Adapted From:

Inertial Measurement Units

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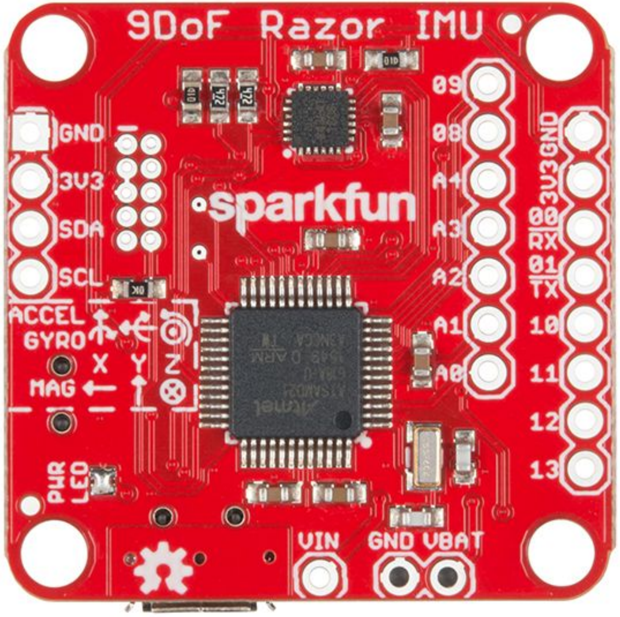
IMUs

An IMU, inertial measurement unit, is a sensor package containing 3 discrete sensors that can be used to track movement and orientation of objects

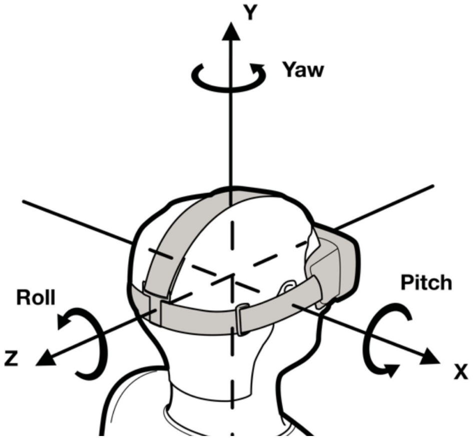


http://www.robo-dyne.com/en/shop/sparkfun-9dof-razor-imu-m0/

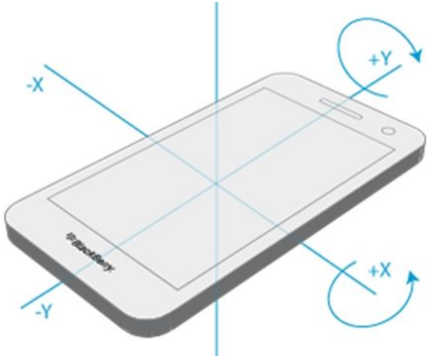
What can you use it for?

- Motion Capture
    - Gaming controllers for motion (Wii), VR Headsets
- Vehicle Tracking
    - IMU with GPS can keep track of moving ground vehicles
- Attitude and Heading Reference System
    - Calculate a vehicle’s heading relative to magnetic north
- Orientation Sensors
    - Phones, tablets, smart watches use to keep track of their orientation

https://stanford.edu/class/ee267/lectures/lecture9.pdf



Inertial Sensors - Dr. Kostas Alexiswww.kostasalexis.com/inertial-sensors.html



What is in an IMU?

Fusion of three sensor types

Gyroscopes -> Angular Velocity (rad/s or deg/s)

Accelerometer -> Linear Acceleration (m/s^2 or g)

Magnetometer -> Magnetic field strength (micro-Tesla or Gauss)

Using a combination of multiple outputs allows us to build robust, complex systems that can achieve higher levels of accuracy

