MEMS IMUs for GNC

(Guidance Navigation Control)

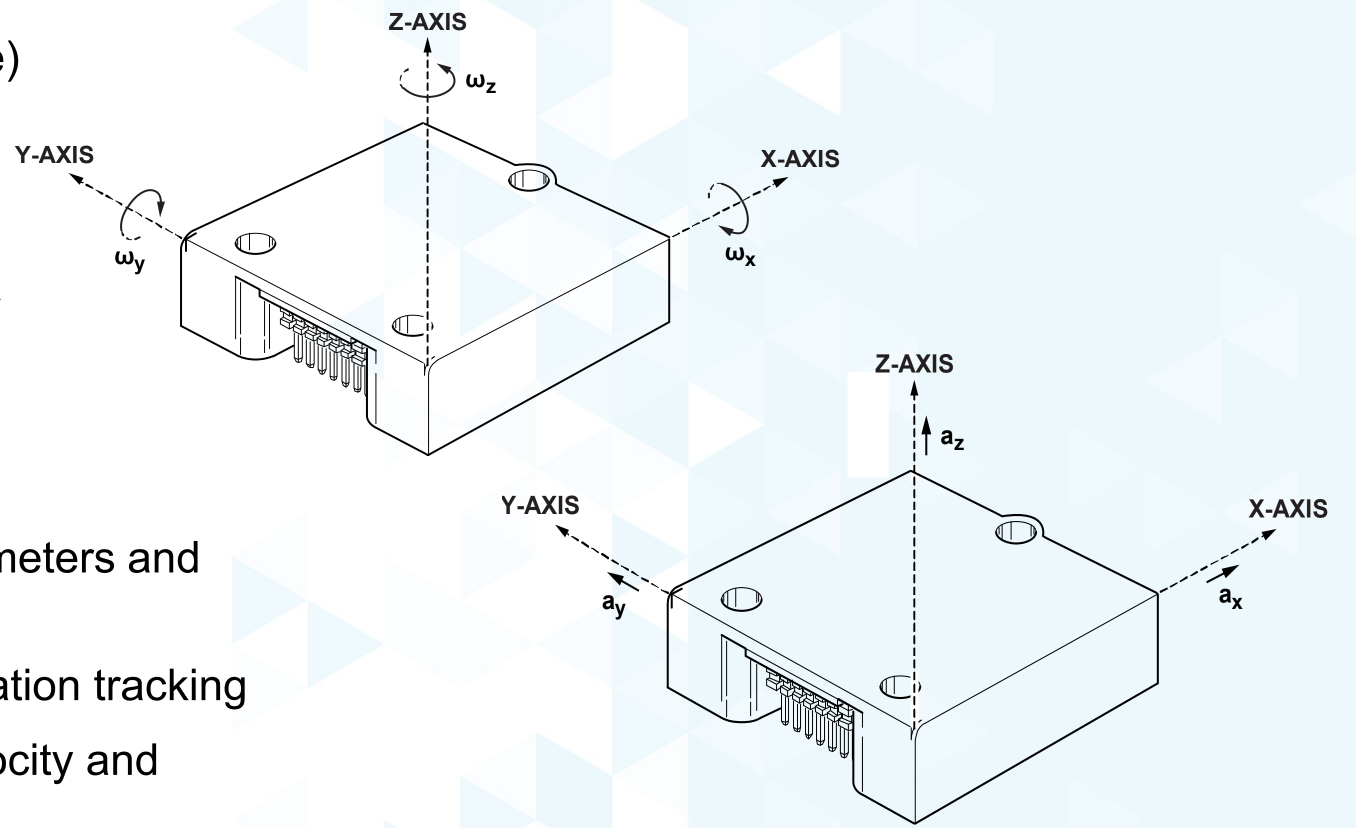
MARK LOONEY

ANALOG DEVICES

AHEAD OF WHAT'S POSSIBLE™

What is an IMU (Inertial Measurement Unit)?

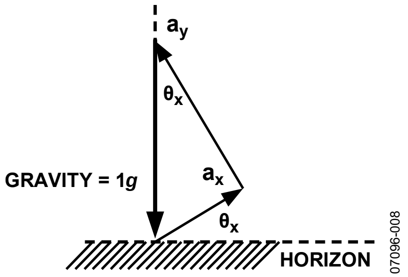
- Angular rate of rotation (spin rate)
  - Delta-angle
- Linear acceleration
  - Delta-velocity
  - Orientation, with respect to gravity (aka….tilt, incline angle)
- Triaxial measurements
  - Mutually orthogonal
- Legacy IMUs also had magnetometers and barometers
- Primary use is in dynamic orientation tracking
- Secondary use in short-term velocity and position tracking



Let’s start with basic pointing and noise influences

What are IMUs used for? Measure angles

- Accelerometers respond to their orientation, with respect to the earth's gravitational field, according to a very simple trigonometric function

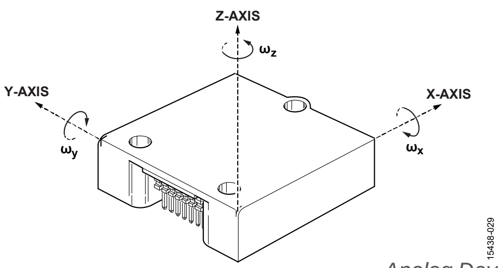


$$\theta_x = a\sin\left(a_x / 1g \right)$$

$$\theta_x = a\tan\left(a_y / a_x \right)$$

Sensor Fusion
Real-time
angle estimation

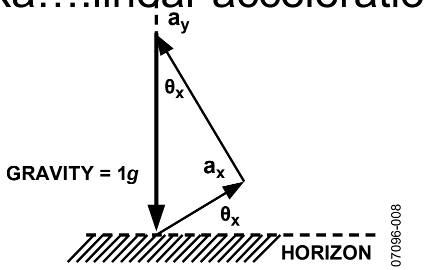
- Gyroscopes measure the angular rate of rotation, around their measurement axis, which enables an simple integration for estimating angle displacement



$$\emptyset_d(t) = \int_{t_1}^{t_2} \omega_m(t) \cdot dt$$

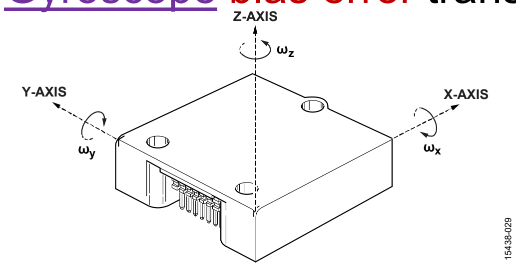
What are IMUs used for? Measure angles

- Accelerometers also respond to linear vibration and changes in linear velocity (aka….linear acceleration)



$$\theta = asin\left(\frac{a_x + vibe + acceleration}{1g}\right)$$

- Gyroscope bias error translates into an angle error, which is proportional to time.



$$\emptyset_d(t) = \int_{t_1}^{t_2} \omega_m(t) + Bias \cdot dt = Real\ Angle + \boldsymbol{Bias\ x\ Time}$$

