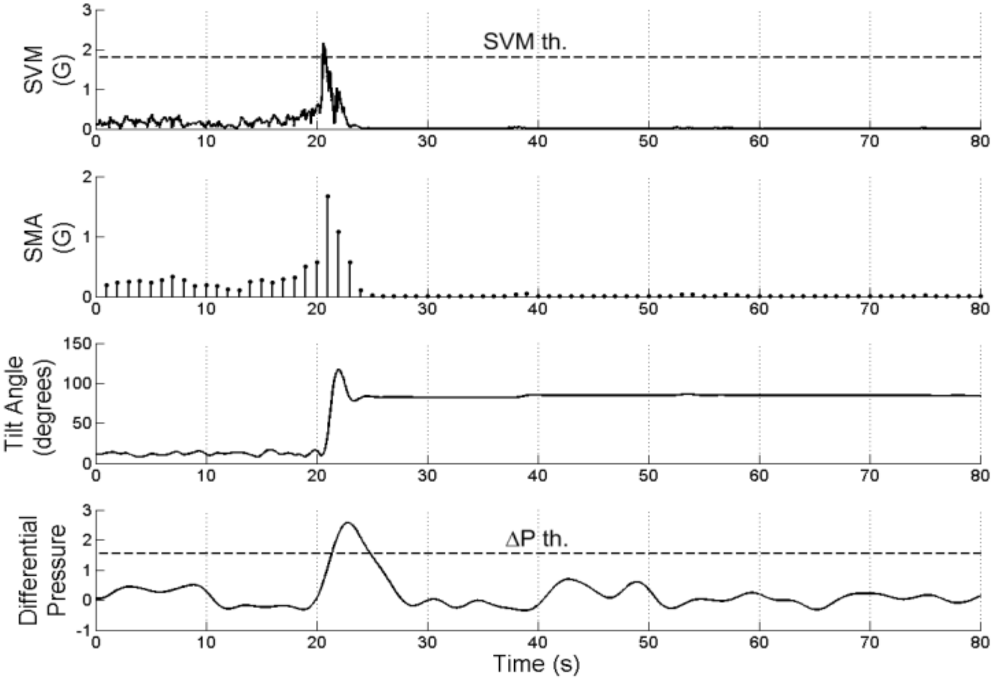
Safety

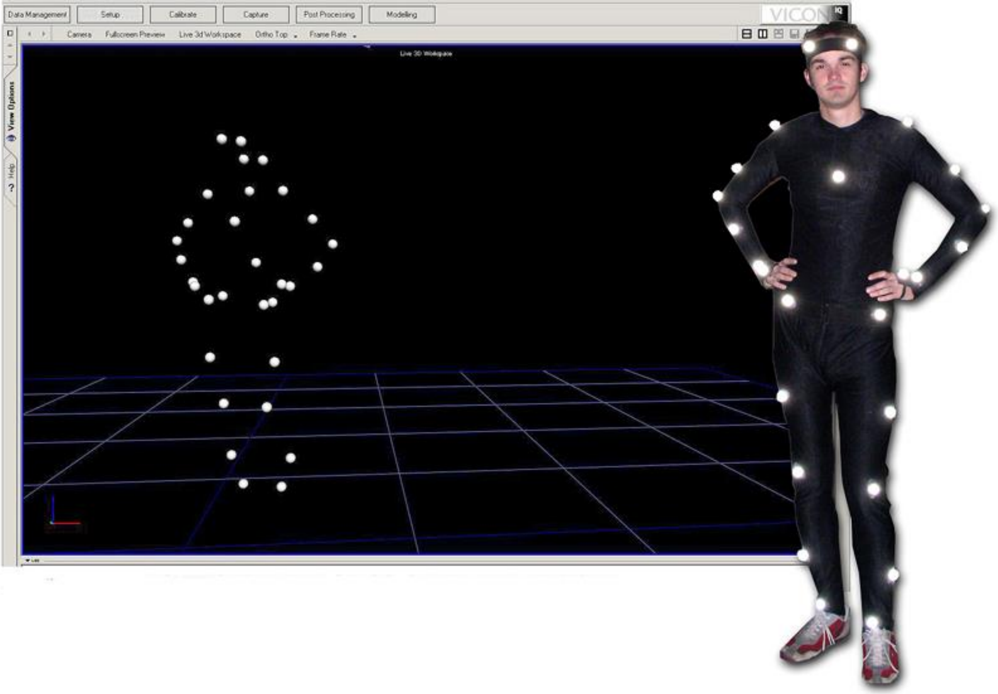
Fall detection











Vicon: https://youtu.be/sA3Kkq9kEiM?t=15s

See also 3:30: Static capture
5:05: Post-processing

BoB: https://youtu.be/79yH4fCXv88?t=1m30s

Motion capture

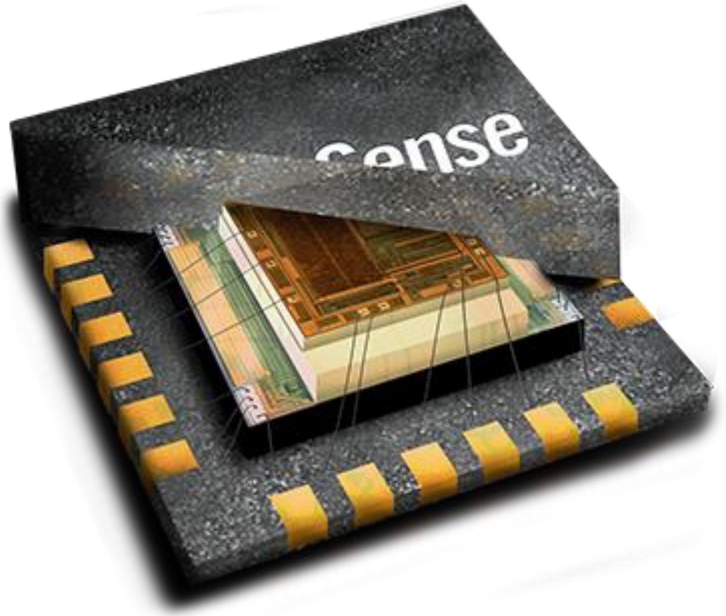
- Xsens motion capture show reel 2013 (Ted: 1:12)

https://youtu.be/PWn5lIoa0aY?t=1m12s

Our objective: Use low-cost motion capture technology to determine gait

- Solution: Inertial Measurement Units (IMUs)
- Place one IMU on each limb (thigh, shank, ankle)
- Determine orientation (attitude) of each IMU in real time.
- Then use knowledge of anatomy (bone lengths, joint constraints etc) to approximate gait.
- So, let’s take a look at these IMUs in more detail.

An Inertial Measurement Unit



- Acceleration, angular velocity, magnetic north (and sometimes more)!

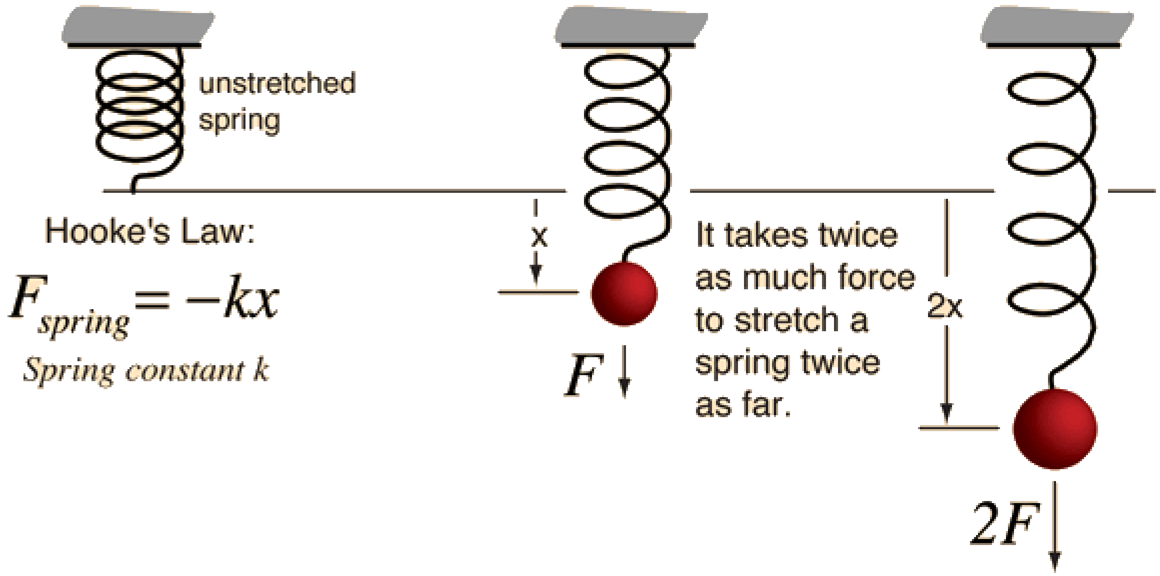
Accelerometer: Newton's second law

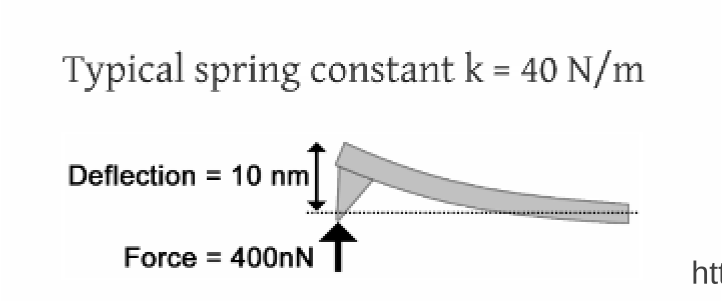
$$F = ma$$

$$a = \frac{F}{m}$$

Hooke’s law

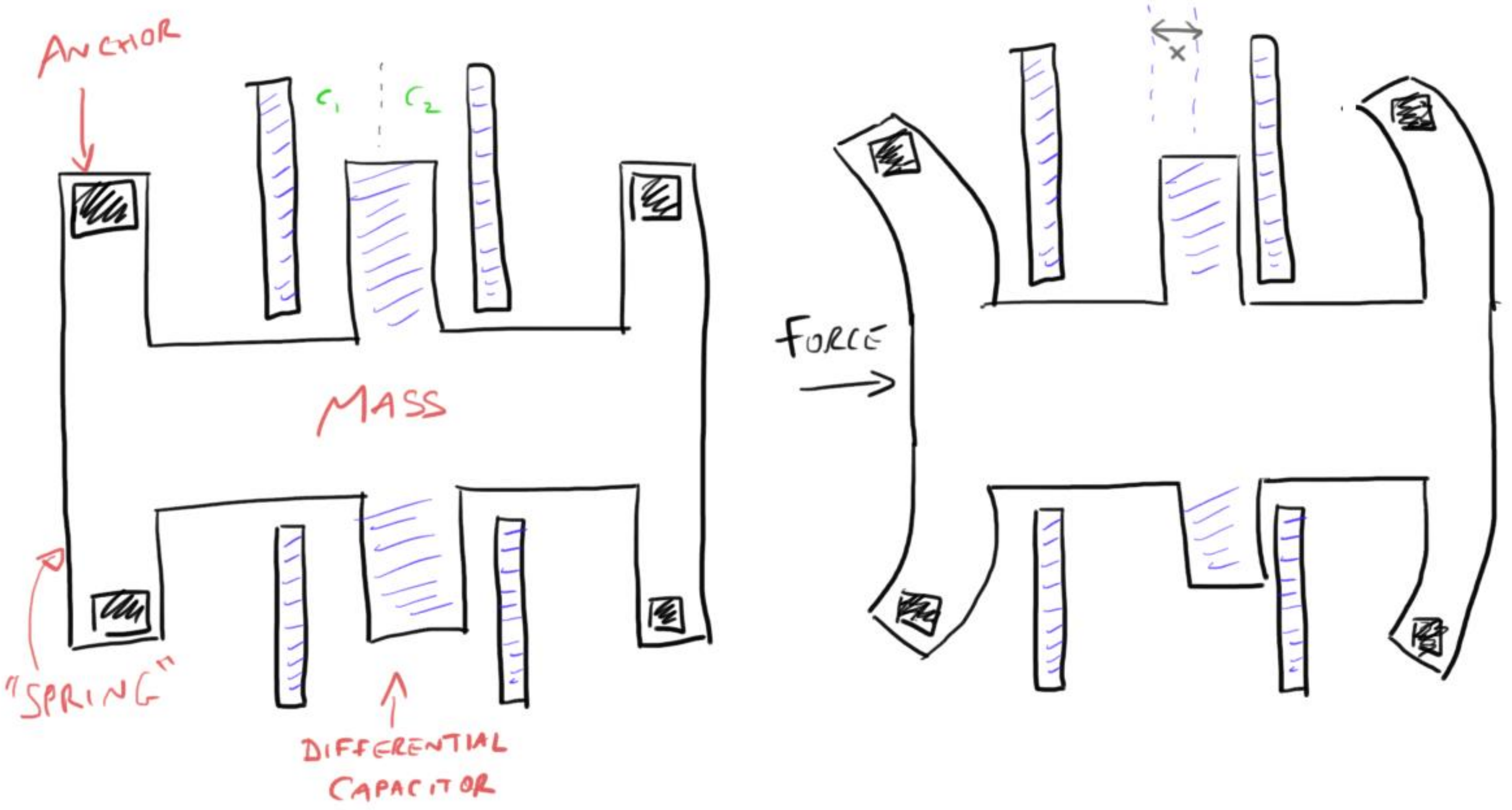
http://hyperphysics.phy-astr.gsu.edu/hbase/imgmec/hook.gif



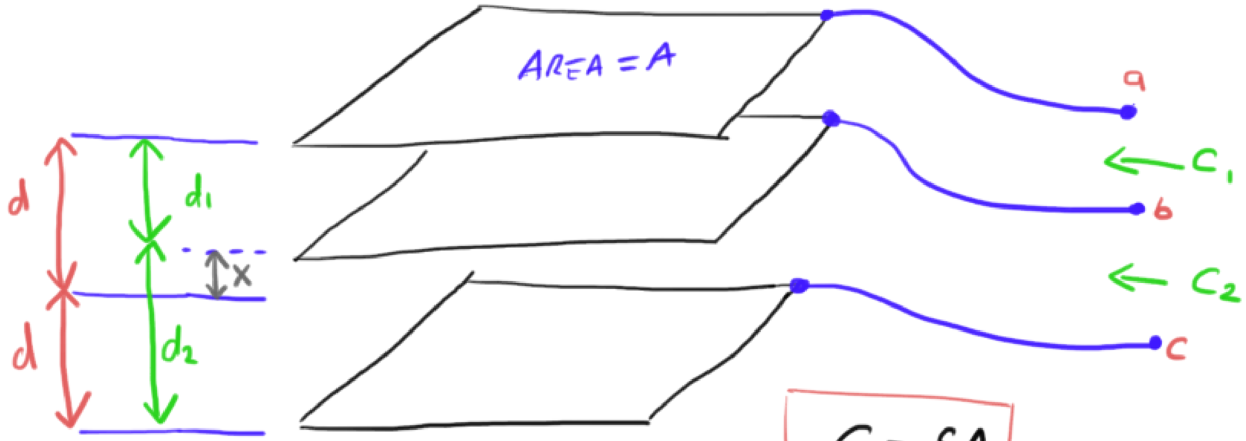


http://www.flinders.edu.au/science_engineering/fms/FCNST/AFMStiffnessWeb.png

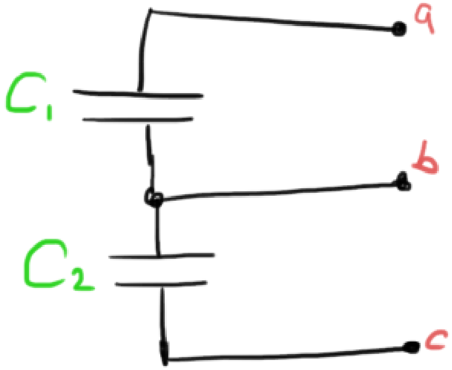
Microelectromechanical systems (MEMS) accelerometer