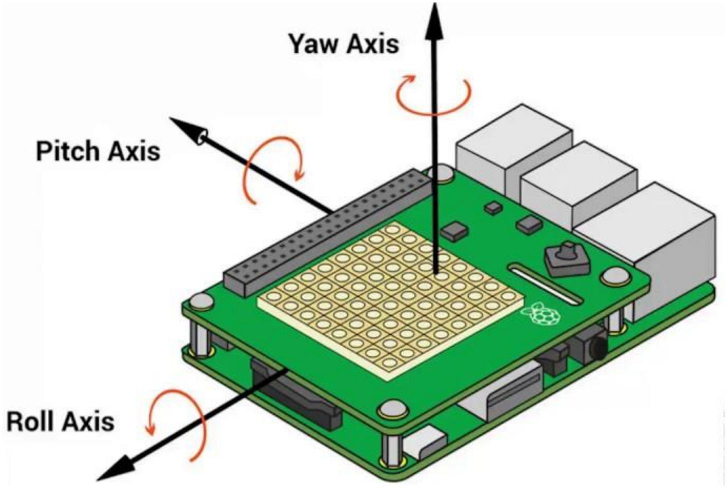
Degrees of Freedom

Typically, one sensor per type needed on each axis

- 6DOF - 3-axis accelerometer + 3-axis gyroscope
- 9DOF - 6DOF + 3-axis magnetometer
- 10DOF - 9DOF + barometric pressure sensor
- 11DOF - 10DOF + GPS

Some manufacturers make other combinations

(Digikey lists accelerometer+magnetometer 6-axis IMUs)



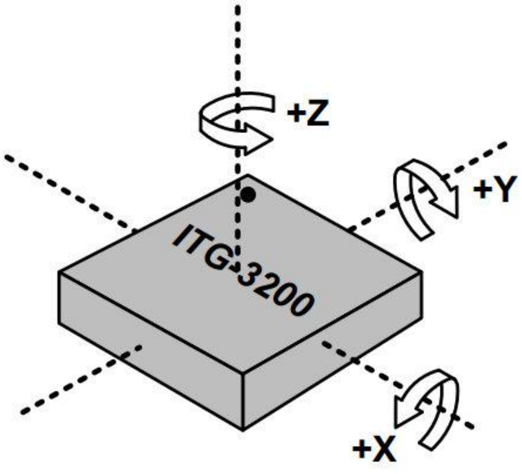
https://projects-static.raspberrypi.org/projects/generic-theory-pitch-roll-yaw/1da6c9e518533fe8c1f70d7445fd6880d7dac12a/en/images/orientation.png

Gyroscope

Gives angular velocity in degrees/second

Has constant bias which is affected by temperature

Bias changes over time (bias stability)



[Gyroscope - learn.sparkfun.comhttps://learn.sparkfun.com/tutorials/gyroscope/all?print=1](https://learn.sparkfun.com/tutorials/gyroscope/all?print=1)

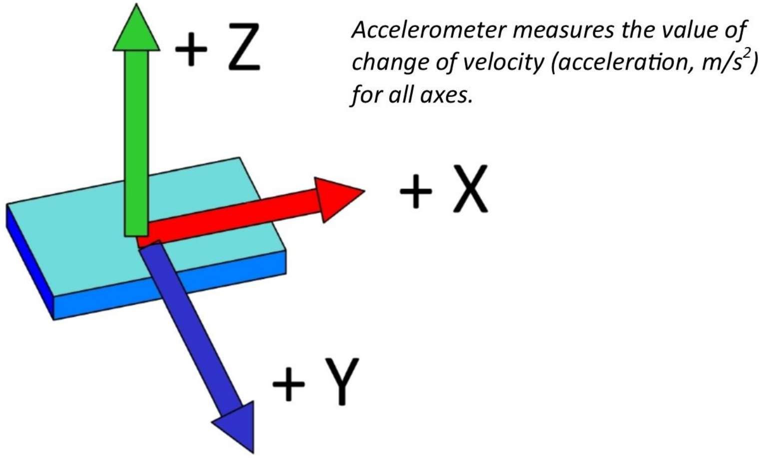
Accelerometer

Essentially measuring displacement value of a system for acceleration

Measured in terms of m/s^2 or *g*

At rest an accelerometer measures the gravity vector pointing up

Accurate long term (no drift) but not short term (noise)



roboticmagazine.com

Magnetometer

Measures magnetic field strength on each axis

Measured in Gauss (unit of magnetic flux)
or μT (unit of magnetic field strength)

Points generally towards magnetic north

Can be distorted by nearby metals or electronics

http://www.iconarchive.com/show/small-n-flat-icons-by-paomedia/compass-icon.html

Choosing an IMU

Principal considerations:

