Control System Design ME155A

Lecture 1 - Introduction to Automatic Control

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1. Practical Information about the Course
2. Introduction to Automatic Control
3. Example of Control Systems
4. Feedback
5. Summary

Theme: What is control? Why should an ME know about it? Open and closed loop systems? Feedback and feedforward. Block diagrams.

1. Practical Information

- Lectures Tue, Th 12.30-1.45 2361 Engineering II
- Lecture notes, homeworks, and solutions on Home page
- Computer tools Matlab with control system tool box
- Office hours: Tuesday 1.45-2.45, Thursday 10.30-11.30
- Teaching assistant: Niklas Karlsson 2235A Engineering II
  - Office hours: Monday 10.00-11.00, Tuesday 9.00-10.00,
- Midterm: Tentatively Nov 2nd
- Final: Dec 8 12.00-3 pm
- Grade: 30% HW, 30% MT and 40% final
- Feedback: astrom@engineering.ucsb.edu, 2324 Eng II

Goals of the Course

- Understand why automatic control is useful for a mechanical engineer
- Recognize the value of integrated control and process design
- Recognize when a process is easy or difficult to control
- Know key ideas and concepts

  Dynamics and feedback
- Know relevant mathematical theory
- Be able to solve simple control problems
- Recognize difficult problems
- Be aware of computational tools

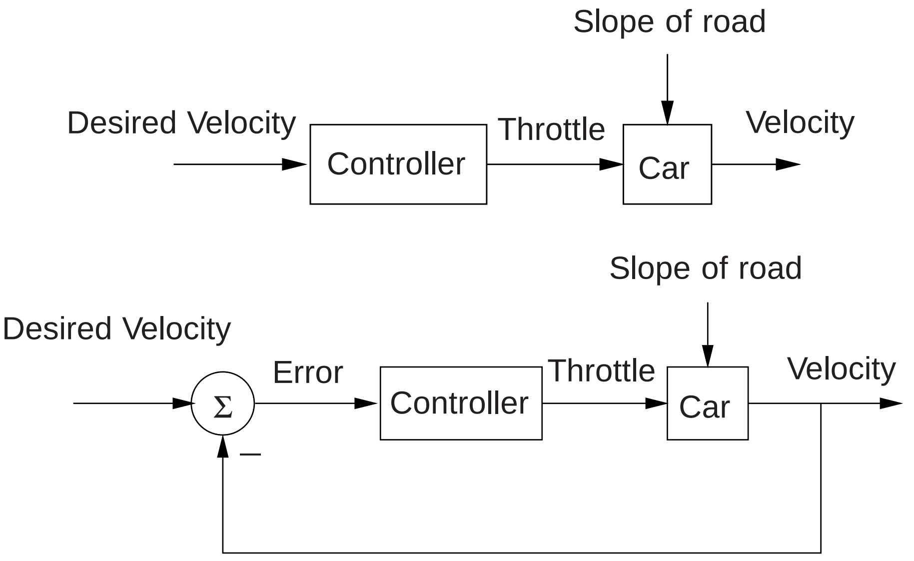
2. An Introduction to Automatic Control

- The discipline of control
- A brief history
- How Control emerged?
- Consequences
- Automation levels
- Applications
- Summary

The Discipline of Control

- Kybernetes, Greek word for navigator, steers-man, related to the Latin gubernator (governor). In "The Republic", by Plato (428-347 BC) steering a ship was compared to steering a community. Aristotle used kybernetike to refer to steering a community.
- A. M. Ampere, "Essai sur la philosophie des science" (Paris, Bachelier, 1838): The science of government should be called "la cybernétique".
- N. Wiener 1945 Cybernetics or control and communication in the animal and the machine. MIT Press 1948
- H. S. Tsien Engineering Cybernetics, 1954
- In the engineering community in the West cybernetics was gradually replaced by control.

