ECE12406
Control Systems

Lecture 1: Introduction to Control

BEng Electrical and Communication Engineering
Year 2 Semester 4
Topics

Introduction to Control

Dynamic System Models

Block Diagrams

System Response

Feedback Control
Module Roadmap

Modelling Dynamic Systems

- System Dynamics
  - Electrical & Electronic
  - Mechanical
  - Electromechanical
  - Process

- System Models
  - Differential equations
  - Transfer function

- Block Diagrams
  - Algebra
  - Reduction techniques

System Analysis

- Time Response
  - Transient
  - Steady-state

- Frequency Response
  - Nyquist/polar plot
  - Bode Diagram

- Stability Analysis
  - Poles & Zeros
  - Routh-Hurwitz Criterion
  - Nyquist Criterion

Feedback Control Design

- PID controller
  - Algorithms
  - Tuning methods

- Phase Lag/Lead controller
  - Root locus method
  - Frequency response method
Objectives

• What is a control system?
• Open-loop vs. closed-loop control
• Examples of control systems
• Control system elements, components, classifications, terminology, methodologies, mathematical models
• Model-based control system design process
• Feedback control
What is “Control”? 

• Control – to regulate, direct, command
  – Make some object (system or plant) behave as we desire

• Control is all around us:
  – Room temperature control (domestic)
  – Car/bicycle driving (human)
  – Voice volume control (electronics)
  – Cruise control or speed control (automotive)
  – Process control (industries)
What is “Feedback”?

Merriam Webster:
The return to the input of a part of the output of a machine, system, or process (as for producing changes in an electronic circuit that improve performance or in an automatic control device that provide self-corrective action) [1920]

Feedback = mutual interconnection of two (or more) systems
• System 1 affects System 2
• System 2 affects System 1
• Cause and effect is tricky, systems are mutually dependent

Feedback is ubiquitous in natural and engineered systems
Need for control systems

• Why do we need control systems?
  – **Convenience** (room temperature control, remote control, washing machine, etc.)
  – **Safety** (dangerous places, bomb removal, vehicles)
  – **Impossible for human** (nano-scale precision positioning, working in small spaces, remote)
  – **Exist in nature** (body temperature, sugar level, climate)
  – Lower **cost**, higher **efficiency** (industrial automation)

• Many examples of control systems around us…
What is a “Control System”?

System: arrangement of physical components, connected or related in such a manner to perform and/or act as an entire unit.

“Control system is an arrangement of components or elements connected or related in such a manner as to command, direct, or regulate itself or another system.”

In a control system, the output of the system is controlled to be at specific value or to change in some prescribed way as determined by the input.

In British Standard 1523, control system is defined as:

“An arrangement of elements (amplifiers, converters, human operators, etc.), interconnected and interacting in such a way as to maintain or to affect in a prescribed manner, some condition of a body, process or machine which forms part of the system.”
Control system can be \textit{simple}... but

- Consider a simple system to control the room temperature of the classroom...
  - Desired temperature/fan speed setting
  - no. of people/equipment in the room
  - Time of day
  - Insulation
- Will room temperature stay constant?
- Controller needs to be \textit{calibrated}
Control system can be complex... but

- If the actual temperature can be measured, the controller can compare with desired temperature and make necessary corrections
- This strategy is called **feedback control**
- A controller can be a human operator (**manual control**) or a device (**automatic control**)
- This strategy requires extra component – instrumentation system (sensor, transducer, signal conditioning, etc.)
## Open-loop vs. Closed-loop

**Open-loop control system**
- Simple to implement
- Good for repetitive processes such as measurement
- Affected by internal/external disturbances – *Calibration* is key
- Inherently stable

**Closed-loop control system**
- Robust – not easily affected by internal/external disturbances and uncertainty
- Higher levels of automation
- Measurement adds initial cost and complexity
- Possibility of instability
Feedforward control

Measure disturbance before it enters the system, and take corrective action before the disturbance has influenced the system.
James Watt’s Flyball Governor (1788)

