

AI Enabled Control Engineering

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Lecture 1 Overview

- Syllabus
- What is control?
- Why study control?
- Why is the inverted pendulum a classical example?
- Model with block diagram
- Input, output, and state
- Open-loop vs closed-loop control

Syllabus

- The course consists of 5 theory lectures, 8 hands-on practice lectures on the real rotary inverted pendulum, and 1 lecture on drone control
- Fundamentals first, then examples and machine learning-based control
- Required background
- Objective:
 - develop understanding of engineering design from a control perspective
 - build intuition from classical control to AI-enabled control
- Grade: Laboratory report (50%), Final exam (50%)

The organization of the lectures

- 1 Syllabus and introduction to control systems
- 2 Linear systems, Laplace transform, and transfer functions
- 3 Closed-loop stability and classical stability analysis
- 4 State-space methods and introduction to reinforcement learning
- 5 DQN for CartPole: algorithm and practice
- 6 Rotary inverted pendulum modeling; hardware system introduction; env setup
- 7 Hardware setup, wiring, and motor test
- 8 PID control
- 9 LQR control
- 10 Observer design and test
- 11 DQN training in simulation
- 12 Sim-to-real deployment on the real system
- 13 UAV example
- 14 Tutorial session
- 15 **Final exam**

Why study control?

Applications arise in many areas, e.g.

- automatic control systems
- robotics and autonomous systems
- mechanical and civil engineering
- aeronautics, navigation, and guidance
- circuit analysis, simulation, and design
- economics, networks, and decision systems

Control is the discipline of making dynamical systems behave as intended.

Origins and history

- Parts of control theory can be traced to 19th century.
- Builds on classical circuits & systems (1920s on) (transfer functions ...).
- First engineering application is in aerospace, 1910s, 1960s
- Transitioned from specialized topic to ubiquitous in 1980s.

What is control?

“Control is what makes systems function as intended.”

- machine:
- intended:
- function as:

We heavily use block diagram in control to explain what is control.

- Input, output, transfer function.
- It is different from circuits network.
- It simply neglect sensor/actuator dynamics.

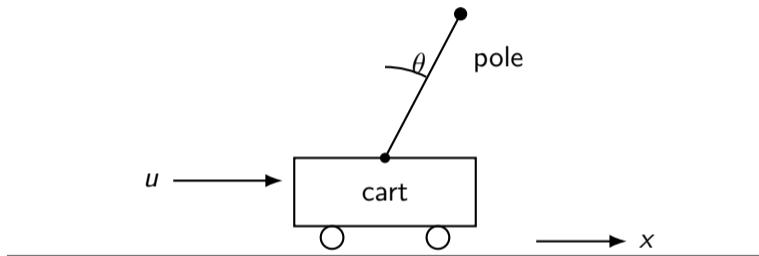
Why is the inverted pendulum a classical example?

The cart-pole inverted pendulum is a canonical benchmark because:

- it is simple to describe physically
- the upright equilibrium is unstable
- the dynamics are nonlinear and coupled
- it clearly demonstrates the need for feedback
- it is useful in both classical control and reinforcement learning

It is one of the best examples for introducing stabilization and learning-based control.

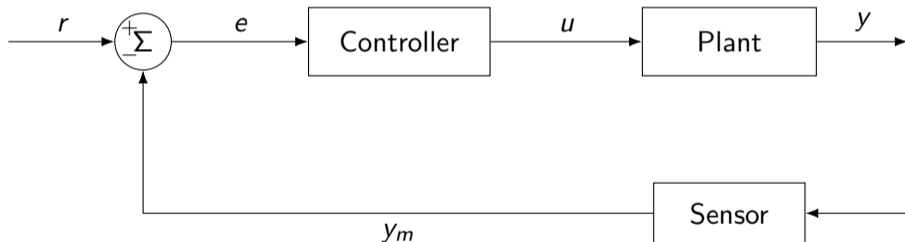
Cart-pole system



- control input: horizontal force u
- output of interest: cart position x and pendulum angle θ

Model with block diagram

We heavily use block diagram in control to explain what is control.



Input, output, and transfer function are central concepts in this language.

Cart-pole in the block diagram language

For the cart-pole system:

- Plant or process: cart and pendulum dynamics
- Actuator: motor or force source that pushes the cart
- Sensor: encoder, camera, or simulator state observation
- Controller: algorithm that chooses the force

Typical signals:

- reference r : desired upright position and desired cart location
- control input u : horizontal force on the cart
- output y : measured position and angle

Input, output, and state

In control, we distinguish:

- input: what we are allowed to manipulate
- output: what we measure or care about
- state: the minimal variables that describe the current system condition

For the cart-pole example, a common state vector is

$$x = [p \quad \dot{p} \quad \theta \quad \dot{\theta}]^T,$$

where p is the cart position and θ is the pendulum angle.

Later, this state description will be the bridge to both state-space control and reinforcement learning.

Open-loop vs closed-loop control

Open-loop control

- the input is chosen without using the current output
- easy to implement, but sensitive to disturbance and uncertainty

Closed-loop control

- the input depends on measured output or state
- feedback can correct errors in real time

Closed-loop = feedback.

In control, “control” implicitly refers to negative feedback control.

Q: Could you please propose any system with feedback control?

Why feedback is necessary for cart-pole

If we try to balance the pendulum in open loop:

- a tiny modeling error will accumulate
- an unknown disturbance will make the pole fall
- the upright equilibrium cannot be maintained robustly

With feedback:

- angle error is measured
- the controller adjusts the cart force
- the system can recover from small perturbations

This is why the inverted pendulum is such a powerful teaching example.

Required background and computer tools

Required math background:

- ODE
- complex variable
- linear algebra

Computer tools:

- Python
- Gymnasium / CartPole environment
- PyTorch for later DQN experiments

Theoretical ideas are most useful when combined with computation.

Summary

- Control is about making dynamical systems behave as intended.
- The inverted pendulum is a classical benchmark because it is simple, unstable, and instructive.
- Block diagram gives us a clean language for process, sensor, actuator, controller, input, and output.
- Open-loop and closed-loop systems are fundamentally different.
- Negative feedback is the central idea of modern control.