What is an IMU?

Skye Sweeney
Skye@fll-freak.com
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Wikipedia says:

- An **inertial measurement unit** (**IMU**) is an electronic device that measures and reports a craft's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes, sometimes also magnetometers.

Definitions

- Inertial: Pertaining to the physics that objects do not like to change orientation or speed.
- Orientation: The pitch, bank, and heading of a body relative to a stationary reference like the Earth.
- Velocity: Speed in a given direction.
- Acceleration: How fast a body is changing its speed.
- Accelerometer: A device that measures a body's acceleration.

Definitions

- Angular rate or rotational speed: How fast a body is spinning about itself. (RPM)
- Gyroscope: A device that measures a body's angular rate.
- Magnetometer: A device that measures the strength of a magnetic field. Often associated with the Earth's magnetic field.
- Gravitational forces: How the body is subjected to accelerations.

Wikipedia says (again):

- An **inertial measurement unit** (**IMU**) is an electronic device that measures and reports a craft's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes, sometimes also magnetometers.

But what is it really?

- An **inertial measurement unit (IMU)** is a device that tells you the following:
  - Pitch, roll, and heading
  - Speeds in your X, Y, and Z axis
  - Accelerations in your X, Y, and Z axis
  - Angular rates in your X, Y, and Z axis
  - Your location in the Earth’s X, Y, and Z axis.
- All this with only measuring physical values of accelerations and angular rates. No touch, vision, encoders, …
- Magnetometers and other sensors are ‘cheating’.

Related Names

- INS Inertial Navigation System
  - Full computer that uses an IMU and other sensors to navigate.
- AHRS Attitude Heading Reference System
  - Just roll, pitch, and heading

Examples

- Aircraft navigation system (INS)
- Guidance system for a missile
- Guidance system for a quadcopter
- Navy ship destroyer navigation system
- 3D mouse

Rainbow of IMUs

- 2D heading
- 2D velocity
- 2D orientation
- 3D orientation (AHRS)
- 3D orientation and velocities
- 3D orientation, velocities, and location
- Hybrids that merge in altimeter, magnetometer, and GPS data

Degrees of Freedom

- A ‘Degree of Freedom’ (DOF) is simply a way to count sensors that measure a unique parameter in a unique axis system.
- An (non enhanced) IMU is a 6 DOF device.
  - X, Y, and Z linear axis
  - P, Q, and R angular axis
- An IMU with magnetometer is 9 DOF
  - X, Y, and Z linear axis
  - P, Q, and R angular axis
  - P, Q, and R magnetometer axis

Accelerometer (Linear)

- Determines the rate of change of a body’s speed in a given direction. (m/s/s)
- Sensors leverage Newton's second law of motion
  - F=m*a or a = F / m
  - Place a known mass on a spring. Measure the force on the spring then divide by the mass.
- Great video(s) to watch (The Engineer Guy)
  - https://www.youtube.com/watch?t=245&v=KZVgKu6v808

Gyroscope (angular rate)

- Spinning mass in gimbal
  - Heavy, large, suffers from ‘Gimbal lock’
- Micro-Electro-Mechanical system (MEMS)
  - Tuning fork
  - Cheap
- Fiber Optic Gyro (FOG)
  - Change in how long it takes light to go around a coil of fiber.
  - $$$
- Ring Laser Gyro (RLG)
  - Change in how long it takes light to go around a race track.
  - $$$
- Resonant Sphere
  - Watch how a ‘bell’ rings.
  - $$$

Math principles

- Integration of measured values to yield desired results.
  - Integrate angular velocity into angular position
    - Roll, Pitch, Heading
  - Integrate linear acceleration into linear speed
    - X, Y, and Z speed
  - Integrate linear speed into linear position.
    - X, Y, and Z position

Integration

- "All" we need is to solve these equations:
- $\phi = \int_0^\infty \dot{\phi}\, dt \qquad \theta = \int_0^\infty \dot{\theta}\, dt \qquad \psi = \int_0^\infty \dot{\psi}\, dt$
- $\dot{x} = \int_0^\infty \ddot{x}\, dt \qquad \dot{y} = \int_0^\infty \ddot{y}\, dt \qquad \dot{z} = \int_0^\infty \ddot{z}\, dt$
- $x = \int_0^\infty \dot{x}\, dt \qquad y = \int_0^\infty \dot{y}\, dt \qquad z = \int_0^\infty \dot{z}\, dt$

WRONG!