- Regulate speed of steam engine
- Reduce effects of variations in load (disturbance rejection)
- Major advance of industrial revolution
Early technological examples

**Thermostat**
- Measures temperature and compare to a desired set-point
- Uses *feedback error* to turn heater on (if temperature is too low and off (if temperature is too high)
- E.g. Honeywell thermostat, 1953

**Cruise control in automobiles**
- Maintains constant vehicle speed
- E.g. Chrysler cruise control, 1958
- A centrifugal governor is used to detect the speed of the vehicle and actuate the throttle
- The reference speed is specified through adjustment spring
Modern examples of feedback control

- Power Generation & Transmission
- Aerospace & Transportation
- Materials & Processing
- Instrumentation
- Robotics & Intelligent Machines
- Network & Computing Systems
- Economics
- Feedback in Nature
Power Generation & Transmission

• Generation & distribution of electrical power – control is “mission critical”
• Many control loops in individual power stations
• Production = consumption
• Major challenges
  – power management for highly distributed system with many generators with long distances and levels
  – Unpredictable power demand
  – Synchronise generators to voltage variations in power network
  – Safety & reliability in the event of large disturbances
• “Smart Grid”
A light seeking control system

A light-seeking control system is used to track the sun. The output shaft is driven by the motor through a worm reduction gear and has a bracket attached on which two photocells are mounted.
Aerospace & Transportation

Themes
- Autonomy
- Real-time, global dynamic interconnectivity
- Ultra-reliable systems; embedded software
- Multi-disciplinary teams
- Modelling for control
  - More than just $\dot{x} = f(x, u, p, w)$
  - Analysable accurate hybrid models

Technology Areas
- Air traffic control, vehicle management
- Mission/multi-vehicle management
- Command and control, human in the loop
- Ground traffic control (air & ground)
- Automotive vehicle & engine control
- Space vehicle clusters
- Autonomous control for deep space travel
Automobile Interior Cabin Temperature Control System

Many luxury automobiles have thermostatically controlled air-conditioning systems for the comfort of the passengers. The driver sets the desired interior temperature on a dashboard panel. The actual interior cabin temperature is measured using a temperature sensor and compared with the desired interior temperature. The thermostat adjusts the air conditioning unit to let an appropriate amount cool/warm air so that the actual interior cabin temperature is equal to the desired interior temperature.
Car speed-position control system

A control system to keep a car at a given relative position offset from a lead car.

High-performance race car with adjustable wings

For a high-performance race car, it is important to maintain good road adhesion using adjustable wings (airfoil) to keep a constant road adhesion between the car’s tires and the race track surface.
An aircraft flight path control system using GPS

The role of air traffic control systems is increasing as airplane traffic increases at busy airports. Engineers are developing air traffic control systems and collision avoidance systems using the Global Positioning System (GPS) navigation satellites. GPS allows each aircraft to know its *position* in the airspace landing corridor very precisely.
Materials & Processing

Multi-scale, multi-disciplinary modelling and simulation

• Coupling between macro-scale actuation and micro-scale physics
• Models suitable for control and analysis

Increased use of in-situ measurements

• Many new sensors available that generate real-time data about microstructural properties
• Sophisticated signal processing and control
• Effective data storage

Other Challenges

• Environmental safety & control
• Increasing energy costs
• Highly integrated and complex processes
A human operator controlled valve system

A manual control system for regulating the level or flow of fluid in a tank by adjusting the output value. The operator views the level or flow of fluid through a meter in the side of the tank.
A chemical composition control system

In a chemical process control system, it is valuable to control the chemical composition of the product. To do so, a measurement of the composition can be obtained by using an infrared stream analyser. The valve on the additive stream may be controlled.
CNC machine position control system

Increasingly stringent requirements of modern, high-precision machinery are placing increasing demands on slide systems. The typical goal is to accurately control the desired path.
Two-input water temperature control system

A common example of a two-input control system is a home shower with separate valves for hot and cold water. The objective is to obtain (1) a desired temperature of the shower water and (2) a desired flow of water.
Information & Networks

