Lecture Note: Control Systems in Autonomous Vehicles

1. Introduction

This lecture completes the AV pipeline:

- Signals & Systems → how data is represented
- Sensors → how data is collected
- Sensor Fusion → how data is combined
- **Control Systems → how the vehicle acts**

Control systems take **perception + planning outputs** and convert them into **physical vehicle actions** (steering, throttle, braking).

2. Learning Objectives

After this lecture, students should be able to:

- Define control system concepts
- Understand feedback control in AVs
- Identify:
  - Vehicle states
  - Control inputs
  - Tracking errors
- Explain impact of roadway geometry on control
- Understand integration in **See–Think–Act architecture**

3. Autonomous Vehicle System Architecture

3.1 See–Think–Act Framework

From the diagram on **slide page 3**, the AV system operates as:

1. See (Perception)

- Sensors gather data from environment
- Build local/global maps

2. Think (Planning)

- Path planning

- Decision-making

3. Act (Control)

- Execute commands via actuators

Loop repeats continuously in real time

3.2 Hierarchy of Decision-Making

From **slide page 5**, control is part of a layered system:

1. **Route Planning**
   - Global path (start → destination)
2. **Behavioral Layer**
   - Decisions based on environment
   - (e.g., stop, yield, lane change)
3. **Motion Planning**
   - Generates trajectory
4. **Control (Local Feedback)**
   - Executes trajectory via:
     - Steering
     - Throttle
     - Brake

4. What is a Control System?

4.1 Definition

- A system = collection of components working toward a goal
- Control system = system that:
  - Regulates behavior
  - Achieves desired output

Control = **manipulating input to achieve desired output**

4.2 Example

- Driving a car:
  - Input → throttle/brake/steering
  - Output → vehicle motion

5. Feedback Control System

5.1 Definition

A feedback system:

- Compares **actual output** with **desired reference**
- Adjusts input to reduce error

5.2 Key Components (from diagram on page 7)

- Reference input
- Controller
- System (vehicle)
- Sensor (measurement)
- Feedback loop

5.3 Key Idea

$$\text{Error} = \text{Reference} - \text{Measured Output}$$

Controller minimizes this error.

5.4 Real-World Example

- Thermostat:
    - Desired temperature = reference
    - Measured temperature = output
    - System adjusts heating/cooling

6. Why Control is Critical in AVs

Autonomous vehicles must:

- Maintain lane position
- Regulate speed
- Avoid obstacles
- Follow traffic rules

Unlike humans:
AVs rely entirely on **automatic feedback systems**

Key Insight

Control theory ensures:

- Stability
- Safety
- Predictability

7. Vehicle as a Dynamic System

7.1 State Variables

- Position (x, y)
- Heading angle (ψ)
- Velocity (v)
- Yaw rate

7.2 Control Inputs

- Steering angle (δ)
- Acceleration (a)

7.3 Models

- Kinematic models (geometry)
- Dynamic models (forces, motion)

8. Reference Path and Tracking

8.1 Reference Path

- Lane centerline or trajectory
- Goal for control system

8.2 Objective

Minimize deviation from path while maintaining:

- Stability
- Comfort

8.3 Tracking Errors

1. Lateral Error

- Distance from lane center

2. Heading Error

- Orientation mismatch

3. Speed Error

- Difference from desired speed

4. Curvature Error

- Path mismatch

Control actions aim to **drive errors to zero**

9. Control Theory in AVs

Control system compares:

- Desired motion (trajectory)
- Actual motion (sensor measurements)

Uses feedback to reduce error

Impact of Road Design

From **slide page 10 & 16**:

- Road geometry defines control difficulty:
  - Curve radius
  - Superelevation
  - Speed limits

Example:

$$a_{lat} = \frac{v^2}{R}$$

Smaller radius → higher control effort

10. Control Methods in AVs

10.1 PID Control

Definition

PID = Proportional + Integral + Derivative

Components

1. **Proportional (P)**
   - Responds to current error
2. **Integral (I)**
   - Corrects accumulated error
3. **Derivative (D)**
   - Predicts future trend

Applications

- Lane keeping
- Cruise control
- Speed regulation

Advantages

- Simple
- Reliable
- Easy to implement

Limitations

- No future prediction
- Poor performance at high speed
- Cannot handle constraints
- Struggles with:
  - Sharp curves
  - Low friction roads

10.2 Model Predictive Control (MPC)

Key Idea

- Predict future motion over time horizon
- Solve optimization problem

Steps

1. Predict future states
2. Optimize control inputs
3. Apply first control action
4. Repeat (receding horizon)

Objective Function

$$J = \sum(\text{tracking error}^2 + \text{control effort}^2)$$

Advantages

- Handles constraints:
  - Lane boundaries
  - Steering limits
- Smooth control
- Multi-objective optimization:
  - Safety
  - Efficiency
  - Comfort

Challenges

- High computational demand
- Requires real-time optimization

11. Simulation and Validation

Before real deployment:

- AVs are tested in simulation
- Digital twin models replicate real-world behavior

Benefits:

- Safe testing
- Extreme scenario evaluation
- Repeatability

12. Role of Civil Engineering

12.1 Infrastructure Impact

Good infrastructure:

- Clear markings
- Smooth curves
- Consistent design

Easier control

Poor infrastructure:

- Increases tracking error
- Reduces safety

12.2 Key Factors

- Curve radius
- Sight distance
- Lane quality
- Signage clarity

12.3 Key Insight

Control + Civil Engineering are **tightly coupled systems**
Better roads → better AV performance

13. Key Takeaways

- Control systems convert decisions into **vehicle motion**
- Feedback control is essential for:
    - Stability
    - Safety
- Key components:
    - States, inputs, errors
- PID:
    - Simple but limited
- MPC:
    - Advanced, predictive, constraint-aware
- Road design strongly affects control performance

14. Final System View

Full AV pipeline:

1. **See** → Sensors + Perception
2. **Think** → Planning + AI
3. **Act** → Control Systems

15. Next Topic

Communication Systems in Autonomous Vehicles