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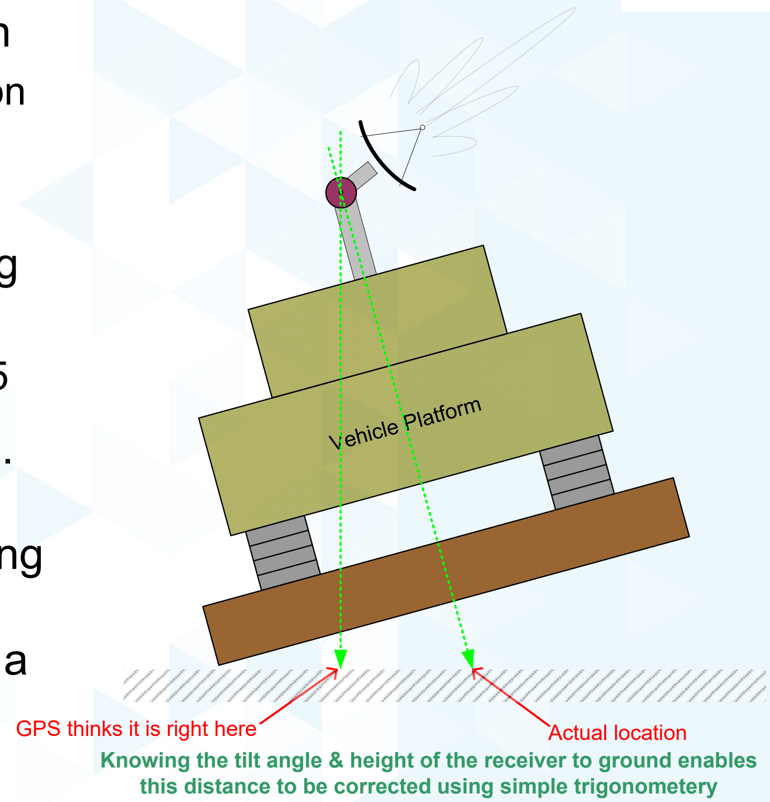
Improvement opportunities

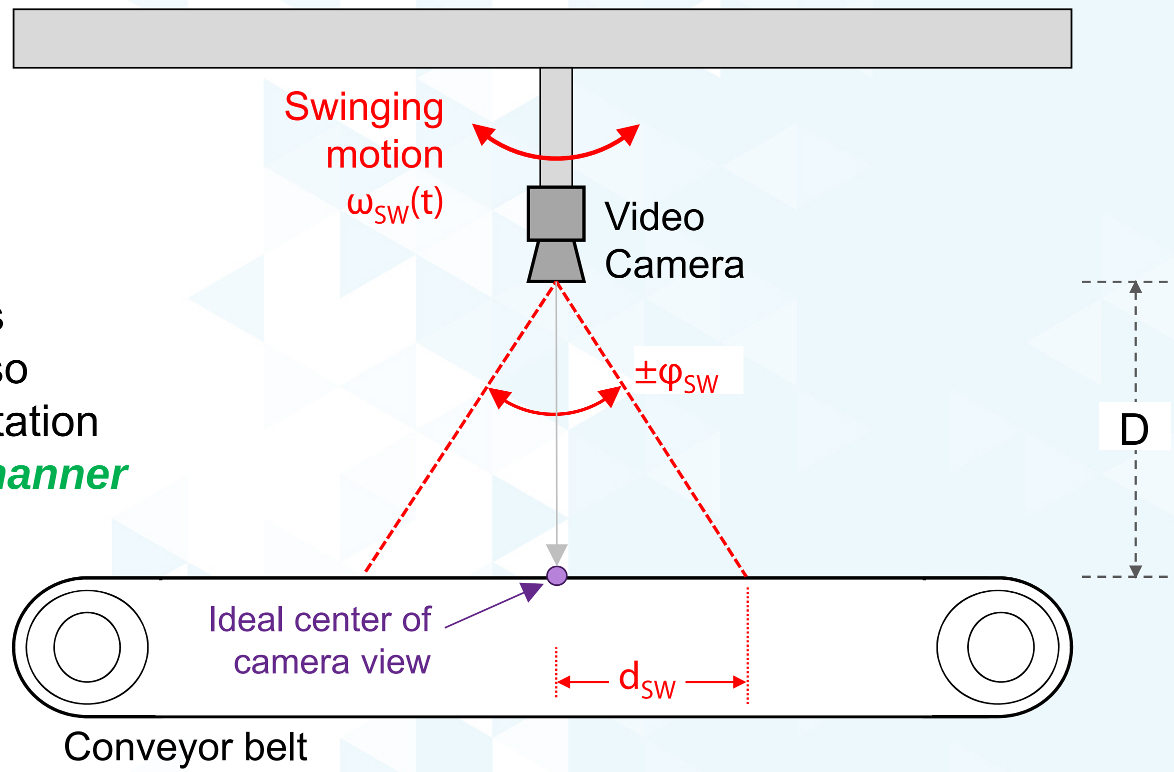
- Full implementation of IMU function
  - Terrain compensation of GPS location data
- Implementing next-generation devices, which represent advancing performance.
  - ADIS16265, ADIS16135, ADIS16385
- Using in-system calibration options. For example, running the robot around a 360° circle while integrating the output, enables application-specific accuracy correction, using a very simple pattern.



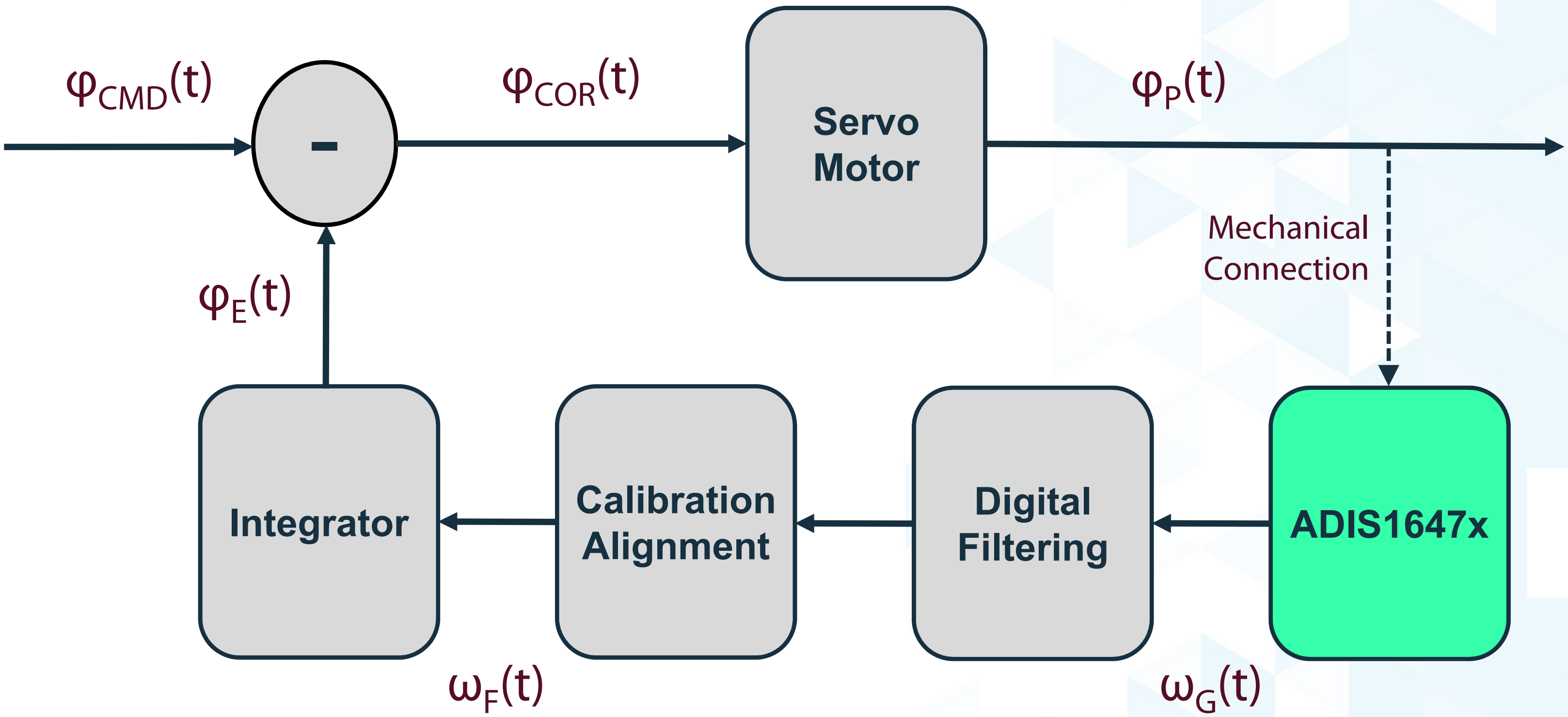
Gyroscopes: feedback sensing element

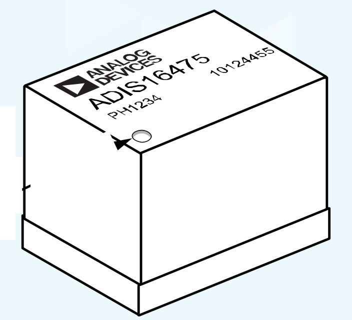
Real-world example

- Optical inspection system
- Problem: swinging motion causes loss of resolution on the inspection surface
- **Solution**: mounting an IMU on the lens of the camera to track the orientation, so that a servo motor can adjust the orientation of the lens in an ***equal but opposite manner***
- The effectiveness of this type of system is directly dependent on how well the IMU can track the orientation of the camera



