Lecture Note: Sensor Fusion and Artificial Intelligence in Autonomous Vehicles

1. Introduction

In this lecture, we study how **autonomous vehicles (AVs) perceive and understand the environment** using:

- Multiple sensors
- Sensor fusion techniques
- Artificial intelligence (AI)

This topic connects directly to previous lectures:

- Signals & Systems → how data is represented
- Sensor Technologies → how data is collected

Now:
Sensor Fusion = how data is combined
AI = how data is interpreted and used for decisions

2. Learning Objectives

After this lecture, students should be able to:

- Describe AV sensors and perception systems
- Explain why **no single sensor is sufficient**
- Define and explain **sensor fusion**
- Understand how **AI and machine learning support perception**
- Differentiate:
  - Neural networks
  - Deep neural networks (DNN)
  - Convolutional neural networks (CNN)
- Recognize how fusion improves **safety and robustness**

3. Sensors and Perception System

3.1 What is a Sensor?

A sensor:

- Detects physical/environmental changes
- Converts them into electrical signals

Examples:

- Camera → light
- Radar → radio waves
- LiDAR → laser
- IMU → motion

3.2 Role of Sensors in AVs

Autonomous vehicles must:

- Perceive the environment
- Understand traffic participants
- Make decisions **in real time**

Sensors act like **eyes and ears** of the system.

3.3 Types of Sensors

1. Exteroceptive (Environment)

- Cameras, LiDAR, Radar, Ultrasonic

2. Proprioceptive (Vehicle State)

- IMU, wheel encoders

3. Positioning

- GPS / GNSS

4. Perception System in AVs

Definition

A perception system:

- Processes **multi-modal sensor data**
- Produces **accurate, robust, real-time understanding**

Key tasks:

- Sense environment
- Interpret objects
- Build world representation

Key Requirements

- **Accuracy** → precise environment understanding
- **Robustness** → works in all conditions
- **Real-time** → immediate decision-making

5. Why Multi-Modal Perception?

Key Insight

❗ **No single sensor is sufficient**

Each sensor has limitations:

- Camera → sensitive to lighting
- LiDAR → expensive, weather sensitivity
- Radar → low resolution

Complementary Roles

- Camera → semantic (what object is)
- LiDAR → geometry (shape & distance)
- Radar → motion & robustness

6. Sensor Fusion

6.1 Definition

Sensor fusion is:

Combining data from multiple sensors to create a more accurate and reliable understanding of the environment

6.2 Goals of Sensor Fusion

- Reduce uncertainty
- Improve reliability
- Compensate for sensor weaknesses

6.3 Role in Perception

Sensor fusion:

- Combines heterogeneous data
- Improves accuracy
- Handles sensor failures

Supports:

- Object detection
- Semantic segmentation
- Localization

6.4 Applications in AVs

1. Object Detection & Tracking

- Camera + LiDAR + Radar
- Enables:
    - 3D mapping
    - Object classification

2. Lane Detection

- Camera + IMU + GPS
- Enables:
    - Lane keeping
    - Safe lane changes

3. Safety Systems

- Collision avoidance
- Emergency braking

6.5 Sensor Fusion for Safety

Fusion improves performance under:

- Poor lighting
- Adverse weather
- Sensor failure

- ➢ Reduces single-point failures
- ➢ Increases reliability and trust

6.6 Common Algorithms

Kalman Filter

- Used for linear systems
- Motion estimation

Extended Kalman Filter

- Used for nonlinear systems
- Localization and pose estimation

7. Artificial Intelligence (AI) in AVs

7.1 What is AI?

AI:

- Performs tasks requiring human-like intelligence
- Learns from data and experience

Applications in AVs:

- Seeing (perception)
- Recognizing objects
- Decision making

7.2 AI in AV Pipeline

1. Perception

- Understand environment

2. Prediction

- Predict behavior of:
  - Vehicles
  - Pedestrians

3. Decision Making

- Actions:
  - Turn
  - Stop
  - Overtake

8. Machine Learning

Definition

- Subset of AI
- Learns patterns from data instead of rules

Key Idea

More data → better performance

Example

- Train model with labeled images:
  - Cars
  - Pedestrians
- Model learns to recognize them in new scenarios

9. Neural Networks

9.1 Definition

- Inspired by human brain
- Made of interconnected neurons

Structure

- Input layer
- Hidden layers
- Output layer

Each layer: Extracts more complex features

9.2 Deep Neural Networks (DNN)

- Many hidden layers
- Learn complex patterns
- Handle large datasets

Applications in AVs:

- Object detection

- Lane detection
- Traffic sign recognition

9.3 Convolutional Neural Networks (CNN)

Specialized for Images

- Automatically extract features:
  - Edges → shapes → objects

Applications

- Object detection
- Lane detection
- Traffic sign recognition

Key Benefit

- No need for manual feature design

10. Sensor Fusion + AI (Multi-Modal Perception)

Integration

- Camera → semantic features
- LiDAR → geometry
- Radar → motion
- AI learns to: Combine all sensor data

Outcome

- Unified environment understanding
- Robust perception system

Example (from slides, p.26)

- RGB image + LiDAR + radar
- Neural network detects:
  - Vehicles
  - Pedestrians
  - Traffic signs

Each object has probability/confidence

11. Challenges in Sensor Fusion

1. High Data Volume

- Multiple sensors generate large data streams

2. Computational Demand

- Requires high processing power

3. Sensor Calibration

- Must align data in time and space

4. AI Explainability

- Hard to interpret AI decisions

12. Connection to Civil Engineering

Sensor performance depends on infrastructure:

Good Infrastructure

- Clear lane markings
- Consistent signage
- Predictable layout
- Improves perception accuracy

Poor Infrastructure

- Leads to perception errors
- Reduces safety

Civil engineering directly impacts AV performance

13. Key Takeaways

- AV perception requires **multiple sensors**
- Sensor fusion is **essential, not optional**
- AI enables:
  - Perception
  - Prediction
  - Decision-making
- Neural networks are core to AV intelligence
- Infrastructure quality affects AV safety

14. Next Lecture

Control Systems in Autonomous Vehicles

- How perception outputs are used
- How vehicles make control decisions