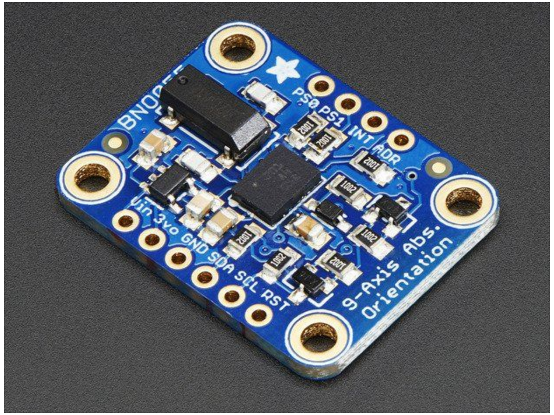
- Price
- Range and Resolution
- Degrees of Freedom
- Interface (Analog/Digital, which bus type)

More considerations:

- Noise distribution
- Power Consumption
- Gyro temperature offset

Option A (Adafruit 9-DOF Absolute Orientation IMU)

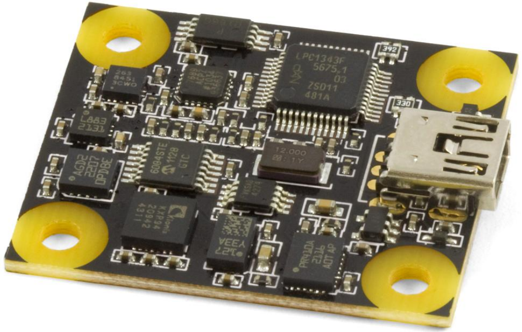
Cost: ~$36



https://cdn-shop.adafruit.com/145x109/2472-00.jpg

Option B (PhidgetSpatial Precision)

Cost: ~$140



https://www.phidgets.com/productfiles/1044/1044_0/Images/3150x-/0/1044_0.jpg

Comparison

	A (Adafruit 9-DOF IMU)	B (PhigetSpatial Precision)
Cost	$36	$140
Resolution	244.2µg, 0.06°/s, 300nT	76.3µg, 0.02°/s, 303nT
Range	±2g/±4g/±8g/±16g ±125°/s to ±2000°/s ±1300µT (x-, y-axis), ±2500µT (z-axis)	±2g/±8g ±400°/s or ±2000°/s ±550µT
Interfaces	I2C, UART	USB
DOF	9	9
Current Draw (max)	12.3 mA (@100Hz)	55 mA (@ 250Hz)
Bonus	Sensor fusion outputs, temperature sensor	Backup sensors for higher range with less precision

Processing the data

Often want more data than what the sensor directly measures

Position, Velocity, Orientation

Examples:

Orientation: Gyroscope gives us our angular velocity, integrating will get position

Linear Velocity: Accelerometer gives us acceleration, integration gives velocity

Position: Knowing orientation and velocity we can predict location based off time

Integrated Orientation

Estimate orientation by integrating angular velocities

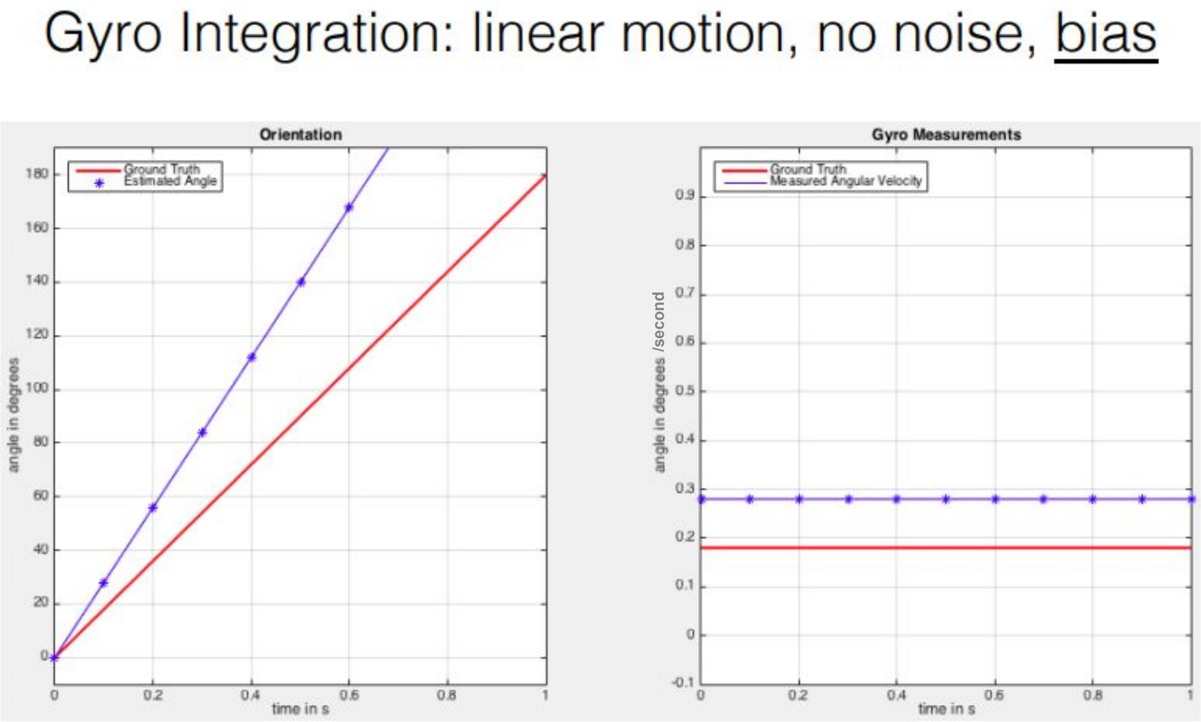
Gyroscope data outputs angular velocity (deg/s)