Pervasive, ubiquitous, convergent networking
• Heterogeneous networks merging communications, computing, transportation, finance, utilities, manufacturing, health, consumer, entertainment…
• Robustness/reliability are the dominant challenges
• Need “unified field theory” of communications, computing, and control

Many applications
• Congestion of control on the internet
• Power and transportation systems
• Financial and economic systems
• Quantum networks and computation
• Biological regulatory networks and evolution
• Ecosystems and global challenge

Control of the network
Control over the network
Robotics & Intelligent Machines

Wiener, 1948, Cybernetics
• Goal: implement systems capable of exhibiting highly flexible or “intelligent” responses to changing circumstances

DARPA, 2003-2007: Grand Challenge
• Goal: build vehicles that autonomously drive themselves in desert and urban environments

Sony AIBO  Exploratory rover  Soccer robot
System biology
• Many molecular mechanisms for biological organisms are characterised
• Missing piece: understanding of how network interconnection creates a robust behaviour from uncertain components in an uncertain environment
• Transition from organisms as genes, to organisms as networks of integrated chemical, electrical, fluid, and structural elements

Key features of biological systems
• Integrated control, communications, computing
• Reconfigurable, distributed control, built at molecular level

Design and analysis of biological systems
• Apply engineering principles to biological systems
• Systems level analysis is required
• Processing and flow information is key
Control = Sensing + Computation + Actuation

Goals

- **Stability**: system maintains desired operating point (hold steady speed)
- **Performance**: system response rapidly to changes (accelerate to 6 m/s)
- **Robustness**: system tolerates perturbations in dynamics (mass, drag, etc.)
The driver uses the difference between the actual and the desired *direction* of travel to generate a controlled adjustment of steering wheel.
Instrumentation

• Measurement as a closed-loop process – accuracy and robustness
• Accelerometer
  – Force feedback (haptic technology)
  – Smart phones & video games
• Hodgkin & Huxley’s *voltage clamp* won 1963 Nobel Prize in Medicine
• Neher & Sakmann’s *patch clamp* won 1991 Nobel Prize in Medicine
• Mass spectrometer
• van der Meer’s *particle accelerator* that won 1984 Nobel Prize in Physics allowed successful experiments at CERN
• Binnig & Rohrer’s *scanning tunneling microscope* won 1986 Nobel Prize in Physics

Voltage clamp method for measuring ion currents in cells using feedback
Elements of a control system

- **Process**: Output is to be controlled. Dynamic behaviour must be understood.
- **Controller**: Compares reference with actual value, produces control signal, e.g., brain, PID controller, computers.
- **Measurement**: Instrumentation system; sensors, transducers, signal conditioning, display units, recording, indicating devices.
- **Actuator**: Amplifies (corrects) control signal from controller, e.g., regulating units, relays, valves, servos, motors, drivers, muscles.
Control System Components

**Process**  Physical system, actuation, sensing
**Controller**  Microprocessor plus conversion hardware (single chip)
**Feedback**  Interconnection between plant output, controller input
Control System Terminology

Control

Manipulated Variables

Process

Disturbance

Controlled Variable

Evaluate

Control Signal

Set Point

Controlled Variable

Measure

Measured Variables

Noise

Input
## Control System Terminology

### Systems & Elements

- **Process:** *plant*
- **Measurement:** *transducer, transmitter, sensor*
- **Evaluation/comparison:** *controller*
- **Control/correction/final control:** *actuator, valve*

### Signals & Variables

- **Process/Controlled variables**
- **Measured variables**
- **Control signal**
- **Set-point signal**
- **Error / Actuating signal**
- **Correction signal**
- **Manipulated variables**
Control System Terminology

<table>
<thead>
<tr>
<th>Terms</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-point</td>
<td>$r$</td>
<td>The desired/reference value for a controlled variable in a process control loop</td>
</tr>
<tr>
<td>Error signal</td>
<td>$e$</td>
<td>The difference in value between the measured signal and the set-point</td>
</tr>
<tr>
<td>Control signal</td>
<td>$u$</td>
<td>The output signal from a controller to the control element</td>
</tr>
<tr>
<td>Manipulated variable</td>
<td>$m$</td>
<td>The variable controlled by an actuator to correct for changes in measured variable</td>
</tr>
<tr>
<td>Controlled variable</td>
<td>$c$</td>
<td>The variable measured to indicate the condition of the process output</td>
</tr>
<tr>
<td>Measured value</td>
<td>$b$</td>
<td>The output signal of measurement system</td>
</tr>
</tbody>
</table>
Multi-loop feedback control system