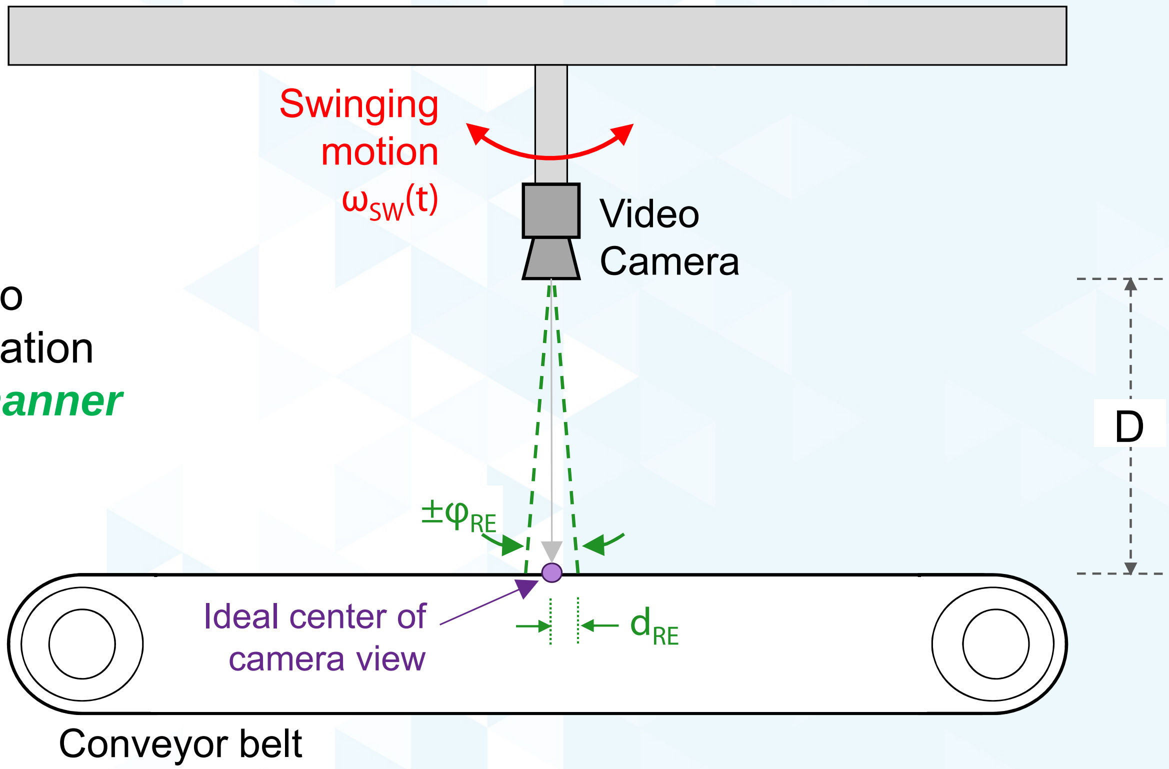
Basic Feedback Control



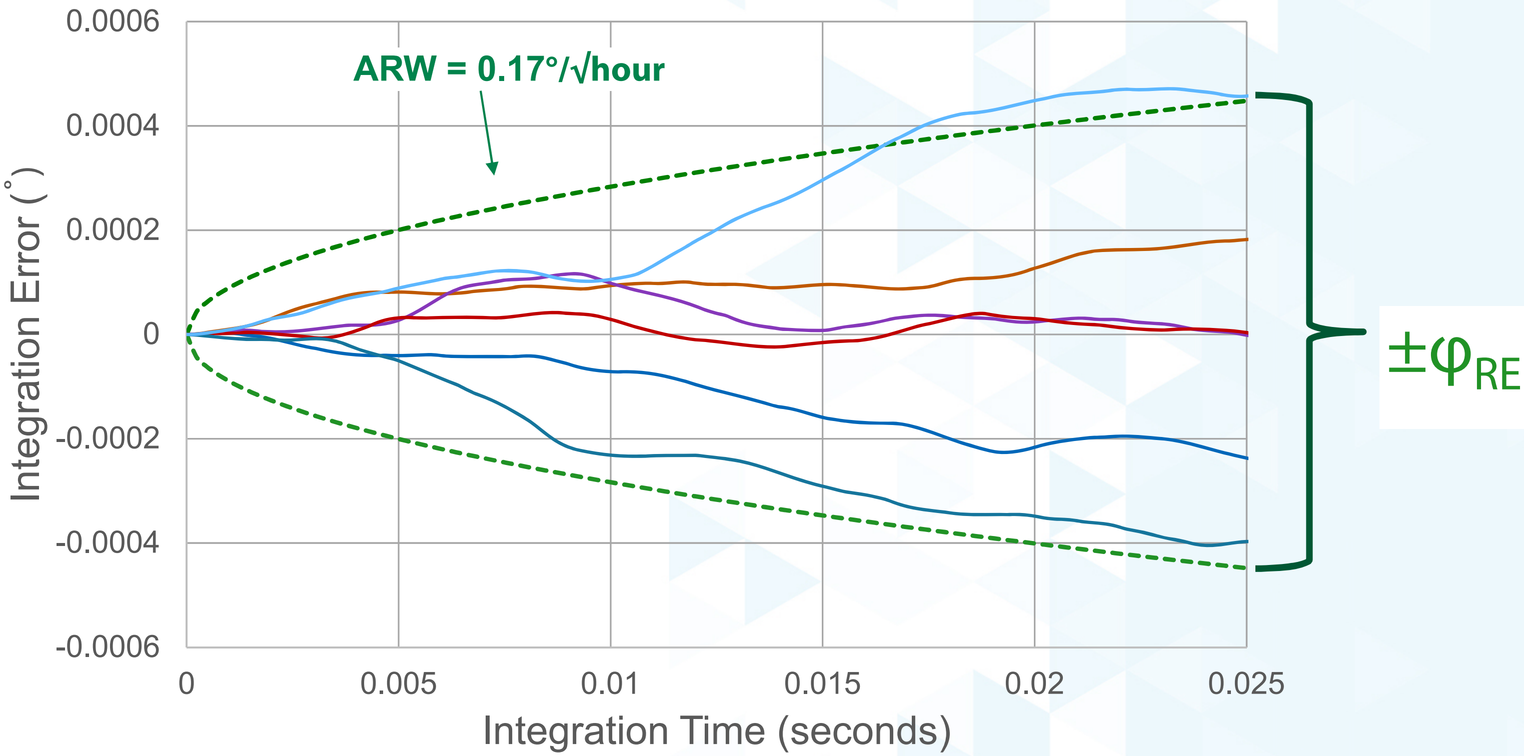


Success!