Differential capacitor



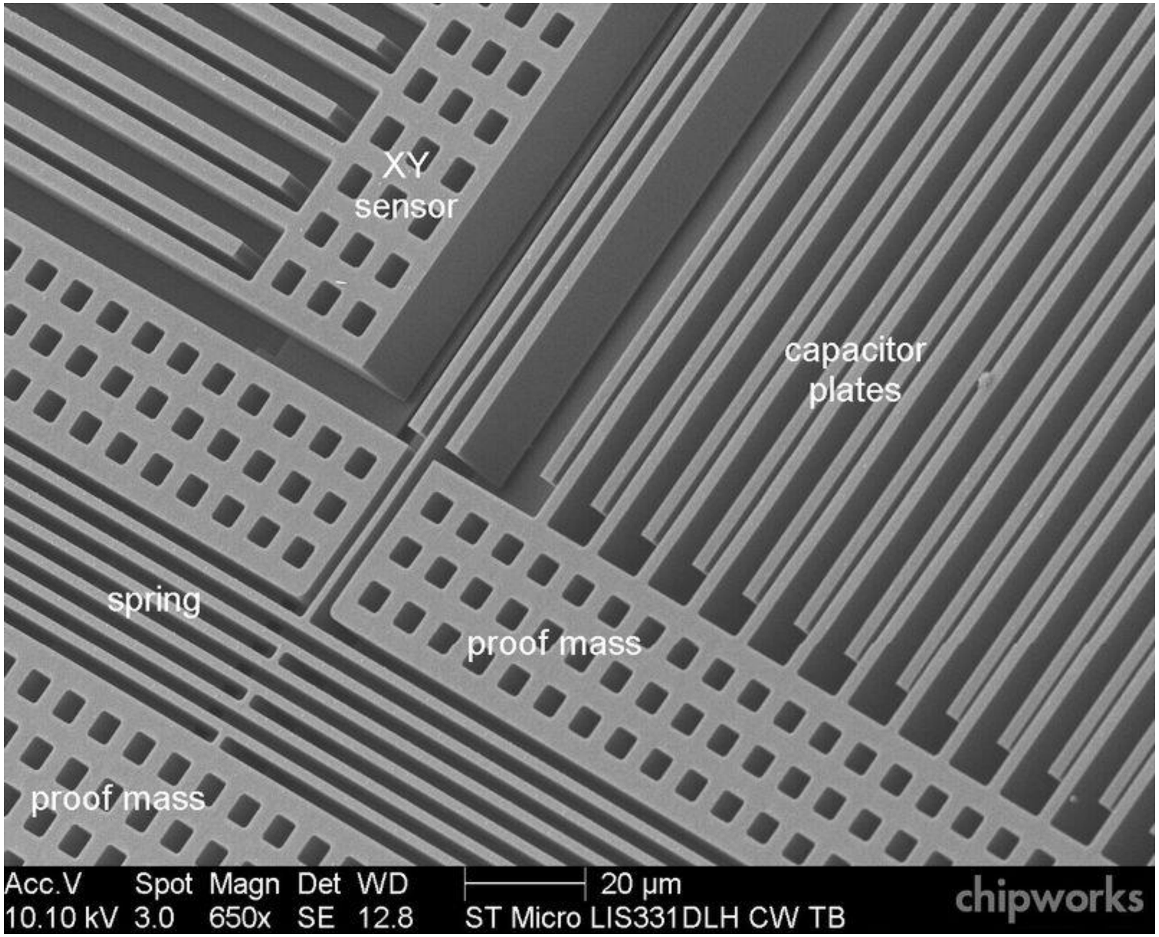
$$\boxed{C = \frac{\varepsilon A}{d}}$$



$$C_1 = \frac{\varepsilon A}{d_1} = \frac{\varepsilon_0 A}{d - x}$$

$$C_2 = \frac{\varepsilon A}{d_2} = \frac{\varepsilon_0 A}{d + x}$$

Microelectromechanical systems (MEMS) accelerometer



Accelerometer: Physics Toolbox Sensor Suite

G-Force Sensor – accelerometer.

Units? Gs – units of gravitational acceleration

$1G = 9.81 \text{ m s}^{-2}$

Question: which directions do x-y-z represent on your phone?

Hint: At rest, the phone will experience 1G acceleration (force required to support device) upwards.

Let's also do some approximation for orientation.

Socrative Question

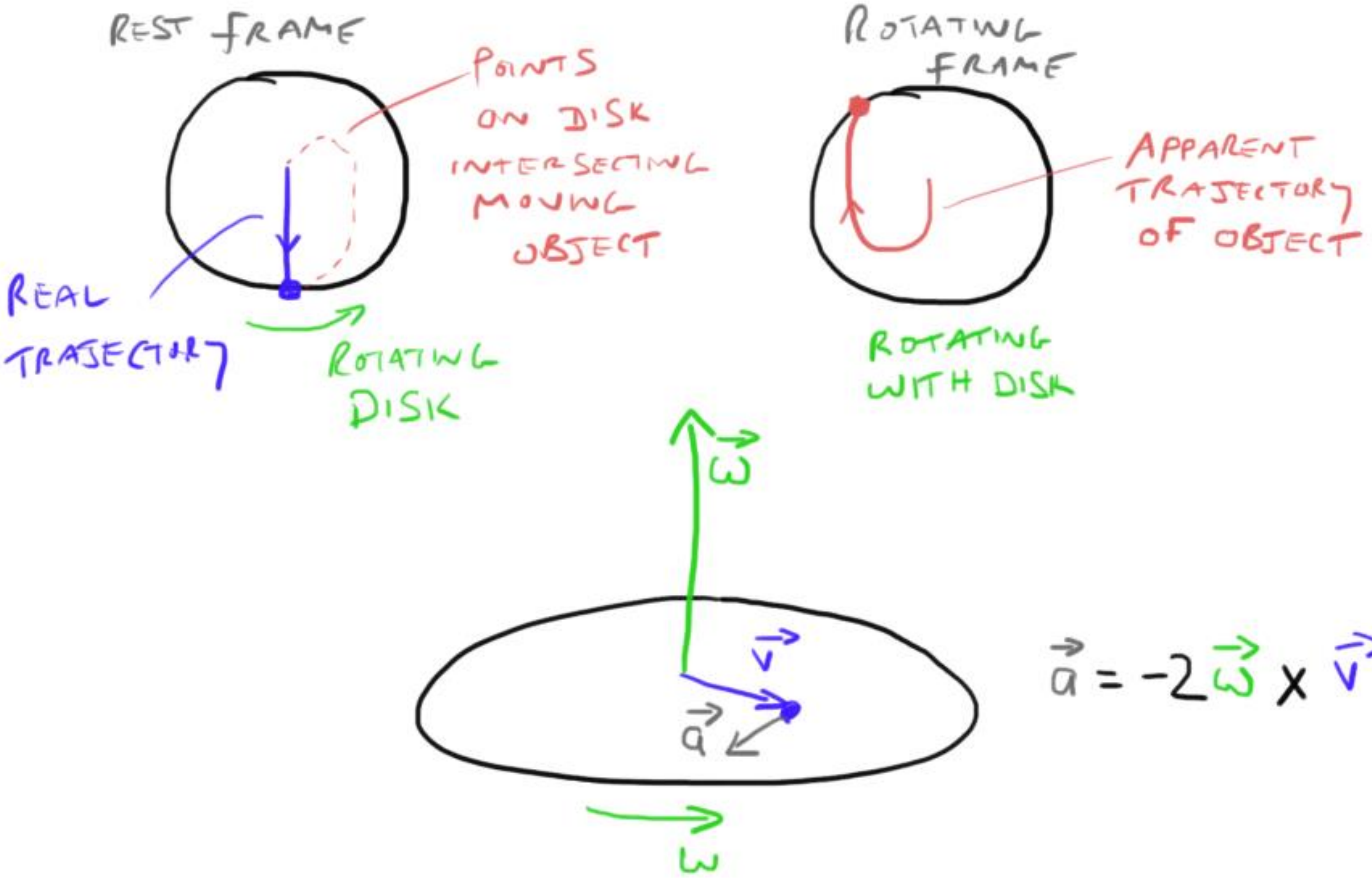
A researcher would like to measure distance travelled by integrating the acceleration signal twice.

Is this a good idea? Why/why not?

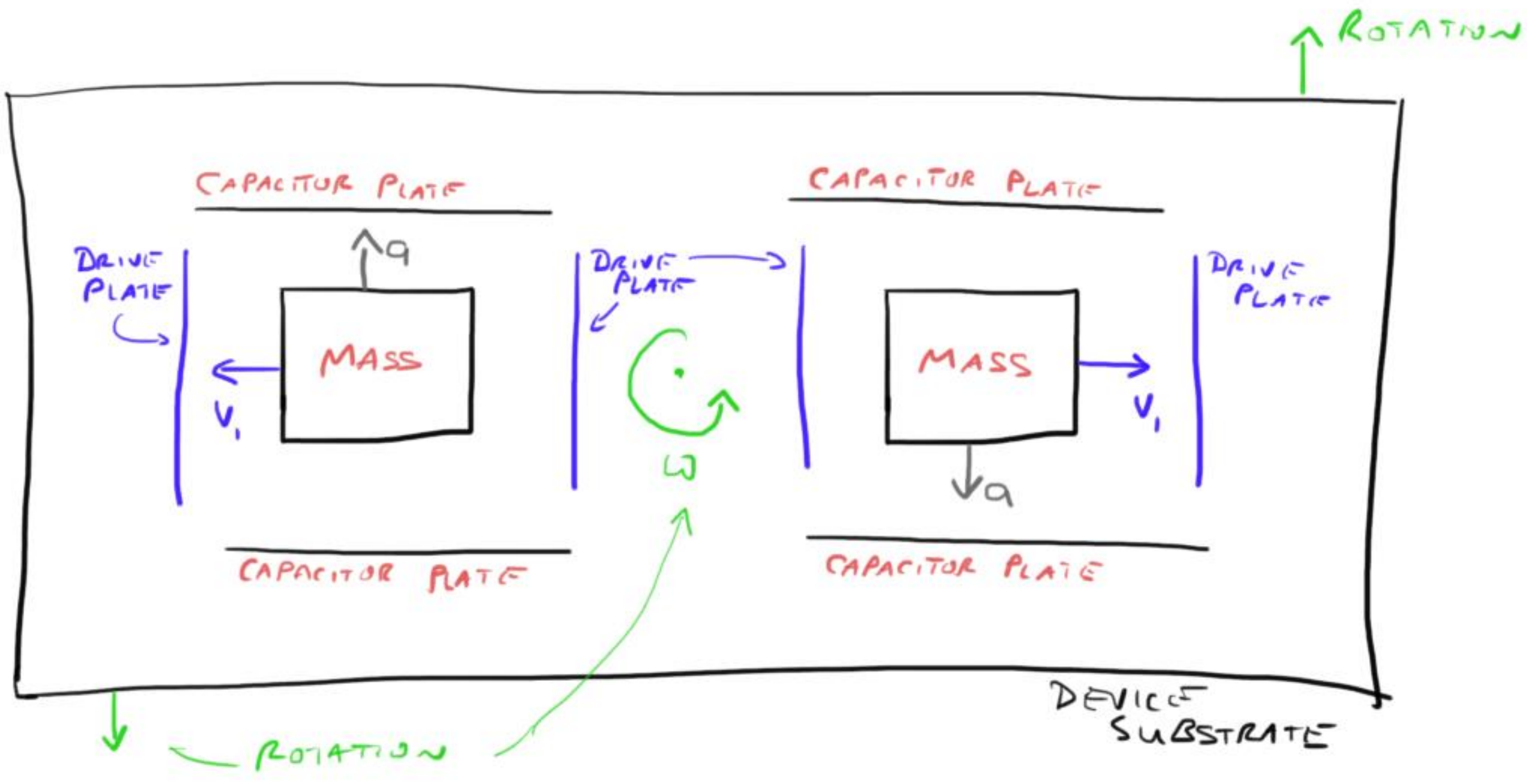
How does a gyroscope work? Let’s imagine ourselves in a playground, on a merry go round

https://recgymnastics.files.wordpress.com/2014/12/spinning-disk.jpg?w=632

Coriolis effect



MEMS gyroscope



Gyroscope: Physics Toolbox Sensor Suite

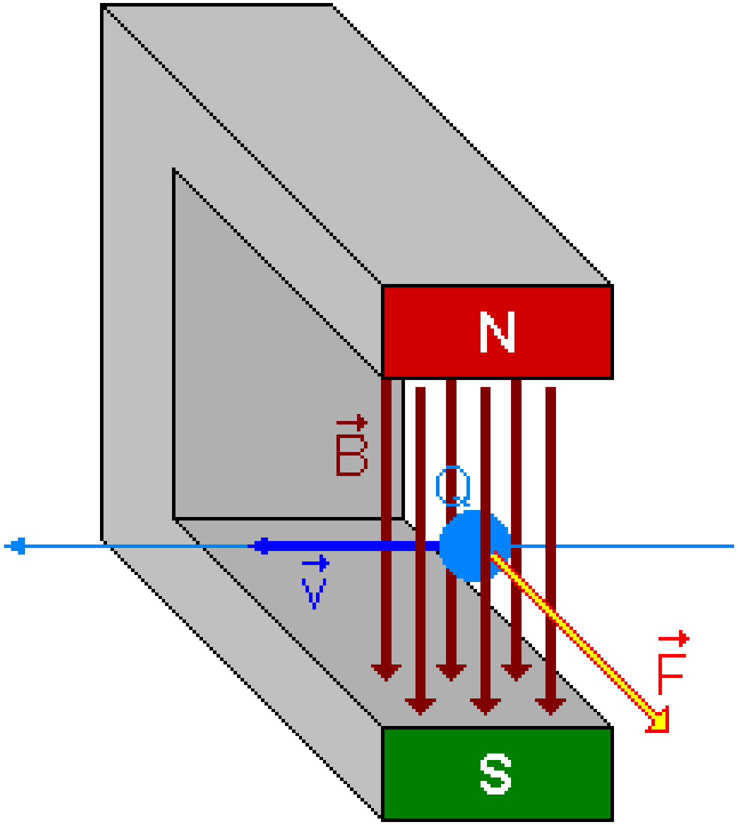
Unit: Rad/s

Angular Velocity – not angular position

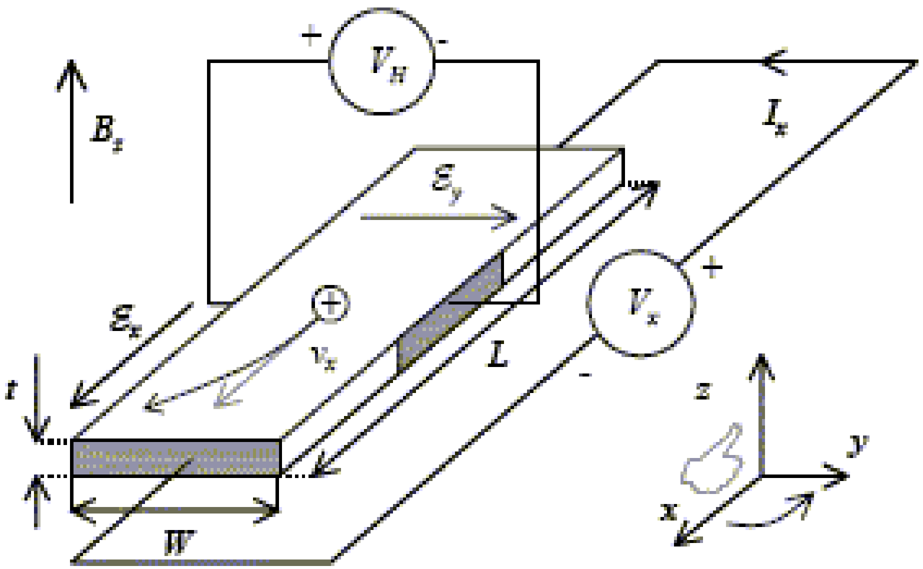
Socrative Question

Using gyroscopes, we can measure:

Lorentz force



Hall effect
(MEMS magnetometer)



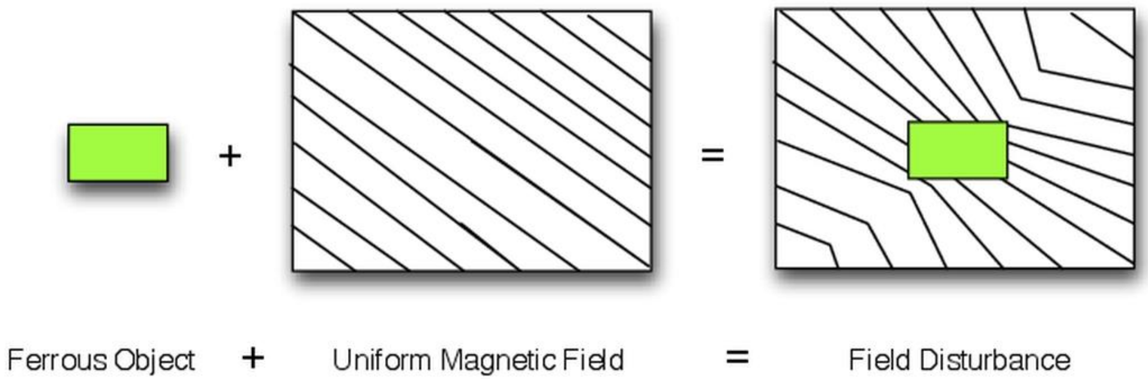
Magnetometer: Physics Toolbox Sensor Suite

Unit: Gauss

Let's try to find true North!

Calibration problems with magnetometers

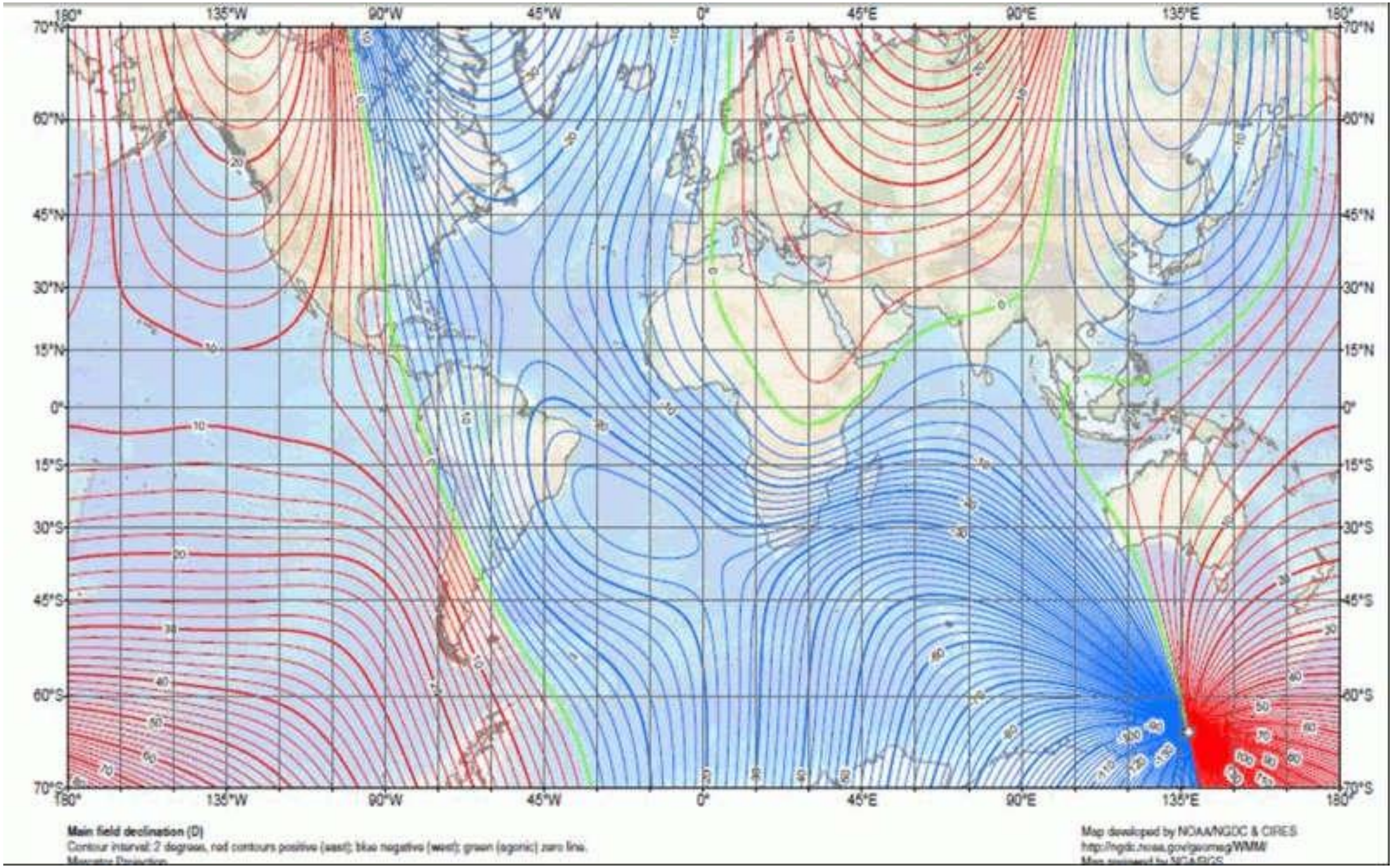
- “Soft iron” (interaction of external field with board)
  - Ferromagnetic material on the sensor board



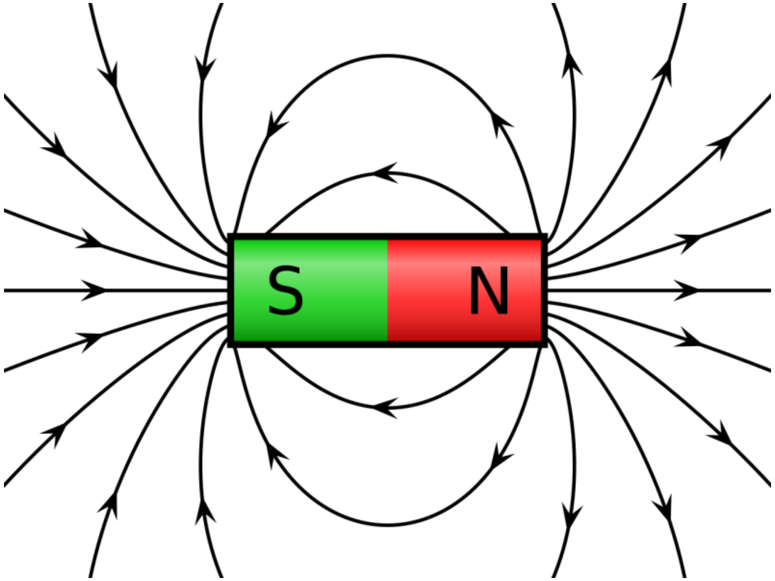
- “Hard iron” (fixed magnetic field on the board)
  - Magnets on sensor board

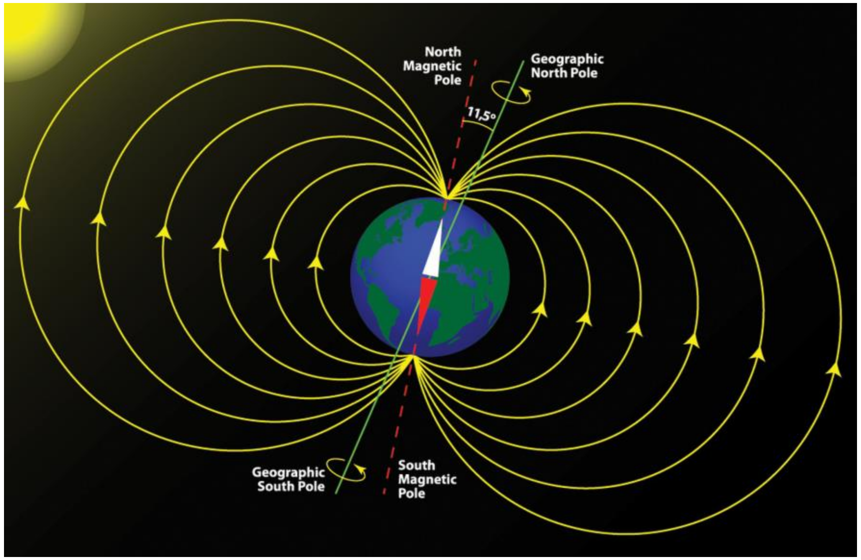
http://www.intechopen.com/source/html/37868/media/fig12.jpg

Magnetic declination



Magnetic fields are not straight and do not follow the curvature of the Earth.

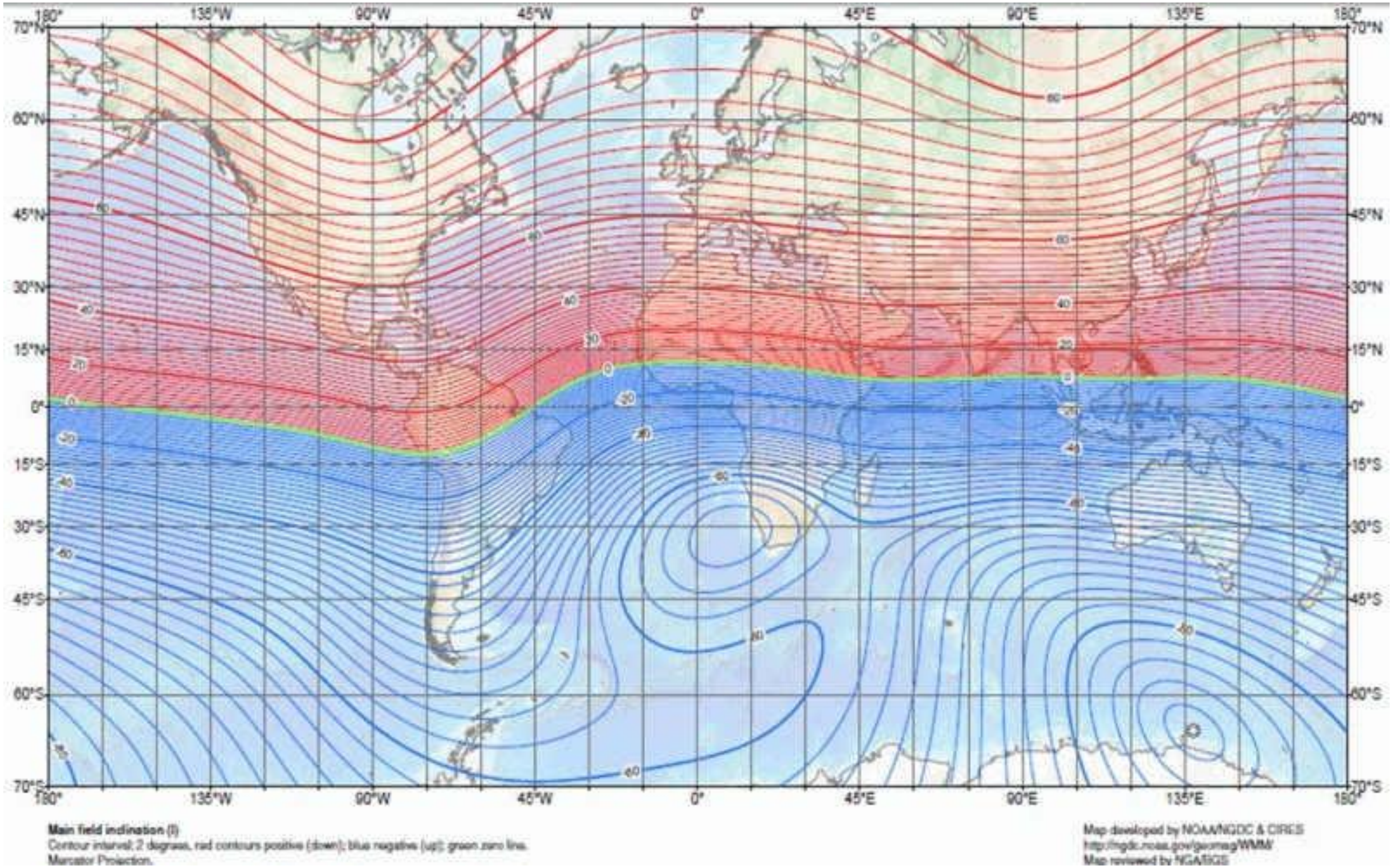




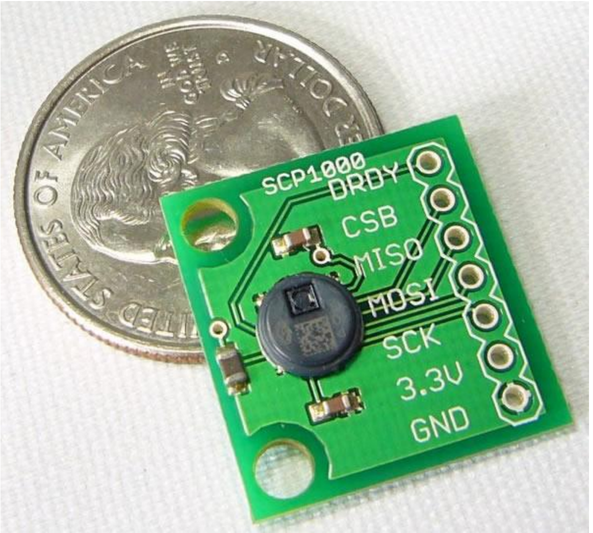
https://upload.wikimedia.org/wikipedia/commons/thumb/0/0c/VFPt_cylindrical_magnet_thumb.svg/1280px-VFPt_cylindrical_magnet_thumb.svg.png

