Systems Analysis and Control

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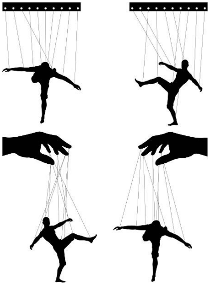
Lecture 1: Introduction to Control Systems and Historical Perspective

Rorschach Test for Control? Which One is Different?



Star Wars Marionette

Lt. Cmdr. Data from Star Trek TNG

Atlas Robot from Boston Dynamics

What do we mean by "Control"?

Control is the study of how to make things do what you want.

The most robust **Controller** is **Human Consciousness**.

- Fly an airplane.
- Drive a car without crashing.

The Subconscious is also not bad

- Keeping your eyes on the instructor.
- Keeping your heart beating.
- Standing up.

In this class we focus on *Automatic Control*.

- Machines are clay. To function, they must be controlled
  - They only speak **Math**.
- Your subconscious is very good at **Math**.

Unfortunately, you conscious mind is NOT (no offense).

Who Am I?

Website: `http://control.asu.edu`

Research Interests: Computation, Optimization and Control

Focus Areas:

- Control of Nuclear Fusion
- Immunology
- Thermostats, Renewable Energy, and Power Distribution
- Soft Robotics

Control Specialization:

- Optimization
- Control of Delayed Systems
- Control of PDE Systems
- Control of Nonlinear Systems

My Background:

- B.Sc. University of Texas at Austin
- Ph.D. Stanford University
- Postdoc at INRIA Paris
- NSF CAREER Awardee

Office: ERC 253; Lab: GWC 531

What is a Control **System**?

Well... What is a System?

- AKA: "process", "machine", "plant", "thing", et c.
- Can be a "real" thing or a mathematical representation (model).

Definition 1.

A **System** is anything with Inputs and Outputs

There should ALWAYS be Inputs and Outputs!

- **If No Inputs**: You can't change anything.
- **IF No Outputs**: Then it doesn't matter anyway.

Let start with some examples.

Example: A Stereo Receiver

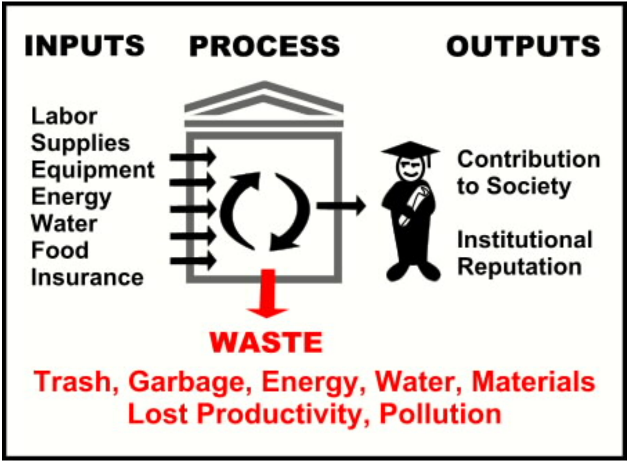
Inputs and Outputs depend on what we are trying to do.

- A system may have multiple Inputs and Outputs.
- But only some of these are relevant to you.

Example of a System: Education

Definition 2.

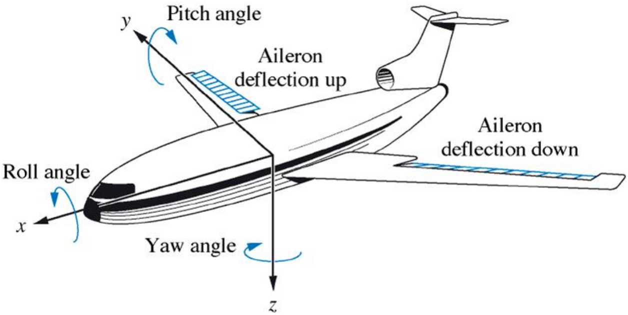
The System to be controlled is called the **Plant**.