Riemann sum provides discrete-time approximation of integration

Riemann Sum Estimation of Orientation:

- $\theta_{approx}(t) = \theta_{approx}(t-1) + \omega(t-1)*\Delta t$

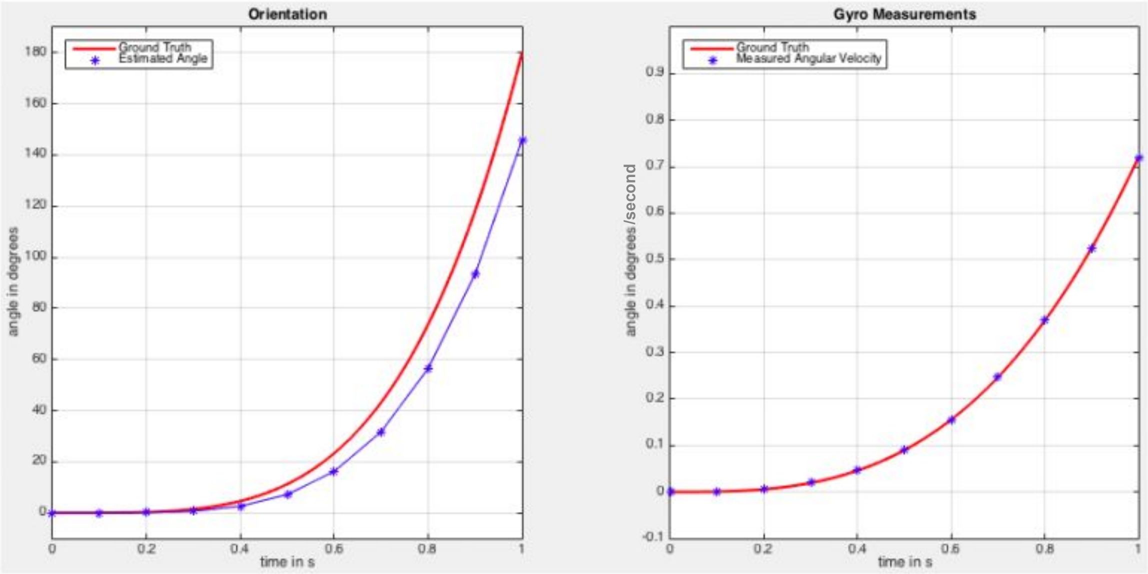
Integrated Orientation: Error due to sensor bias



https://stanford.edu/class/ee267/lectures/lecture9.pdf

Integrated Orientation: Error due to sampling rate

Gyro Integration: nonlinear motion, no noise, no bias



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Solution: Sensor Fusion

Combination of multiple sensors to extract one measurement

Between IMU sensors: Attitude Heading Reference System (AHRS)

Can also fuse IMU with other sensors (e.g. GPS)

