Head Tracking and IMUs

CS 6334 Virtual Reality

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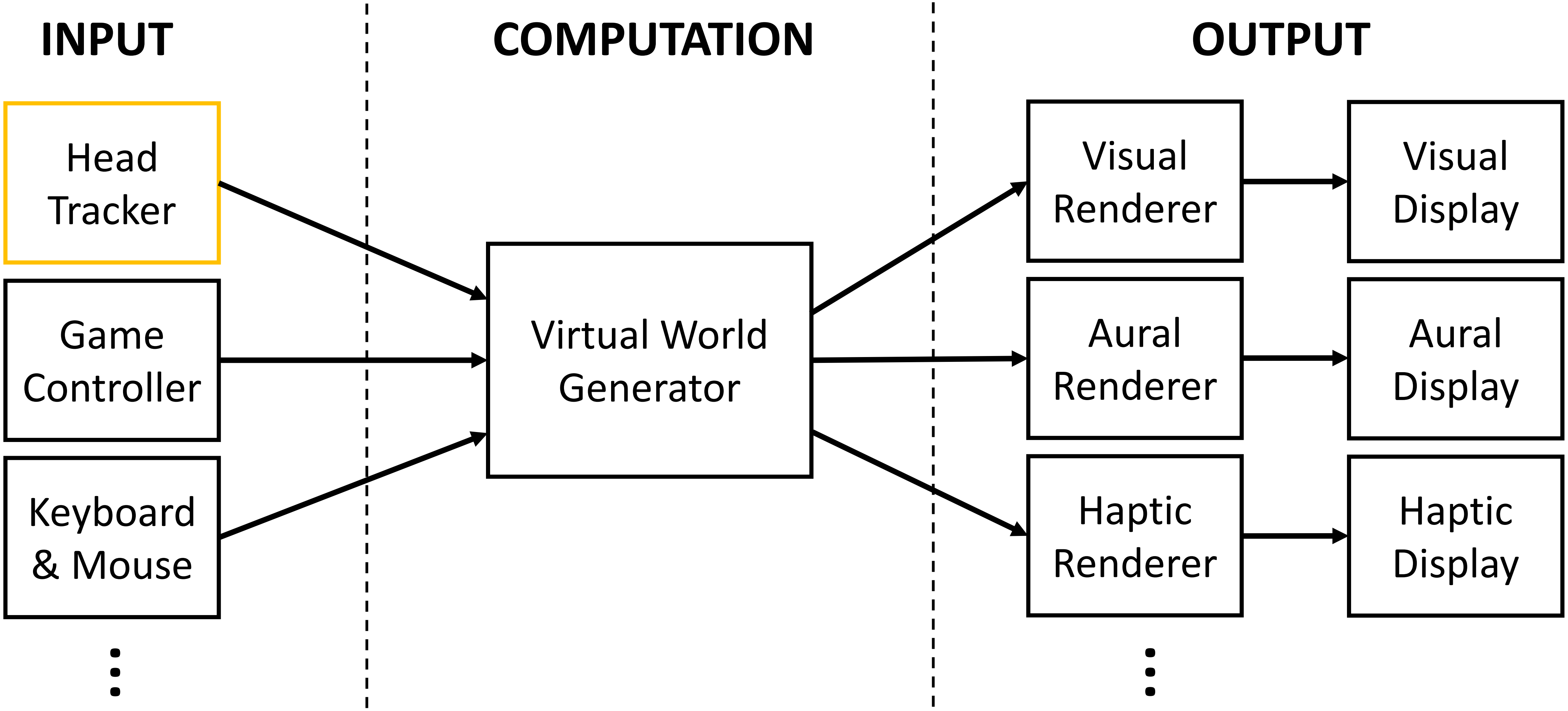
The University of Texas at Dallas

Some slides of this lecture are courtesy Gordon Wetzstein

Review of VR Systems



INPUT

COMPUTATION

OUTPUT

Head Tracker

Game Controller

Keyboard & Mouse

⋮

Virtual World Generator

Visual Renderer

Aural Renderer

Haptic Renderer

⋮

Visual Display

Aural Display

Haptic Display

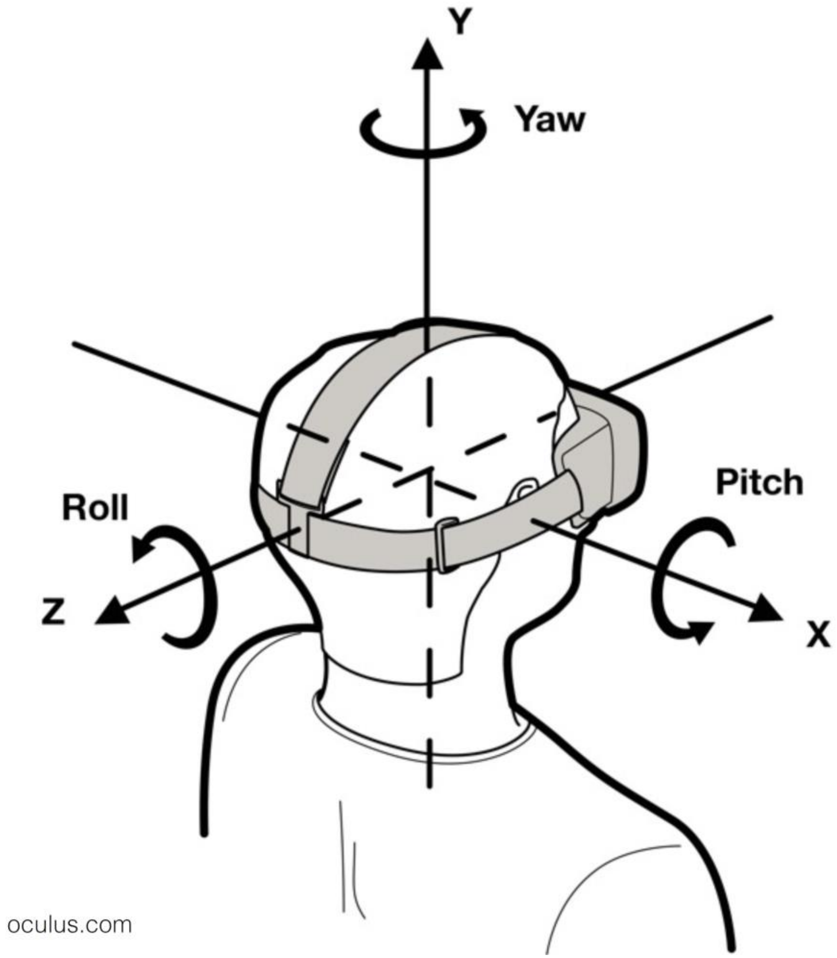
Tracking in VR

- Tracking the user’s sense organs
  - E.g., Head and eye
  - Render stimulus accordingly

- Tracking user’s other body parts
  - E.g., human body and hands
  - Locomotion and manipulation

- Tracking the rest of the environment
  - Augmented reality
  - Obstacle avoidance in the real world