- Optical inspection system
- Problem: swinging motion causes loss of resolution on the inspection surface
- **Solution**: mounting an IMU on the lens of the camera to track the orientation, so that a servo motor can adjust the orientation of the lens in an ***equal but opposite manner***
- The effectiveness of this type of system is directly dependent on how well the IMU can track the orientation of the camera.
- Primary limitation, in this case, is noise, or Angle Random Walk

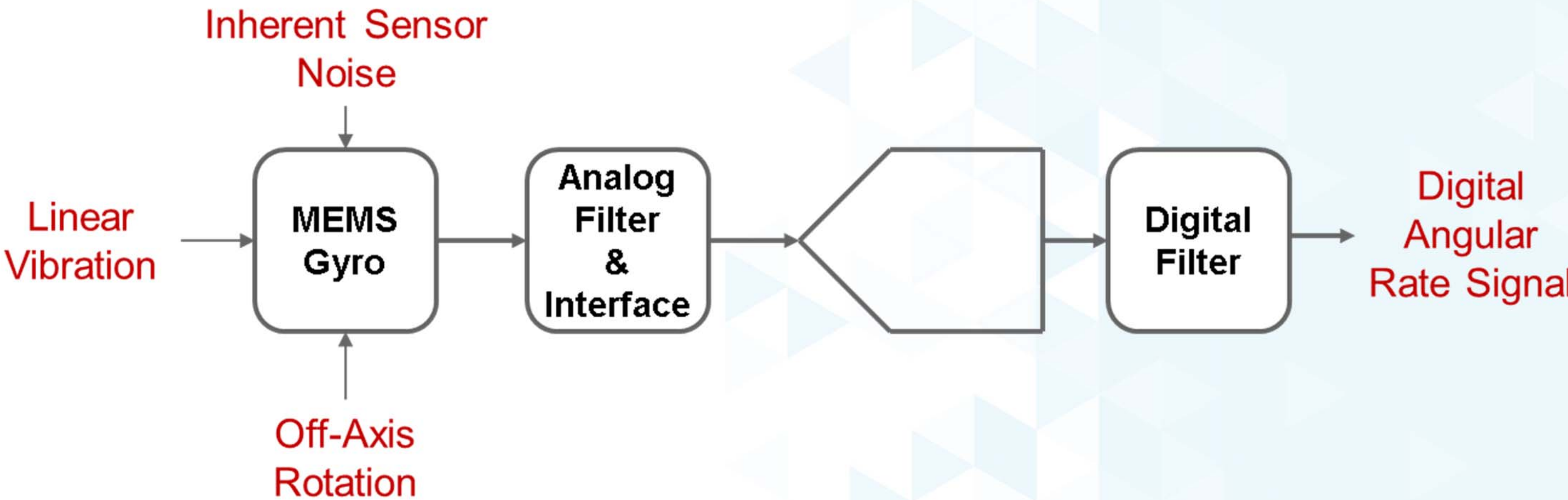


Why does noise performance matter?



What messes up your measurements?

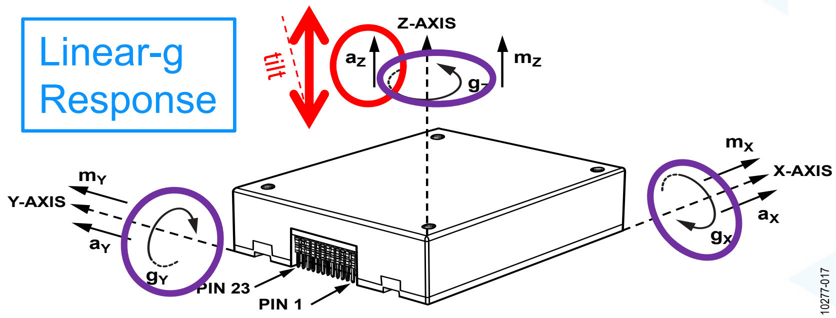
- REDERENCES:
  - http://www.analog.com/en/technical-articles/critical-noise-sources-mems-gyroscopes.html
  - http://www.analog.com/en/analog-dialogue/articles/low-noise-feedback-control.html



What nobody talks about……

ie: Vehicle-mounted antenna, camera, other optics, etc.

Linear-g Response

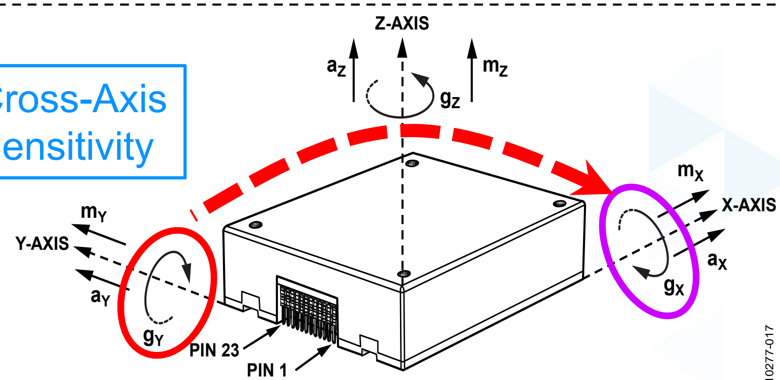


Rough conditions cause up/down vibration (±2g-rms) in the z-axis
High Linear-g sensitivity (G_L) will cause angular jitter on all three gyroscopes.

$$\varnothing_{ROLL} = \mathbf{G_L} \text{ x } A_Z$$

Typical Device Spec: 0.1 °/s/g ADI Spec: 0.015 °/s/g

Cross-Axis Sensitivity

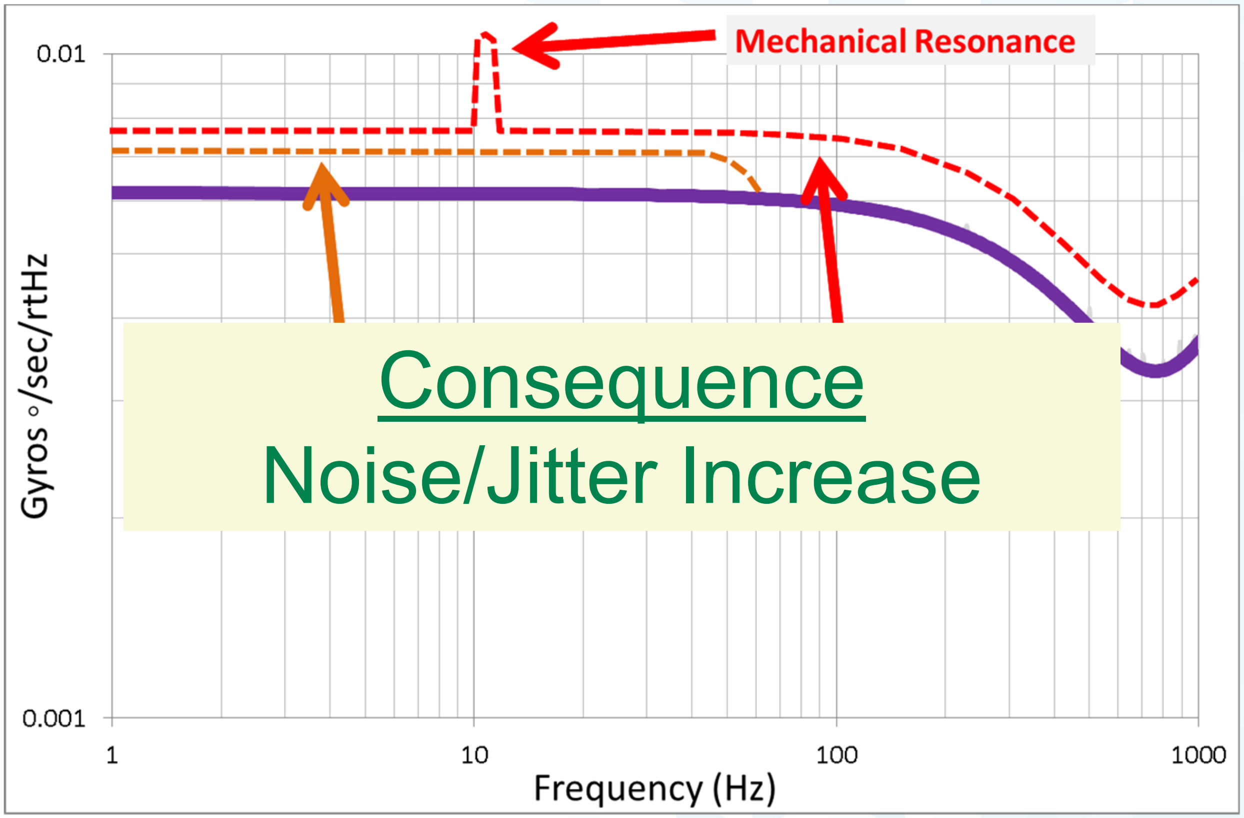


Rough conditions cause angular vibration (±10°/sec) in the y-axis (pitch).
High cross-axis sensitivity (G_{CAS}) will cause angular jitter on the x-axis (roll).

$$\varnothing_{ROLL} = \mathbf{G_{CAS}} \text{ x } \theta_{PITCH}$$

Typical Device Spec: +/-2% ADI Spec: <0.087%

Vibration/Cross-axis on top of noise



What matters?