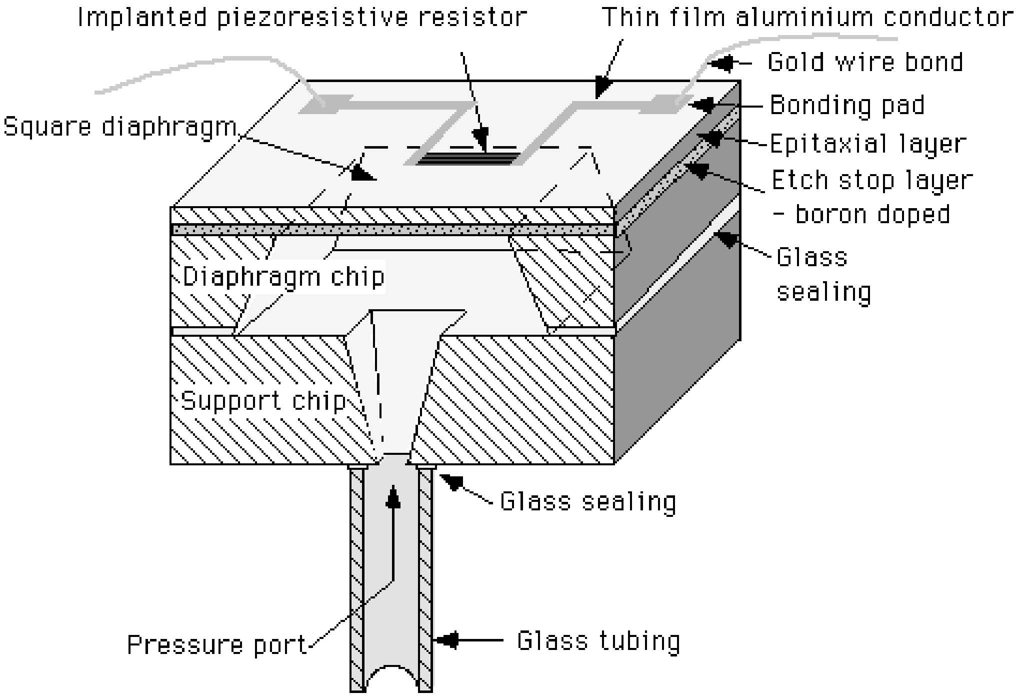
https://www.livescience.com/31795-earth-magnetic-field-reversal.html