Open and Closed Loop Cruise Systems



The Idea of Feedback

- Compare the actual result with the desired result.
- Take actions based on the difference.
- This seemingly simple idea is tremendously powerful.
- Feedback is a key idea in the discipline of control.

A Brief History

- The roots (before 1940!)
  - Early use of feedback in windmills, steam engines, engines, ships, airplanes, process control, telecommunication
- The field emerges (1940-1945)
  - The Second World War
  - Spread like wildfire: education, industry, organization
- The second wave (1960-)
  - Demanding applications: Space, process industry
  - New components: digital computers

How to make an Airplane

Lecture by Wilbur Wright 1901:

Men know how to construct airplanes.
Men also know how to build engines.
Inability to *balance and steer* still confronts
students of the flying problem.
When this one feature has been worked out,
the age of flying will have arrived, for
all other difficulties are of minor importance.

The Wright Brothers figured it out and flew the Kitty Hawk on December 17 1903!

The Feedback Amplifier

The feedback amplifier was invented by Harold Black in 1927. The patent procedure took 9 years because engineers did not believe that it would work. Black got a major IEEE medal in 1957, on this occasion it was said that:

It is no exaggeration to say that
without Black's invention (of the feedback amplifier),
the present long-distance telephone and television networks
which cover our entire country
and the transoceanic telephone cables
would not exist.

Feedback plays a major role in the Internet and in cellular communication.

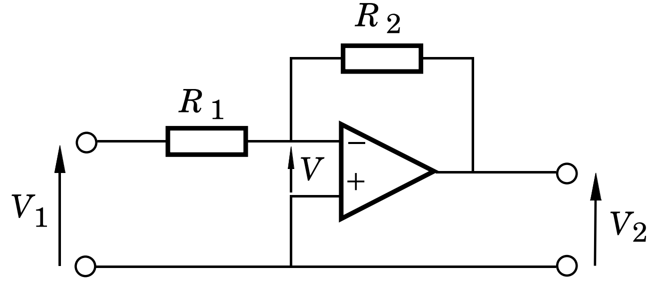
The Feedback Amplifier: Black 1934

However, by building an amplifier whose gain is deliberately made, say 40 decibels higher than necessary and then feeding the output back on the input in such a way as to throw away the excess gain, it had been found possible to effect extraordinary improvement in constancy of amplification and freedom from non-linearity.

Stabilized feedback processes other advantages including reduced delay and delay distortion, reduced noise disturbance from the power supply circuits and various other features best appreciated by practical designers of amplifiers.

Gain is the "hard-currency" that can be traded for many other qualities! The operational amplifier.

The Feedback Amplifier



Let the raw gain of the amplifier be A, i.e. $V_2 = -AV$, then

$$G = \frac{V_2}{V_1} = -\frac{R_2}{R_1}\frac{1}{1+\frac{1}{A}\left(1+\frac{R_2}{R_1}\right)}, \qquad \frac{dG}{G} \approx \frac{R_1}{AR_2}\frac{dA}{A}$$

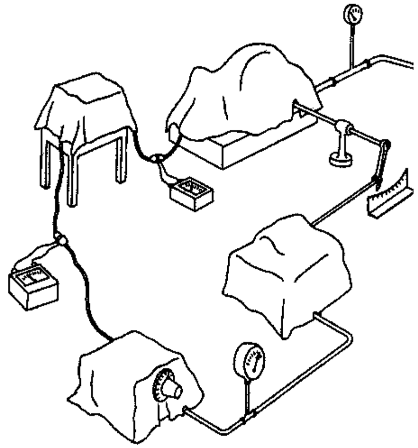
Notice that the gain is determined by the passive components! Example $A = 10^5$, $R_2/R_1 = 100$.

How the Field Emerged

- Feedback was invented patented and used in a wide range of fields, often with revolutionary consequences
- It was not realized that very different technical problems were indeed very similar and that they could be approached with the same methods
- Concepts and theory were lacking
- The pieces fell in place when persons from different backgrounds were brought together in the war effort
- The beginning of “systems thinking”
- Why did it take so long?

