Control Theory SC42015

Lecturer: Tamás Keviczky

Teaching Assistants: Daniel Jarne Ornia,
Steven Adams, Frederik Mathiesen

Offices: C-3-310, C-2-310, C-3-230, C-3-260
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Delft Center for Systems and Control (DCSC)
Delft University of Technology
The Netherlands

Comments

- Control Theory (SC42015, 6 EC)

  For those who specialize in control. In depth course with proofs.

  Requires solid background in classical control (e.g. Bachelor 3mE).

  Is **obligatory** for MSc programme **Systems and Control**.

- Control System Design (SC42001, 5 EC)

  Emphasizes broader concepts of control. More application-oriented.

  For students without in-depth knowledge of classical control and without the intention to specialize in control in later studies.

Schedule

- Mondays, 13:45-15:30, 3mE-CZ A/D
  Tuesdays, 10:45-12:30, 3mE-CZ B/C
  Thursdays, 10:45-12:30, Pulse 6/10
- Exception: Oct 7 (mid-term exam)
- Mid-Term Exam, Thursday, October 7, 10:45 - 12:30, on-campus (online via Ans as backup)
- Final Exam, Thursday, November 5, 9:00-12:00, on-campus (online via Ans as backup)
- Changes, deviations from this schedule or information will be posted on Brightspace!
- Please follow the announcements posted on Brightspace about the course!

Schedule

Schedule Control Theory (SC42015) - Fall 2021 — **Version 31-08-2021**

Date			Time	Room	Lecture (nr)	Subject	Material (Friedland)	Material (Åström & Murray)
mon	tue	thu						
6/9			13:45	3mE CZ-A/D	1	Introduction to control; Introduction to dynamical systems	1; 2.1-2.4	1; 2.1-2.3, 4.1-4.2, 5.4
	7/9		10:45	3mE CZ-B/C	2			
		9/9	10:45	Pulse 6/10		Instruction/exercise session 0 & 1		
13/9			13:45	3mE CZ-A/D	3	Solutions of linear systems	3.1-3.6	4.3-4.4, 5.1-5.3, 8.1-8.3
	14/9		10:45	3mE CZ-B/C	4			
		16/9	10:45	Pulse 6/10		Instruction/exercise session 2		
20/9			13:45	3mE CZ-A/D	5			
	21/9		10:45	3mE CZ-B/C	6	Controllability and stabilizability	5.1-5.4, 6.1-6.3, 6.5	6.1-6.3
		23/9	10:45	Pulse 6/10		Instruction/exercise session 3		
27/9			13:45	3mE CZ-A/D	7			
	28/9		10:45	3mE CZ-B/C	8			
		30/9	10:45	Pulse 6/10		Instruction/exercise session 4		
4/10			13:45	3mE CZ-A/D	9	LQ optimal control	9.1-9.5	4.4, 6.4
	5/10		10:45	3mE CZ-B/C	10			
		07/10	10:45	on-campus OR online		Mid-term exam	Material: Lectures 1-8	until but not including LQ control
11/10			13:45	3mE CZ-A/D	11	Observability, separation, realizations	7.1-7.3	7.1-7.3, 7.5, 8.1-8.3
	12/10		10:45	3mE CZ-B/C	12			
		14/10	10:45	Pulse 6/10		Instruction/exercise session 5		
18/10			13:45	3mE CZ-A/D	13	Tracking and disturbance rejection	5.5, 6.4, 7.4, 8.5, 9.6	3 (examples), 6.4
	19/10		10:45	3mE CZ-B/C	14			
		21/10	10:45	Pulse 6/10		Instruction/exercise session 6		
05/Nov/21			9:00-12:00	on-campus OR online		Final written examination		
20/Jan/22			13:30-16:30	on-campus OR online		Resit written examination		

room numbers of instructors: **C-2-310 (Daniel Jarne Ornia), C-3-230 (Steven Adams), C-3-260 (Frederik Mathiesen),**

Examination and Exercise Sessions

We have scheduled a written mid-term exam (15% of total mark, 1.5 hours) and a written final exam (85% of total mark, 3 hours). A written resit exam (100%, 3 hours) is planned after the second quarter (January 20, 2022).