Helps to minimize effects of bias

Many approaches and types of filters/algorithms

Some sensors do these calculations onboard

Gravity and Magnetic Field as References

Two natural phenomena that provide valuable references

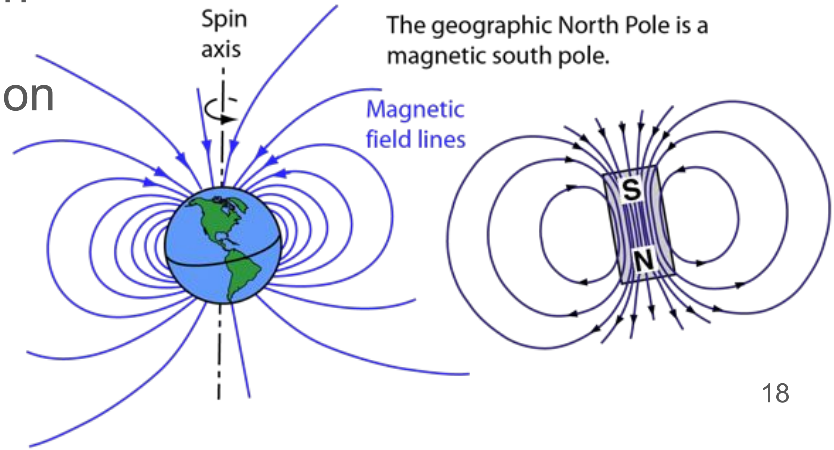
Acceleration due to gravity: 1g up

Magnetic Field Vector: Points generally “north”

If location known, can find real direction

Can utilize these values to supplement integration

hyperphysics.phy-astr.gsu.edu/hbase/magnetic/MagEarth.html



Many algorithms, each with their own strengths

Complementary Filter

Easy to visualize and implement

Kalman filter

High performance, but complex and computationally expensive

Madgwick Filter

Computationally efficient for use in low-resource systems

Example: Complementary Filter to Find Orientation

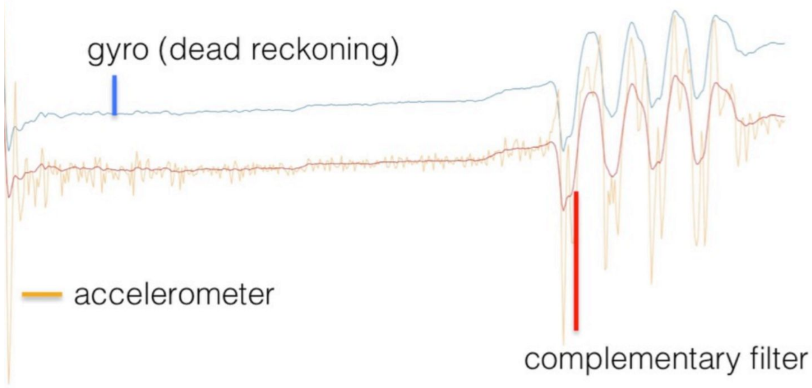
Gyroscope, Accelerometers, Magnetometers provide relevant data

Accelerometers can measure pitch/roll at rest, but suffer from noise when moving

Integration of gyroscope compounds low-frequency bias over time

Low-pass filter on accelerometers, magnetometer

High-pass filter on gyroscopes



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Example: Real Time Navigation

Problem:

Plane navigation systems and local robots cannot rely on GPS to give them accurate position

Goal:

Create a device that can process current data to get a sense of its direction without the use of a dedicated GPS system

Real Time Navigation

Data we have:

- Our last position
- Orientation measurements
- Velocity measurements

Let that be the data we input into a filter and let the output be our position now

