Lecture Note: Sensor Technologies in Autonomous Vehicles

1. Introduction and Context

In the previous lecture, we introduced **signals and systems**, including:

- Types of signals
- Noise and disturbances
- System interconnections

In this lecture, we extend those concepts to **sensor technologies**, which are fundamental for **perception, localization, and control** in autonomous vehicles (AVs).

2. Learning Objectives

By the end of this lecture, students should be able to:

- Identify major AV sensors:
  - LiDAR, Radar, Cameras, Ultrasonic, GPS, IMU
- Explain how each sensor works
- Compare sensors in terms of:
  - Range
  - Accuracy
  - Environmental sensitivity
- Understand applications such as:
  - Perception
  - Localization
  - Obstacle detection
- Recognize limitations of each sensor
- Understand the need for **sensor fusion**

3. Role of Sensors in Autonomous Vehicles

Autonomous vehicles rely on sensors to:

- Understand their **environment (perception)**
- Determine their **position (localization)**
- Make **decisions independently**

Similar to humans using vision and awareness while driving, AVs use sensors to:

- Know **where they are**
- Understand **what is around them**
- Decide **how to act safely**

4. Main Sensor Categories

4.1 Perception Sensors (Environment Awareness)

- LiDAR
- Radar
- Cameras
- Ultrasonic sensors

These detect:

- Objects
- Obstacles
- Road features
- Traffic participants

4.2 Positioning Sensors

- GPS
- IMU
- Wheel sensors

These determine:

- Vehicle location
- Motion and orientation

5. Sensor Coverage and Complementarity

- Different sensors cover **different regions and ranges**
- Overlapping coverage ensures:
  - Redundancy
  - Reduced blind spots
- No single sensor is sufficient → multiple sensors are required

6. LiDAR (Light Detection and Ranging)

6.1 Working Principle

- Emits **laser pulses**
- Measures **time-of-flight**
- Calculates distance using speed of light

6.2 Key Characteristics

- High-resolution **3D mapping**
- Range: ~200–300 meters
- Works in day and night (independent of lighting)

6.3 Applications

- 3D environment perception
- Object detection (vehicles, pedestrians)
- Localization and mapping (SLAM)
- Motion tracking
- Path planning

6.4 Advantages

- Accurate geometry and distance
- Real-time mapping
- Wide coverage (360°)

6.5 Limitations

- Affected by weather (rain, fog, snow)
- Expensive hardware
- High computational demand
- Cannot directly measure velocity
- Performance reduced on:
  - Dark or absorptive surfaces
- Mechanical wear due to rotating parts

7. Radar (Radio Detection and Ranging)

7.1 Working Principle

- Uses **radio waves**
- Measures:
  - Distance (time delay)
  - Velocity (Doppler effect)

7.2 Key Characteristics

- Robust in adverse weather
- Long sensing range
- Direct velocity measurement

7.3 Applications

- Object detection and tracking
- Adaptive cruise control
- Collision avoidance
- Emergency braking systems

7.4 Advantages

- Works in rain, fog, snow
- Measures relative speed
- Lower computational requirements

7.5 Limitations

- Low spatial resolution
- Poor object classification
- Multipath reflections → false detections
- Limited accuracy at long range
- Weak detection of non-metal objects

8. Cameras

8.1 Types of Cameras

- 2D cameras (RGB)
- 3D cameras (depth)

- Thermal cameras

8.2 2D Cameras

Features:

- Capture color and texture
- Provide rich semantic information

Limitation:

- No direct depth measurement

8.3 3D Cameras

Features:

- Provide depth per pixel
- Generate depth maps or point clouds

Methods:

- Time-of-flight
- Structured light

8.4 Thermal Cameras

Features:

- Detect heat signatures
- Work in low-light or night conditions

Applications:

- Pedestrian detection
- Animal detection
- Safety in low visibility

8.5 Applications of Cameras

- Object classification
- Traffic sign recognition
- Lane detection

- Scene understanding
- Driver monitoring (ADAS)

8.6 Advantages

- High semantic understanding (color, shape)
- Low cost
- Flexible placement

8.7 Limitations

- Sensitive to:
  - Lighting (night, glare)
  - Weather (rain, fog)
- No direct depth/velocity (unless fused)
- Affected by occlusion and clutter
- Requires high computational processing

9. Ultrasonic Sensors

9.1 Working Principle

- Emit **high-frequency sound waves**
- Measure return time → calculate distance

9.2 Characteristics

- Range: 0.2 m – 5 m
- Low cost
- Simple processing

9.3 Applications

- Parking assistance
- Blind spot detection
- Close-range obstacle detection

9.4 Limitations

- Very short range
- Poor performance at high speed
- Cannot classify objects

- Sensitive to:
  - Temperature
  - Surface angles

10. GPS (Global Positioning System)

10.1 Working Principle

- Uses satellite signals
- Provides:
  - Latitude, longitude, altitude
  - Speed

10.2 Characteristics

- Accuracy: ~3–5 meters
- Update rate: 1–10 Hz
- Global coverage

10.3 Applications

- Global localization
- Navigation and route planning

10.4 Limitations

- Signal blockage:
  - Tunnels
  - Dense urban areas
- Not lane-level accurate
- Cannot detect obstacles

11. Supporting Sensors for Localization

11.1 IMU (Inertial Measurement Unit)

- Measures:
  - Acceleration
  - Rotation
- Useful when GPS fails

11.2 Wheel Speed Sensors (Tachometers)

- Measure wheel rotation
- Estimate:
    - Speed
    - Distance traveled

11.3 Role

- Provide continuous motion estimation
- Bridge gaps during GPS loss
- Improve localization accuracy when fused with GPS

12. Need for Sensor Fusion

Key Idea

No single sensor is sufficient because:

- Each sensor has strengths
- Each sensor has limitations

Example

- LiDAR → accurate geometry
- Radar → velocity and weather robustness
- Camera → semantic understanding

Sensor Fusion Benefits

- Improved accuracy
- Increased robustness
- Reliable performance in all conditions

13. Key Takeaways

- AVs rely on **multiple complementary sensors**
- Sensors fall into:
    - Perception
    - Localization
- Each sensor has:
    - Strengths

    - Limitations
- **Sensor fusion is essential** for safe and reliable operation

14. Preview of Next Lecture

Next topic:

- **Sensor Fusion Techniques**
    - Combining multiple sensor data
    - Improving perception and control