You will have the opportunity to train whether you have reached the study goals on the basis of several sets of exercises that are posted on Brightspace. *Hand-written* solutions of the worked out sets should be handed in via Brightspace before every Thursday 8:00 on the week indicated by the deadline.

If you do not work out all exercise sets and hand them in before the deadlines, you cannot participate in the mid-term exam.

Examination and Exercise Sessions (cont'd)

Questions arising while solving these sets can be discussed during the exercise sessions (bring a copy of your solutions and those posted online!). Worked out sets will not be graded, but can be picked randomly for discussion. We will also solve some extra exercises during these sessions, which are not in the posted sets.

It will not make sense to just look at the solutions. If you do not try to solve them yourself, you will most probably not pass the exams!

Your questions will only be answered during the exercise sessions and the online office hours. You can also post questions in the Brightspace discussion forum. There is plenty of opportunity - use it when available.

In particular we do not answer technical questions by email. Not even last minute question before the exam!

Material

- [F] B. Friedland, Control System Design: An Introduction to State-space Methods. Dover Publications, 2005

- [AM] K.J. Aström, R.M. Murray, Feedback Systems: An Introduction for Scientists and Engineers, Princeton University Press, Princeton and Oxford, 2009 (available online for free with Wiki, see link on Brightspace.)

- Lecture Slides

This and only this material (without personal calculator) can be used during the exams!

Expected Background

Although we provide a brief introduction to some fundamental concepts in systems and control, you need to have followed a solid course on classical control (such as the one in the Bachelor's program of 3mE).

Mathematically we touch upon these fields:

- Linear algebra (basic aspects up to Jordan canonical form)
- Calculus (Smoothness, Jacobian, Gradient)
- Differential equations (Existence, Uniqueness, Laplace)

Since linear algebra will play a major role in this course we will provide a list of the most relevant topics with pointers to the book

> David C. Lay, Linear Algebra and its Applications, Addison Wesley, Third Edition , 2006.

See also the appendix of [F] for a good brief recap of the essential issues.

Expected Background (cont'd)

In addition, some students might find it useful to look at the Lectures 3-10, 14, 21, 22, 25, 29 of Prof. Gilbert Strang at MIT as a refresher of linear algebra basics, and how to solve them efficiently by pen and paper:

http://ocw.mit.edu/courses/mathematics/18-06-linear-algebra-spring-2010/video-lectures/

A Very Very Brief View on Control

- Feedback
- Control
- Examples

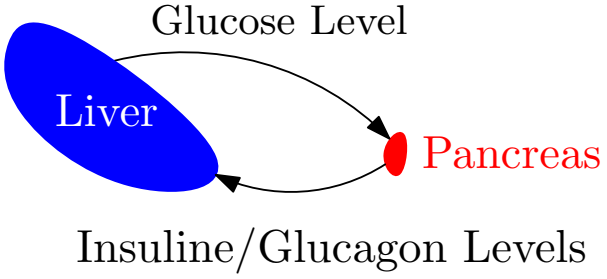
Reading: Chapter 1 of [AM] and Chapter 1 of [F].

Feedback

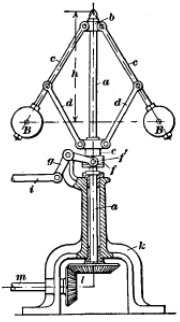
The variables in **dynamical systems** change over time, very often in response to external stimuli.

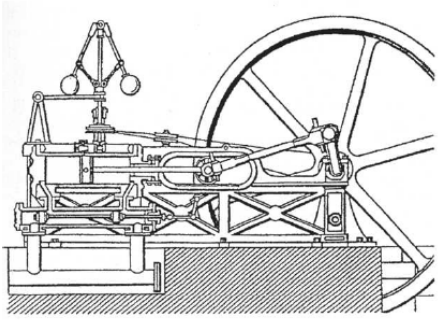
Feedback refers to a situation in which two or more dynamical systems are connected together and influence each other's evolution over time.

Example: Regulation to a constant glucose level in bloodstream



Example: Centrifugal Governor





- Keeps rotational speed at constant value
- This speed is largely independent from engine load

Principle known since 17th century. Attributed to Watt/Boulton (1788).
Theoretical stability analysis: Maxwell (1868) and Hurwitz (1895).