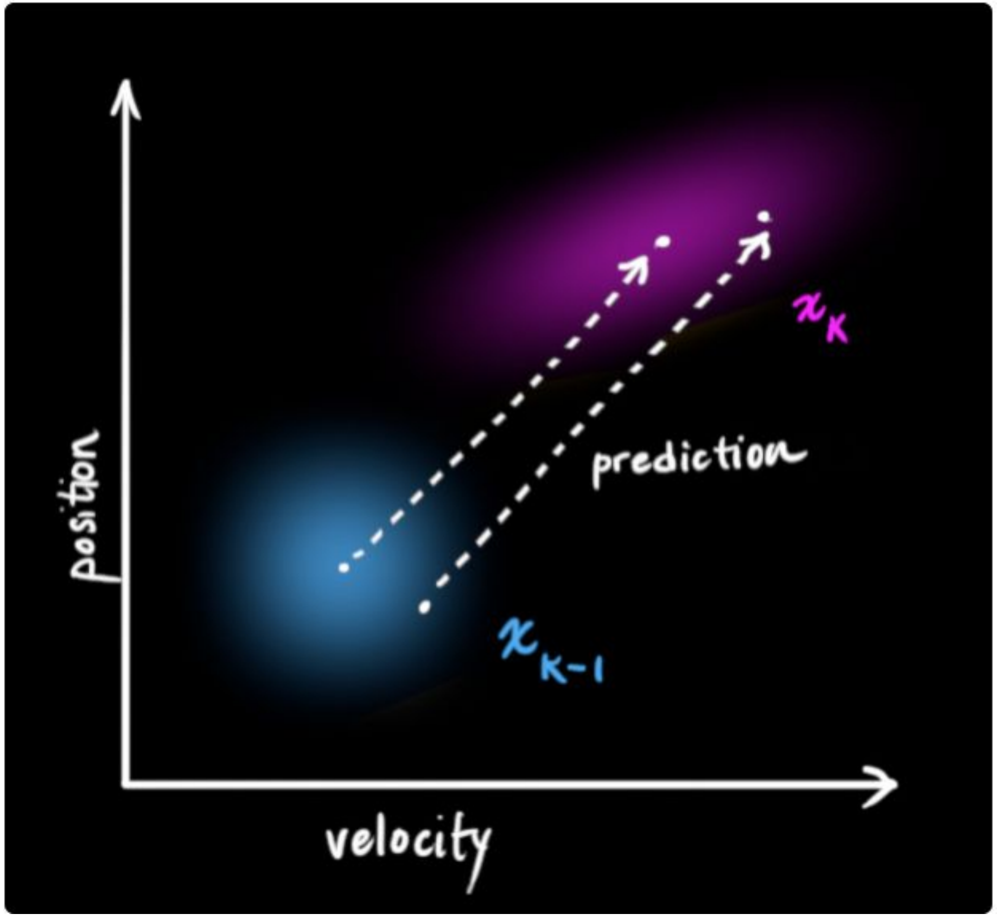
- Such a filter is called a Kalman Filter

Kalman Filter

- A recursive algorithm to predict current state by combining real time measurements, a mathematical model of the system, and our previous states
    - Kalman(last position, current_orientation, current_velocity, mathematical model) → current position
- This prediction algorithm is more accurate than just taking one single variable (i.e. just our previous trajectory or just current measurements)

Kalman Filter: Algorithm Overview

http://www.bzarg.com/p/how-a-kalman-filter-works-in-pictures/



Step 1:

At t0, keep track of a previous state distribution (estimation of location and all possible locations) -- blue

Step 2:

At t1, create a new probability distribution of location based off your previous state (mathematical model) -- pink

