Teaching Module: Sensor Evaluation & Engineering Trade-Offs in Robotics and UAVs

Course: Advanced Mobile Robotics / Unmanned Aerial Systems (UAVs)

Target Audience: Undergraduate / Master's Level Engineering Students

Topic: Empirical Sensor Evaluation, Failure Modes, Power/Weight Trade-offs, and System Integration

1. Executive Summary & Pedagogical Goals

When designing autonomous systems, students often assume sensors operate under ideal mathematical assumptions. In practice, sensor selection is driven by physical environment noise, payload weight limits, and battery constraints.

Key Learning Objectives

1. **Analyze physical sources of sensor inaccuracy** across LiDAR, cameras, and IMUs—with special emphasis on UAV dynamics.
2. **Evaluate the power-weight-throughput triangle** in aerial vs. ground robotics.
3. **Formulate concrete sensor fusion strategies** that compensate for individual sensor failure modes without exceeding onboard energy budgets.

2. Sensor Inaccuracies & Failure Modes

A. LiDAR (Light Detection and Ranging)

LiDAR measures time-of-flight (Δt) of emitted laser pulses to compute distance $d = \frac{c \cdot \Delta t}{2}$.

- **Ground Robotics Failure Modes:**
    - **Narrow Beam / Target Miss:** A narrow beam (e.g., 1°) hitting a small target at range r can easily miss or slip past edges, causing "infinite" distance readings or wall reflections behind the target.
    - **Specular Reflection & Absorbent Surfaces:** Dark matte materials absorb the beam; glossy/glass surfaces cause specular bounce, directing the return signal away from the receiver.

- **UAV-Specific Failure Modes:**
  - **High-Frequency Motor Vibration:** Rotor vibration induces high-frequency angular jitter ($\Delta\theta$). At a distance of $r = 50\ \mathrm{m}$, an angular jitter of $\Delta\theta = 0.5^\circ$ creates a positional drift error $\Delta y \approx r \cdot \tan(\Delta\theta) \approx 0.43\ \mathrm{m}$.
  - **Incidence Angle Deviation:** As a drone tilts (pitches/rolls) to maneuver, the laser beam strikes the ground or targets at oblique angles, spreading the footprint and lowering signal-to-noise ratio.
  - **Dust, Fog, and Prop Wash Dust:** Propeller wash near the ground kicks up particulates, causing false-positive obstacle detection.

B. Visual Sensors & RGB-D Cameras

- **Ground Robotics Failure Modes:** Lighting variation, motion blur at high angular turning rates, scale ambiguity in monocular setups.
- **UAV-Specific Failure Modes:**
  - **Rapid Exposure Changes:** Moving quickly from shaded canopy to bright sunlight causes sensor saturation.
  - **High-Speed Rolling Shutter Artifacts:** Unmanned aircraft moving at $\geq 5\ \mathrm{m/s}$ experience image warping when using low-cost rolling shutter CMOS sensors.
  - **Computational Overhead:** Processing $1080\mathrm{p}$ video streams at $30\ \mathrm{FPS}$ for optical flow or visual SLAM consumes significant CPU/GPU power.

C. Inertial Measurement Units (IMU) & GPS/GNSS

- **UAV Multi-Pathing & Drift:** GPS signal reflections off buildings (multipathing) lead to sudden $2\text{–}10\ \mathrm{m}$ position jumps. Relying solely on dead reckoning with an uncalibrated MEMS IMU leads to quadratic error growth over time ($E \propto t^2$).

3. Power, Weight, and Energy Constraints

In ground robotics, adding a $1\ \mathrm{kg}$ sensor suite increases motor draw slightly. In aerial robotics (UAVs), payload mass penalizes flight time non-linearly.

