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Control System Synthesis - Introduction

PHD CLASS - FALL 2020

Content overview

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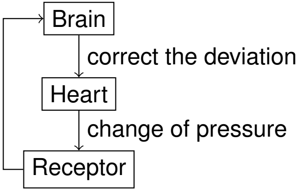
Brief history and motivations

1. Bennett, S. (1996). *A brief history of automatic control.* IEEE Control Systems Magazine
2. Bissell, C. (2009). *A history of automatic control.* In Springer handbook of automation
3. Åström, K. J., and Kumar, P. R. (2014). *Control: A perspective.* Automatica

It all starts with feedback: interaction between different systems
⟶ Necessity to study the system as a whole

- Feedback in nature
  (response to stress, regulation of blood pressure) and economical systems (offer and demand)



Homeostasis principle

Brief history and motivations

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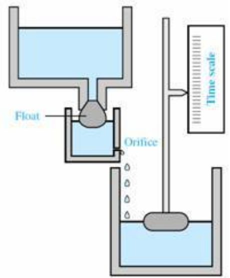
It all starts with feedback: interaction between different systems

⟶ Necessity to study the system as a whole

- Feedback in nature
- Also used for more than 2000 years: feedback mechanism to control water clocks (Ktesibios, 285–222 BC)



Brief history and motivations

- Nowadays, control is everywhere! (homes, cars, telecommunication, aeronautics, aerospace, process control, power grid, ...)
- The development of control as the modern field we know reflects the growth of our technological society
- In [1], four eras are considered:
  - Before 1940: “Tasting the Power of Feedback Control",
  - 1940–1960: “The Field Emerges",
  - 1960–2000: “The Golden Age",
  - After 2000: “Systems of the Future".

Brief history and motivations

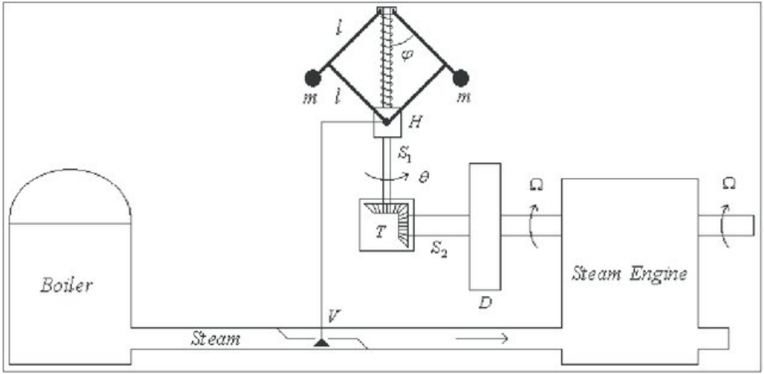
“Tasting the Power of Feedback Control"

www.control.lth.se

Brief history and motivations
“Tasting the Power of Feedback Control"

The centrifugal governor

→ Used to maintain a constant speed in steam engines



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Flight control

- compromise between stability and maneuverability

$\longrightarrow$ the Wright Flyer was unstable, the pilot had to maintain the plane stable

- motivation that led to the development of the autopilot, based on the feedback concept
- feedback can be used to stabilize an unstable system
- Modern fighter airplanes are also unstable in certain flight regimes, such as take-off and landing

Brief history and motivations

Before 1940: "Tasting the Power of Feedback Control"

- Major development of control coincided with the industrial revolution because of the advantages of feedback control:
- Applications: centrifugal governors, autopilots for ships and aircrafts, process control
- Controllers were based on mechanical, hydraulic, pneumatic and electric technologies

$\longrightarrow$ These components were exploring proportional, integral and derivative actions without understanding the similarities between the different fields

- Electronic analog computing was emerging and used to simulate control systems
- Feedback control can also create instabilities $\longrightarrow$ Routh–Hurwitz stability criterion, Nyquist criteria