Kalman Filter: Algorithm Overview

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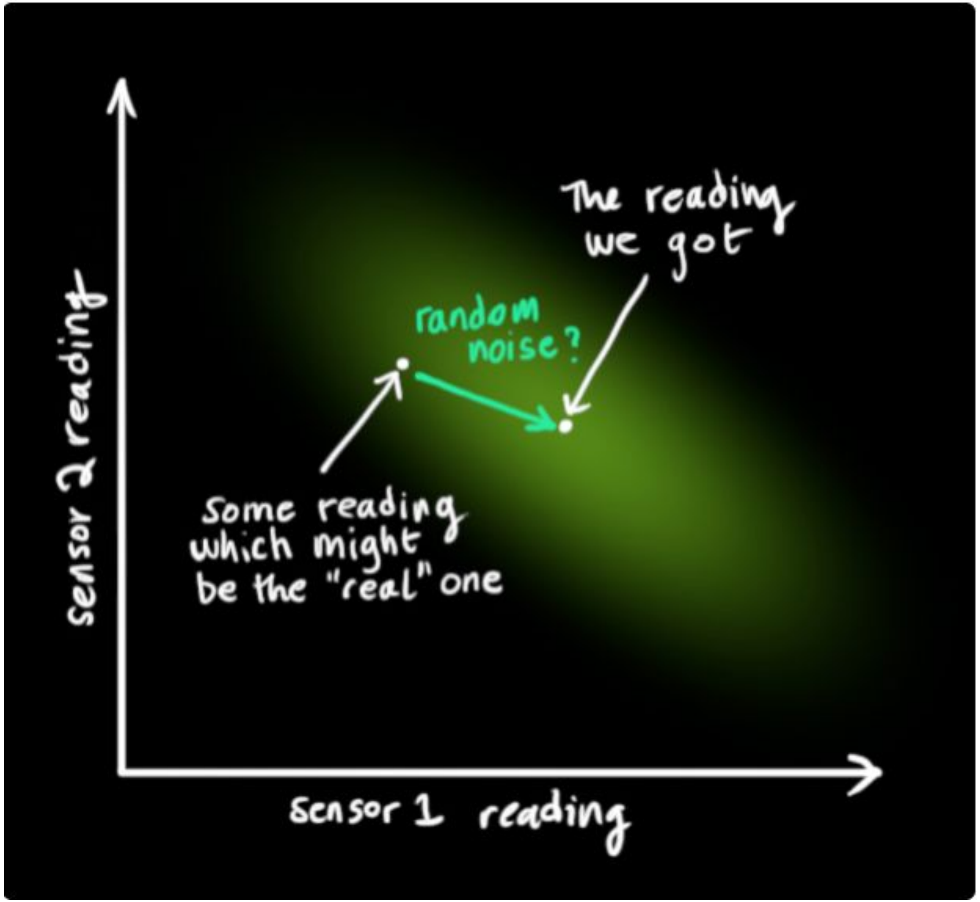
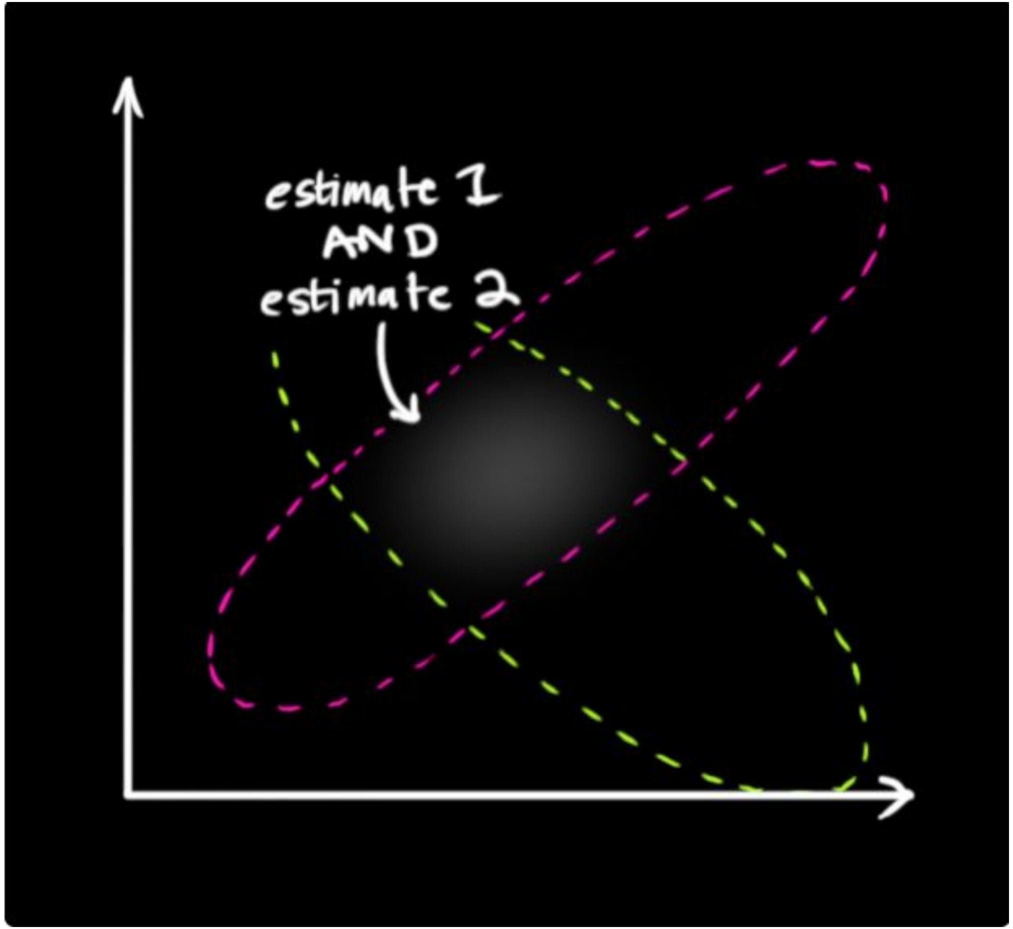