The UAV Payload Energy Penalty

Hover thrust required is directly proportional to total mass m:

$$T = m \cdot g$$

Power required for a multirotor to hover scales according to momentum theory:

$$P_{\text{hover}} \propto T^{1.5} \propto (m \cdot g)^{1.5}$$

Adding a 500 g mechanical LiDAR package to a 2 kg drone increases mass by 25%, but increases hover power draw by approximately:

$$1.25^{1.5} \approx 1.398 \quad \text{(a 40\% increase in energy consumption)}$$

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|                    THE SYSTEM TRADEOFF                      |
|                                                       |
|  +--------------------+        Higher Weight       +----------------+  |
|  |  Heavy Sensor    | --------------------------> | Short Flight  |  |
|  |  (High Precision) |                       |   Duration   |  |
|  +--------------------+                   +----------------+  |
|           |                               ^          |
|           | High Data Rate                       |          |
|           v                               |          |
|  +--------------------+        High Wattage       +----------------+  |
|  | Onboard Compute  | --------------------------> | Battery Drain |  |
|  |  (GPU/Edge AI)    |                       |             |  |
|  +--------------------+                   +----------------+  |
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Sensor Category Comparison Matrix

Sensor Type	Typical Weight	Power Draw	Accuracy Range	Primary Failure Mode	Best Engineering Use Case

Mechanical LiDAR	$500\text{g} -$	$10\text{W} -$	High ($\pm 1 -$)	Vibration, High Power, Mass	High-precision 3D Terrain Mapping
Solid-State LiDAR	$100\text{g} -$	$2\text{W} -$	Medium-High ($\pm 3 -$)	Limited Field of View ($60^\circ -$)	UAV Frontal Obstacle Avoidance
Stereo Camera	$50\text{g} -$	$1.5\text{W} -$	Medium (Degrades with range)	Low light, Featureless walls	Close-range VIO & Landing Alignment
Ultrasonic Rangefinder	$10\text{g} -$	$<$	Low ($\pm 5 -$)	Soft surfaces, Angular limits	Low-altitude Ground Proximity Hold

4. Classroom Case Studies & Practical Exercises

Case Study 1: The Multi-Robot Contaminated Barrel Cleanup (Ground)

- **Context:** A ground robot must approach, attach to, and transport toxic barrels.
- **Failure Encountered:** The 1° LiDAR beam misses small target barrels at range $> 3\text{ m}$, returning inf.
- **Engineering Outcome:** Re-architect system roles. Use the camera (blob detection) for mid-range tracking and estimation, restricting LiDAR to close-range ($< 1\text{ m}$) collision prevention.

Case Study 2: Powerline Inspection UAV (Aerial)

- **Context:** Autonomous drone scanning thin powerlines ($1 - 2\text{ cm}$ diameter) at 15 m distance.
- **Failure Encountered:** Solid-state LiDAR FOV misses thin wires when the drone yaws rapidly. Stereo cameras fail due to sun glare.

- **Engineering Outcome:** Combine a high-frame-rate solid-state LiDAR ($100\ \mathrm{Hz}$) with an IMU-driven kalman filter. Enforce a flight speed cap ($v \leq 2\ \mathrm{m/s}$) to bound braking distance within the maximum detection range.

5. Homework & Lab Assignment Ideas

Assignment 1: Sensor Trade-Off Calculations

Task: Given a $1.8\ \mathrm{kg}$ baseline quadcopter with a $4\mathrm{S}\ 5000\ \mathrm{mAh}$ battery ($74\ \mathrm{Wh}$), calculate total hover time under two payloads:

1. **Option A:** Stereo Camera Suite ($120\ \mathrm{g}$, $2.5\ \mathrm{W}$ power draw).
2. **Option B:** Mechanical 3D LiDAR ($850\ \mathrm{g}$, $18\ \mathrm{W}$ power draw).

Students must apply the $P \propto m^{1.5}$ *relationship and account for sensor electrical draw to plot flight time degradation.*

Assignment 2: Failure Mode Analysis & FSM Design

Task: Design a state machine (or RoboChart) for an inspection drone encountering sensor degradation.

- **Condition 1:** Camera lens is covered in dust (Image entropy drops below threshold).
- **Condition 2:** LiDAR returns zero valid points for $> 500\ \mathrm{ms}$.
- **Required Student Solution:** System must safely transition to a stable altitude hold using IMU/barometer and initiate a controlled vertical land or return-to-home protocol.

6. Seminar Discussion Prompts

1. *"Why might a $50 ultra-sonic sensor be a better choice for low-altitude UAV altitude hold than a $1,500 lightweight LiDAR?"*
   (Key points: Power draw, mass penalty, low compute needs, reliability over flat non-absorbing surfaces).
2. *"If a system's reported sensor accuracy is high in simulation, why does performance often degrade significantly when deployed on real hardware?"*
   (Key points: Sensor noise models in simulators are often Gaussian and ignore environmental interference like prop-wash, glare, temperature drift, and dynamic vibration).