Magnetic inclination

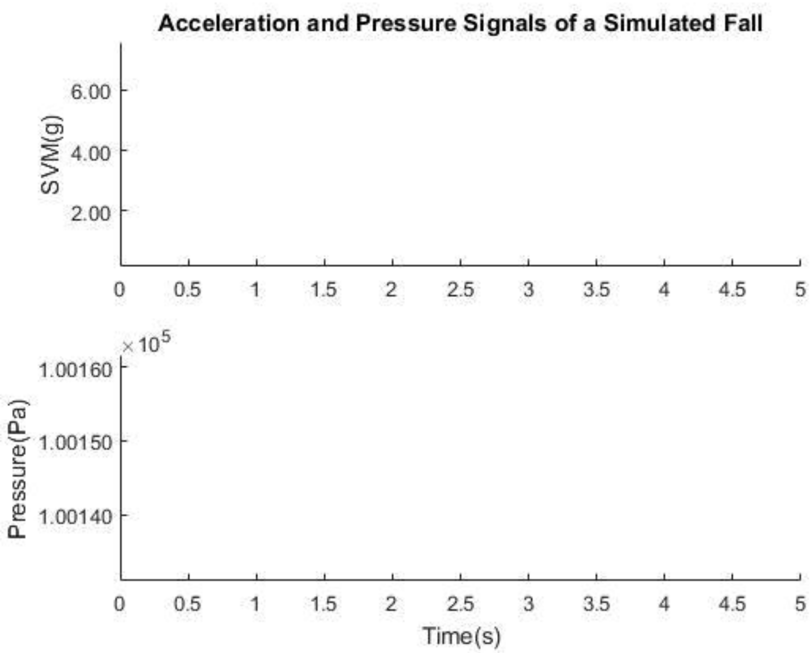


MEMS barometer

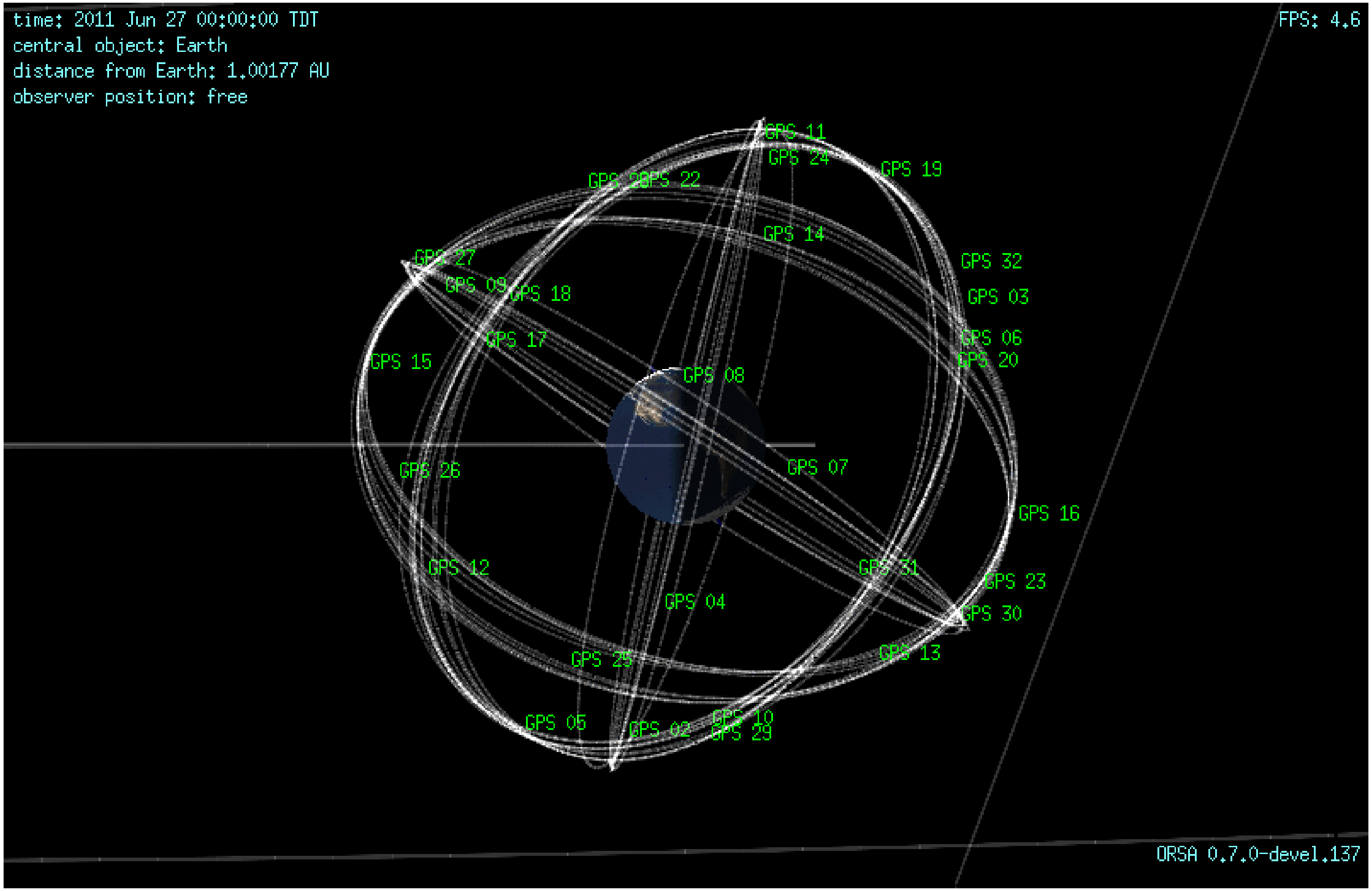




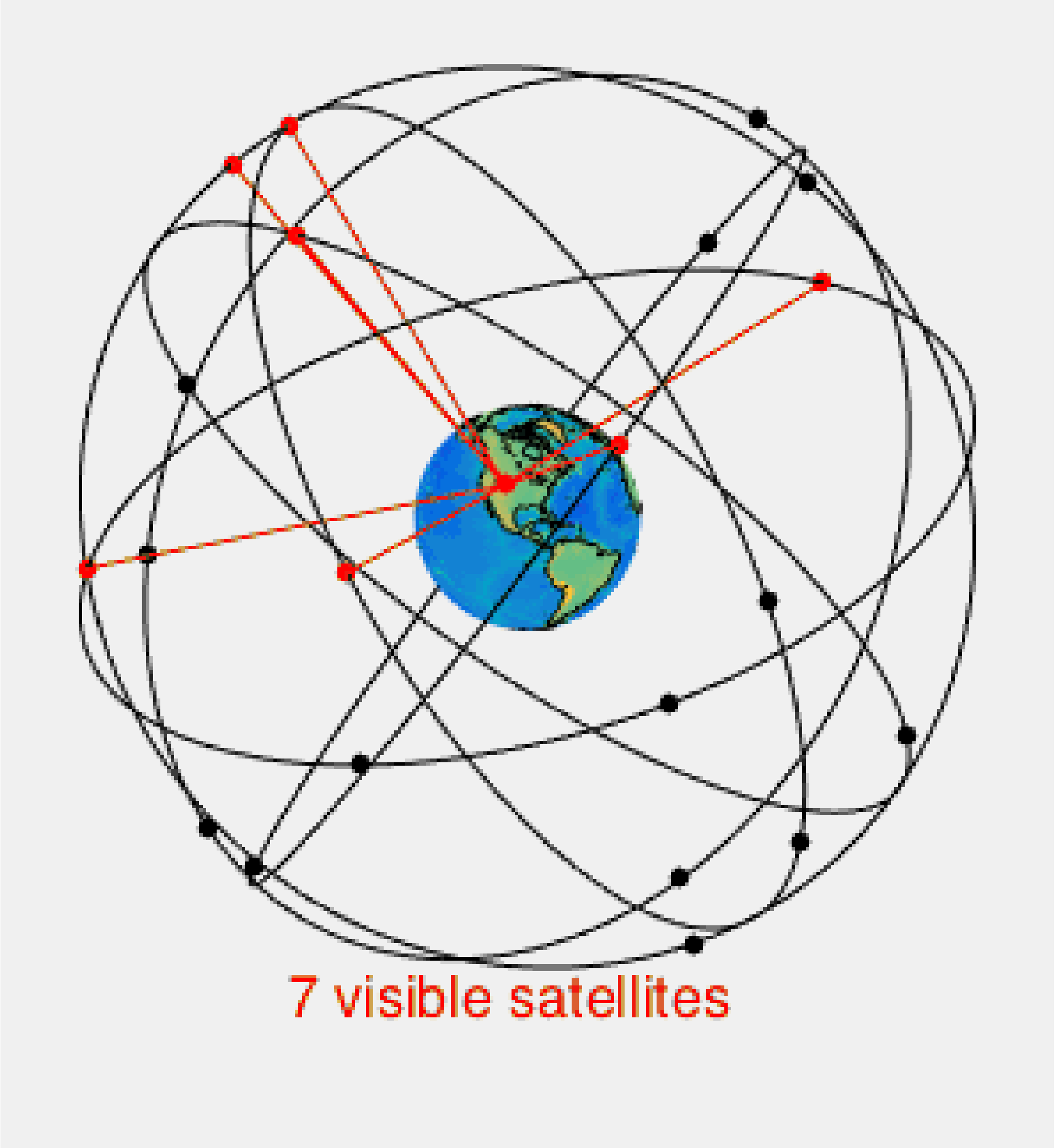
Fall detection



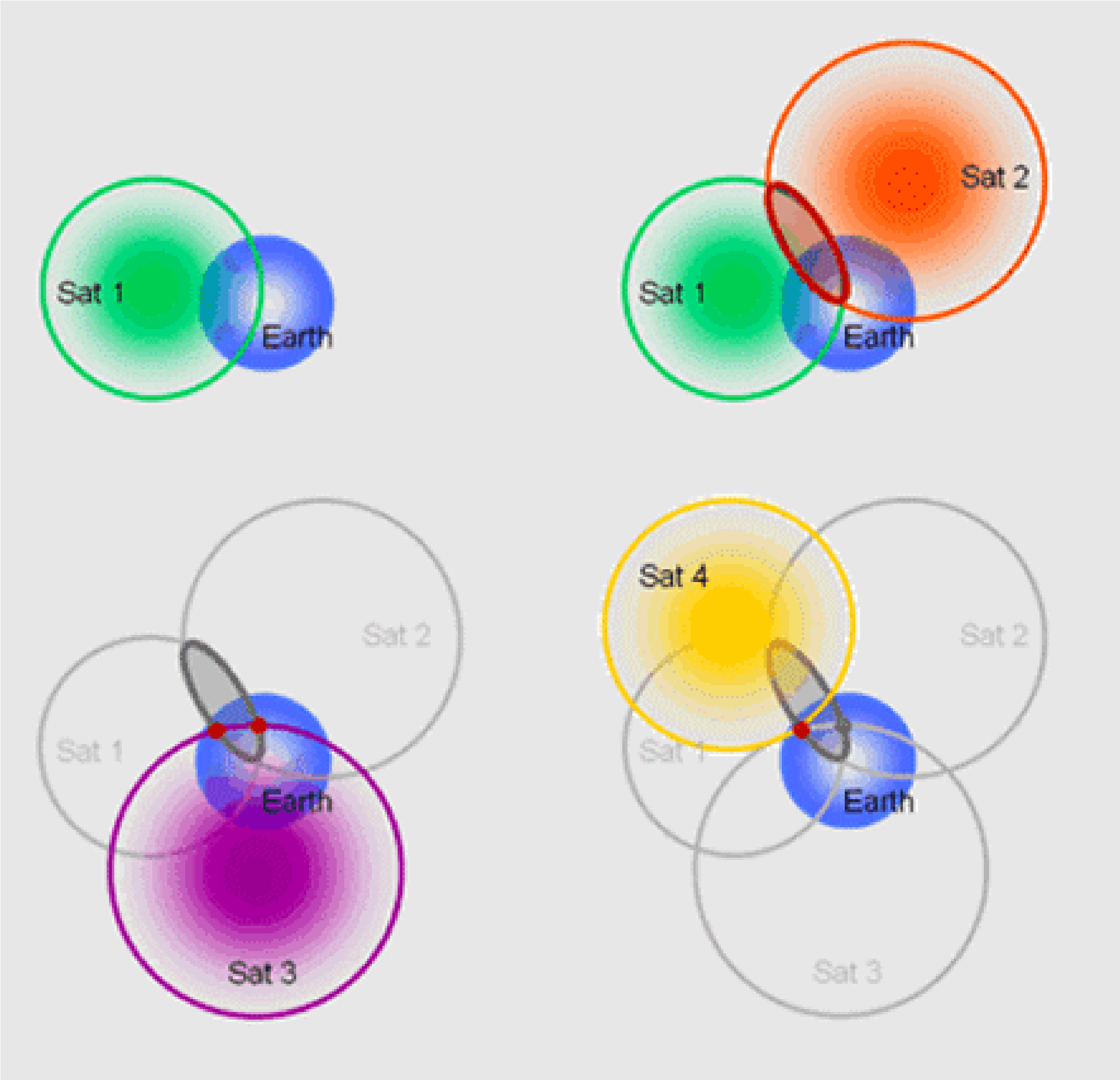
Global Positioning System



http://orbit.psi.edu/~tricaric/pub/2011MD_GPS.gif



https://en.wikipedia.org/wiki/Global_Positioning_System

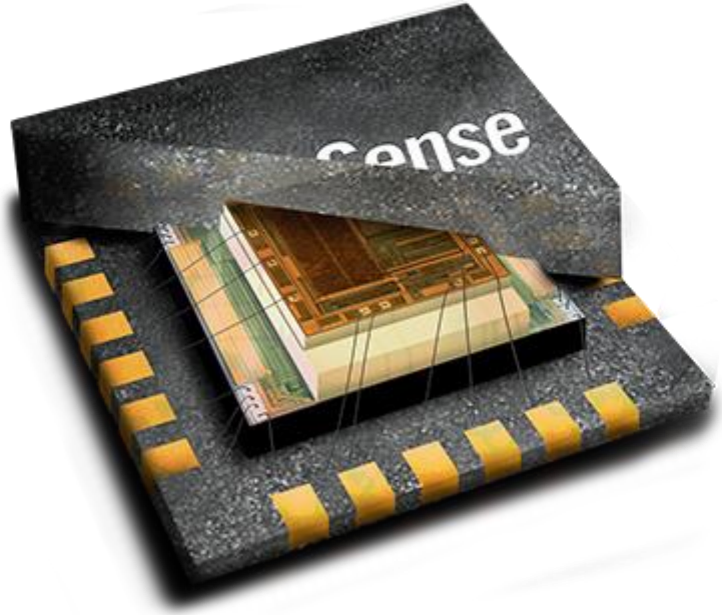


http://giscommons.org/chapter-2-input/

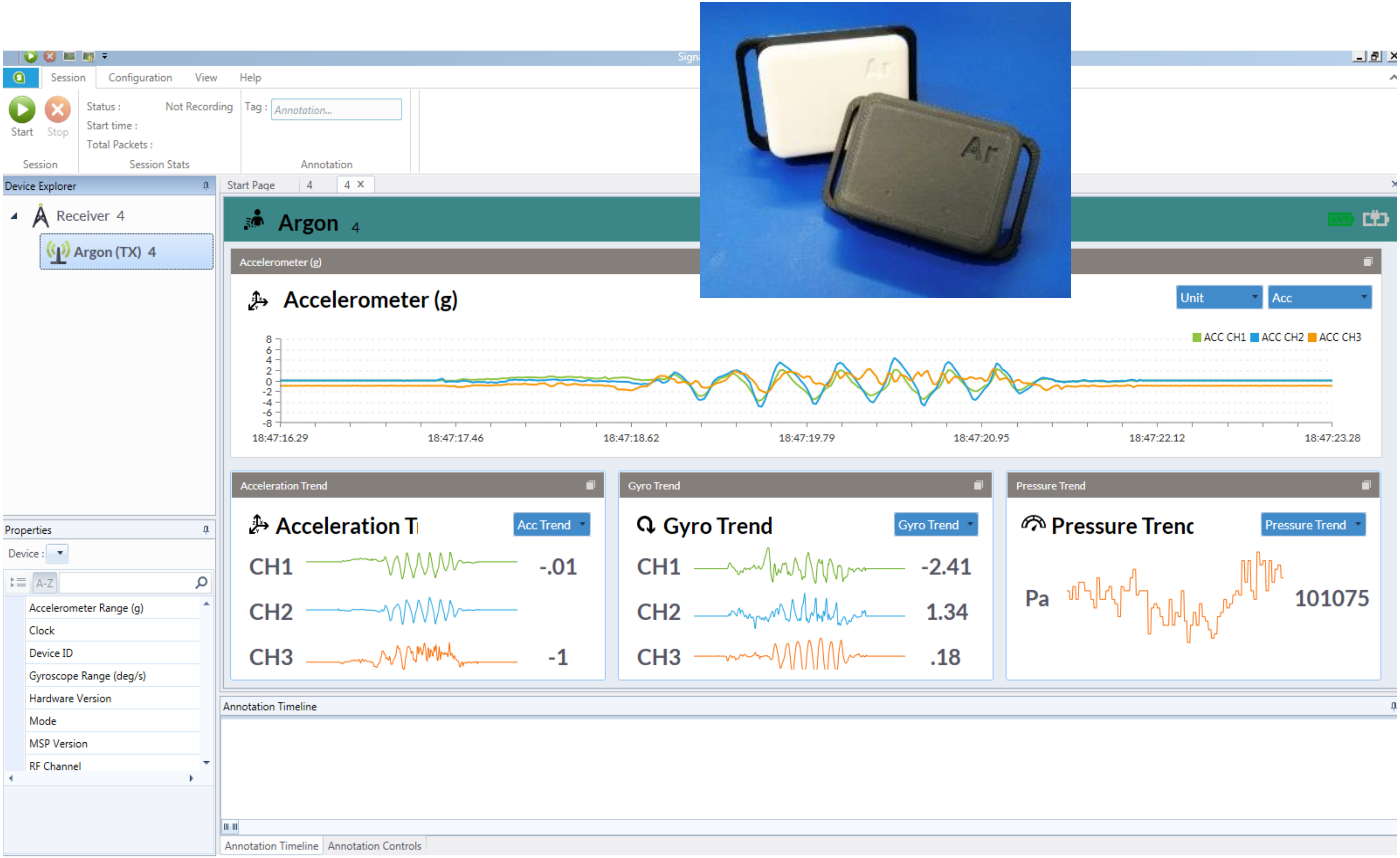
Question:

Can you determine velocity and acceleration from GPS? Are there any limitations to this approach?

9-axis MEMS IMU



Arduino tutorial on IMU sensors:
https://www.youtube.com/watch?v=eqZgxR6eRjo


Session
Configuration
View
Help
Start
Stop
Status :
Not Recording
Start time :
Total Packets :
Tag :
Annotation...
Session
Session Stats
Annotation
Device Explorer
Receiver 4
Argon (TX) 4
Start Page
Argon 4
Accelerometer (g)
Unit
Acc
ACC CH1
ACC CH2
ACC CH3
18:47:16.29
18:47:17.46
18:47:18.62
18:47:19.79
18:47:20.95
18:47:22.12
18:47:23.28
Acceleration Trend
Acc Trend
CH1
-.01
CH2
CH3
-1
Gyro Trend
CH1
-2.41
CH2
1.34
CH3
.18
Pressure Trend
Pa
101075
Properties
Device :
A-Z
Accelerometer Range (g)
Clock
Device ID
Gyroscope Range (deg/s)
Hardware Version
Mode
MSP Version
RF Channel
Annotation Timeline
Annotation Controls
Ar

Here come the drones…some fun applications of IMUs

- Drones playing ping pong:

https://www.youtube.com/watch?v=3CR5y8qZf0Y

- “The Astounding Athletic Power of Quadcopters”
  Raffaello D'Andrea, TED Talks

https://www.youtube.com/watch?v=w2itwFJCgFQ

2:28: Balance pole

4:30: Balance glass

10:10: Skynet!

- World's first manned flight with an electric multicopter (1:41)

https://youtu.be/L75ESD9PBOw?t=1m41s

Vector magnitude and unit vectors

Vector:

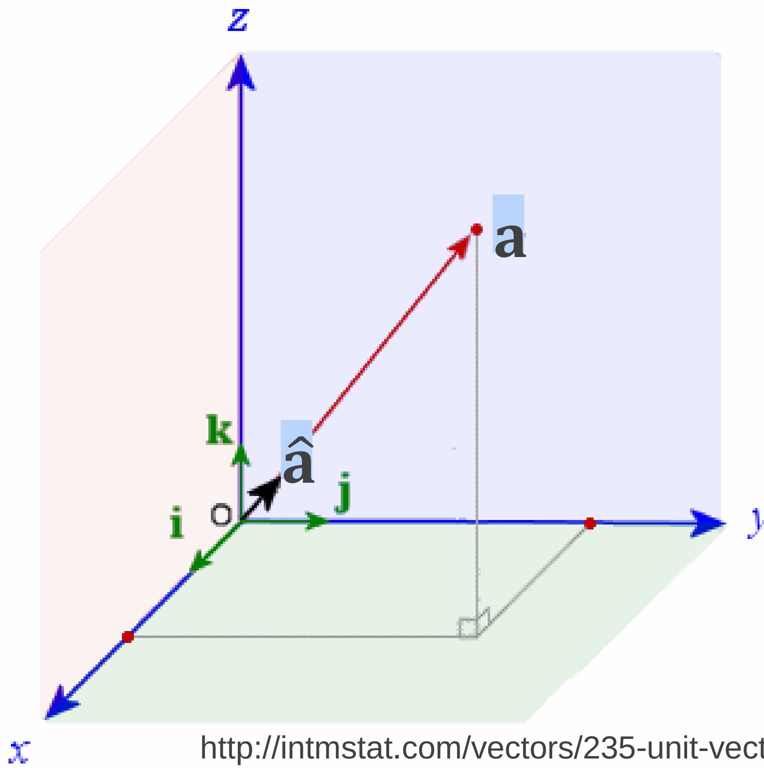
$$\mathbf{a} = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}$$

Magnitude:

$$\|\mathbf{a}\| = \sqrt{{a_1}^2 + {a_2}^2 + {a_3}^2}$$

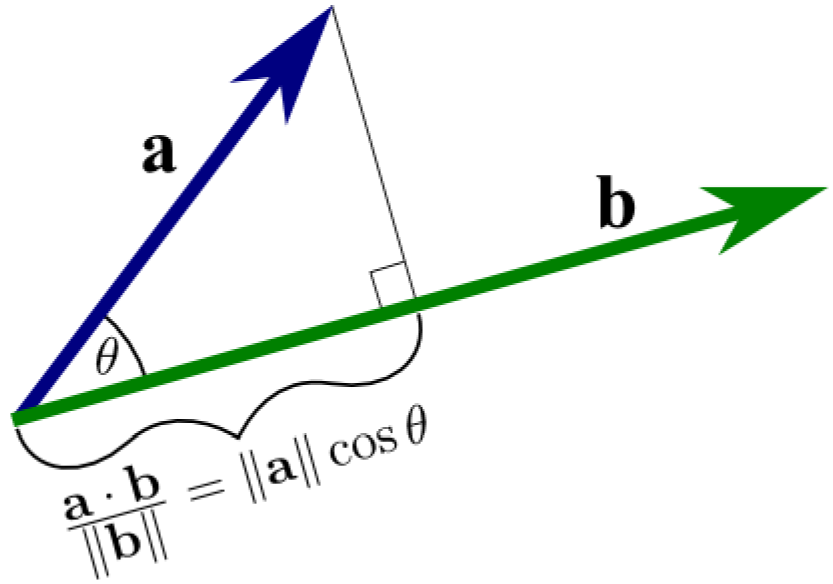
Unit vector:

$$\hat{\mathbf{a}} = \frac{\mathbf{a}}{\|\mathbf{a}\|} = \begin{pmatrix} a_1/\|\mathbf{a}\| \\ a_2/\|\mathbf{a}\| \\ a_3/\|\mathbf{a}\| \end{pmatrix}$$



http://intmstat.com/vectors/235-unit-vector.gif

Dot (scalar) product



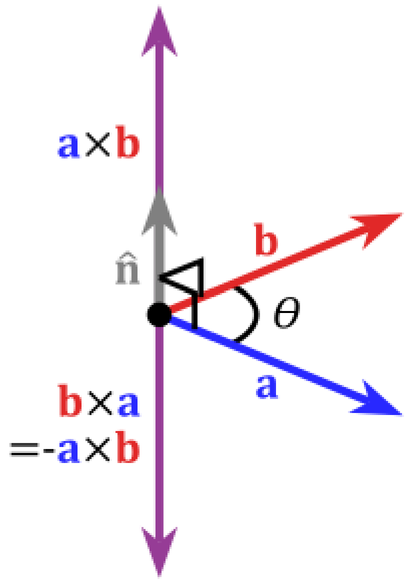
$$\mathbf{a}\cdot\mathbf{b} = \|\mathbf{a}\|\,\|\mathbf{b}\|\cos\theta$$
$$= a_1 b_1 + a_2 b_2 + a_3 b_3$$

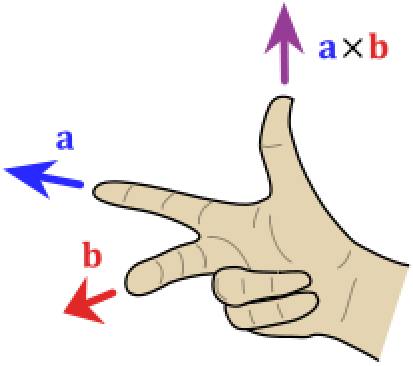
http://mathinsight.org/media/image/image/dot_product_projection.png

Cross (vector) product

$$\mathbf{a} \times \mathbf{b} = \hat{\mathbf{n}} \|\mathbf{a}\| \|\mathbf{b}\| \sin\theta$$

$$= \begin{pmatrix} a_2 b_3 - a_3 b_2 \\ a_3 b_1 - a_1 b_3 \\ a_1 b_2 - a_2 b_1 \end{pmatrix}$$

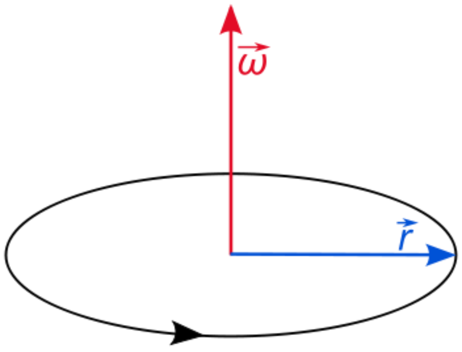




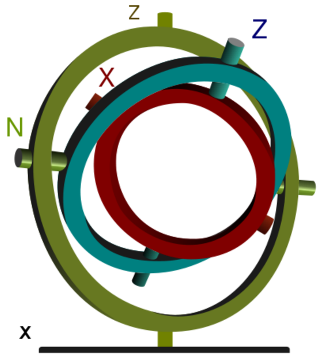
https://en.wikipedia.org/wiki/Cross_product

Angular velocity

- Angular distance (which we just call the angle) in radians:
  - Angle = Distance along arc / radius



- Angular velocity
  - (Angle around axis of rotation) / second
  - (Speed ⊥ to axis of rotation) / radius



- Angular velocity vectors add

Quaternions

- Extension of complex numbers:

$$\boldsymbol{q} = q_r + q_x\mathbf{i} + q_y\mathbf{j} + q_z\mathbf{k}$$

- Can be used to do rotation by θ about an axis $\mathbf{u}$ if written in following way:

$$\boldsymbol{q} = \cos\frac{\theta}{2} + \sin\frac{\theta}{2}\left(u_x\mathbf{i} + u_y\mathbf{j} + u_z\mathbf{k}\right)$$

