MEMS IMUs for GNC (Guidance Navigation Control)

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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:

\[
\theta_x = a \sin \left( \frac{a_x}{1g} \right) \\
\theta_x = a \tan \left( \frac{a_y}{a_x} \right)
\]

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

\[
\phi_d(t) = \int_{t_1}^{t_2} \omega_m(t) \cdot dt
\]

Sensor Fusion
Real-time angle estimation
What are IMUs used for? Measure angles

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

\[
\theta = \arcsin \left( \frac{a_x + \text{vibe} + \text{acceleration}}{1g} \right)
\]

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

\[
\phi_d(t) = \int_{t_1}^{t_2} \omega_m(t) + \text{Bias} \cdot dt = \text{Real Angle} + \text{Bias} \times \text{Time}
\]
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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.
Gyrosopes: 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

\[ \varphi_{\text{CMD}}(t) \rightarrow \varphi_{\text{COR}}(t) \rightarrow \text{Servo Motor} \rightarrow \varphi_{P}(t) \]

- \( \varphi_{E}(t) \)
- \( \omega_{F}(t) \)
- \( \omega_{G}(t) \)

Integrator → Calibration Alignment → Digital Filtering → ADIS1647x

Mechanical Connection

OPENING IN PACKAGE LID

15436-046
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?

Integration Error (°)

Integration Time (seconds)

ARW = 0.17°/√hour

±φ_{RE}
What messes up your measurements?

- REFERENCES:
What nobody talks about……

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

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.

$$\phi_{\text{ROLL}} = G_L \times A_Z$$

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

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

$$\phi_{\text{ROLL}} = G_{\text{CAS}} \times \theta_{\text{PITCH}}$$

Typical Device Spec: +/-2%   ADI Spec: <0.087%
Vibration/Cross-axis on top of noise

Consequence
Noise/Jitter Increase
What matters?

- Stability/Repeatability (long term drift; scale and bias)
- Noise (angle random walk)
- Vibration rectification
- Hysteresis
- Non-linearity
- \( g \)-effect error (linear accel)
- Offset / Bias
- Scale / Gain Error
- Tempco’s
- Cross Axis Sensitivity

Inherent to sensor performance (limited opportunity to calibrate)

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

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

- 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

\[ \omega_{\text{gyro}} = K \times \omega_{\text{rate}} \]

\[ \theta_H = \int \omega \cdot dt \]

Independent steering & drive control for all 4 wheels!
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.
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:

\[ L = \pi \times D \times \frac{N_E}{N_C} \]

- \( L \) = Length/Displacement
- \( D \) = (Tire Diameter)
- \( N_C \) = Number of encoder counts per rotation
- \( N_E \) = Number of encoder counts read into Inverse Kinematics
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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**
Seekur comes with the SICK LSM111 Laser Range Finder system.

- **270° scan angles**
- 25-50Hz scan rates
- 20m range
- Some conditions require a stop to get stable measurements.
What are IMUs used for?

Indoor: Gyroscope feedback

Indoor: Poor or no gyro feedback

Massive improvement, expansion of robot capability

Outdoor:
- Uncertain terrain
- GPS obstruction management

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.

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

Ideal Gyroscope Equation

\[ \omega_G = K \times \omega_{rate} \]

\[ K = \text{ideal sensitivity, } ^\circ/\text{sec/LSB} \]
**Actual Gyroscope Equation**

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

- \( \epsilon_S = \text{Sensitivity error} = \epsilon_{SI} + \epsilon_{ST} \)
- \( \epsilon_{SI} = \text{initial sensitivity error} \)
- \( \epsilon_{ST} = \text{sensitivity error due to temperature changes} \)
- \( \epsilon_{ST} = \text{Sensitivity Temperature Coefficient} \times \text{Change in temperature} \)
- \( \epsilon_B = \text{Bias error} = \epsilon_{BI} + \epsilon_{BT} + \epsilon_{BV} \)
- \( \epsilon_{BI} = \text{initial sensitivity error} \)
- \( \epsilon_{BT} = \text{sensitivity error due to temperature changes} \)
- \( \epsilon_{BT} = \text{Bias temperature coefficient} \times \text{Change in temperature} \)
- \( \epsilon_{BV} = \text{sensitivity error due to power supply changes} \)
- \( \epsilon_{BV} = \text{Bias change with supply} \times \text{Change in power supply} \)
- \( \phi_N = \text{Total noise} = \phi_D \times \text{Noise Density} \)

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

**Ideal Gyroscope Equation**

\[ \omega_g = K \times \omega_A \]

- \( K = \text{ideal sensitivity, \( \frac{^\circ/\text{sec}}{\text{LSB}} \)} \)

\[ \omega_{gyro} = K \times \omega_{rate} \]

**Axis of rotation**
MEMS Gyroscope Implementation
Important performance parameters, scale accuracy

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

\[ \theta_H = \int_{t_1}^{t_2} (1 + \varepsilon) \cdot K \cdot \omega \cdot dt = \int_{t_1}^{t_2} K \cdot \omega \cdot dt + \int_{t_1}^{t_2} \varepsilon \cdot K \cdot \omega \cdot dt \]

- \( \theta_m \) — Measured angle displacement
- \( \theta_d \) — Actual angle displacement

Error = \( \theta_m - \theta_d \)
MEMS Gyroscope Implementation
Important performance parameters: bias accuracy

- Noise is dependent on bandwidth and will impact bias estimates.
- Allan 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.
Quick reference to typical cause/effect

**Sensitivity error**
causes heading and position errors during a turn

**Nonlinearity (2nd 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 = $\psi_e$
Position error = $d_e$

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