Numerical integration

- Rather than symbolic integration, we use numerical integration.
  - No college course needed.
  - Pretty easy to understand.

An example

- You are in a car traveling west.
- For the first hour you are going 10 MPH
- The second hour you are going 20 MPH
- The third hour you are going 10 MPH

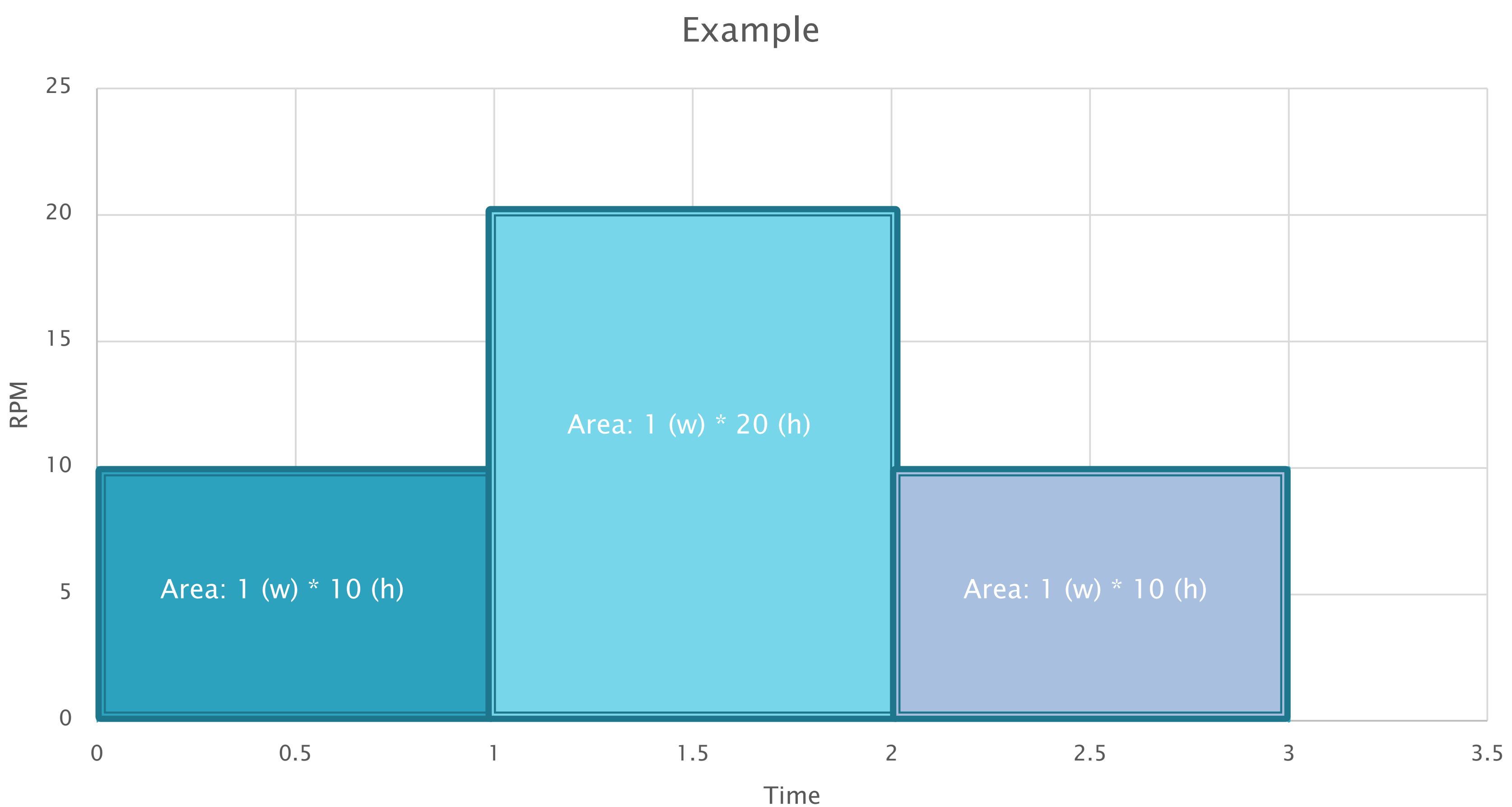
- How far did you travel after the first hour?
  - 1H * 10 MPH = 10 miles
- How far did you travel after the second hour?
  - (1H * 10 MPH) + 1H * 20 MPH = 30 miles
- How far did you travel after the third hour?
  - (1H * 10 MPH + 1H * 20 MPH) + 1H * 10 MPH = 40 miles