Brief history and motivations

Properties of feedback

- Performance: correcting action according to the difference between the desired behaviour and the actual one
- Robustness to uncertainty (disturbances or process variations)
- Stabilization and/or shaping a desired dynamics
- Modularity

Brief history and motivations

Properties of feedback

- Performance: correcting action according to the difference between the desired behaviour and the actual one
- Robustness to uncertainty (disturbances or process variations)
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- Modularity

Challenges:

- Possibility of instability
- Obtain a stable controlled system even under perturbations
- Measurement noise
- Implementation complexity

Brief history and motivations

1940–1960: “The Field Emerges"

- Intensive military research during WWII (fire-control systems, autopilots for ships, airplanes, and torpedoes)
- Recognition of a common foundation for all control problems
- Development of servomechanism theory: block diagrams, transfer functions, frequency response, analog computing, stochastic processes and sampling, exploring mathematical knowledge on linear systems, complex variables, and Laplace transforms.
- Many tools were developed
  - modeling from data, based on the frequency response
  - graphical design and analysis techniques (Bode and Nyquist)
- Analog computing was used both for implementation and for simulation
- Well established field by 1960

Brief history and motivations

1960–2000: "The Golden Age"

- Space race and use of digital computers
- Development of control theory ahead of the implementation and technology
  - State-space representations (Kalman, used for estimation, filtering and LQ design)
  - Lyapunov theory on stability of differential equations
  - approach based on functional analysis (small gain theorem, passivity theorem).
  - optimal control theory (Pontryargin)
  - dynamic programming (Bellman, foundation of adaptive control)
  - development of system identification
  - robust control theory

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Brief history and motivations

After 2000: “Systems of the Future"

- Efficient and low-cost computational power
- New applications: large scale networks (smart power grids, traffic control), autonomous cars
- Systems of increasing complexity (transport of goods and information)
- Closer interaction between control, computing and communication
- More and more data available
- Hybrid systems
- Many applications in medicine and biology

Brief history and motivations

Control is a rich field

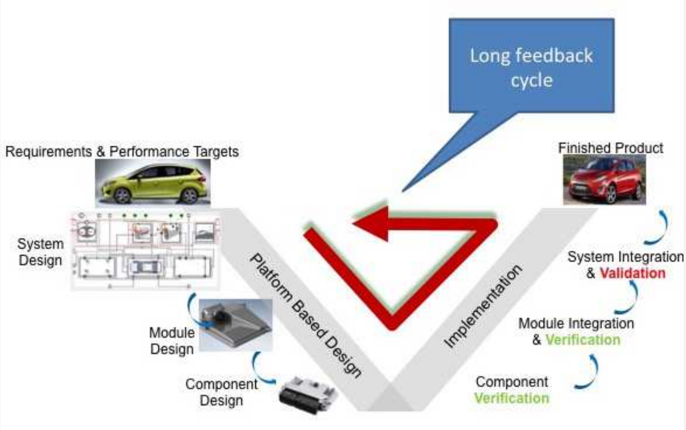
- Wide range of applications
  - Power systems
  - Aero
  - Process industry
  - Instrumentation
  - Robotic and autonomous systems
  - Networks
- Numerous design techniques and tools
- Control is inherently multidisciplinary
  - Sensors and actuators linked through a communication network
  - Controllers are implemented using digital computers
    $\longrightarrow$ need for real-time computing knowledge
  - Design and/or analysis of control systems requires knowledge about the controlled process
    $\longrightarrow$ modelling, system identification, ...

Brief history and motivations

Why should you study control?