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- ❑ Stability/Repeatability (long term drift; scale and bias)
- ❑ Noise (angle random walk)
- ❑ Vibration rectification
- ❑ Hysteresis

→ Inherent to sensor performance (limited opportunity to calibrate)

- ❑ Non-linearity
- ❑ *g*-effect error (linear accel)

→ Theoretically capable of being corrected through test and calibration, to limits of resolution and stability

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- ❑ Offset / Bias
- ❑ Scale / Gain Error
- ❑ Tempco's
- ❑ Cross Axis Sensitivity

→ Correctable through test and calibration, to the limits of resolution and stability

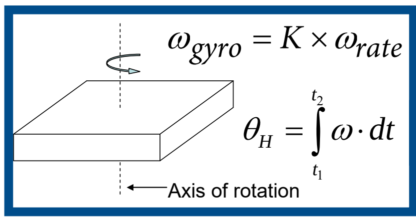
ADI Designed-in Performance at MEMs Sensor Level

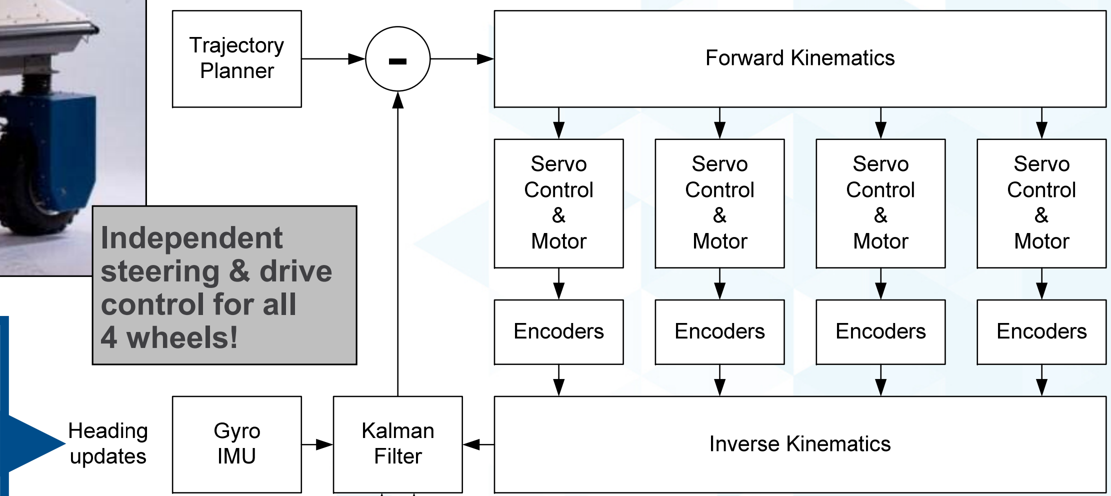
ADI System-Level Calibration Focus

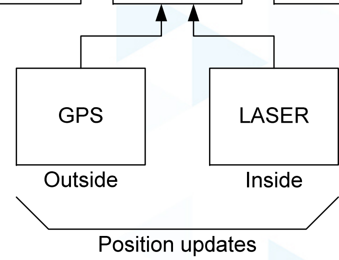
- Architected to Reject Performance Limiting Errors
- Sensor Conditioning and Filtering Optimized for Reliable Precision at Application Level
- Packaging Minimizes Stress; avoids long-term drift (ie: from overmold/moisture)
- Sub-System Test & Calibration Ensures out-of-box best Precision, & Reliability
- Fully, Conservatively, Specified

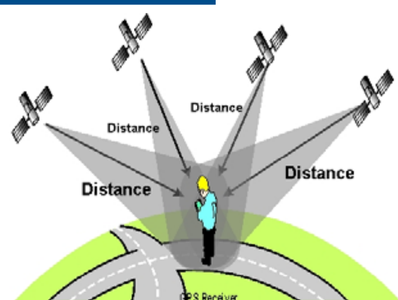
Guidance Navigation Systems

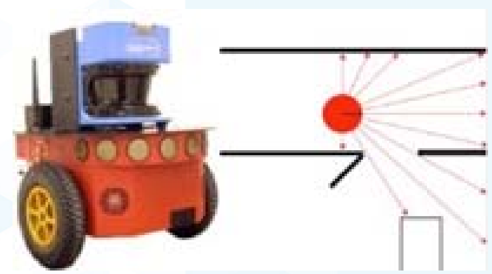
Ground Vehicle Example



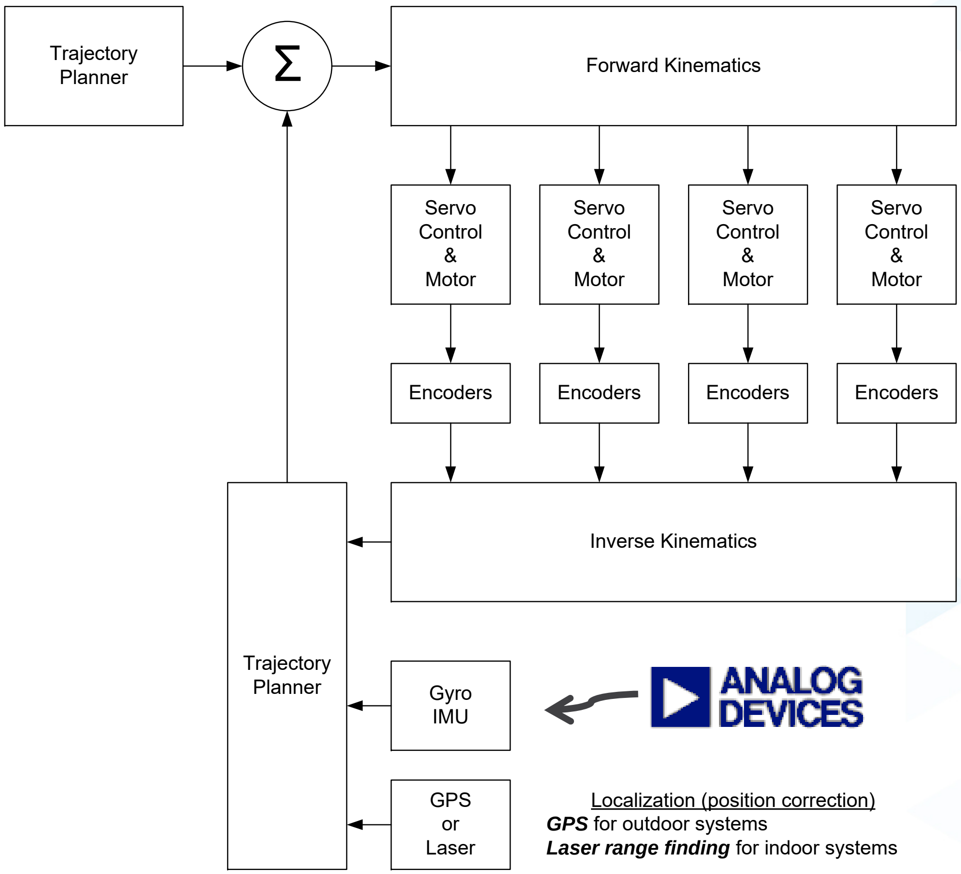








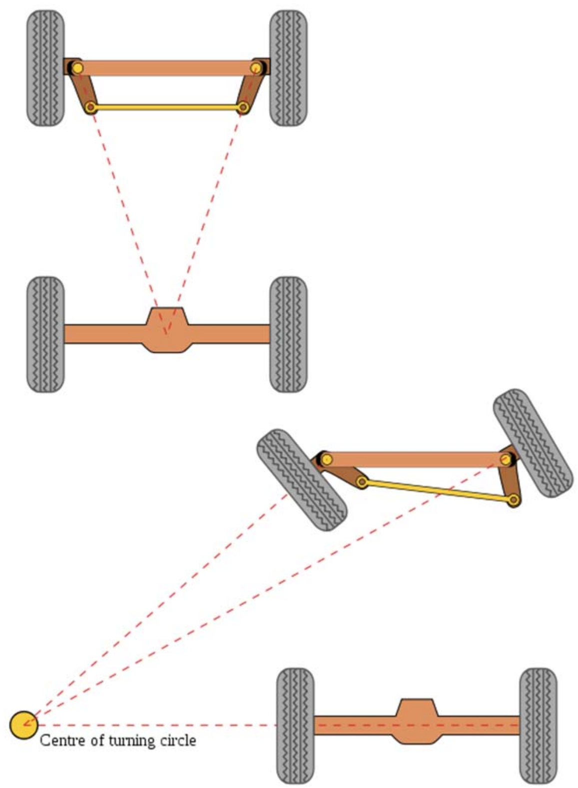
What are IMUs used for?