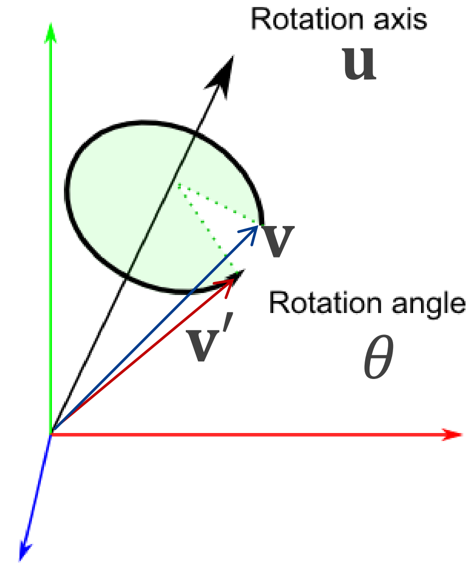
where $\|\mathbf{u}\| = \sqrt{{u_x}^2 + {u_y}^2 + {u_z}^2} = 1$, a unit vector

Axis-angle rotations

- Do a rotation of point $\mathbf{v} = v_x\mathbf{i} + v_y\mathbf{j} + v_z\mathbf{k}$ by θ radians around the unit vector $\mathbf{u}$:

$$\mathbf{v}' = \boldsymbol{q}(0 + v_x\mathbf{i} + v_y\mathbf{j} + v_z\mathbf{k})\boldsymbol{q}^*$$

$$\mathbf{v}' = \left(\cos\frac{\theta}{2} + \sin\frac{\theta}{2}(u_x\mathbf{i} + u_y\mathbf{j} + u_z\mathbf{k})\right) .(0 + v_x\mathbf{i} + v_y\mathbf{j} + v_z\mathbf{k}) .\left(\cos\frac{\theta}{2} - \sin\frac{\theta}{2}(u_x\mathbf{i} + u_y\mathbf{j} + u_z\mathbf{k})\right)$$



The rules!

$$\mathbf{ij} = \mathbf{k}, \quad \mathbf{ji} = -\mathbf{k},$$
$$\mathbf{jk} = \mathbf{i}, \quad \mathbf{kj} = -\mathbf{i},$$
$$\mathbf{ki} = \mathbf{j}, \quad \mathbf{ik} = -\mathbf{j},$$
$$\mathbf{i}^2 = \mathbf{j}^2 = \mathbf{k}^2 = -1$$

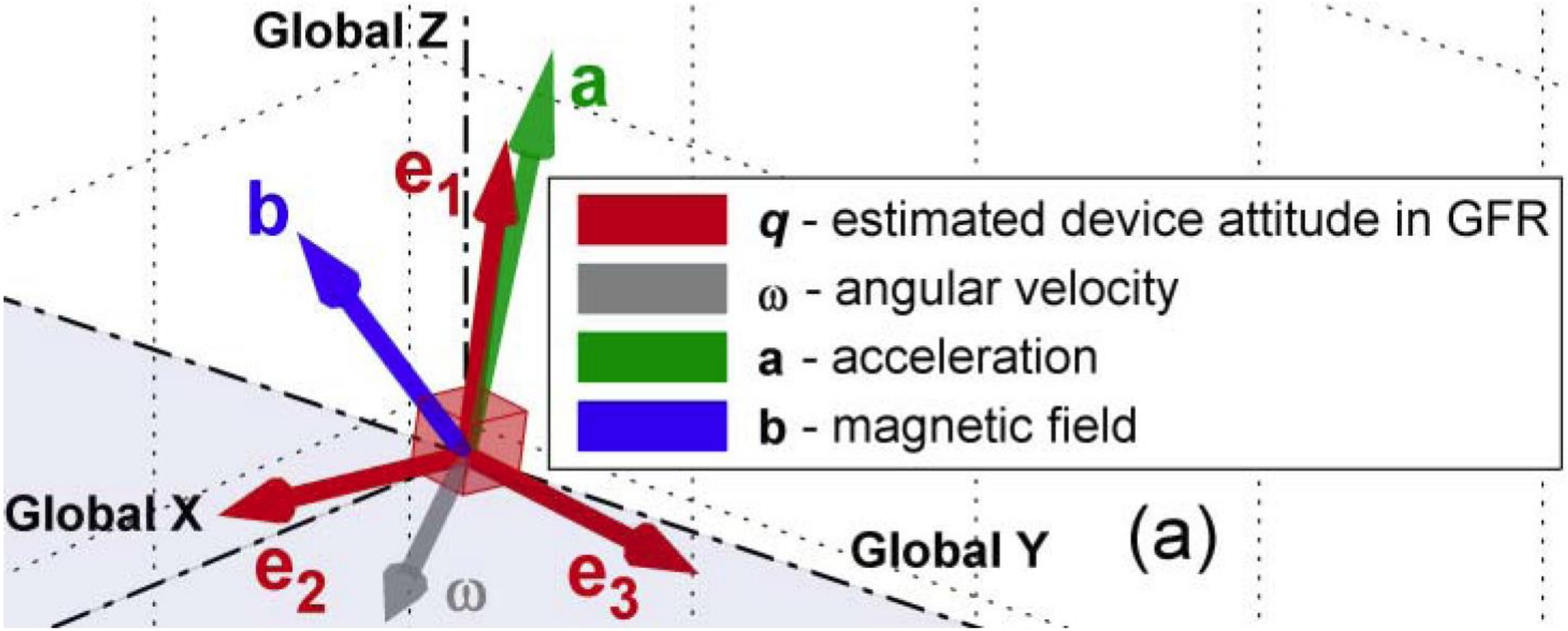
Sensor fusion using quaternions

Goal:

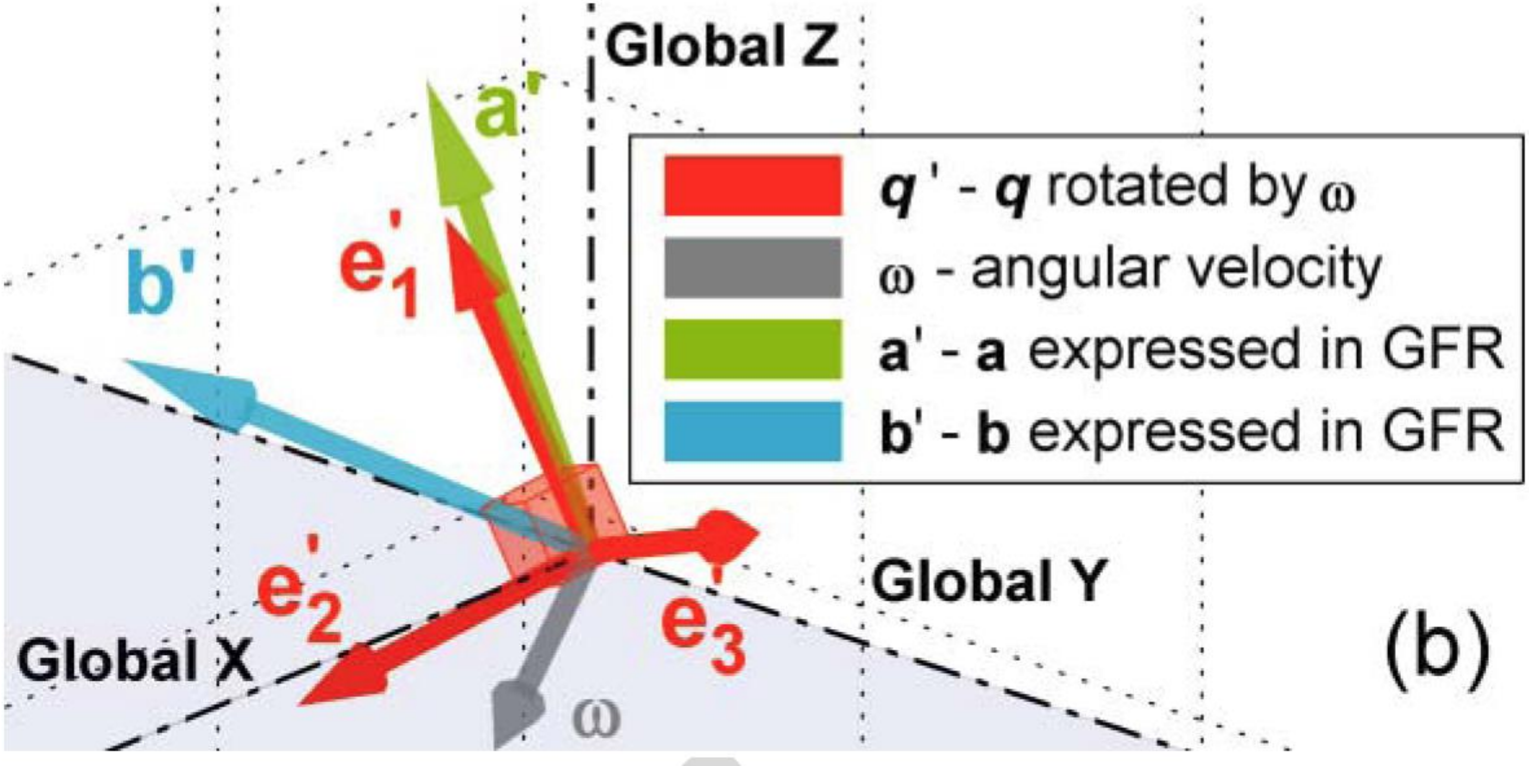
- To measure approximate orientation using the gyroscope measurements

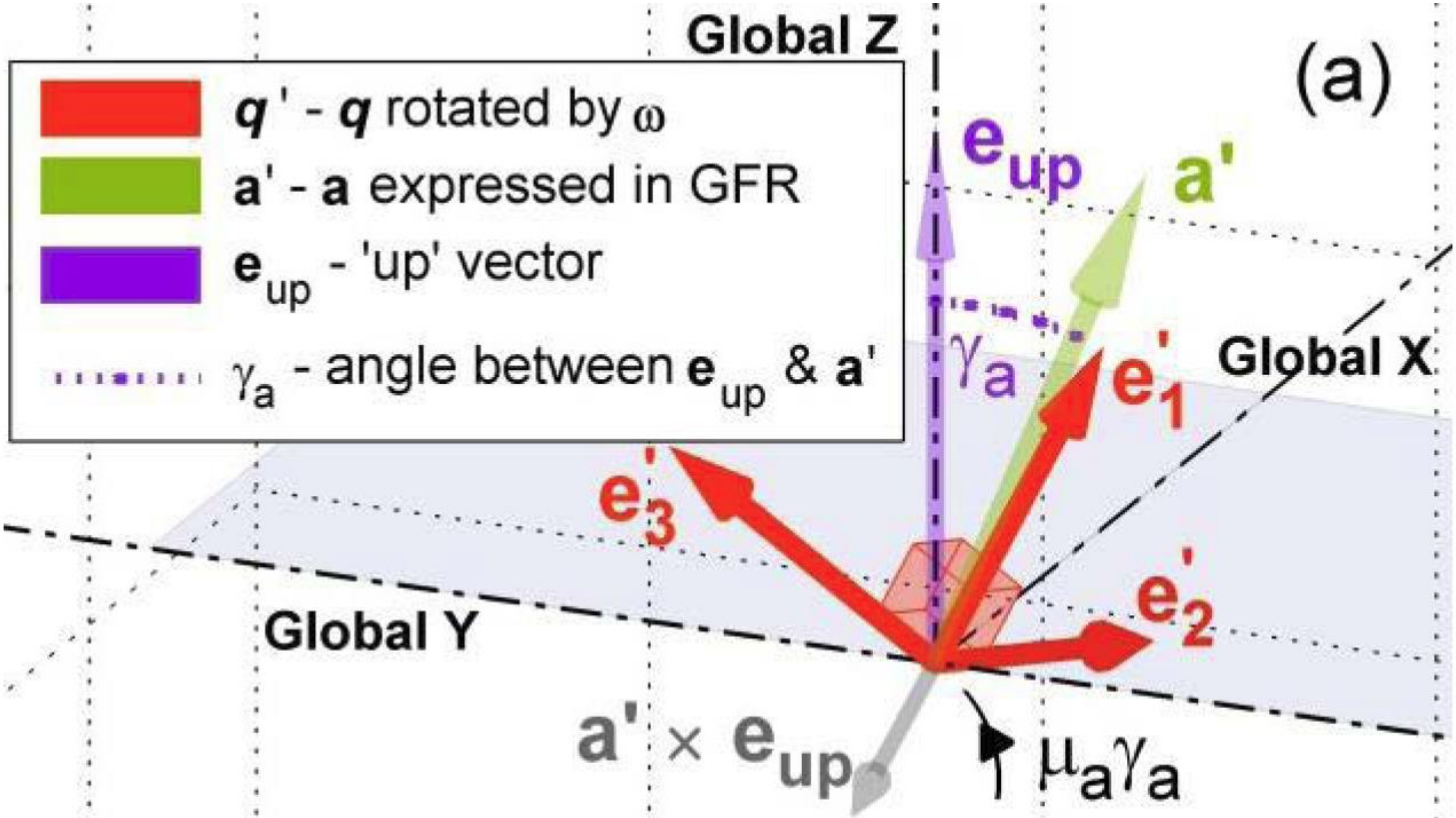
- Then to correct that estimate using accelerometer and magnetometer measurements