Block Diagrams - A Real Break Through

- Capture the essence
- Standard “drawing”
- Abstraction
- Information hiding
- Also some limitations



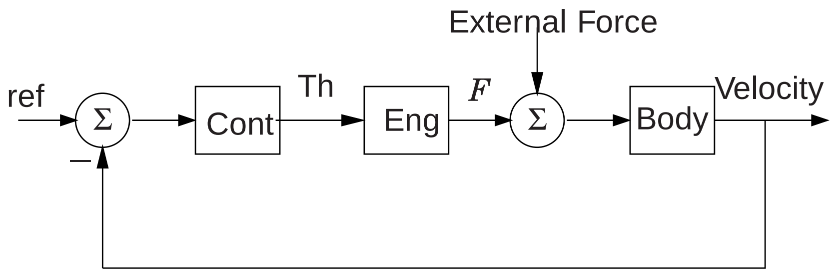
Block diagrams made it possible to see the similarity between different types of control systems.

Stop and Think!!

Try to sketch a block diagram of cruise control for a car. Make small groups and discuss!

The Audience is Thinking ...

Block Diagram of Cruise Control



Modeling

- Understand how the system works!
- What are the important signals?
- Where is the essential dynamics

Consequences

- Education: Courses in automatic control spread like wildfire and became an important part of the education of all engineers
- Applications: The ideas were used in a wide range of fields often with drastic consequences. Lots of technology transfer.
- Industrialization: Formation of new companies
- Organizations:
  - IFAC International Federation of Automatic Control
  - ASME
  - ACC American Control Council
- Information dissemination : conferences, journals, books

Engineering Education

- Traditional Division: CE, ME, EE, ..
  - Traditional
  - Reflects 19th century industry
  - Todays problems are different: Systems and materials
- Automatic control - the first systems discipline
- Many activities across departments at UCSB
- Why should a mechanical engineer know control?
  - Feedback is ubiquitous (appears everywhere)
  - Feedback gives designers extra freedom
  - Codesign of systems and control increasingly important
  - Concepts and tools have wide applicability

Automatic Control

- Understanding feedback systems (cybernetics) and dynamics
- Feedback gives designers extra freedom
- Use of feedback often revolutionary
- General methods and theories
  - \+ Problems from different domains are similar if viewed in the right way
  - \+ Large application areas
  - \+ Technology transfer
  - \+ Business opportunities
  - \- Abstract (Easy to use your foothold)
- Static and dynamic systems

3. Where Control is Used

- Generation of energy
- Transmission of energy
- Communication
- Transportation
  - Cars
  - Trains
  - Ships
  - Aircrafts
  - Space-crafts
- Industrial processes
- Discrete manufacturing
- Mechatronics
- Instrumentation
- Consumer electronics
- Scientific instruments
- Economy
- Biology
- Medicine

How Control is Used

- Control a given process (add on)
- Codesign process and control

  Systems are frequently designed based on steady state considerations. Problems often occur in operation.

  Example Rear Wheel Steering.

  Essential to consider control up front in the design process.

  New freedom for the designer to solve design conflicts

  New functionality
- Control systems are becoming mission critical

  Space vehicles, flight control systems, CD players, optical memories, automotive

Two Ways to Build an Accelerometer

$$m\frac{d^2x}{dt^2} + d\frac{dx}{dt} + kx = ma$$

Gain $g = m/k$

Bandwidth $w = \sqrt{\frac{k}{m}} = \frac{1}{\sqrt{g}}$

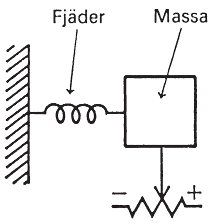
Difficult compromise to get high gain and high bandwidth $\omega^2 k = 1$!

Feedback resolves the compromise! Force Balance!