Continued

- You are spinning on a merry-go-round.
- For the first minute you are going 10 RPM
- The second minute you are going 20 RPM
- The third minute you are going 10 RPM

- How far did you rotate after the third minute?
  - 1M * 10 RPM + 1M * 20 RPM + 1M * 10 RPM
  - Or 40 revolutions

A graphical approach

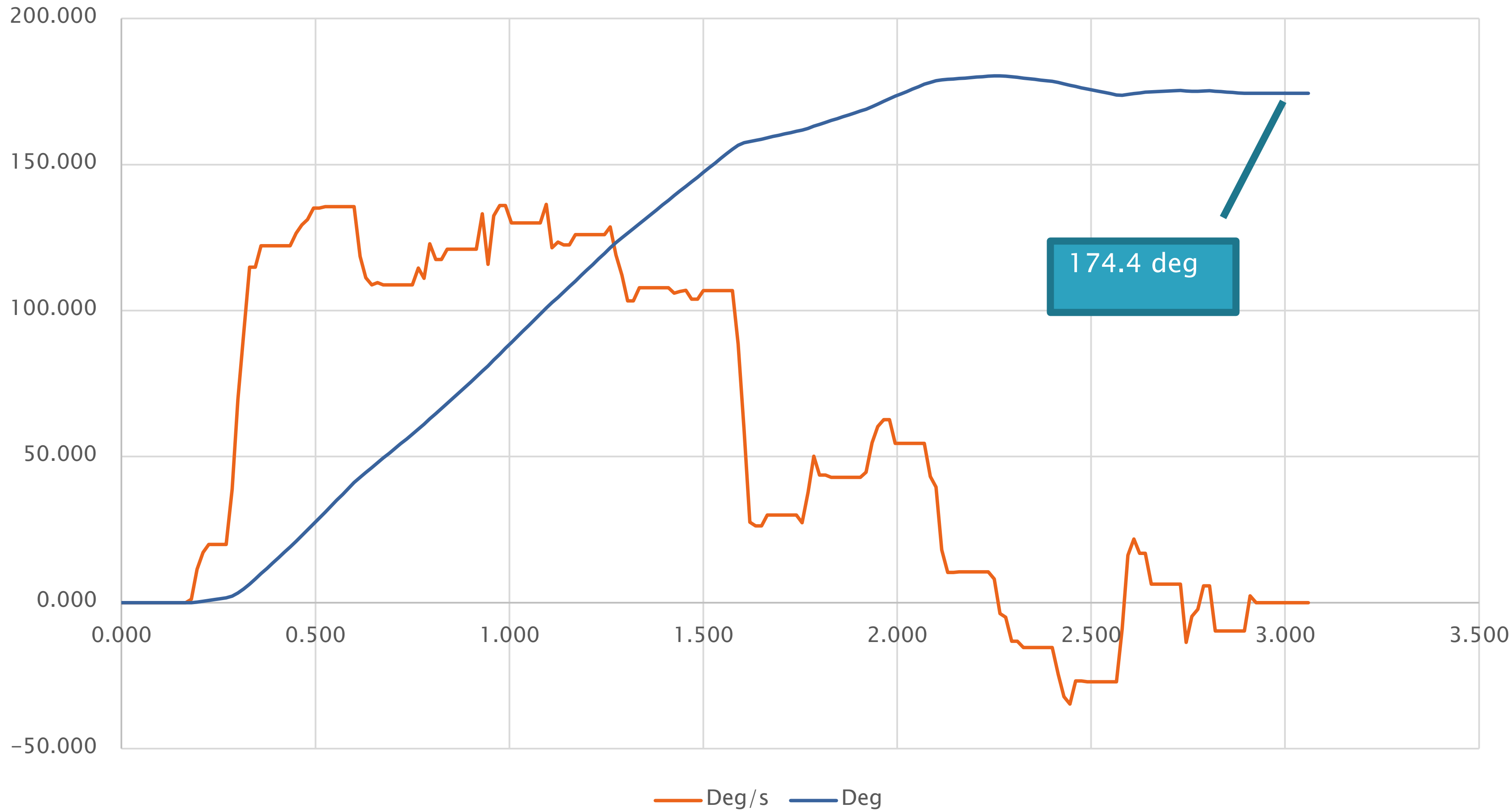


Basic Implementation

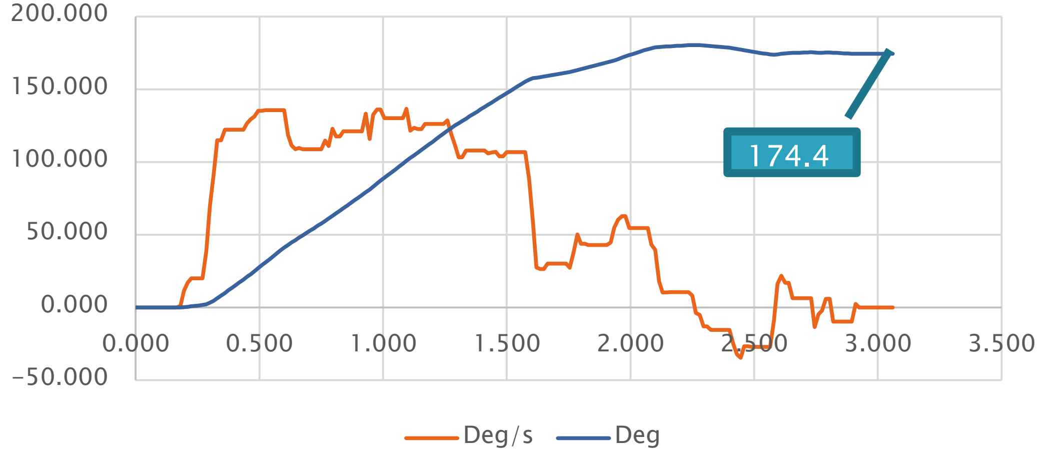
- Roll = Roll + RollRate * timeInc;
- Pitch = Pitch + PitchRate * timeInc;
- Heading = Heading + PitchRate * timeInc;

- xSpeed = xSpeed + xAccel * timeInc;
- …
- xPosition = xPosition + xSpeed * timeInc;
- …

Real Data for a 180 turn



Something to Notice



What happened to the 5.6 degrees?

Sensor Specs

- Accuracy (how right the answer is)
  - The less the accuracy depends on temperature, magnetic fields, vibration, … the better.
- Precision (how many decimal points you get)
  - The more precise the better.
  - All sensors are analog at the start. Unless you are using an analog computer, the analog value must get converted to a number at some point. The better the converter the better your results.
- Range
  - Best to just cover the rates and accelerations you need. A +- 100 g accelerometer on an indoor robot robs you of precision. A +-1g accelerometer on a rocket will saturate.
- Random errors
  - Due mostly to noise in the sensor.

Sample/Integration Rate

- How often you sample
- The faster you sample the finer detail you can account for.
- The faster you sample, the more computation power you need.
- I have used systems that operate from as low as 10 to as much as 10,000 times a second.