Multi-variable feedback control system
Process Control and Servo Systems

**Difference**

The emphasis in process control is on the performance of the loop as a *Regulator*, i.e. disturbance rejection.

In servo systems, the emphasis is on how well the control system can follow changes in the reference or desired input signals.
Control Systems
Classification

A control system may be classified in terms of the control strategy employed, the control objective, the component used, or the control application.

Control strategy employed may be open-loop or closed-loop (feedback)

The objective of the control may be to regulate (maintain) and/or to follow pre-defined path/value

Control systems are applied in industrial processes (process control) and robotics (motion control)

A control system may consist of analogue and/or digital components
Active Control Methodologies

Black box methods

Basic idea: learn by observation or training
Examples: auto-tuning regulators, adaptive neural networks, fuzzy logic

No need for complex modelling or detailed understanding of physics
Works well for controller replacing human experts

No formal tools for investigating robustness and performance
Don’t work well for high performance systems with complicated dynamics

Model-based methods

Use a detailed model (PDEs, ODEs) for analysis and design
Examples: optimal regulators, $H_\infty$ control, feedback linearisation

Works well for highly coupled, multivariable systems
Rigorous tools for investigating robustness and performance (using models)

Tools available only for restricted class of systems (e.g. linear, time-invariant)
Requires control-oriented physical models; not always easy to obtain
Model-based control system design

Commissioning & Operation

Controller → Actuator → Plant

System

Sensor

Digital & Analogue

Implementation

Control Algorithm

Classical & Modern design techniques

Design

System Model

Modelling

Theory & Experiment

Transient, steady-state, stability, robustness performance

Analysis
Control System Models

Differential equations
- $t$-domain

Transfer function
- $s$-domain
- $z$-domain

Difference equation
- $kT$-domain

State-space model
- $z$-domain
- $t$-domain
- $s$-domain
Block diagram terminology

Summing point

Input Signal

System

Take-off point

Output Signal

Input Signal

Signals cannot join without a block

Multiple I/O signals represented by thick lines

A block can only have single I/O
System Response

**Time-domain analysis**
- Transient response
  - First-order response
  - Second-order responses
  - Higher-order responses
- Steady-state error
  - Final value theorem
  - Error constants

**Frequency-domain analysis**
- Stability criterion
  - Routh-Hurwitz
  - Nyquist
  - Gain & Phase margins
- Bode diagrams
  - Relations & Minimum Phase Systems
  - Gain & Phase
Feedback Control

Feedback system analysis
- Robustness (Sensitivity & disturbance rejection)
- Dynamic response
- Steady-state response

On off control
- Dead-zone
- Hysteresis

PID control
- Algorithms (ideal, parallel, velocity feedback)
- Implementations (electronic, digital, pneumatic, etc.)
- Tuning methods
PID Control: Introduction

Three-term controller
• Present: feedback proportional to current error
• Past: feedback proportional to integral or past error
  – Ensures that error eventually goes to 0
  – Automatically adjusts setpoint of input
• Future: derivative of the error
  – Anticipates where we are going

PID facts
• Wide-range of control applications
• More than 95% are PID controllers

PID designs
• Choose gains Kp, Ki, Kd to obtain the desired behaviour
• Stability: solutions of the closed-loop dynamics should converge to
• Performance: output system $y$ should track reference $r$
• Robustness: stability & performance properties should hold in face of disturbances and plant uncertainty

\[ u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \]
Summary

• What is a control system?
• Open-loop vs. closed-loop control
• Examples of control systems
• Control system elements, components, classifications, terminology, methodologies, mathematical models
• Model-based control system design process
• Feedback control