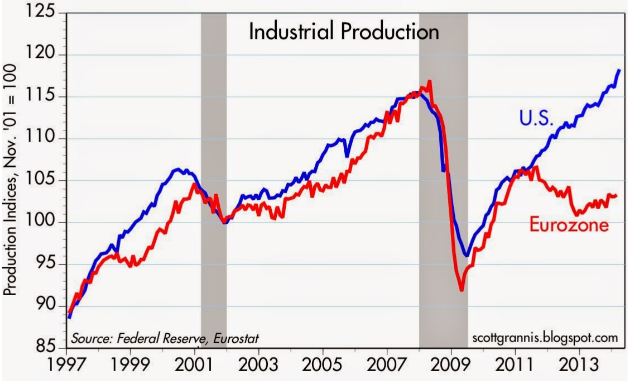
WASTE is ALSO an Output!

Example of a System

Aircraft



Example: The economy



This is a tough one...

- Consider a small-scale economy.

Example: Dinner at House of Tricks

There can be **Multiple Subsystems**!

- You tip the waiter based on quality of service.
- The waiter can improve his service to increase his tip.

Feedback: When the Outputs affect the Inputs.

Inputs and Actuators

Inputs can be created by **Actuators**.

Definition 3.

An **Actuator** is any mechanism/signal/communication which can affect the Outputs.

Examples:

- Ailerons, Rudder
- Force Transducers: Servos/Motors
  - Robots
  - Engines
- Money (Prices)

Sensors, Outputs and Feedback

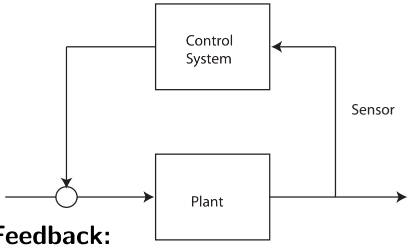
Outputs are measured by **Sensors**.

Definition 4.

A **Sensor** is any mechanism/communication/signal which can be used to measure an Output.

Definition 5.

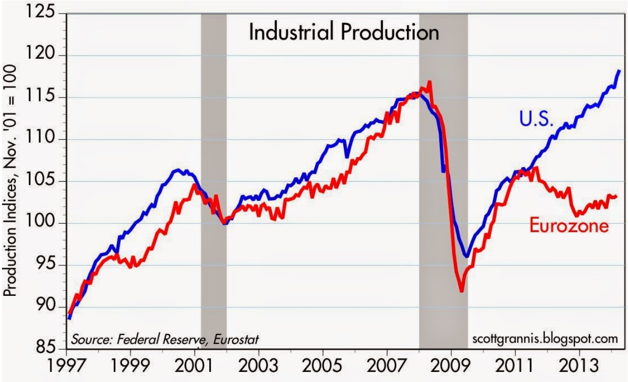
A **Closed Loop Controller** creates a loop between *Sensors* and *Actuators*. This loop is referred to as **Feedback**.



More Examples of Feedback:

- Pool Maintenance

Back to the economy

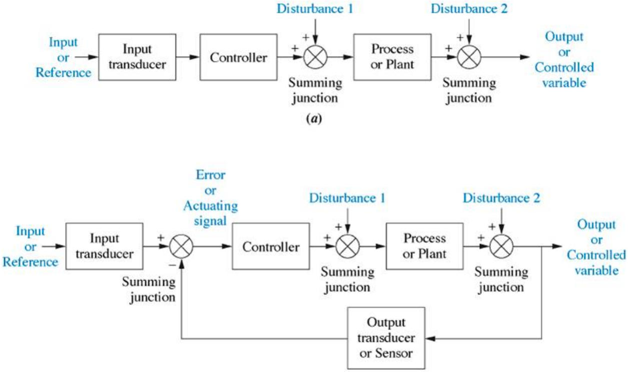


Prices are the feedback

- Markets price goods by how much they are needed.
  - Scarcity and Demand to Price
- People produce goods based on how much money they can make.
  - Price and Cost of production to Production

Definition 6.

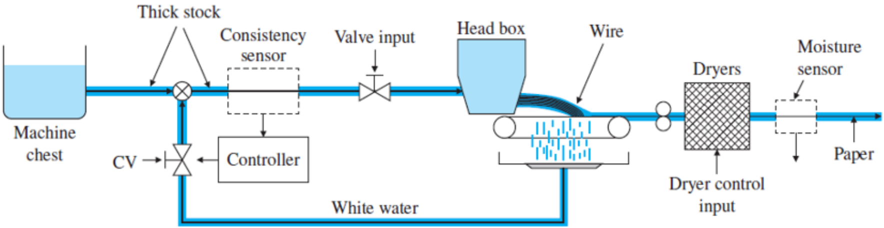
A **Control System** is a system which modifies the inputs to the *plant* to produce a desired output.