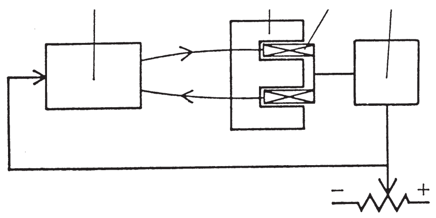
Sensitive components:

- Spring
- Current measurement

Open loop system



Closed loop system

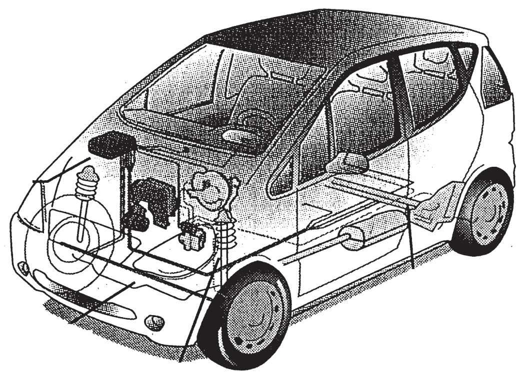


The California Emission Standard

William E. Powers VP of Ford at the 1999 World Congress of IFAC:

The automobiles of the 1990s are
at least 10 times cleaner
and twice as fuel efficient
as the vehicles of the 1970s.
These advancements were due in large part to
distributed microprocessor-based control systems.
Furthermore the resultant vehicles are
safer, more comfortable and more maneuverable.

The Mercedes A-class



A difficult situation rescued by control!

Summary

- A well developed discipline with strong concepts, rich theory and effective design methods
- Methodology for control system design
  - Modeling
  - Analysis and simulation
  - Design
  - Implementation
  - Commissioning and operation
- Control systems are ubiquitous
- Control systems are increasingly mission critical
- Use of feedback has often been revolutionary

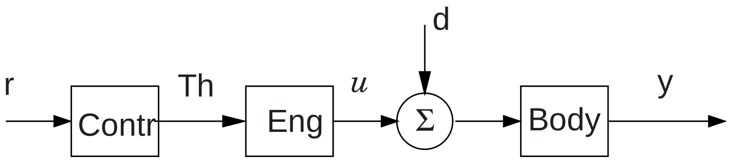
4. Feedback

Recall definition of feedback: *Compare the actual result with the desired result. Take actions based on the difference.*

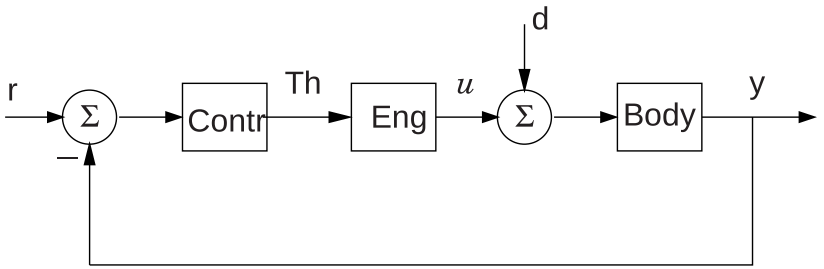
- A closer look at properties of feedback systems.
- Comparison of feedback systems and open loop systems.
- Some common forms of feedback
- PID control.

Open and Closed Loop Cruise Control

Open loop:



Closed loop:



Comparison of Open and Closed Loop Control

A very simplistic analysis based on *static* models

Process Model:

$$y = k_p u + k_p d$$

Open Loop Control: $u = k_c y_r$

$$y = k_p k_c y_r + k_p d$$

Closed Loop Control: $u = k_c(y_r - y)$

$$y = \frac{k_p k_c}{1 + k_p k_c} y_r + \frac{1}{1 + k_p k_c} k_p d$$

This simple analysis gives useful insight but it is important to also consider *dynamics*.