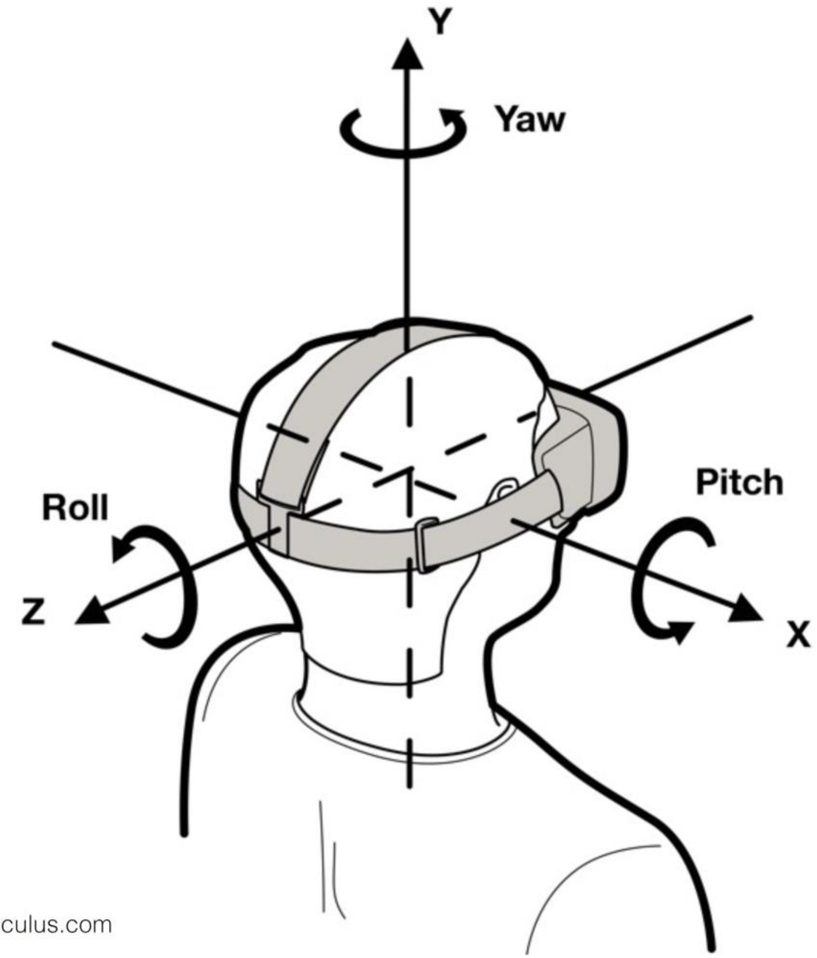
Head Tracking



oculus.com

- Track orientation of the head
- Orientation is the rotation of the device w.r.t. world or inertial frame
- Euler angle representation: yaw, pitch, roll

Head Tracking



oculus.com

- Determine the viewpoint of the user
- In visual rendering

$$\overset{\text{vertex in clip space}}{\overset{\downarrow}{v_{clip}}} = \underset{\text{projection matrix}}{\underset{\uparrow}{M_{proj}}} \cdot \underset{\text{view matrix}}{\underset{\uparrow}{M_{view}}} \cdot \underset{\text{model matrix}}{\underset{\uparrow}{M_{model}}} \cdot \overset{\text{vertex}}{\overset{\downarrow}{v}}$$

$$M_{view} = \overset{\text{rotation}}{\overset{\downarrow}{R}} \cdot \overset{\text{translation}}{\overset{\downarrow}{T}}(-eye)$$

$$R = \overset{\text{roll}}{R_z(-\theta_z)} \cdot \overset{\text{pitch}}{R_x(-\theta_x)} \cdot \overset{\text{yaw}}{R_y(-\theta_y)}$$

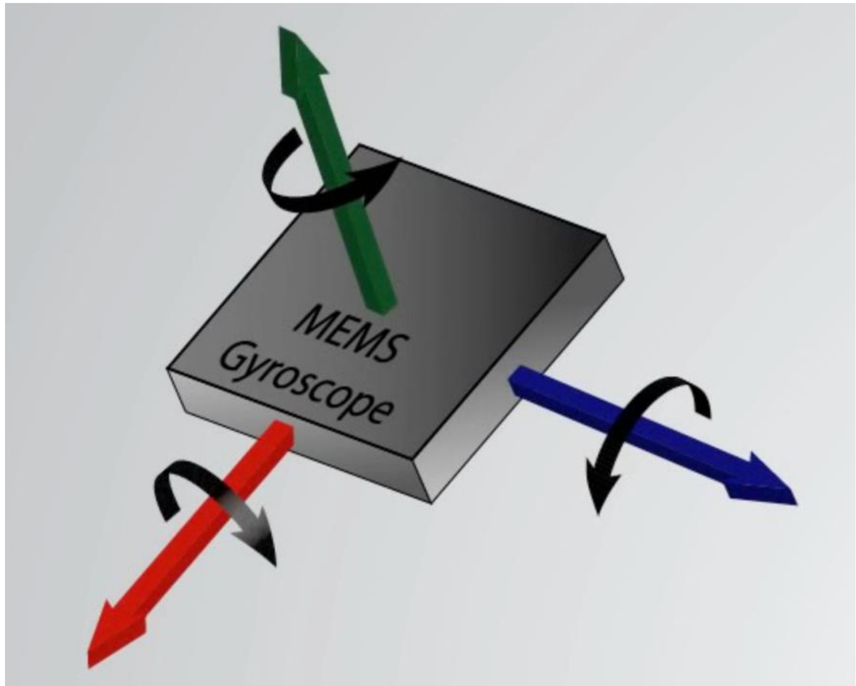
Inertial Measurement Unit (IMU)

- Gyroscope measures angular velocity $\tilde{\omega}$ in degrees/second
- Accelerometer measures linear acceleration $\tilde{a}$ in m/s^2
- Magnetometer measures magnetic field strength $\tilde{m}$ in uT (micro Tesla) or Gauss, 1 Gauss = 100 uT