(a) (b)

Example of a System

Paper Mill

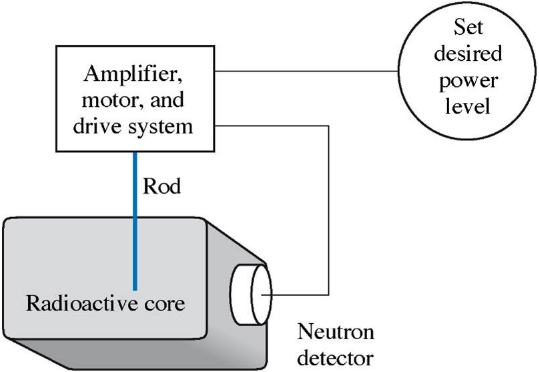


Things to look for:

- Dynamics
- Sensors
- Actuators
- Regulated Outputs
- Disturbances

Example of a System

Nuclear Reactor



Things to look for:

- Dynamics
- Sensors
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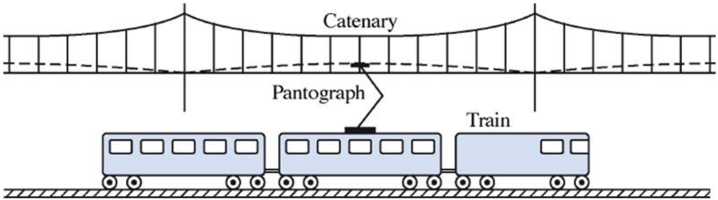
- Regulated Outputs
- Disturbances

Example of a System

Pantograph (High-Speed Electric Train)



Things to look for:

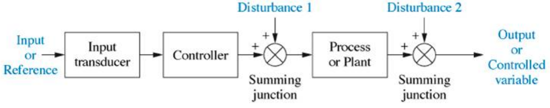
- Dynamics
- Sensors
- Actuators
- Regulated Outputs
- Disturbances

Of Course there is also Open-Loop Control

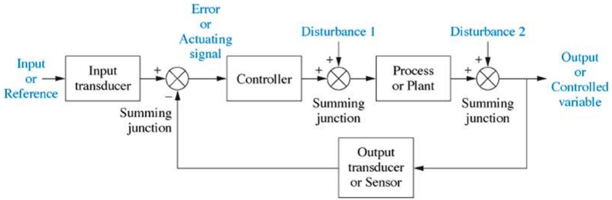
Definition 7.

An **Open Loop Controller** has an actuator, but makes no measurements.

- No way to tell how well you are doing...



(a)



(b)

Examples of Open-Loop Control

- Choosing a Class
- A Pop-up Toaster
  - Actuators, Inputs, Outputs?
- Irrigation Systems

Problems?

Lets Compare Open- and Closed-Loop Driving

3D Google Maps Driving Simulator

2D Google Maps Driving Simulator

2D Driving Simulator without Google Maps

Model-Based vs. Model-Independent Control

A Last Bit of Nomenclature

Open-Loop Control requires detailed knowledge of the System and Environment.

- How much knowledge is needed?
- How is this knowledge represented?

Definition 8.

A **Mathematical Model of a System** is any tool which allows us to *predict the output of the system* for any given input.

Examples: Differential Equations, Transfer Functions, Functions

- Comes from: Physical Principles; System Identification; Machine Learning

Definition 9.

A **Model-Based Controller** is a controller which uses a Mathematical Model of the system to map inputs to outputs (sensor signals to actuator signals).

Definition 10.

A **Model-Independent Controller** is a controller which is designed to work for ANY system.

Automatic Control throughout History: The Measurement of Time

Egyptian Water Clocks 1600BC

Significant in Commerce, Industry, Science, Medicine and Military

Time left is given by the amount of water left in the pot.

Problem: Measurement is limited to time left and by amount of water in pot.

History of Water Clocks

Time passed is amount of water in pot.
Problem: Water flow varies by amount of water in the top pot.
Solution: Maintain a constant water level in top pot.