Using the gyroscope

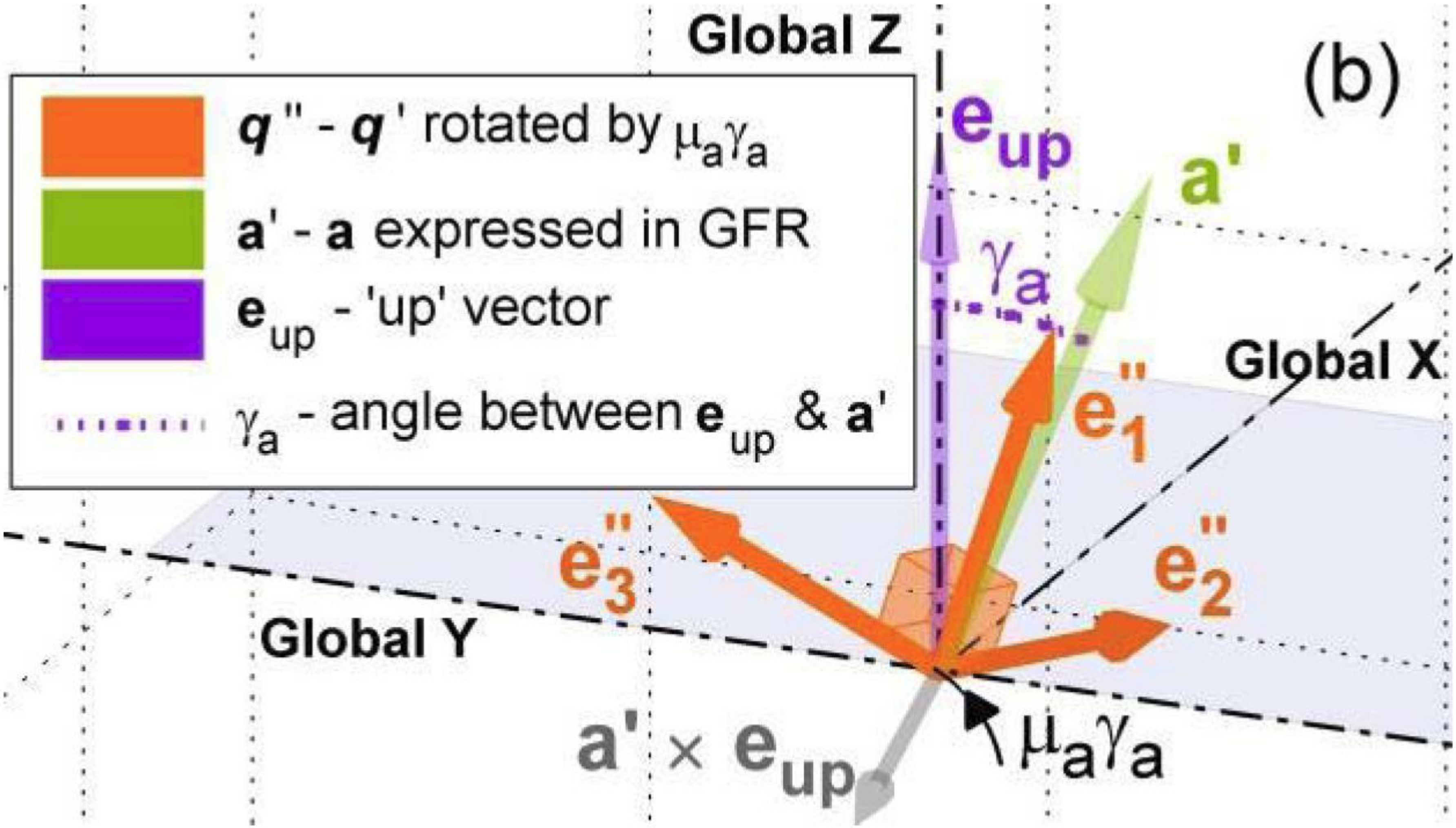


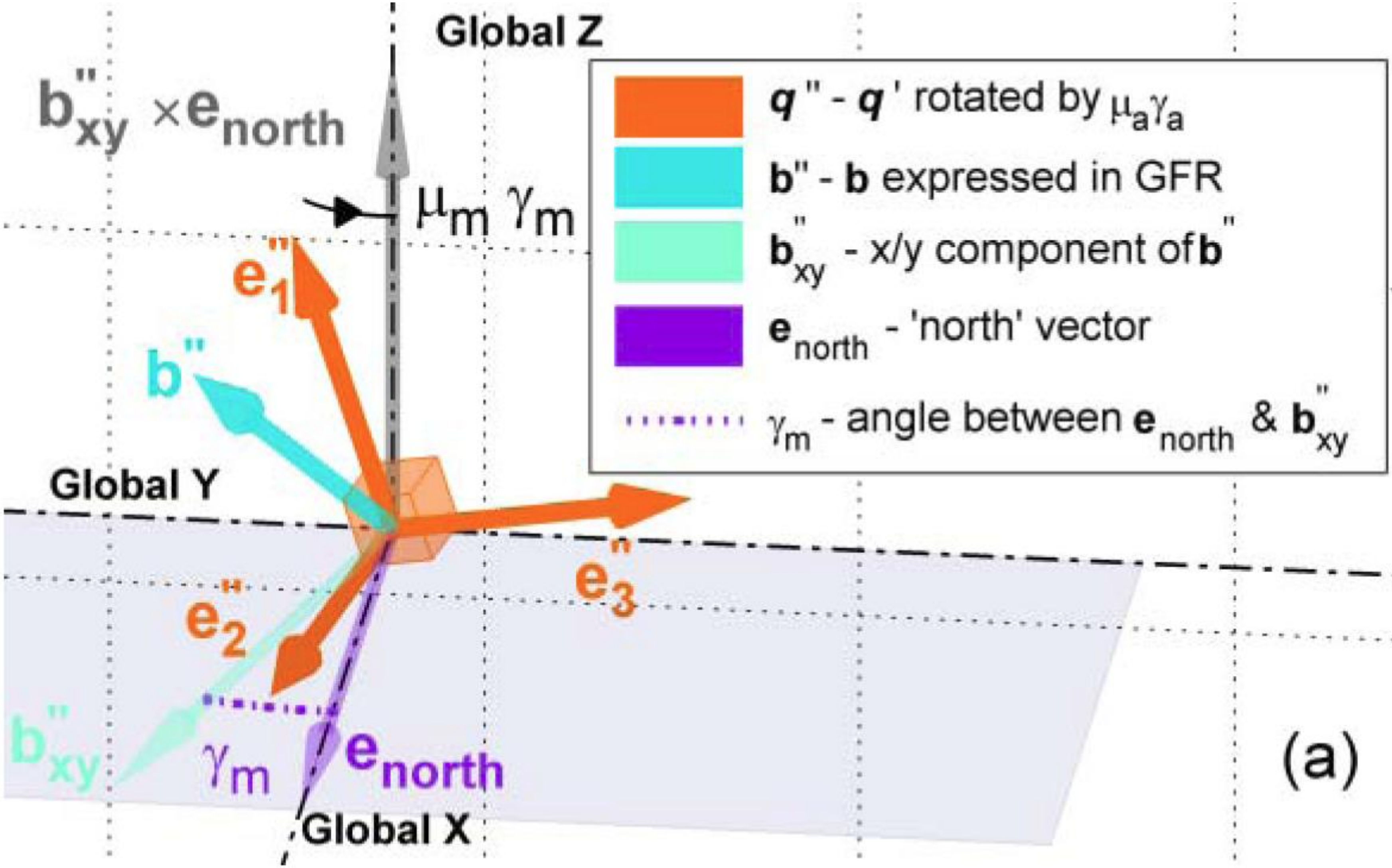
Using the gyroscope

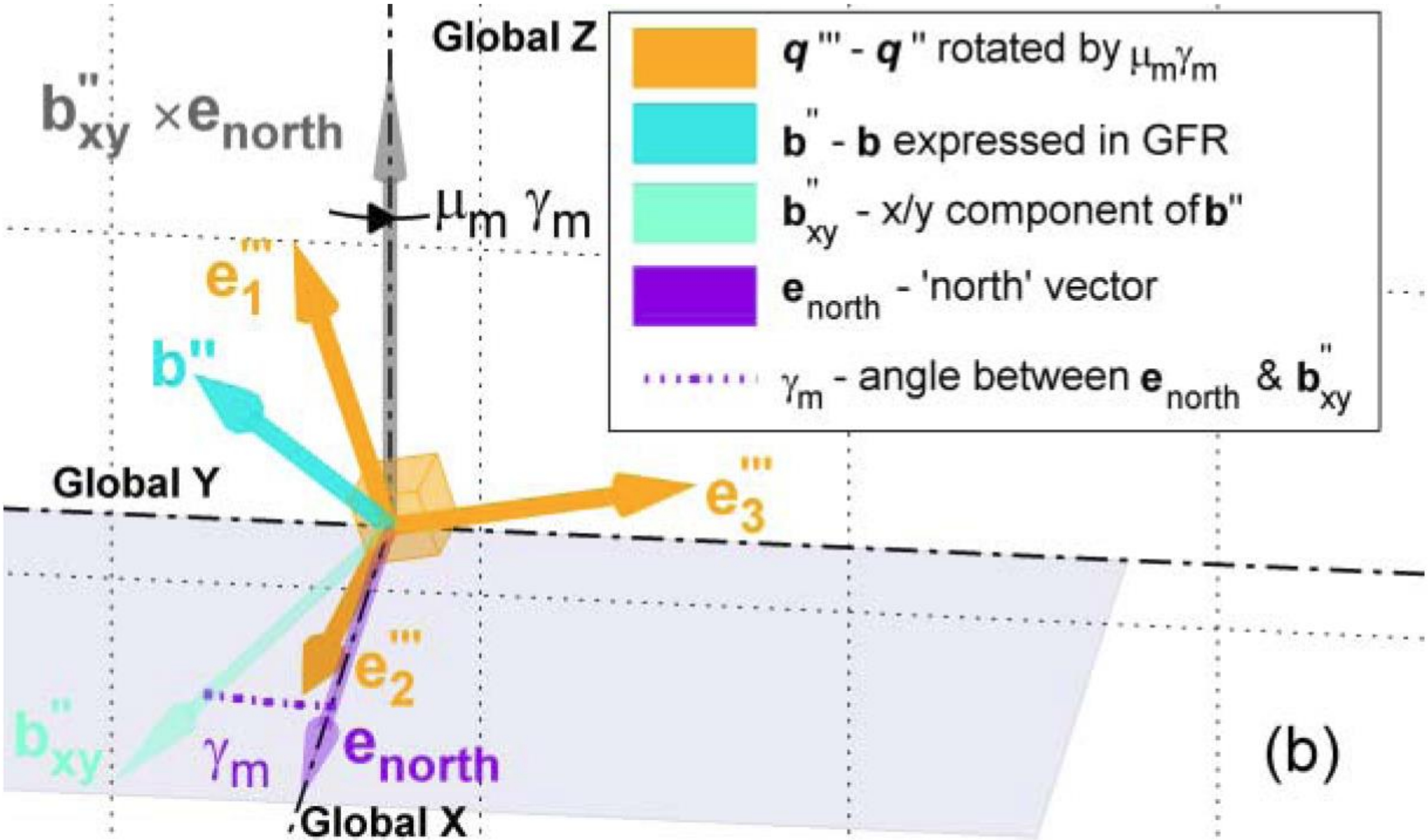




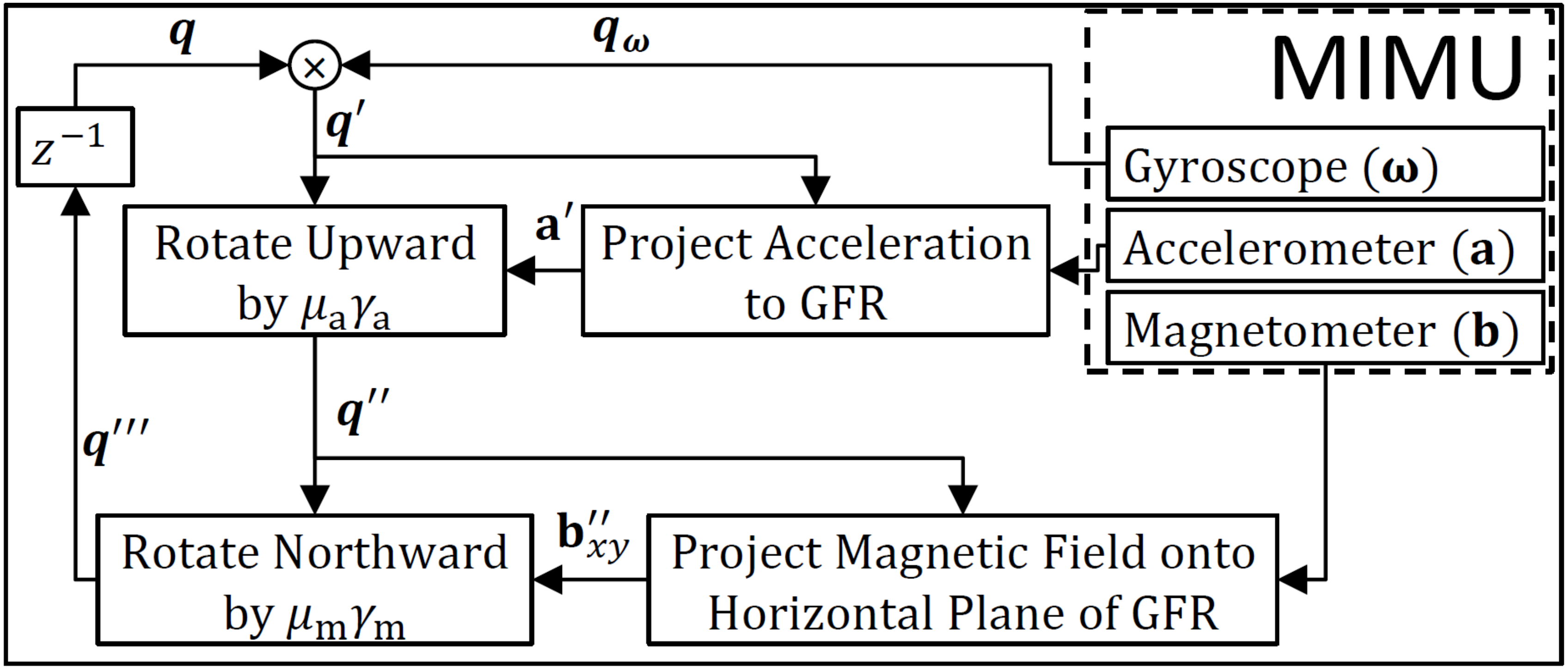
Global Z
(a)
q ' - q rotated by ω
a' - a expressed in GFR
e up - 'up' vector
γa - angle between e up & a'
e up
a'
γa
e'1
Global X
e'3
e'2
Global Y
a' × e up
μaγa


Global Z
(b)
q'' - q' rotated by $\mu_a\gamma_a$
a' - a expressed in GFR
e_{up} - 'up' vector
γ_a - angle between e_{up} & a'
e_{up}
a'
γ_a
Global X
e''_1
e''_3
e''_2
Global Y
a' × e_{up}
$\mu_a\gamma_a$


Global Z
$b''_{xy} \times e_{north}$
$\mu_m \gamma_m$
$\boldsymbol{q}''$ - $\boldsymbol{q}'$ rotated by $\mu_a\gamma_a$
$\mathbf{b}''$ - $\mathbf{b}$ expressed in GFR
$\mathbf{b}''_{xy}$ - x/y component of $\mathbf{b}''$
$\mathbf{e}_{north}$ - 'north' vector
γ_m - angle between $\mathbf{e}_{north}$ & $\mathbf{b}''_{xy}$
e''_1
b''
Global Y
e''_3
e''_2
b''_{xy}
γ_m
e_{north}
Global X
(a)