- It is easy to get wrapped up in the entire system
- While remembering that we are looking to support accurate motion representation….
- Look for context with each system, environment, as we help customers understand their performance needs
- For those who seem to "start cheap," the discussion is in how complex the other inertial observers need to be
- For those who are moving from more expensive technologies, it is about what they have to add/understand, to make ADI IMUs work

Example Robot System

Steering control



- The forward kinematics system employs Ackermann Steering on all four wheels to help minimize tire slip and improve efficiency.
- Each tire will have a different steering angle.
- The example shown is for a rack and pinion system, which employs the Ackermann relationship mechanically.
- The Mobile Robots Seekur employs this individually on each wheel, using separate servo motors

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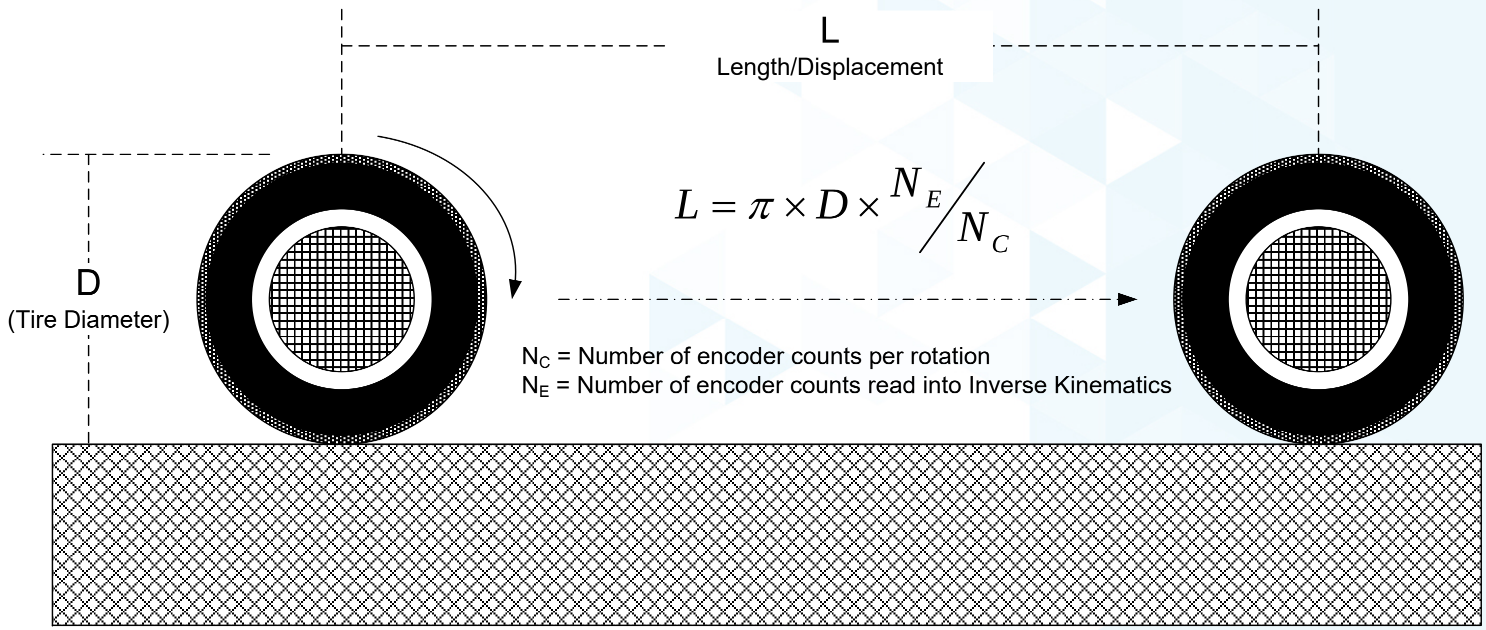
Kinematics Basics, Dead Reckoning via Odometry

The basic idea is that each wheel uses an optical encoder to measure the wheel rotation, which can be translated into distance traveled, using the following relationships



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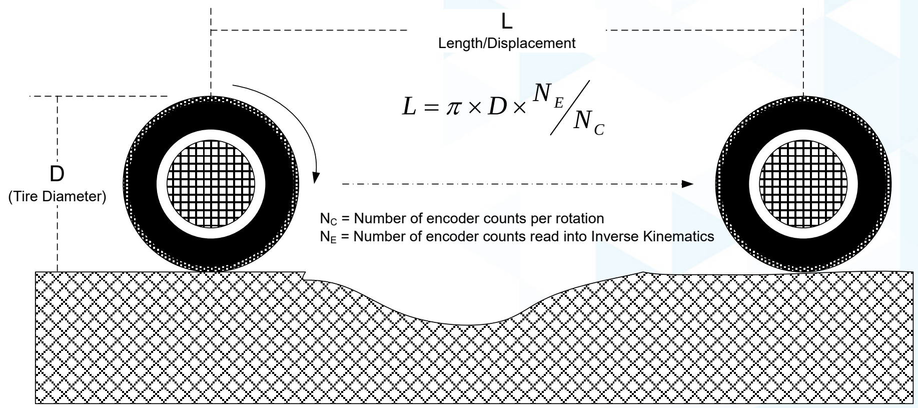
Odometry error sources

- Tire diameter is dependent on:
  - Temperature, tread wear, air pressure
- **Gear backlash in the drive and steering system**
- Vehicle geometry: relative tire positions
- **Tire slip**
- Non-uniform surface
- **Flex in the structure of the robot**
- BOTTOM LINE: With well-calibrated tires, the odometry-based dead reckoning provides useful position data over short distances, up to 20 meters



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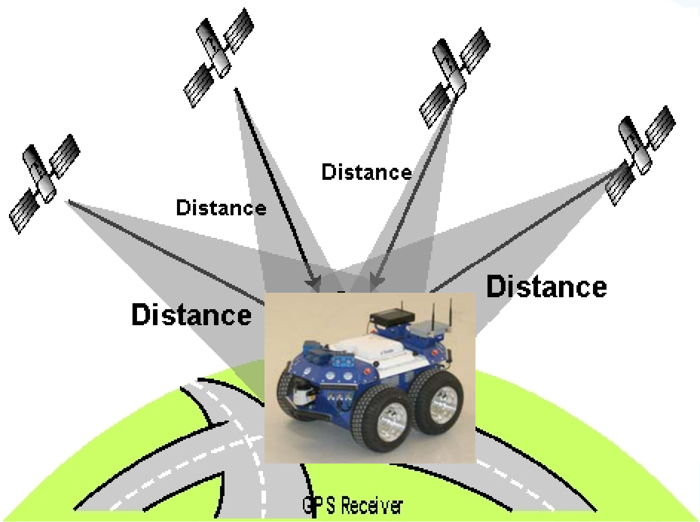
GPS: Outdoor position/velocity measurement & correction