History of Water Clocks

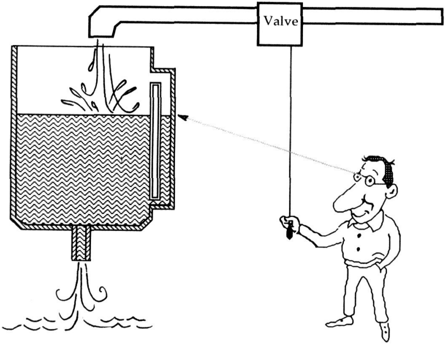


FIGURE 1.1. Level Control System. A sight tube and operator's eye form a sensor: a device which converts information into electrical signal.

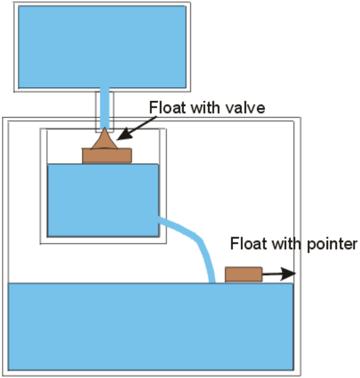
Problem: Manually refilling the top pot is labor intensive and inaccurate.
Solution: Design a control System (Inputs, Outputs?).

History of Water Clocks

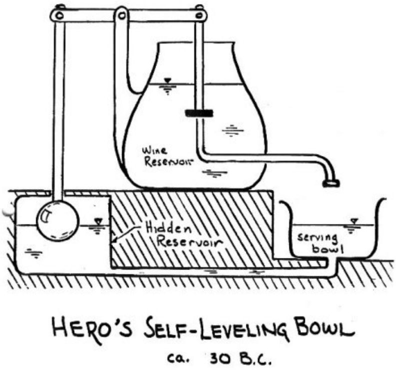
Ctesibius c. 220-285 BC

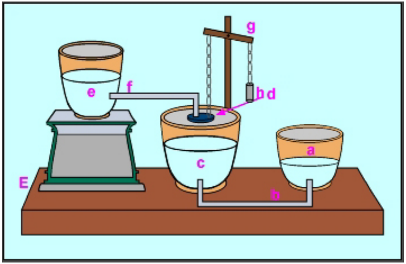
Father of pneumatics

- Lived in Abject Poverty
- Created most accurate clock until Huygens (1657 AD)
- Overshadowed by better-known student Heron (Hero) of Alexandria



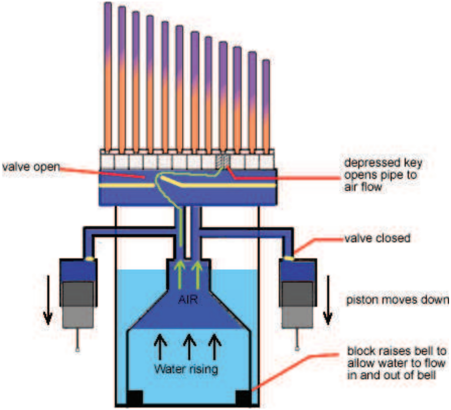
As any good student, Hero used Ctesibius' water clock to perform party tricks.



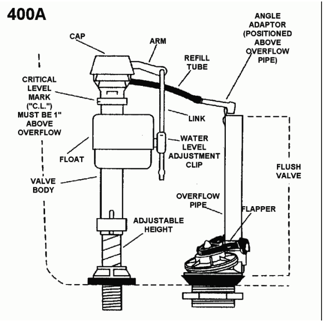


The self-replenishing wine bowl. (Inputs, Outputs?)

Ctesibius himself applied the principle of pneumatic control to create a pipe organ.



What do we use Ctsebius' water clock for today?



The Industrial Revolution

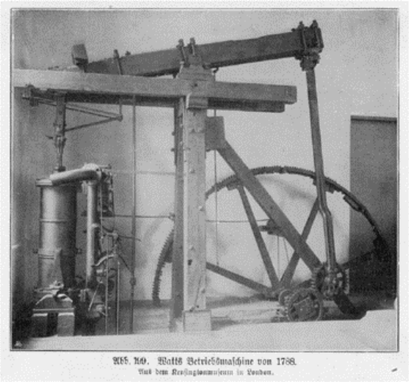
More Serious Applications

In addition to wine bowls, Heron also developed the steam engine.

Unfortunately, the Aeolipile was NOT CONTROLLED.