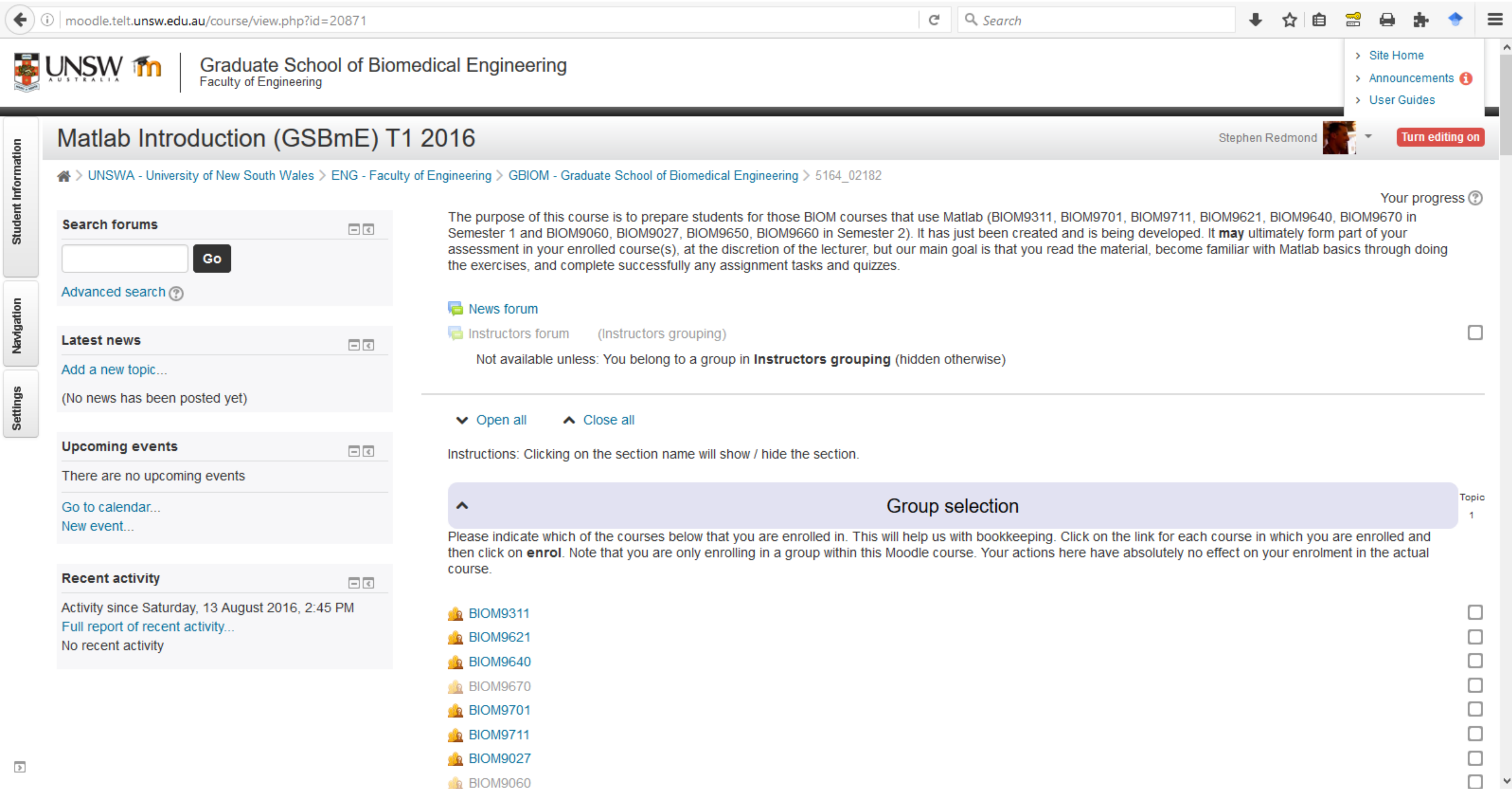


Global Z
$b''_{xy} \times e_{north}$
$\mu_m \gamma_m$
q''' - q'' rotated by $\mu_m\gamma_m$
b'' - b expressed in GFR
b''_{xy} - x/y component of b''
e_{north} - 'north' vector
γ_m - angle between e_{north} & b''_{xy}
e'''_1
b''
Global Y
e'''_3
e'''_2
b''_{xy}
γ_m
e_{north}
Global X
(b)



Del Rosario et al., IEEE Sensors Journal, 2016
http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=7480371

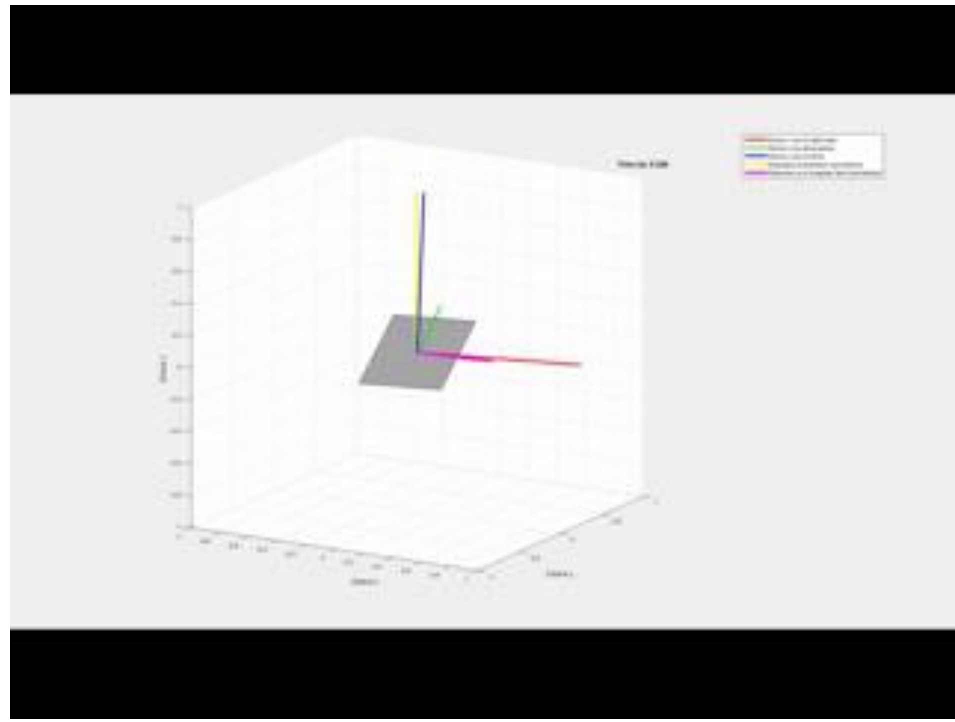
MATLAB tutorial on Moodle



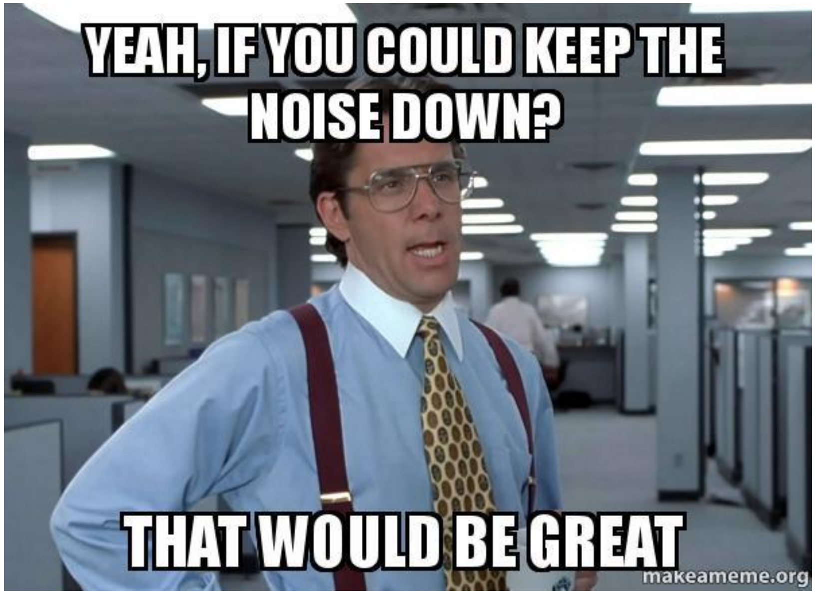
MATLAB tutorial on Moodle

- This week, go through the online MATLAB tutorial on Moodle yourself: https://moodle.telt.unsw.edu.au/course/view.php?id=30486
- To use MATLAB free, create a Mathworks account using your UNSW email address, then go here and login: http://au.mathworks.com/products/matlab-online/
- Or attend a UNSW computer lab where MATLAB is installed on computers

Demo of attitude determination



What if we have lots of noise?



Kalman filter

- A more formal means of using noisy data if we have a 'system model'
- Predict using a model:

$$\hat{\mathbf{x}}_k = \mathbf{A}\mathbf{x}_{k-1} + \mathbf{B}\mathbf{u}_k$$

  – For yaw, using 1-D gyro, we may have something like…

$$\hat{\theta}_k = \theta_{k-1} + \omega_k T$$

Predicted angle

Time between samples

Previous estimate

Angular velocity from gyro

- Correct using a measurement, z_k:

$$e_k = z_k - \hat{\theta}_k$$

Error between measured and predicted

Some measured angle from magnetometer

$$\theta_k = \hat{\theta}_k + K_k e_k$$

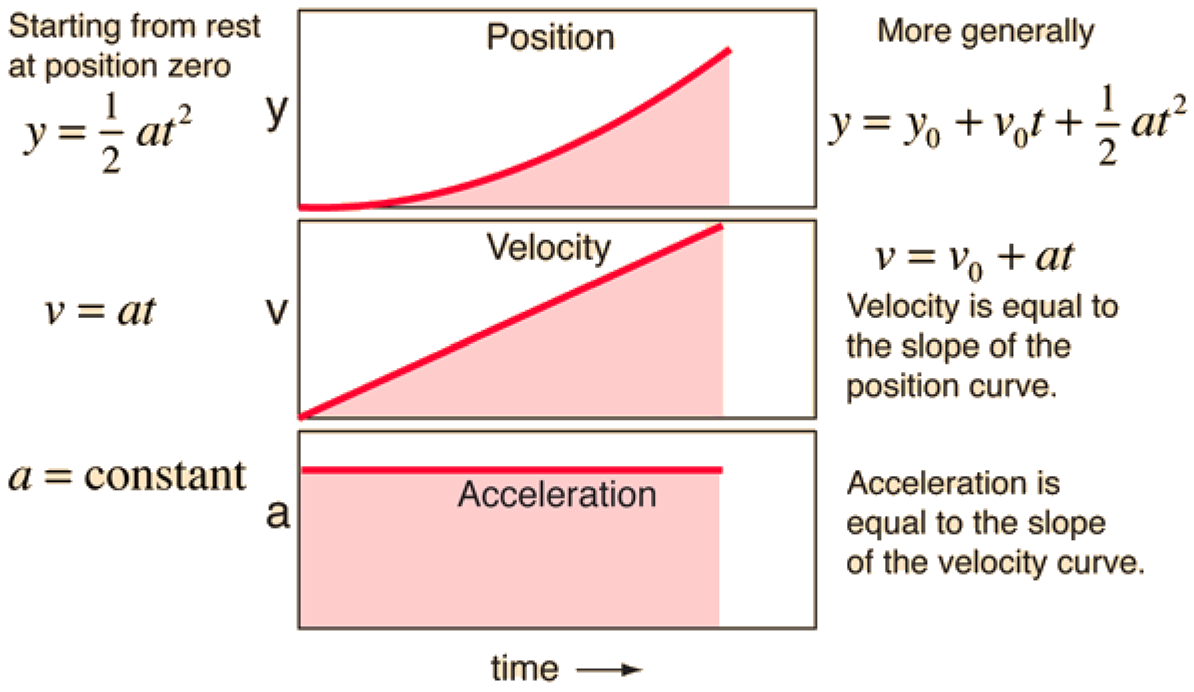
Kalman gain = how much we trust the measurement relative to the prediction:

$$\boldsymbol{K}_k = \frac{\boldsymbol{\sigma}_{\mathrm{gyro}}}{\boldsymbol{\sigma}_{\mathrm{gyro}} + \boldsymbol{\sigma}_{\mathrm{magno}}}$$

Kalman filter demo

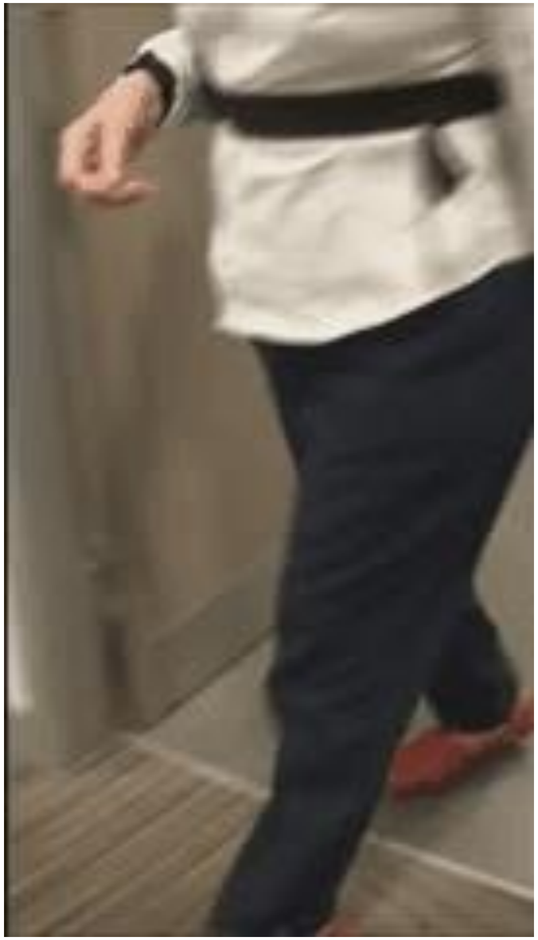
- A willing volunteer happy to listen to loud music and be blindfolded!?

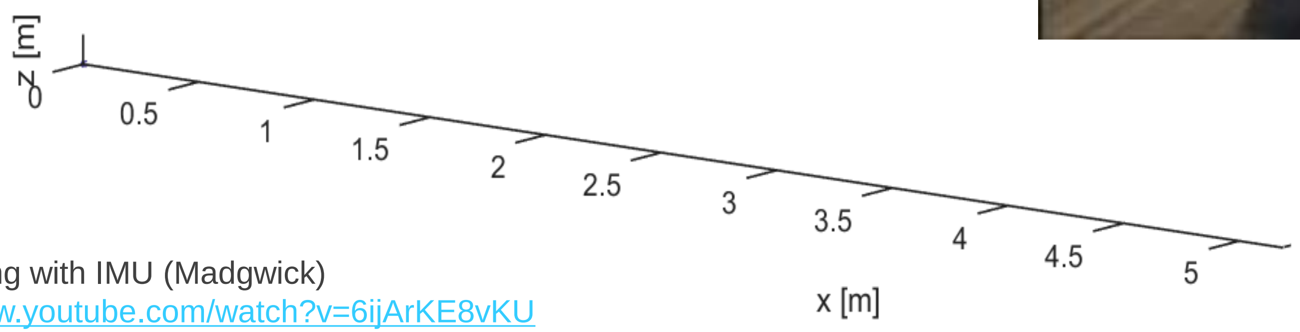
Dead-reckoning



- Integrate acceleration twice to get position
- But the acceleration signals are noisy
- Causes severe drift in position over time
- Need to update velocity or position regularly…

Zero-velocity update





3D Tracking with IMU (Madgwick)
https://www.youtube.com/watch?v=6ijArKE8vKU

Tutorial preparation

- I have made available on Moodle some sensor recordings of me rotating my phone, and video of this exciting event
- Tutorial instructions are online
- Do the online MATLAB tutorial this week: https://moodle.telt.unsw.edu.au/course/view.php?id=30486
- Use our lab computers or bring a laptop to the tutorial, ideally with MATLAB installed or access to MATLAB Online in your browser via a Mathworks account (sign-up with your UNSW email)

  http://au.mathworks.com/products/matlab-online
- If you have an Android phone, install Physics Toolbox Suite

  https://play.google.com/store/apps/details?id=com.chrystianvieyra.physicstoolboxsuite&hl=en
- If you have an iPhone, ~~you should consider buying an Android phone~~ download the Physics Toolbox Suite from the Apple Store https://itunes.apple.com/au/app/physics-toolbox-sensor-suite/id1128914250?mt=8

Bye!

- I hope you found some of this interesting!
- Good luck with the rest of the course
- Any questions?