All measurements taken in sensory/body coordinates

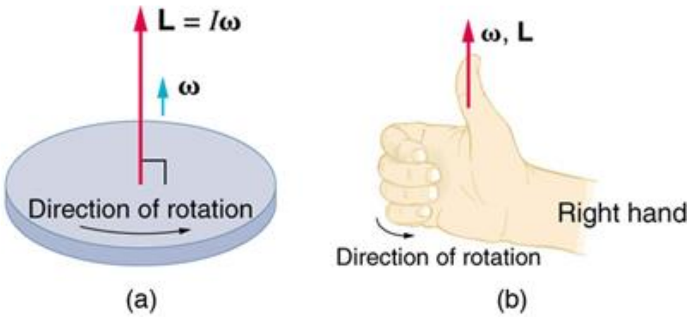
Gyroscopes

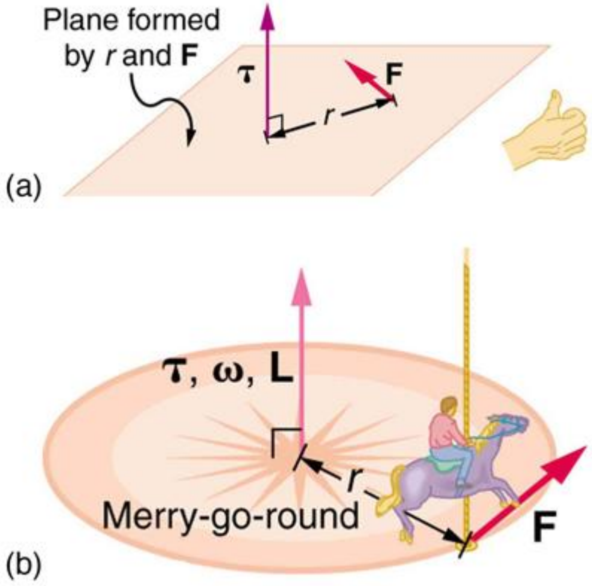
- Measure angular velocity

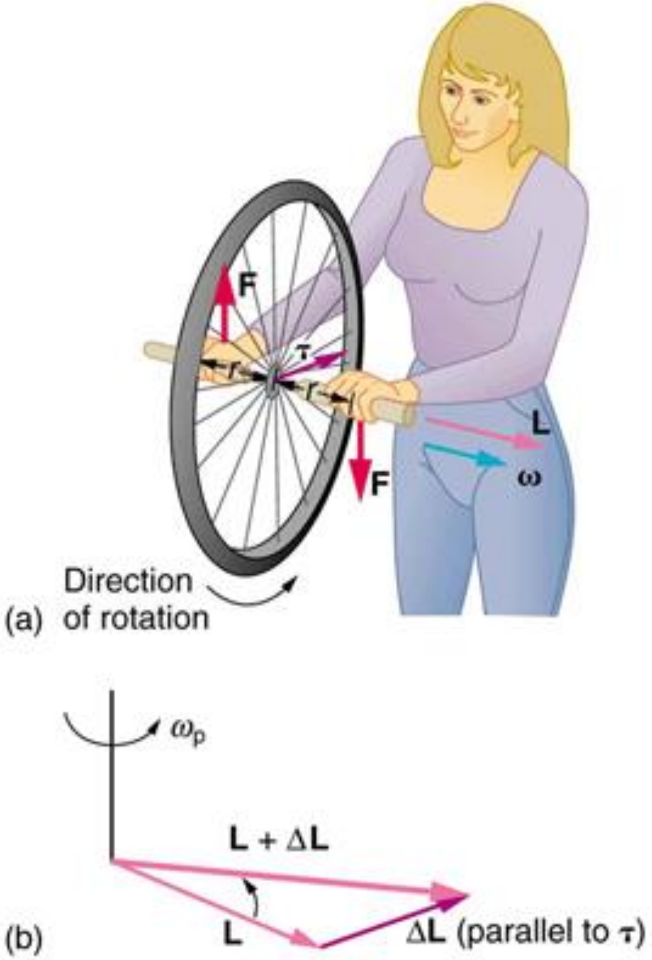


https://robotacademy.net.au/lesson/how-gyroscopes-work/

Gyroscopic Effects: Vector Aspects of Angular Momentum







Angular velocity
Angular momentum

https://courses.lumenlearning.com/physics/chapter/10-7-gyroscopic-effects-vector-aspects-of-angular-momentum/
https://www.youtube.com/watch?v=8H98BgRzpOM

Gyroscopes

- Gyro model $$\tilde{\omega} = \omega + b + \eta \qquad \eta \sim N\left(0, \sigma^2_{gyro}\right)$$

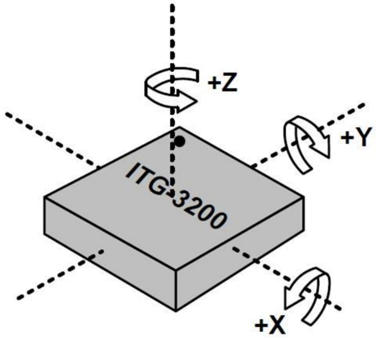
measured angular velocity

true angular velocity

bias

additive, zero-mean Gaussian noise

3DOF: 3-axis gyro that measures 3 orthogonal axes



Gyroscopes

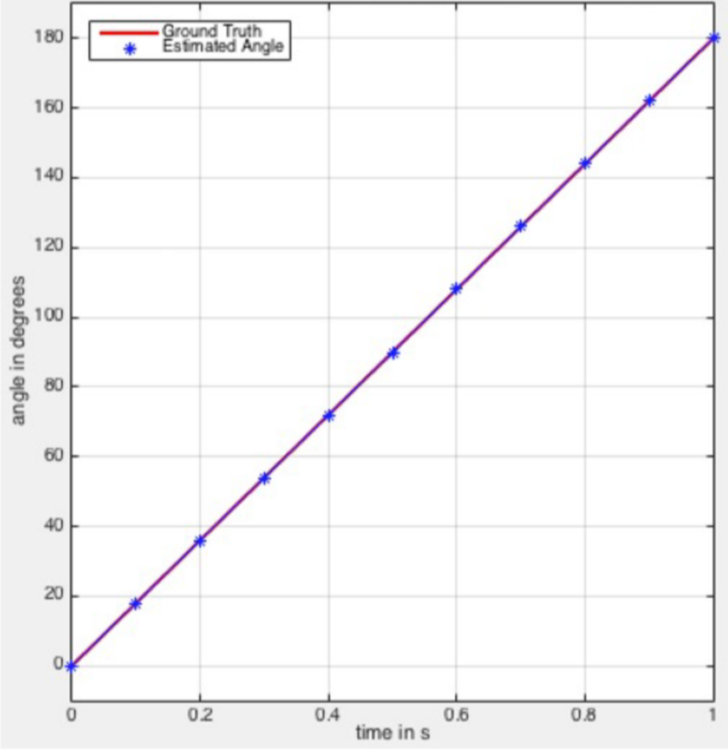
- From gyro measurement to orientation
  - Taylor expansion

$$\underbrace{\theta(t+\Delta t)}_{\text{Angle at current time step}} \approx \underbrace{\theta(t)}_{\text{Angle at previous time step}} + \underbrace{\frac{\partial}{\partial t}\theta(t)}_{\text{Gyro measurement (angular velocity)}} \overbrace{\Delta t}^{\text{Time step}} + \underbrace{\varepsilon}_{\text{Approximation error}}, \varepsilon \sim O(\Delta t^2)$$