- No Feedback
- Missed chance for an industrial age?

The Modern Aeolipile



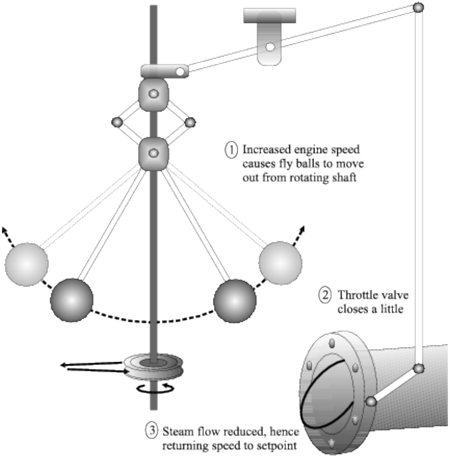
Problem: To be useful, steam engines must rotate a piston at a *fixed speed*.

The Flyball Governor

Flyballs regulate rotation rate.

- Faster rotation = More centrifugal force.
- Centrifugal force lifts the flyballs, which closes a valve, reducing flow of steam.
- Reduced flow of steam decreases engine/piston speed.

Gain: A key parameter is the ratio of lift to throttle.

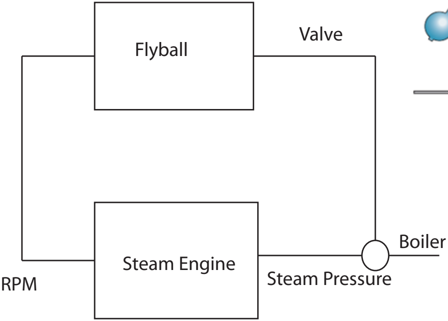


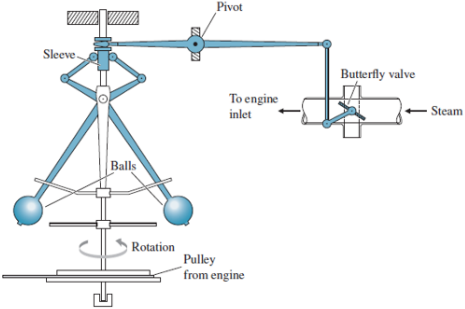
Identify the inputs and outputs.

The Flyball Governor

Decompose the Problem:

- Inputs and Outputs
- Plant and Controller
- Disturbances?



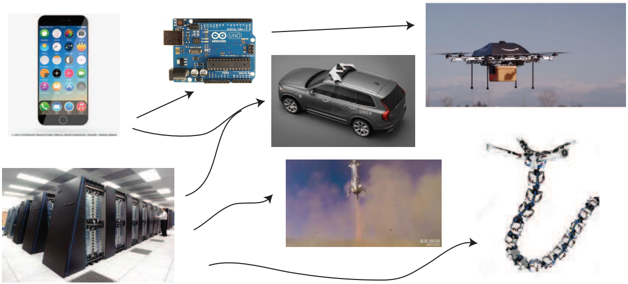


The Flyball Governor in Operation

Stuart-Turner No9 Steam Engine

Factoid: What does it mean to be going “Balls Out”?

What are the challenges for control in the 21st century?



Megatrends:

- Increased Complexity (Embedded Computation and Control)
- Increased Connectivity (Internet of Things)
- Robots, Drones and Self-Driving Cars
- Increased Demands (Higher Standards)
- Mobile Computing (Mobile Apps)

Challenges for Control in the 21st century

Privatization of Space Travel

Challenges

- Safety
- Complexity
- Uncertainty

Links:
Blue Origin Successful Landing
Blue Origin Successful Landing: Flight 3
SpaceX Landing, Second Attempt
Proton M launch Failure (FCS was for wrong rocket)
Kepler Space Telescope

Challenges for Control in the 21st century

UAVs and Drones (Delay, Sampled-Data)

Safe Interaction with

- Crowded Airspace
- Real-Time Obstacle Avoidance

Precision Control with

- Delayed Feedback
  $$\dot{x}(t) = Ax(t) + Bu(t - \tau)$$
- Lossy Connections
  $$\dot{x}(t) = Ax(t) + Bu(t_k)$$