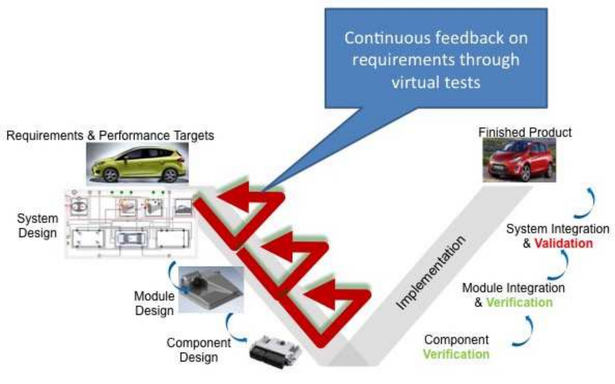
- Control is an essential element in countless engineering systems and cross the traditional academic boundaries
- No need to be an expert to avoid poor performances
- Possibility to gain some degrees of freedom
- Nice theory and applications

Model Based Design 1 - Open Loop



Final test comes late

Model Based Design 2 - Closed loop



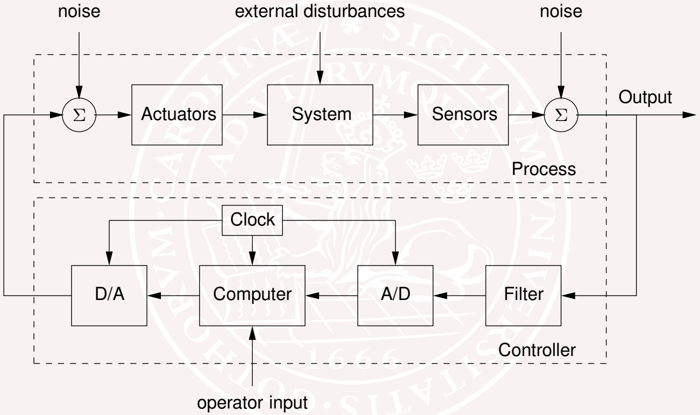
Models are uses as virtual systems SIL & HIL
Errors caught early, very useful when changes are made.

Brief history and motivations

The big picture

Class overview

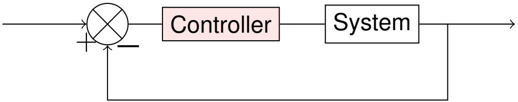
Implementation - Computer Control



Sense, reflect (compute) and act

The big picture

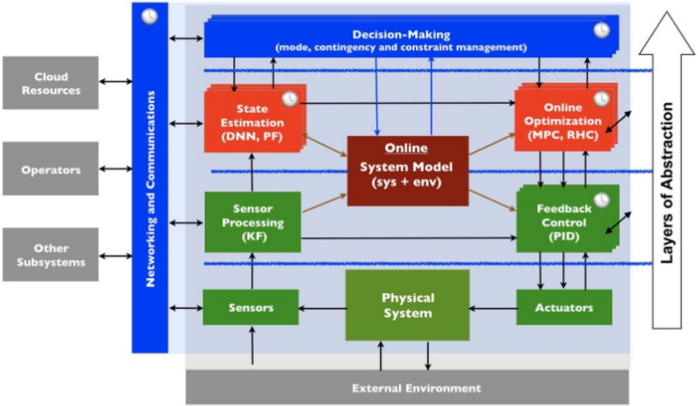
A basic control scheme



- Very different from the real implementation!
- Continuous vs Discrete time:
  - discretization issues, beware of computing time!
  - continuous design techniques have a sampled counterpart
  - continuous equations are usually simpler

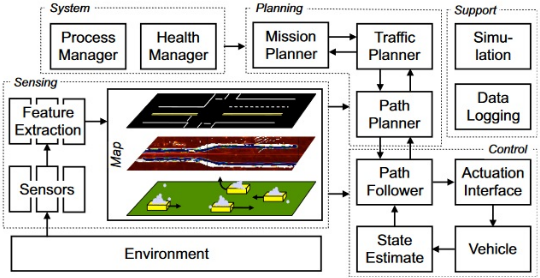
The big picture
Different architectures, different levels of abstraction

Top-down architecture



The big picture
Different architectures, different levels of abstraction

Top-down architecture



The big picture

Different architectures, different levels of abstraction

Bottom-up architecture

- building complex systems from standard parts
- interconnecting low-level control systems to design controllers
- What happens when different loops are interconnected?