Effects of Feedback

Positive

- Make system resilient to external influences

  Increase of glucose by eating. Change of load on governor.

- Render system robust against changes/uncertainty in components

  Change of liver consistency. Change of mass of governor wheel.

  Reliable operational amplifier from cheap/uncertain components.

- Enforce linear behavior on nonlinear system

  Auto-pilots in fighter aircraft. Power electronics.

Adverse

- Can create dynamic instabilities (oscillations/runaway)

  Reduction of friction lead to oscillations in governor.

- Can increase sensitivity to external influences/component changes

  Increase effect on sensor noise in engineering system.

Control

The term control has many meanings in different communities. In this course we are mainly interested in engineered controllers.

The purpose of **control** is to design components of an engineered feedback system so as to achieve a desired overall behavior.

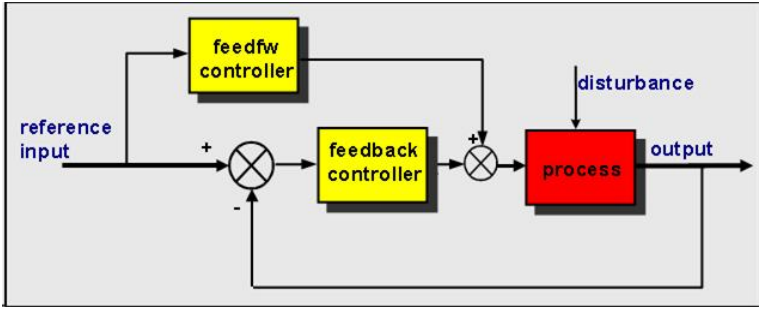
Examples are

- Set-point control in chemical or materials engineering
- Auto-pilot design for highly maneuverable fighter aircraft
- Router protocols for internet traffic control
- Real-time resource management systems (supply-chains)

Control theory provides the **insights, tools, algorithms and technology** for achieving this task.

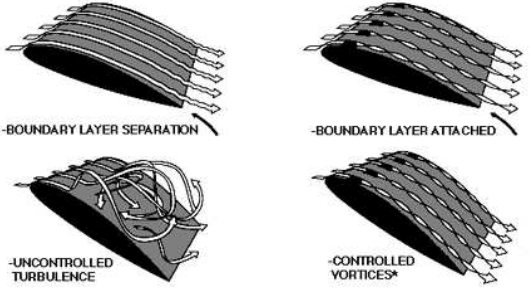
Observe

- Difference between open-loop and closed-loop (feedback) control
- Control "versus" process design
- Technological importance - need for theory (tools – math)
- Frequency domain tuning and "structured" model-based design



Many controllers are not sensor-to-actuator

Controlling turbulence:



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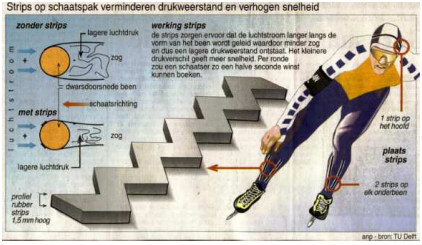
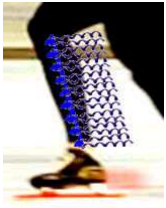
J.C. Willems (EECI 2009)

Nagano 1998 Winter Olympics





Gianni Romme (gold)
Rintje Ritsma (silver)
& Bart Veltkamp (bronze)

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J.C. Willems (EECI 2009)

Many controllers are not sensor-to-actuator

controlling drag:

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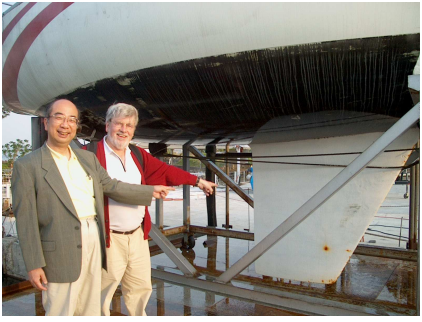
J.C. Willems (EECI 2009)