Links:
X47 Drone Carrier Landing
Raff's TED talk

Challenges for Control in the 21st century

Self-Driving Vehicles

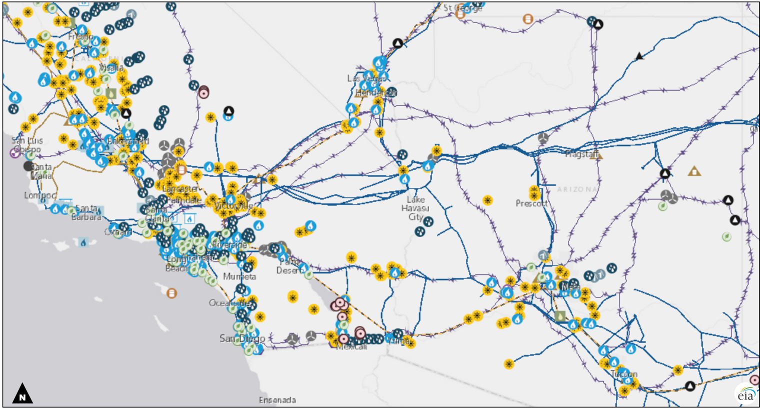
Challenges:

- Safety (Provable)
- Uncertainty (in model, environment)
- Other Drivers (Multi-Agent)
- Obstacles

Self-Driving Vehicles

- Google (Waymo)
- Über
- Tesla, Mobileye
- Toyota, Nutonomy

Links:
Toyota's Research Expansion in Automation
Uber's self-driving Taxis are in Pittsburg
Self-Driving Cars Flood into Arizona



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0 15 30 60 Miles

- Surface Coal Mine
- Underground Coal Mine
- Biomass Power Plant
- Coal Power Plant
- Geothermal Power Plant
- Hydroelectric Power Plant
- Natural Gas Power Plant
- Nuclear Power Plant
- Other Power Plant
- Petroleum Power Plant
- Pumped Storage Power Plant
- Solar Power Plant
- Wind Power Plant
- Petroleum Refinery
- Biodiesel Plant
- Ethanol Plant
- Natural Gas Processing Plant (z)
- Ethylene Cracker
- HGL Market Hub (z)
- Natural Gas Market Hub (z)
- Electricity Border Crossing
- Natural Gas Pipeline Border Crossing

Challenges for Control in the 21st century

Robotics (Hybrid and Nonlinear Dynamics, PDE systems)

HARD Robots

- Uncertain Terrain
- Interactions with the environment

`If x(t)>0:`

$$\dot{x}(t) = Ax(t)$$

`If` x_1`(t)=0 AND` x_2`(t)<0:  Set`

$$x_2(t) = -x_2(t)$$

Link:

Boston Dynamics, Atlas Mark 3

SOFT Robots

- Infinite Degrees of Freedom
- Material Dynamics

Link:

Robotic Worm

Trends:

- Rapid prototyping
- Internet of Things
- Control is Everywhere

Challenges

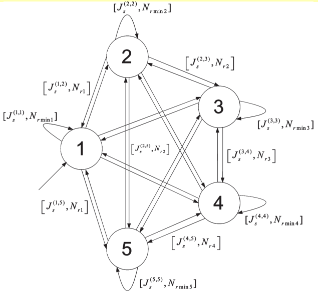
- Noisy Sensors
- Data-Driven Modeling
- Dynamics with logical switching

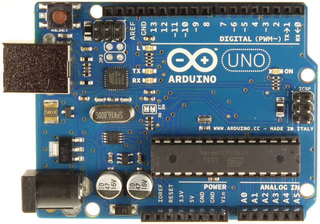
$$\dot{x} = Ax + Bu(t)$$

`If Occupied=True :`

$$u(t) = K_1 x(t)$$

`Else :` $\quad u(t) = K_2 x(t)$





Overview of Course Objectives

Will that be on the final???

Part 1: System Analysis

- Given a system model:
  - Given an input, find the output
  - Predict the effect of Standard Inputs (Impulse, Step, Ramp, etc.)
  - Determine Stability
- Introduction to the Frequency Domain
- Given a desired response:
  - Determine the characteristic root locations

Part 2: Controller Design

- Given a system model:
  - Plot the effect of proportional gain (Root-Locus)
  - Plot the response to sinusoidal input (Bode Plot)
- Given a desired response:
  - Propose feedback controllers (PID and lead-lag) to achieve the desired response.