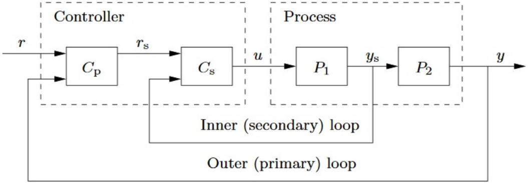


Figure: Cascade control (multi-sensors)

The big picture
Different architectures, different levels of abstraction

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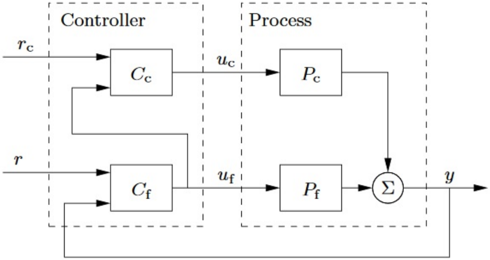


Figure: Mid-range control (multi-actuators)

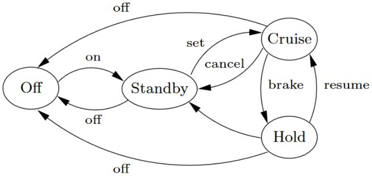
The big picture
Combination of feedback and logic

- Different operating conditions

→ manual interaction, equipment protection, saturating actuators

Cruise control

(a) User interface



(b) State machine

Class overview

The big steps:

1. Define the requirements and the performance objectives
2. Control design and analysis
3. Implementation $\longrightarrow$ not treated here

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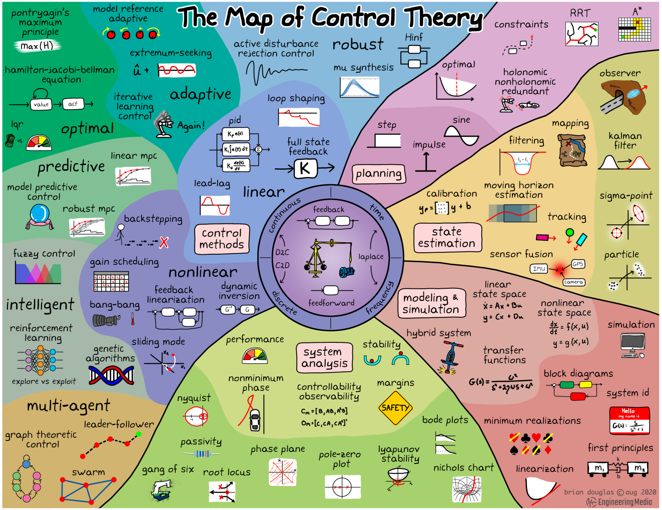
Class overview



made by Brian Douglas (https://engineeringmedia.com/)

Class overview

In this class:

→ information on the process? type of model if any?
Do not take the model for granted!!

→ how to express the specifications? what are the performance limitations? how to formulate a control problem?

→ which design technique ?
Design always involves many criteria, trade-offs and compromises

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Class overview

1. Introduction
2. Fundamentals: problem formulation
   1. System representation and feedback basics
   2. Specifications and performance limitations
3. Design techniques
   1. PID control
   2. LQG
   3. Hinf
   4. Model Predictive Control (MPC)
   5. Adaptive Control
   6. Data-driven Control

Class overview

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   4. Model Predictive Control (MPC)
   5. Adaptive Control + exercise session 3
   6. Data-driven Control
4. Presentations and concluding remarks

Class overview

About the presentations

- Groups of 1-2 people, 15-20 minutes
- Topics to be defined by mid-October
- List of possible topics:
  - Other control techniques or tools
  - An interesting control application
  - Any suggestion is welcome