Step 3:

At t1, take measurements and create probability distribution of a location based on the data (measurement model)

Kalman Filter: Algorithm Overview

http://www.bzarg.com/p/how-a-kalman-filter-works-in-pictures/



Step 4:

At t2, create a new distribution that is intersection of the two models

Pink: probability model

Green: measurement model

White: intersection of models

Kalman Filter: Algorithm Overview

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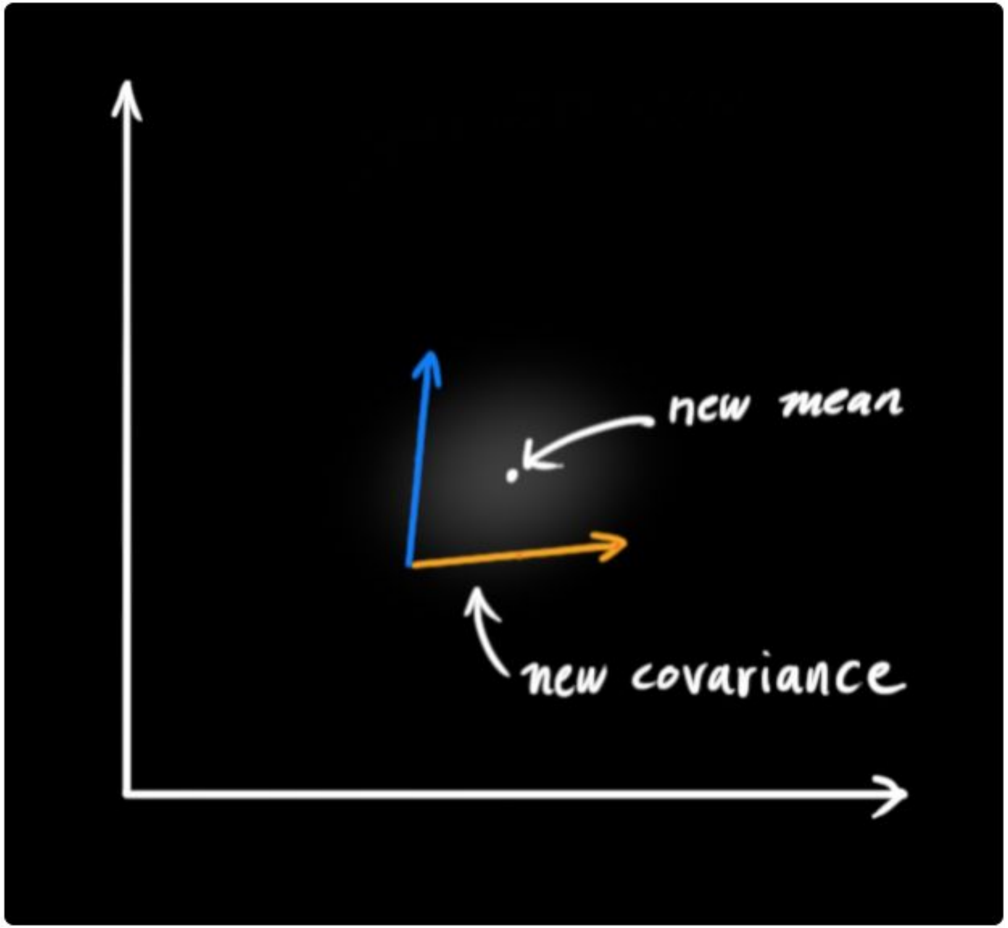

Step 5:

At t2, the new distribution is now the previous state and repeat steps 1 - 4

Conclusion

- Where IMUs are used
  - See them in multiple industries being used for movement tracking
- What makes up an IMU
  - 3 sensors and outputs:
    - Accelerometer for linear acceleration
    - Gyroscope for angular velocities
    - Magnetometer for heading
- How to choose one
  - Pay attention to price, range and resolution, and degrees of freedom
- How to get useful data
  - Sensor Fusion helps us combine multiple sensor to get more accurate readings
    - Multiple techniques: Kalman, Complementary and Madgwick filtering

Sources

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- http://www.pieter-jan.com/node/11