Calibration

- Scale factor
  - Datasheet may say full scale is 100 degrees/ second but in fact it is 98.7.
- Offset
  - When the unit is still, the voltage is rarely 0.0 or the count 0.
- Solution
  - realValue = (rawSensor – offset) * scaleFactor;
  - Offset can be determined by reading the “at rest” value.
  - Scale factor is more difficult…

Scale Factor

- Accelerometer
  - At rest, the vertical (z) axis will experience 9.8m/s/s (1g) due to gravity.
  - Record the raw value then invert the sensor.
  - Now the sensor is under 1g the other way.
  - Record this raw value.
  - The difference is raw values is equal to 2 g's of acceleration.
- Gyro
  - Need a rate table. Repurpose an old phonograph! You can get 33.3 and 45 RPM from one!

Temperature Effects

- MEMS sensors are fairly sensitive to temp
  - Calibrate at different temperatures
  - Or
  - Maintain the device at a constant temperature
    - Heater inside a temp controlled oven

Absolute vs Relative

- A strict IMU (nothing but inertial sensors) is for the most part a relative sensor.
- It can only tell you how far you have turned or moved from when it was first turned on.
  - It can only tell that you are now 40 revolutions from the start, not that you are now heading at 43.2°
- The exception is pitch and roll.

Enhanced IMUs

- IMUs that add other sensors such as
  - Magnetometers
  - GPS
  - Barometers
  - RADAR / LIDAR
  - Radio altimeters
  - …
- Enhanced IMUs can now give absolute answers to some parameters.

If you have a GPS why use an IMU at all?

- GPS does not give you pitch and roll.
- The accuracy of GPS is great long term, but not so good short term.
- The accuracy of an IMU is great short term, but terrible long term.
- Merge the two and you get the both of best worlds!
  - Kalman filter (KF)
  - Enhanced Kalman filter (EKF)
  - Complimentary filter

Magentometers

- Magnetometers are often used in enhanced IMUs.
- By measuring the Earth's magnetic field you can determine your absolute heading.
- But…
  - Heading is relative to magnetic north not true.
  - Calibration is somewhat complex.
  - Very sensitive to:
    - Ferrous metals
    - Magnetic fields such as drive and servo motors
    - Magnetic fields such as created by electric circuits.

What can I expect?

- If you have
  - MEMS type sensors
  - 100 Hz integration rate
  - Fully calibrated
  - Minimal vibration
  - Under 1 g accelerations
  - Under 200 deg/sec turn rates
    - In angular space **at best** 15 deg/hour
    - In linear space about %5 percent/hour
- All errors grow in time.
  - Position is the worst due to double integration.

What can I expect?

- Invest $100,000
  - FOG or RLG
  - Vibration damped
  - Top of line accelerometers
  - High computation power
    - 1 degree per hour
    - 0.1% per hour linear

Ready to go IMUs

- UM7 (LT) ($130 from Pololu)
  - 9 DOF (acc, gyro, mag)
  - GPS support
  - EKF
  - Unknown sensor supplier
- BNO055 ($35 from AdaFruit)
  - 9 DOF
  - EFK
  - Bosh based

Roll Your Own (Sparkfun)

- Various 6 axis MEMS devices
  - Invensence and ST based
- Various 9 axis MEMS devices
  - Invensence and ST based
- DIYDrones ArduIMU (IMU + GPS)
- Buying guide:
  - https://www.sparkfun.com/pages/accel_gyro_guide

Roll Your Own (AdaFruit)

- 9 DOF ($20)
  - ST based
- 10 DOF ($25)
  - ST based

Roll Your Own (Pololu)

- Pololu
  - Mini IMU ($20)
    - 9 DOF based on ST parts
  - Alt IMU ($22)
    - 10 DOF based on ST parts
  - 3 DOF accel
  - 3 DOF gyro
  - 3 DOF mag

Sensor Manufacturers

- Hobbyist tier
  - ST
  - Invensense
  - Analog Devices
- Pro tier
  - Sensonor
  - Murata
  - Moog-Crossbow
  - KVH
  - Various defense contractors

Questions?