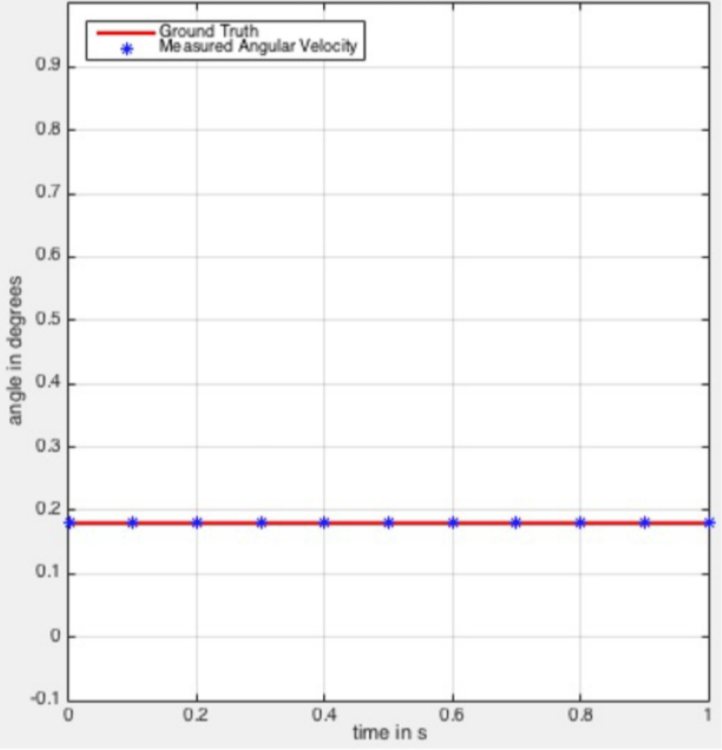
Gyro Integration

- Linear motion, no noise, no bias

Orientation



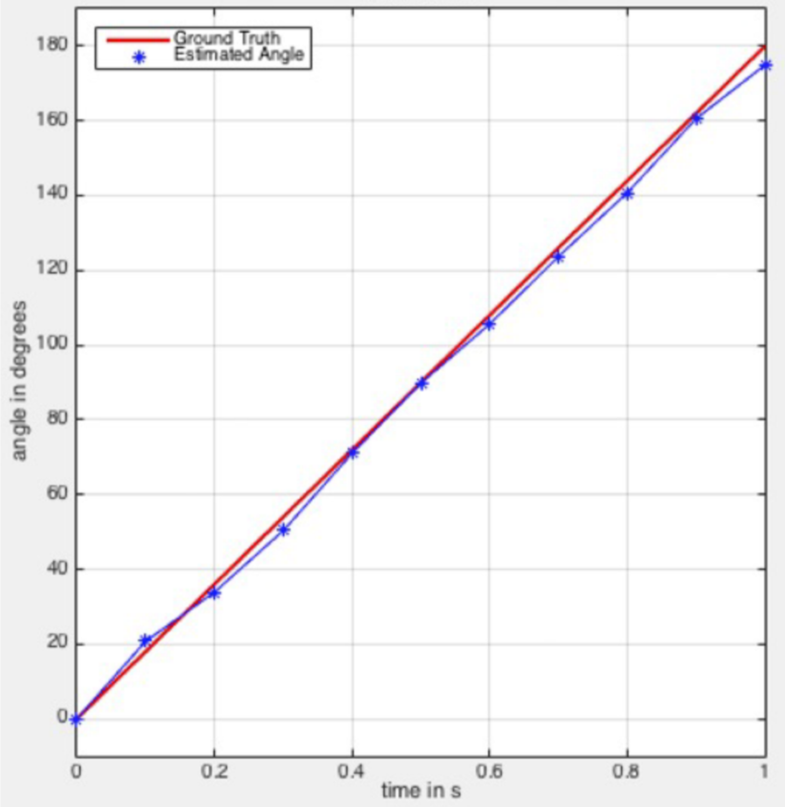
Gyro Measurements: angular velocity



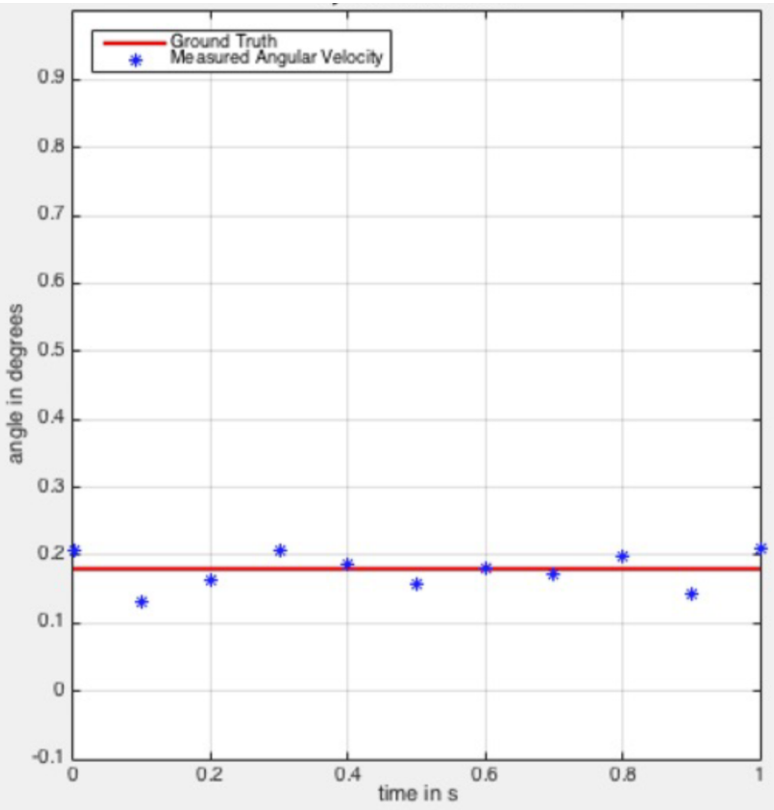
Gyro Integration

- Linear motion, noise, no bias

Orientation



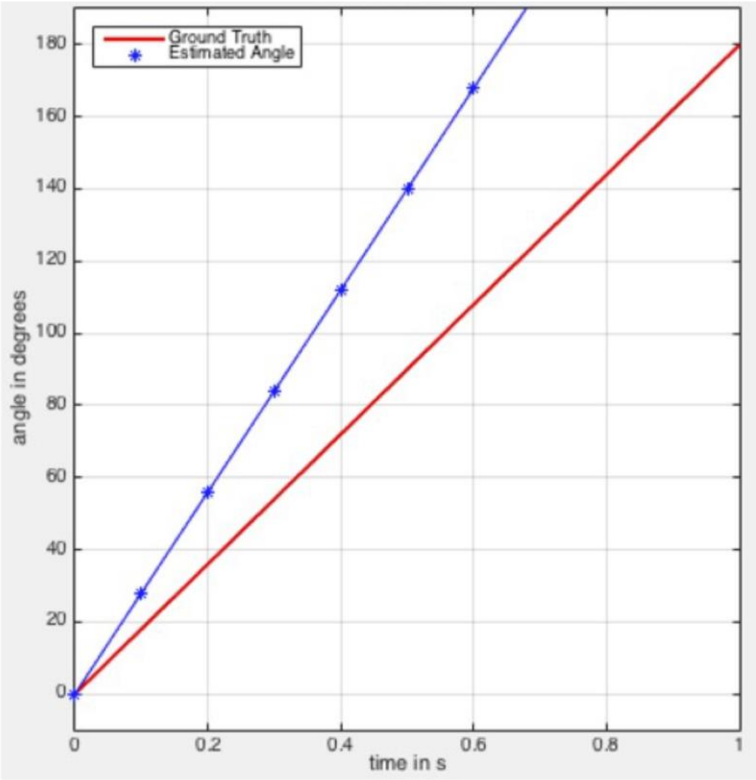
Gyro Measurements: angular velocity



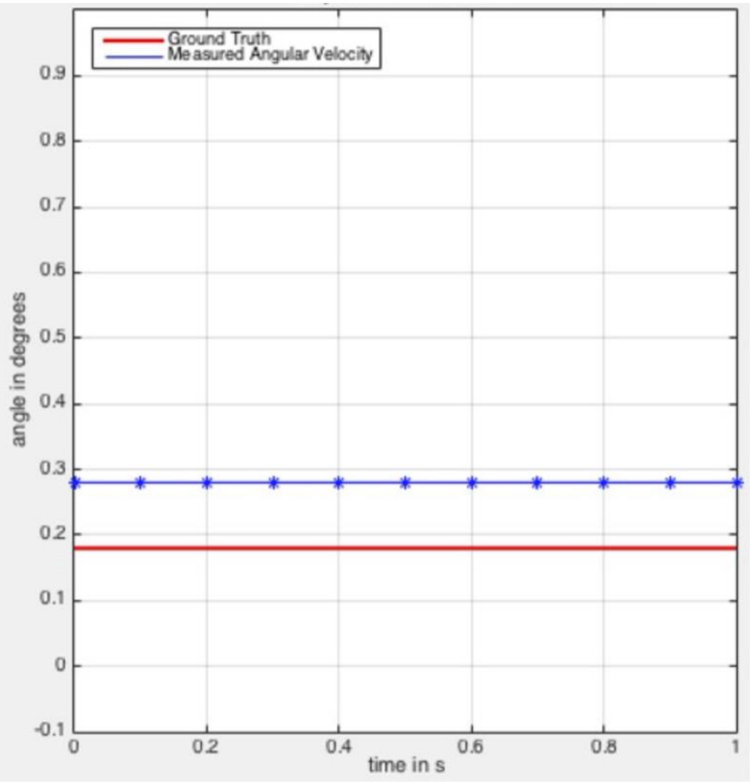
Gyro Integration

- Linear motion, no noise, bias

Orientation



Gyro Measurements: angular velocity

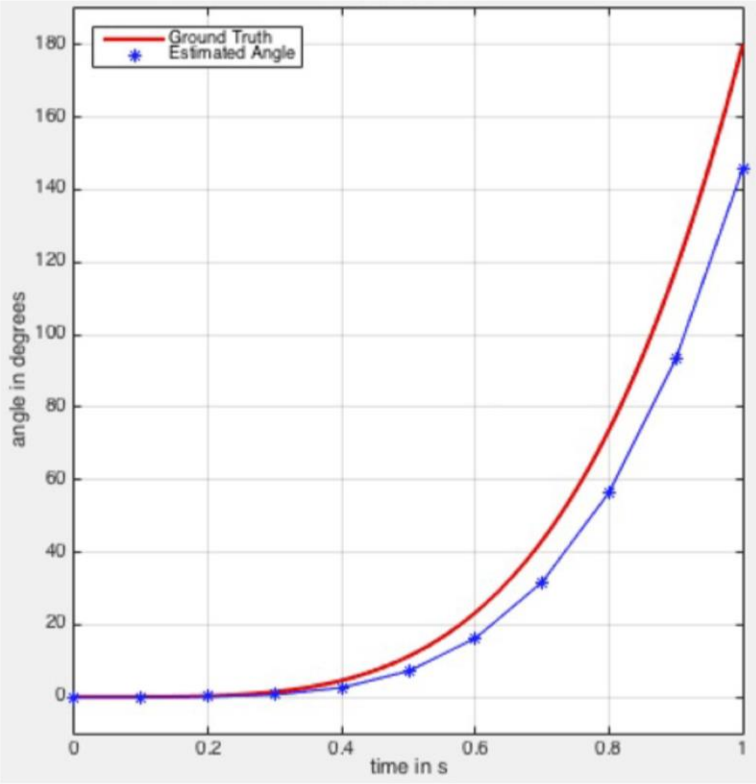


Gyro Integration

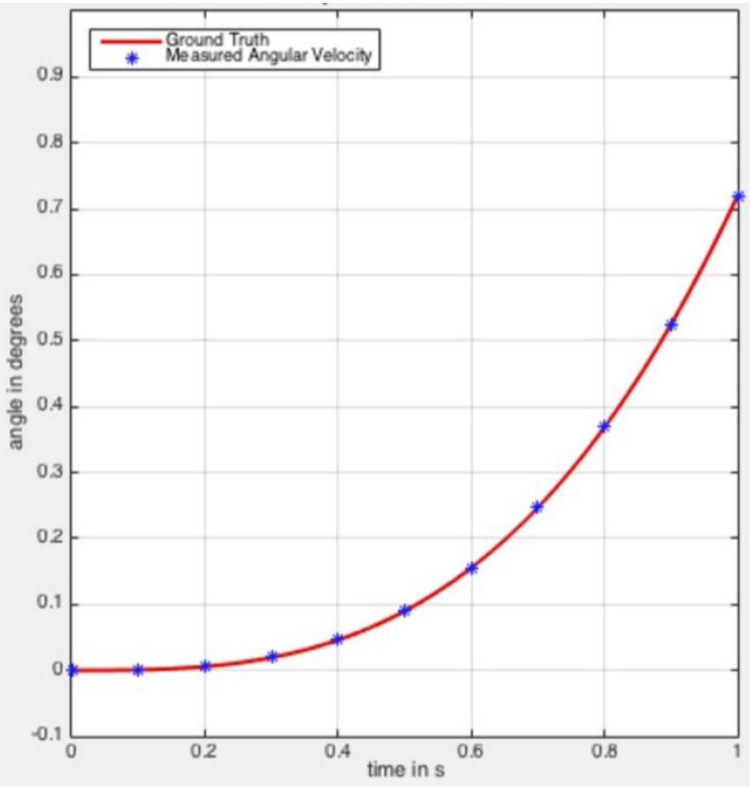
- Nonlinear motion, no noise, no bias

Due to approximation error in Taylor expansion for nonlinear motion

Orientation



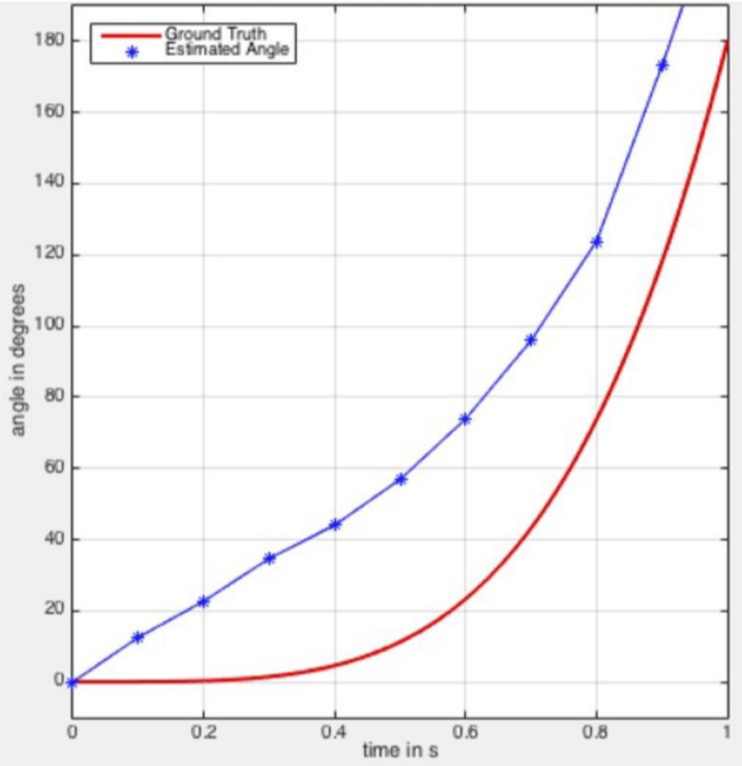