- **GPS receiver receives coded messages from 3-10 satellites, out of a constellation of 24-32.**
- Flight times are used to measure distance to each satellite.
- **Positions of each satellite are fixed**
- Triangulation techniques lock in on the position
- Differential GPS uses fixed receiver to reference platform measurements
- **Challenges: Requires line of sight, only provide fixed time position, 1-4SPS**

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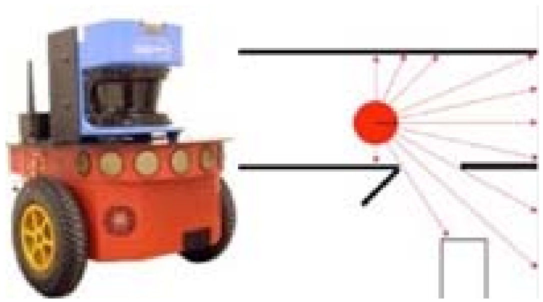
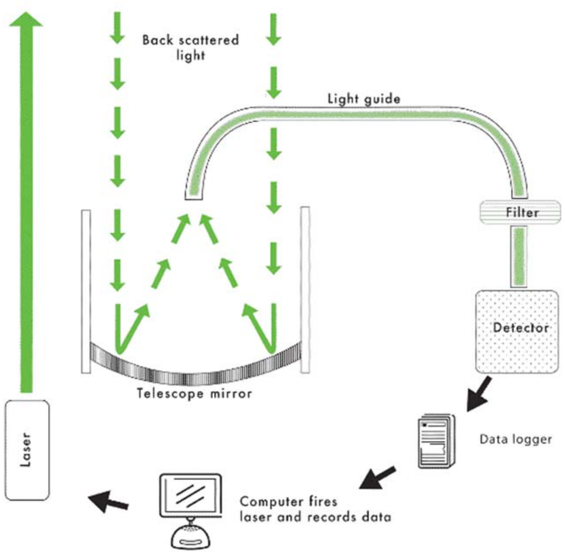
Laser: Indoor position measurement & correction

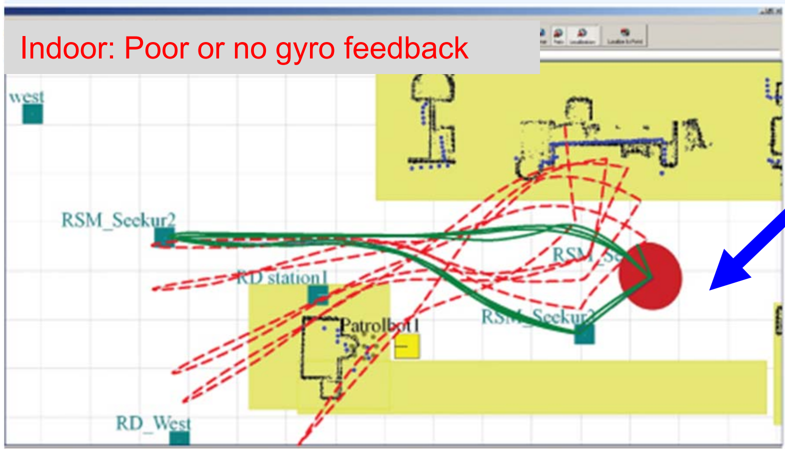




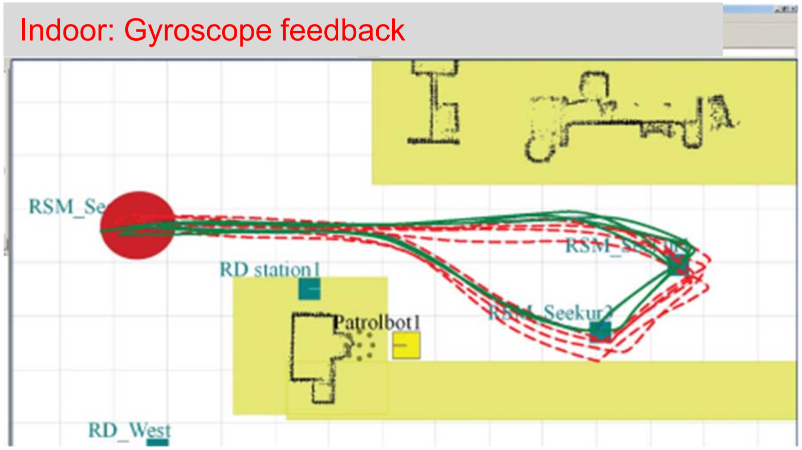
- Seekur comes with the SICK LSM111 Laser Range Finder system.
- **270° scan angles**
- 25-50Hz scan rates
- 20m range
- Some conditions requires a stop to get stable measurements.

What are IMUs used for?

Indoor: Poor or no gyro feedback

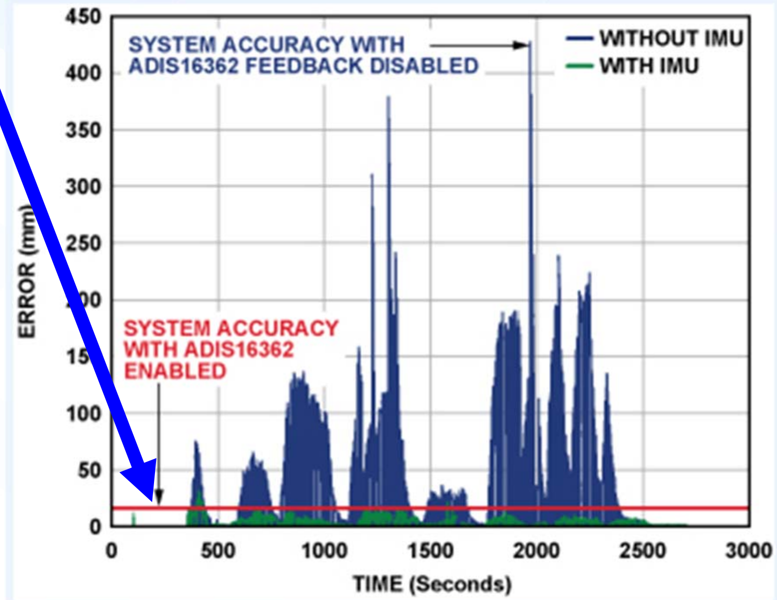


Indoor: Gyroscope feedback



Massive improvement, expansion of robot capability

Outdoor:
- Uncertain terrain
- GPS obstruction management



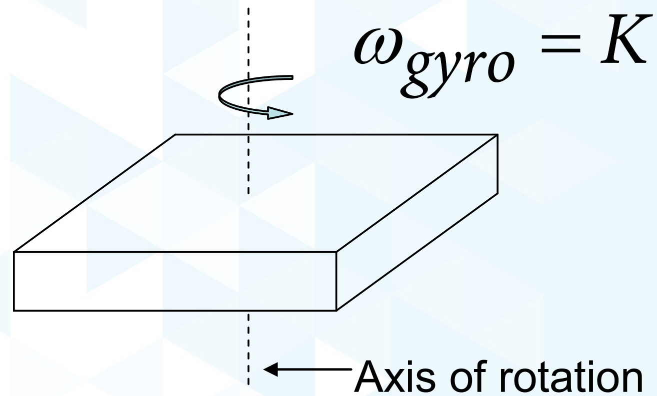
http://www.analog.com/en/analog-dialogue/articles/inertial-sensors-and-autonomous-operation-in-robots.html

MEMS Gyroscopes

Typical Block Diagram

- Gyroscopes are angular rate sensors
- **They provide a simple relationship between angular rate and the electrical output signal.**
- Assuming a single-axis (yaw/z), the heading estimate is calculated by integrating the angular rate.