Feedback and Feedforward

- Feedback
- Closed loop
- Market Driven
- Acts only when there are deviations
- Robust to model errors $|S| < 1$ for some ω
- Risk for instability

- Feedforward
- Open loop
- Planning
- Acts before deviations show up
- Not robust to model errors $|S| = 1$ for all ω
- No risk for instability

Properties of Feedback

\+ Reduce effects of process disturbances

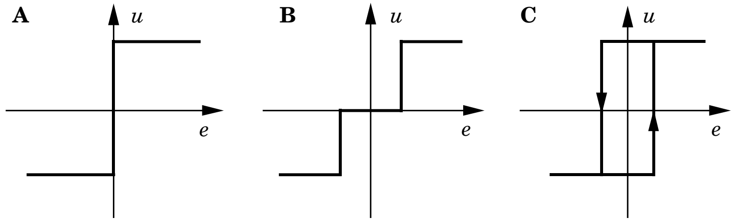
\+ Makes system insensitive to process variations

\+ Stabilize an unstable system

\+ Create well defined relations between output and reference

\- Risk for instability

On-off and Proportional Control



On-off control (Thermostat):

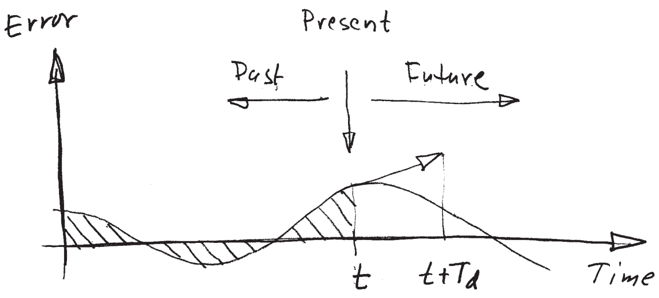
$$u = \begin{cases} u_{\max}\,, \text{if } e > 0 \\ u_{\min}\,, \text{if } e < 0 \end{cases}$$

Proportional control

$$u = u_b + ke$$

PID Control

- On-off control: A thermostat
- Proportional Control (P): $u = ke$
- Proportional and integral control (PI): $u = ke + k_i \int_0^t e(\tau)d\tau$
- PID control: $u = ke + k_i \int_0^t e(\tau)d\tau + k_d \dfrac{de}{dt}$



The Amazing Property of Integral Action

Consider a PI controller

$$u = ke + k_i \int_0^t e(\tau) d\tau$$

Assume that there is an equilibrium with constant $e(t) = e_0$ and constant $u(t) = u_0$. Then we must have $e_0 = 0$.

Can you explain this?

The Audience is Thinking ...

The Amazing Property of Integral Action ...

Consider a PI controller

$$u = ke + k_i \int_0^t e(\tau) d\tau$$

Assume that there is an equilibrium with constant $e(t) - e_0$ and constant $u(t) = u_0$. Then we must have $e_0 = 0$.

Assume $e_0 \neq 0$, then

$$u = ke_0 + k_i \int_0^t e(\tau) d\tau = ke_0 + k_i \int_0^t e_0 d\tau = ke_0 + k_i e_0 t$$

The right hand side is different from zero. Hence a contradiction unless $e_0 = 0$.

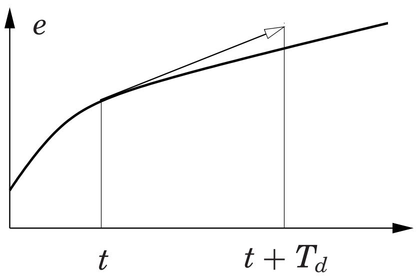
This fact was rediscovered and patented many times in different applications!

Derivative Action as Prediction

Replace the error in proportional control with the predicted error

$$e_p(t) = e(t) + T_d \frac{de(t)}{dt}$$

Prediction by linear extrapolation!



More sophisticated controllers predicts using mathematical model of the process.

5. Summary

- What is control?
- How did the discipline emerge?
- Why is it useful for a Mechanical Engineer?
- The idea of Block Diagram
- Feedback and feedforward
- On-off and PID Control (past, present and future)

Next Time
Cruise Control - Our first Control Design