Gyro Measurements: angular velocity



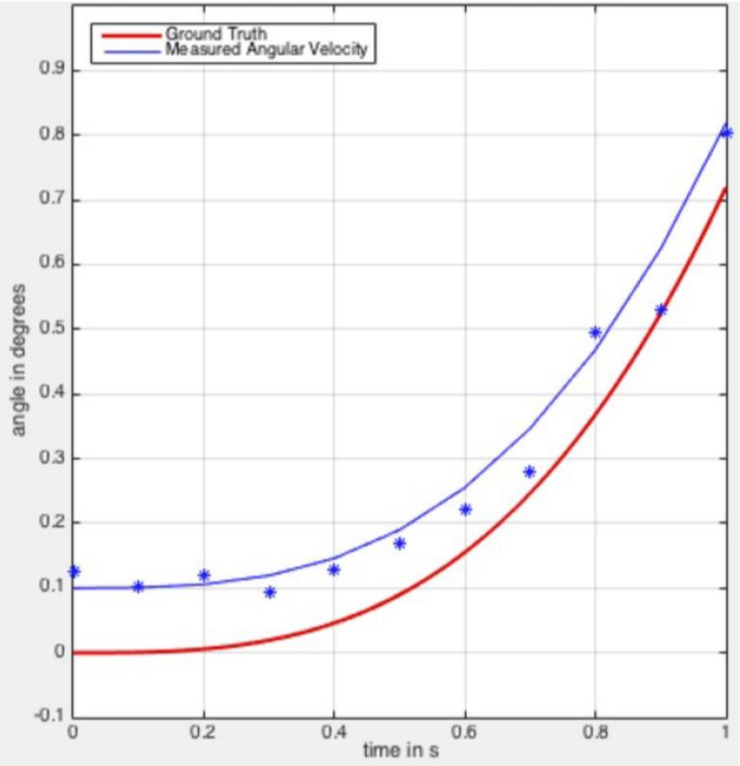
Gyro Integration

- Nonlinear motion, noise, bias

Orientation



Gyro Measurements: angular velocity



Gyro Integration

- Works well for linear motion, no noise, no bias (unrealistic)

- Integration drift
  - Errors in measured angular velocity result in errors in orientation
  - Errors accumulate in time

- Gyro integration is accurate in short time, but not reliable in long term due to drift

- Bias/noise variance can be estimated, other sensor measurements can be used to correct drift, e.g., vision, accelerometer

Accelerometers

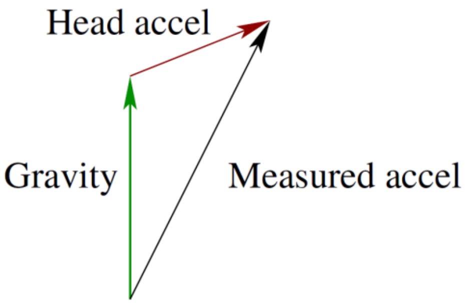
- Measure linear acceleration

$$\tilde{a} = a^{(g)} + a^{(l)} + \eta, \quad \eta \sim N\left(0, \sigma_{acc}^{2}\right)$$