Many stabilizers are not sensor-to-actuator

Stabilization:



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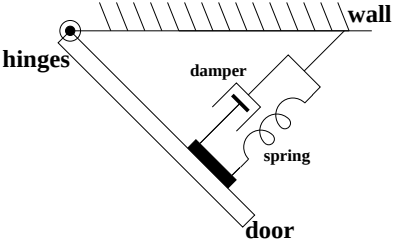
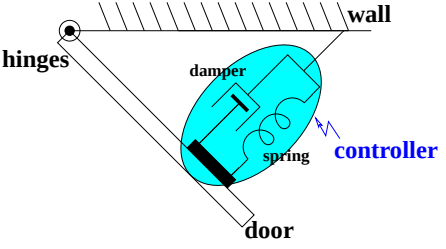
J.C. Willems (EECI 2009)

Door closing mechanism





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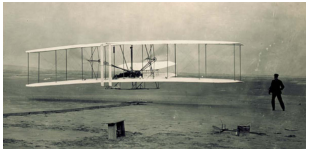
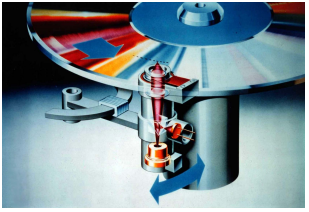
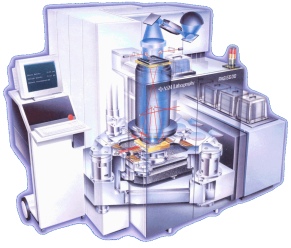
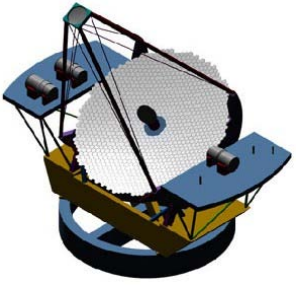
J.C. Willems (EECI 2009)

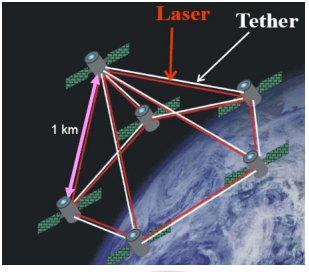
Control is Ubiquitous

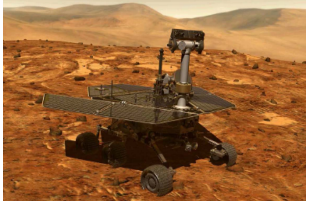


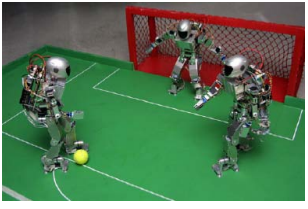


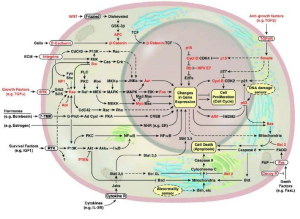








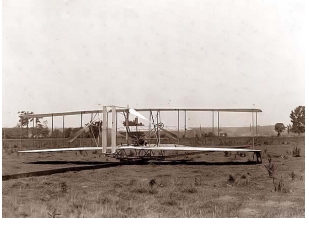




Technology breakthroughs from control

- Steam Engine controller - Watt's governor (1788)
- Airplane flight - Wright Brothers (1903)

> "*We 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*"
> (Wilbur Wright, 1901)



- Electronic feedback amplifier (Black, 1928)
- Sputnik launch (1957)
- Optical storage systems (CD, DVD) (1981)
- Atomic Force Microscope (1989)
- Wafer scanners for IC-production with linewidths of 32nm (ASML-2008)

The Impact of Control Technology - Overview, Success Stories, and Research Challenges

`http://www.ieeecss.org/general/impact-control-technology`

Course Structure

- Lecture 1: Introduction to Dynamical Systems
- Lecture 2: Solutions of Linear Systems
- Lecture 3: Controllability and Stabilizability
- Lecture 4: Linear Quadratic Optimal Control
- Lecture 5: Observability, Separation Principle, Realizations
- Lecture 6: Tracking and Disturbance Rejection