$$\omega_{gyro} = K \times \omega_{rate}$$



$$\theta_H = \int_{t_1}^{t_2} \omega \cdot dt$$

<u>Ideal Gyroscope Equation</u>

$$\omega_G = K \times \omega_A$$

$$K = ideal\ sensitivity, \frac{°/sec}{LSB}$$

*i*Sensor®

Understanding specifications – mathematical representation

Actual Gyroscope Equation

$$\omega_G = [K \times \omega_A \times (1 + \epsilon_S)] + \epsilon_B + \varphi_N + \sum_{m=2}^{M} K_m \times \omega_A^m$$

$$\epsilon_S = Sensitivity\ error = \epsilon_{SI} + \epsilon_{ST}$$

$$\epsilon_{SI} = initial\ sensitivity\ error$$

$$\epsilon_{ST} = sensitivity\ error\ due\ to\ temperature\ changes$$

$$\epsilon_{ST} = Sensitivity\ Temperature\ Coefficient \times Change\ in\ temperature$$

$$\epsilon_B = Bias\ error = \epsilon_{BI} + \epsilon_{BT} + \epsilon_{BV}$$

$$\epsilon_{BI} = initial\ sensitivity\ error$$

$$\epsilon_{BT} = sensitivity\ error\ due\ to\ temperature\ changes$$

$$\epsilon_{BT} = Bias\ temperature\ coefficient \times Change\ in\ temperature$$

$$\epsilon_{BV} = sensitivity\ error\ due\ to\ power\ supply\ changes$$

$$\epsilon_{BV} = Bias\ change\ with\ supply \times Change\ in\ power\ supply$$

$$\varphi_N = Total\ noise = \varphi_D \times Noise\ Density$$

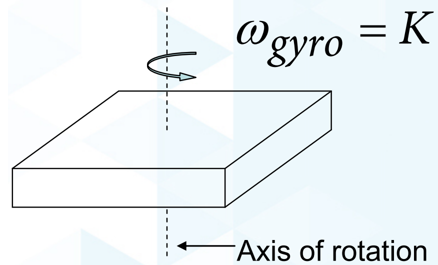
$$\sum_{m=2}^{M} K_m \times \omega_A^m = Nonlinearity\ (typically\ lumped\ into\ one\ term)$$

Ideal Gyroscope Equation

$$\omega_G = K \times \omega_A$$

$$K = ideal\ sensitivity, \frac{{}^\circ/sec}{LSB}$$

$$\omega_{gyro} = K \times \omega_{rate}$$



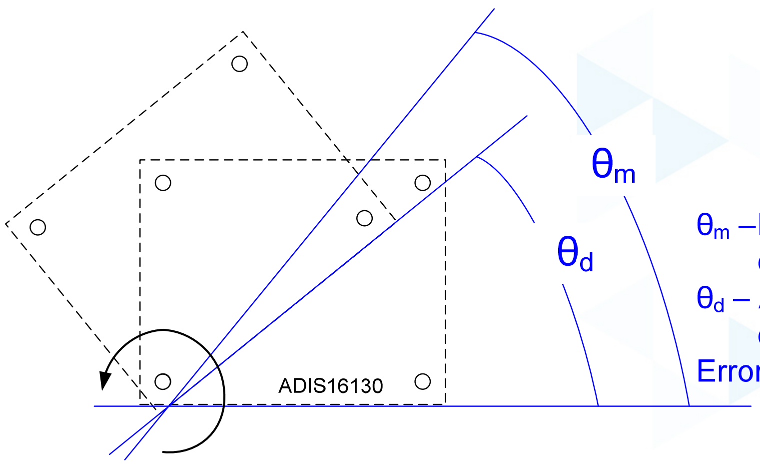
MEMS Gyroscope Implementation

Important performance parameters, scale accuracy

- **Sensitivity error directly translates to heading error when the gyroscope is rotating.**

$$\theta_H = \int_{t_1}^{t_2} (1+\varepsilon)\cdot K\cdot\omega\cdot dt = \underbrace{\int_{t_1}^{t_2} K\cdot\omega\cdot dt}_{\text{Correct Heading}} + \underbrace{\int_{t_1}^{t_2} \varepsilon\cdot K\cdot\omega\cdot dt}_{\text{Error term from sensitivity error}}$$

Sensitivity Error



θ_m –Measured angle displacement
θ_d – Actual angle displacement
Error = θ_m - θ_d

MEMS Gyroscope Implementation

Important performance parameters: bias accuracy

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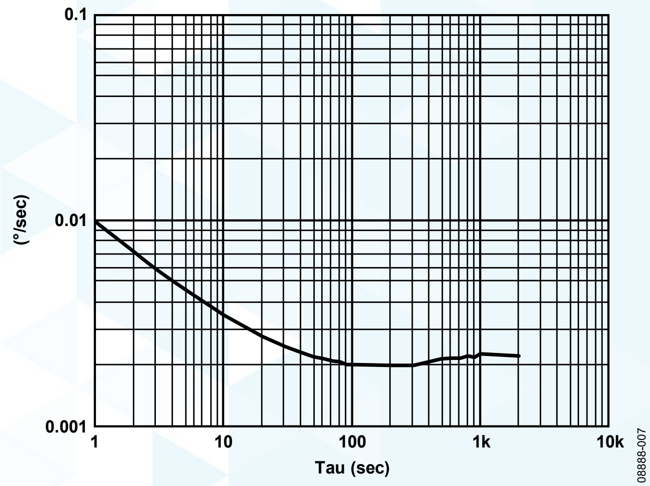
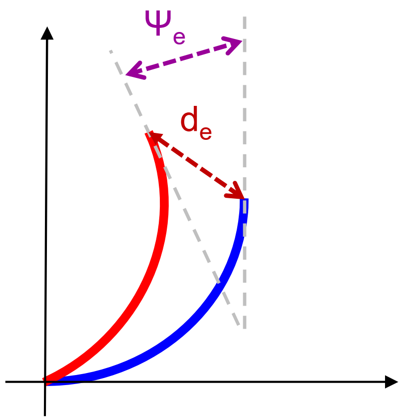
- Noise is dependent on bandwidth and will impact bias estimates.
- Alan Variance curves provide a relationship between bias accuracy and averaging time.
- For the Seekur system to get the best bias accuracy out of the ADIS16135, the Allan Variance shows that an average of 100 seconds will provide ~0.002 °/sec of bias accuracy.
- The Allan Variance curve also provides accuracy for lower average times, in case the application doesn't have 100 seconds
- In-run bias stability is the minima on the curve. This time also sets the optimal integration time (t2-t1) for the heading calculation.
- In the case of the ADIS16135, t2-t1 = 100 seconds will provide the best accuracy.



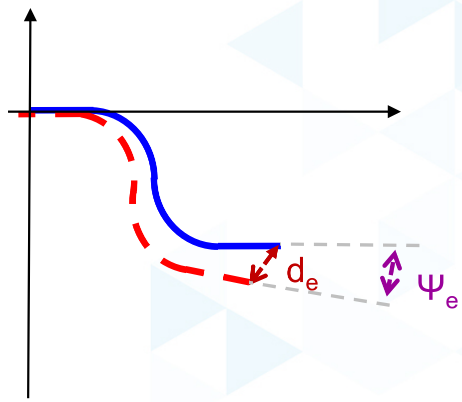
$$\theta_H = \int_{t_1}^{t_2} \omega \cdot dt$$

Quick reference to typical cause/effect

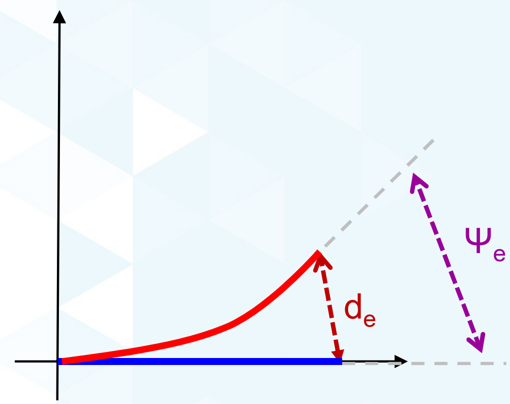
Sensitivity error causes heading and position errors during a turn



Nonlinearity (2^{nd} order) causes a heading error that can show up in patterns like an S-turn



Bias causes a drift in heading and position errors, even when there is zero turning.



Proper path, heading position in blue

Error-burdened path in red

Heading error = Ψ_e

Position error = d_e

ADIS16495:
+/-0.2% error over temperature
0.05% end of life!

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