Gravity acceleration (pointing up)

external acceleration

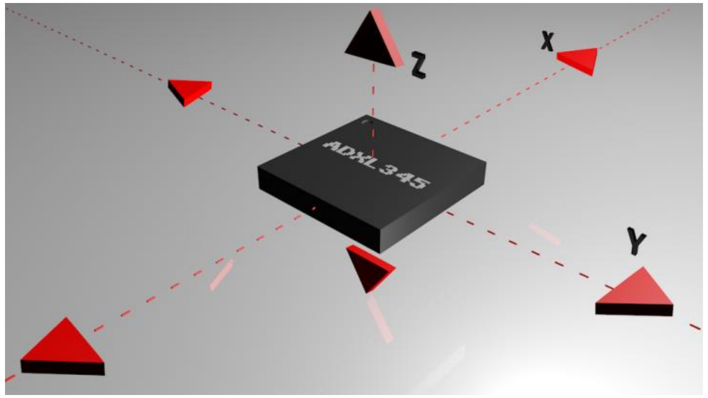
additive, zero-mean Gaussian noise



Think about the force of the table
pushing the device upwards

Accelerometers

- Pros
  - Points up on average with magnitude of 1g
  - Accurate in long term because there is no drift

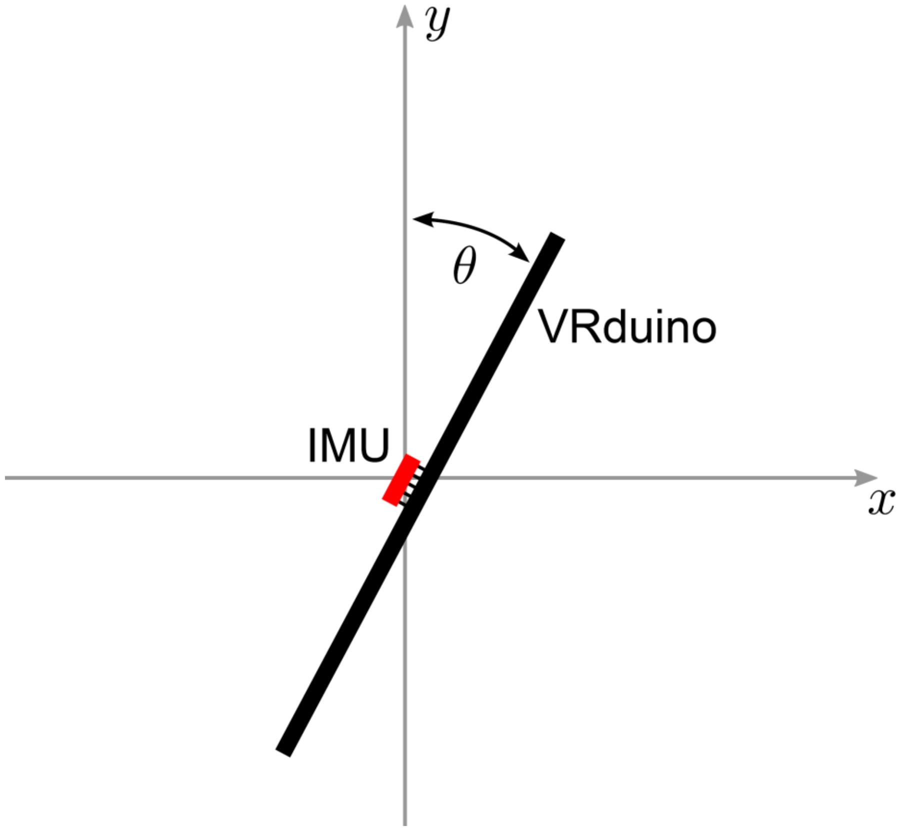


- Cons
  - Noisy measurements
  - Unreliable in short run due to motion and noise

- Complementary to gyro measurements
- Fusing gyro and accelerometer data: 6DOF sensor fusion

Orientation Tracking Example

- Track angle θ in 2D space
- Sensors
  - 1 gyro
  - 2 accelerometers
- Goal: understand sensor fusion



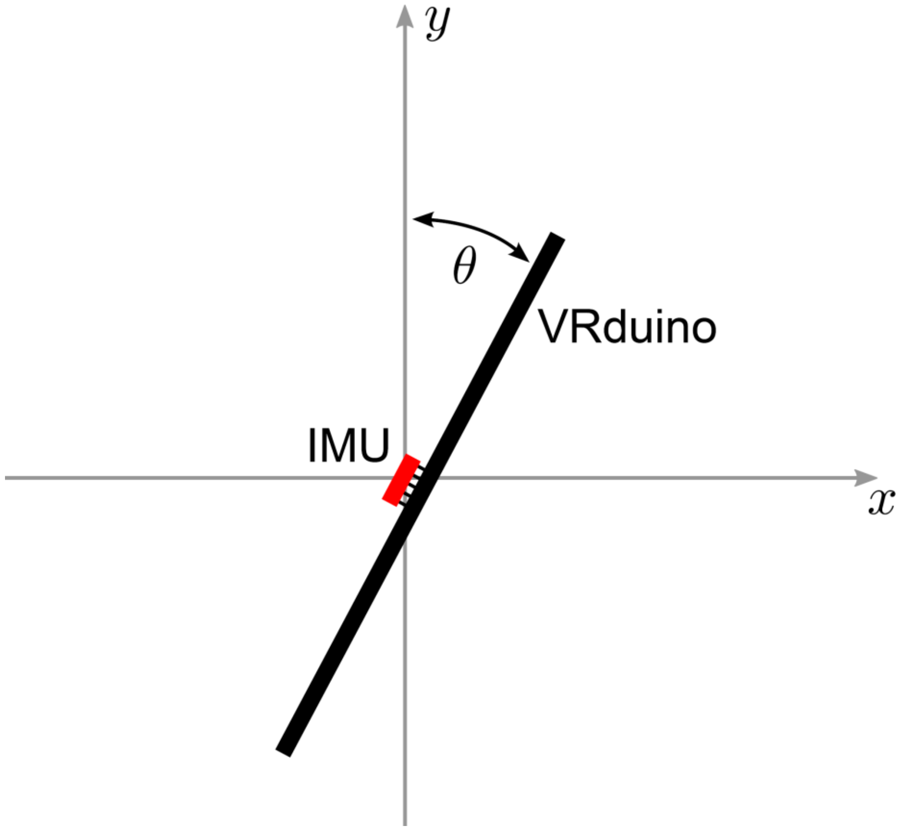
Orientation Tracking Example

- Gyro integration

$$\theta_{gyro}^{(t)} = \theta_{gyro}^{(t-1)} + \tilde{\omega}\Delta t$$

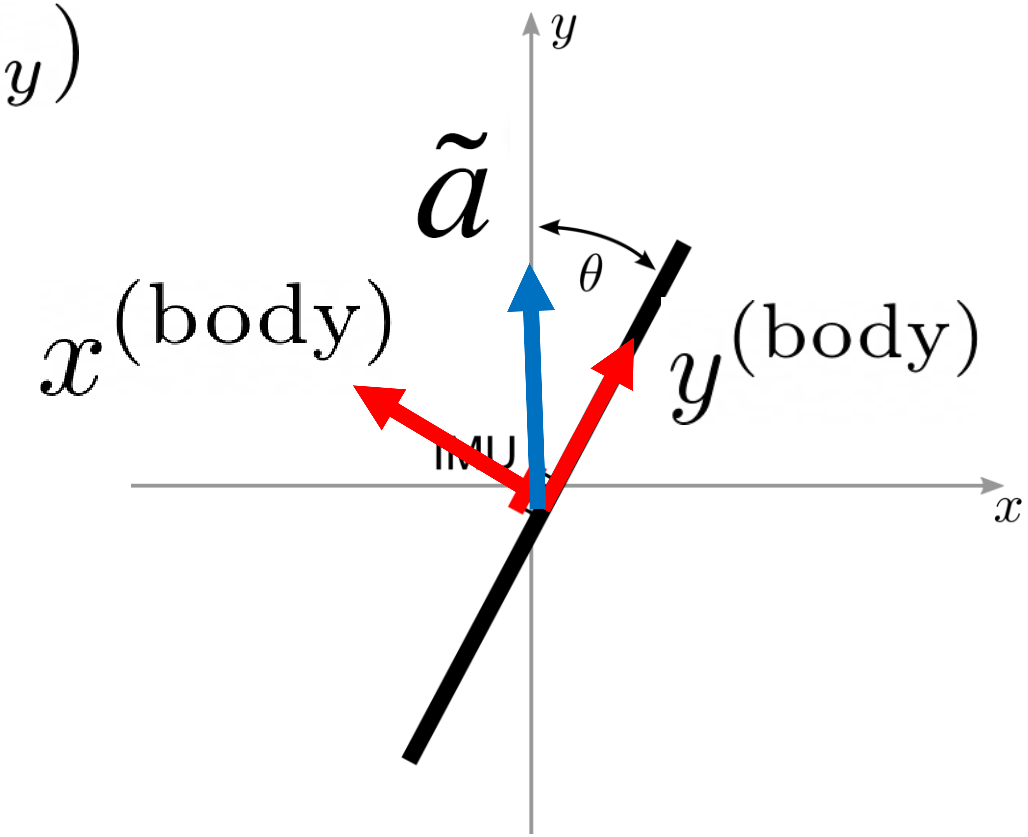
$$\theta_{gyro}^{(0)} = 0$$

Problem: Drift



Orientation Tracking Example

- Angle from accelerometers
  - Measurements in body $\tilde{a} = (\tilde{a}_x, \tilde{a}_y)$
  - Corresponds to gravity in world

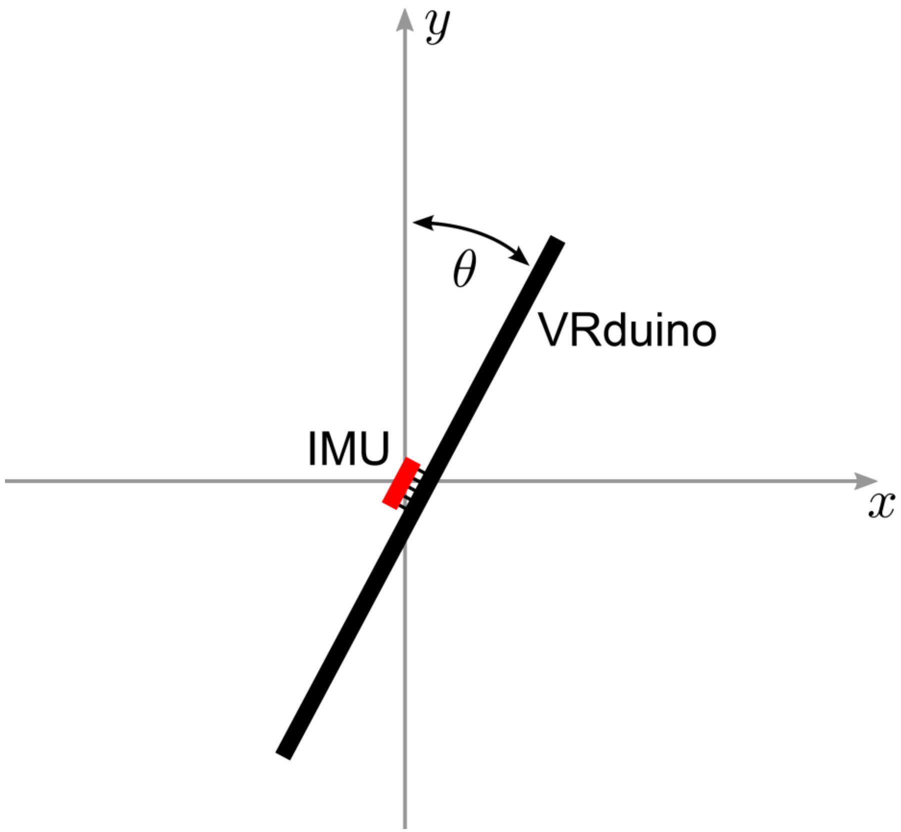


$$\theta_{acc} = \tan^{-1}\left(\frac{\tilde{a}_x}{\tilde{a}_y}\right)$$

Problem: noises

Orientation Tracking Example

- Sensor fusion
  - Combine gyro and accelerometer measurements



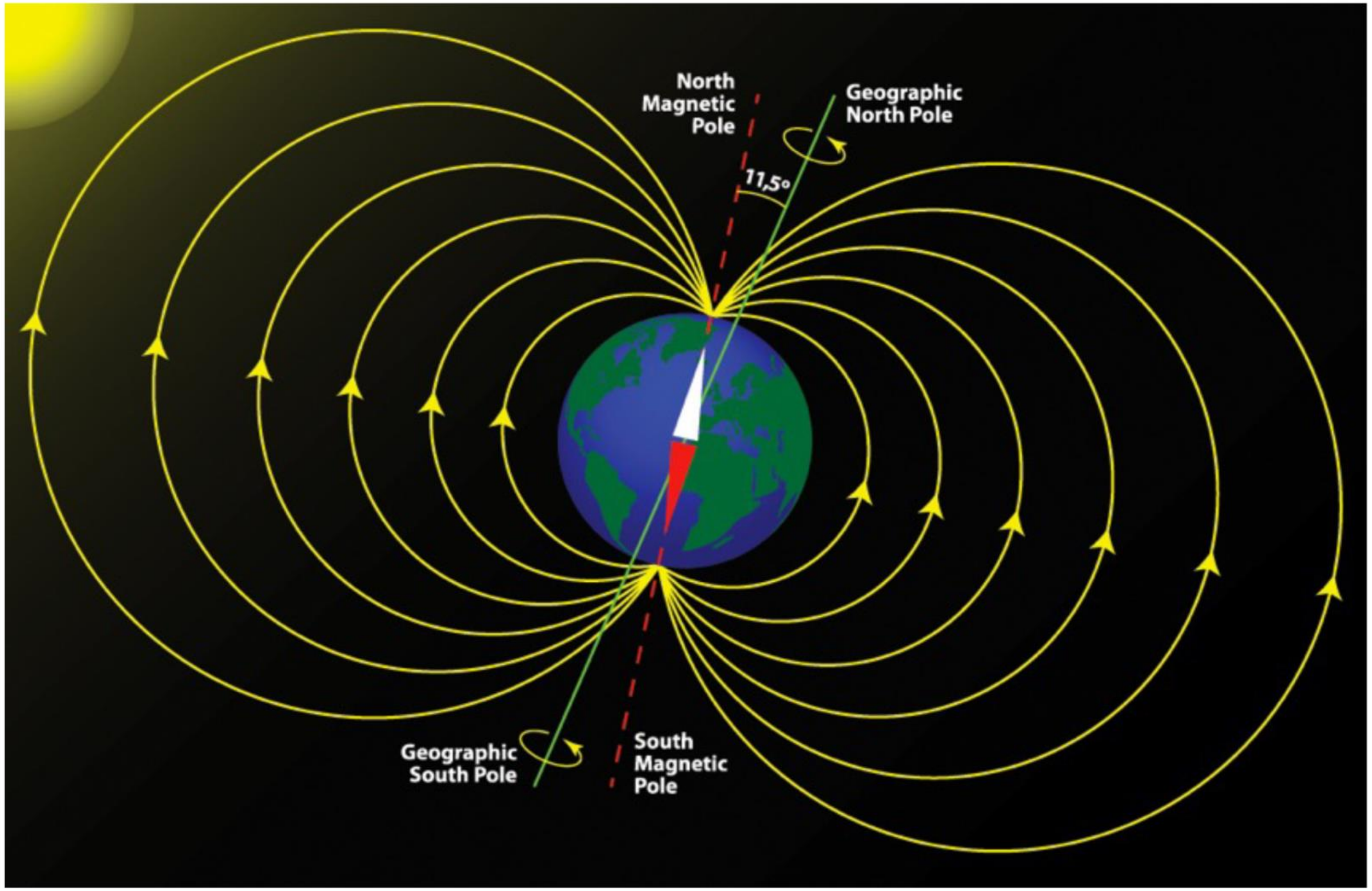
$$\theta^{(t)} = \alpha\left(\theta^{(t-1)} + \tilde{\omega}\Delta t\right) + (1-\alpha)\,\mathrm{atan2}\left(\tilde{a}_x, \tilde{a}_y\right)$$

complementary filter

Magnetometers

wikipedia

Compass



lifescience.com

Magnetometers

- Measure earth's magnetic field in Gauss or uT (micro Tesla)
- 3 orthogonal axes
  - Vector pointing along the magnetic field
- Actual direction depends on latitude and longitude
- Distortions due to metal or electronics objects in room or in HMD

Magnetometers

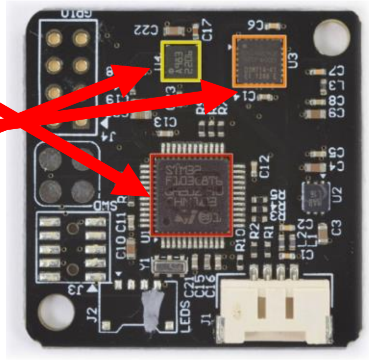
- Pros
  - Complementary to accelerometers

- Cons
  - Affected by metal, distortions of magnetic field
  - Need to know location even when calibrated (e.g., GPS)

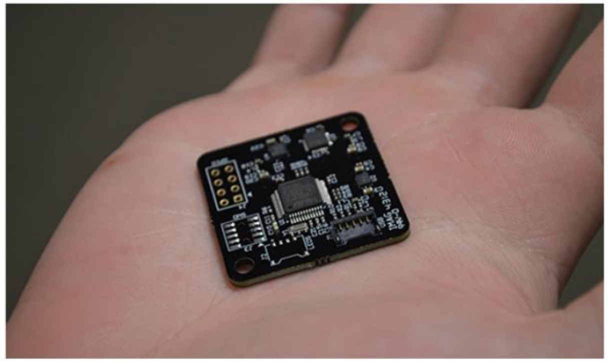
- Together with gyros and accelerometers, 9 DOF sensor fusion

Oculus Rift

- STMicroelectronics 32F103C8 ARM Cortex-M3 microcontroller



- Invensense MPU-6000 (gyroscope + accelerometer)
- Honeywell HMC5983 magnetometer
- 3-axis gyro, 3-axis accelerometer, 3-axis magnetometer all on one chip



S. LaValle, A. Yershova, M. Katsev, M. Antonov. Head Tracking for the Oculus Rift. ICRA'14

Head Orientation Tracking in Oculus Rift

- Gyro integration
  - Problem: drift
- Accelerometers for tilt correction
  - All drift errors except for rotation about the vertical axis
- Magnetometers for yaw correction
  - Rotation about the vertical axis

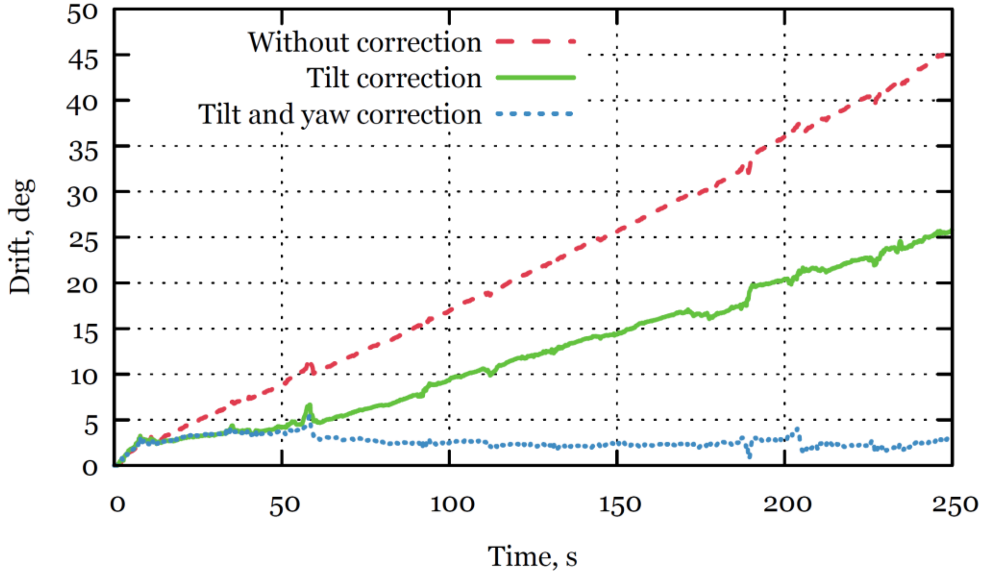


Fig. 7. Effect of correction methods on the overall drift.

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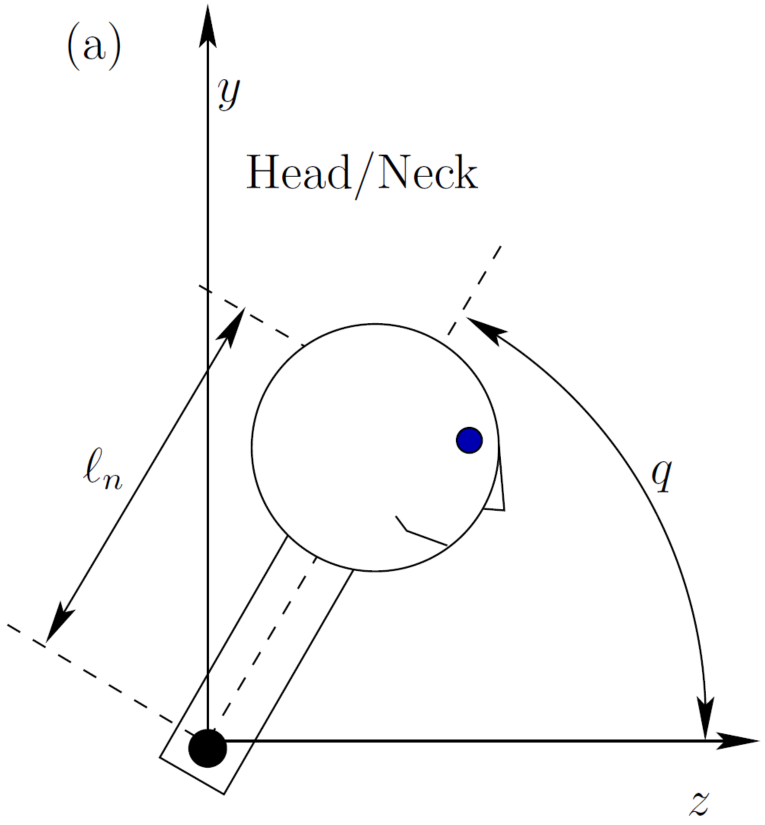
Head Position Tracking in Oculus Rift



$$p = f(q)$$

Head position

Quaternion of head orientation

$$p = f(q) = q * (0, \ell_n, 0) * q^{-1}$$

Use quaternion to rotate a vector

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Further Reading

- Sections 9.1, 9.2 in Virtual Reality, Steven LaValle

- Stanford EE 267 course note on 3DOF orientation tracking and IMUs
  - https://stanford.edu/class/ee267/notes/ee267_notes_imu.pdf

- Head Tracking for the Oculus Rift
  - http://msl.cs.illinois.edu/~lavalle/papers/LavYerKatAnt14.pdf