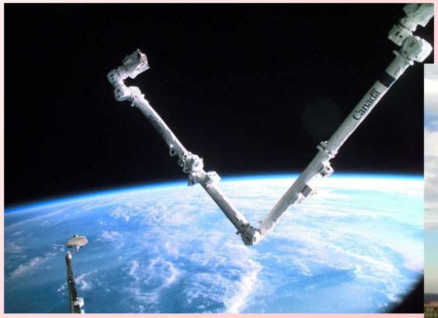
EE406
Laboratory of Feedback Control Systems

Department of Electrical and Electronics Engineering
Spring 2022

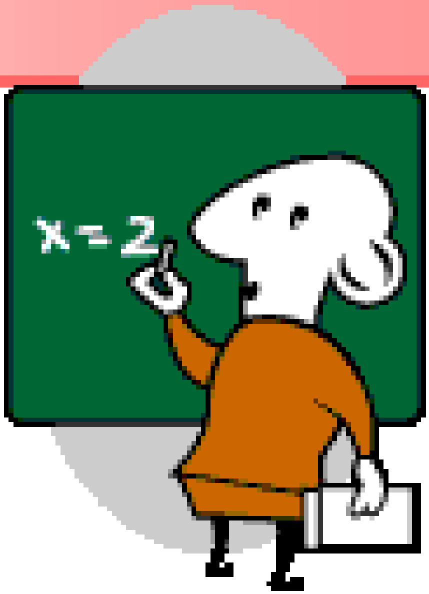
Dr. Afşar Saranlı

Assistants:
Ayşegül Kılıç, Özgür Diyar Kozan




Your Instructor?

Prof.
Afşar Saranlı



Lab Assistants

Ayşegül Kılıç

Özgür Diyar Kozan

Your Instructor?

BS in METU-EE

MSc in Imperial College, London, UK

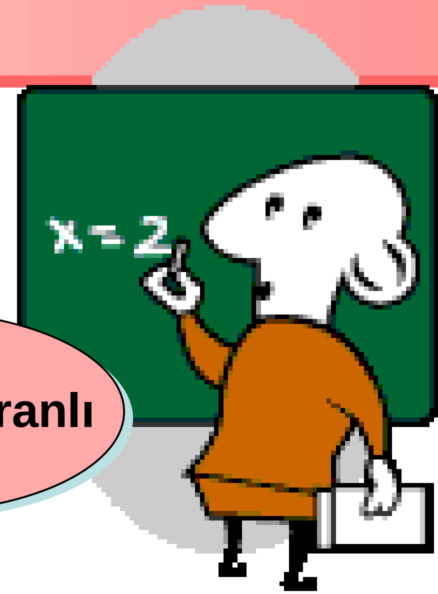
PhD. in METU-EE

R&D in Industry, Toronto, Canada

Now Here

Almost 18 years!

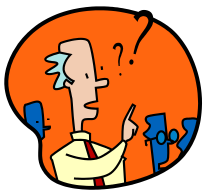
Dr. Afşar Saranlı



The Class – A short Survey

1. What are your goals in taking this course (or selecting the control option)?
2. What do you expect professionally from this term?
3. What do you expect personally from this term?
4. What is your biggest challenge this term?

The Course? The Staff and Hours



Instructor:

Prof. Dr. Afşar Saranlı
Office: EZ-10, Phone: 210-4529 / D-104 Phone: 210-2301
e-mail: afsars@metu.edu.tr

Laboratory Assistants:

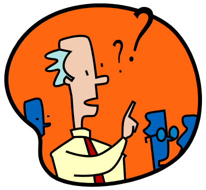
Ayşegül Kılıç
Office: F-Block Control Lab
e-mail: kilica@metu.edu.tr

Özgür Diyar Kozan
Office: F-Block Control Lab
e-mail: kozan.ozgur@metu.edu.tr

Lecture Hours:

Wednesday 09:40-10:30 EA-209
Note: Laboratory Hours to be determined by our Assistants with input from the students.

The Course? Prerequisites



Course Support Web Site:

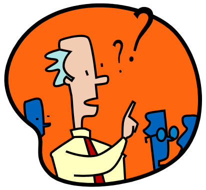
http://odtuclass.metu.edu.tr (Login with student account) (Lecture Videos, Lab sheets, support materials, etc. will be made available.) **Note:** Please check that you have your active e-mail registered in odtuclass and also check it regularly for materials.

Pre-Requisites/Co-Requisites:

EE402. The student should be taking (if offered this term) or should have taken EE402 with a letter grade to register for EE406. Students which have not taken EE402 or with W or NA grades from the course cannot take EE406.

The Course? Objectives

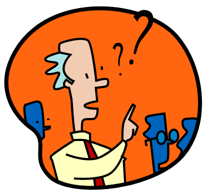
Course Objectives:

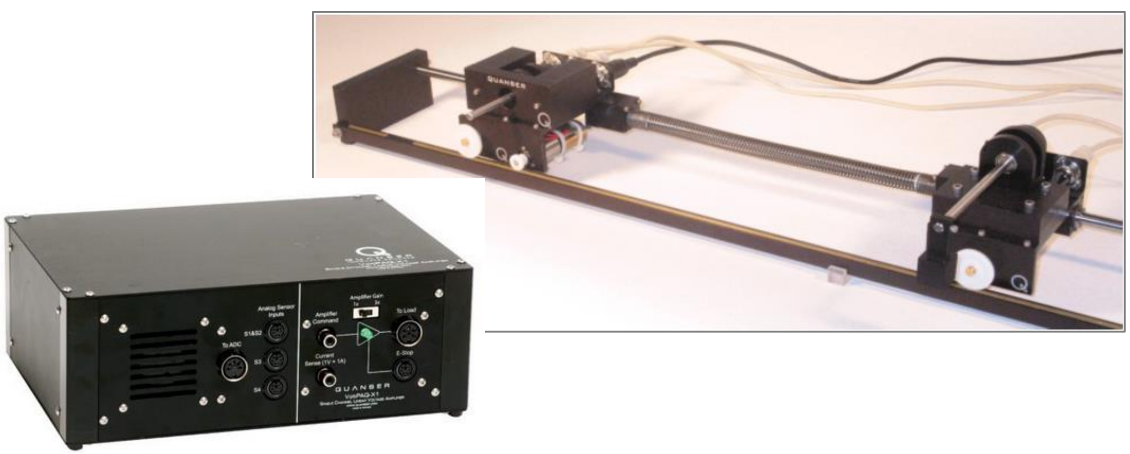


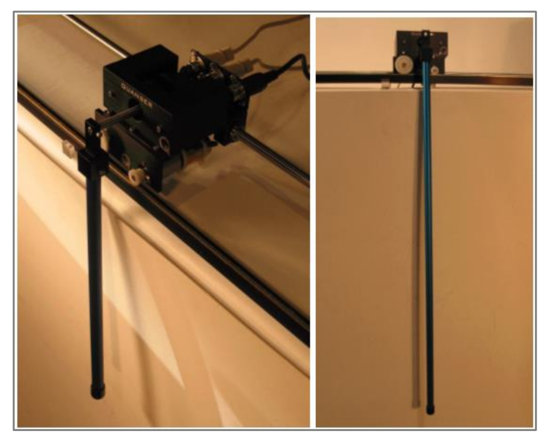
The laboratory course aims to equip you with a thorough understanding and appreciation of the components of a complex system consisting of sensors, actuators and computer based control hardware. The lab is based on the theory in EE302, EE402 and some additional concepts covered during the lectures. You will gain implementation insight and practical skills to develop and test actual control systems. You will be exposed to realistic experimental setups that will challenge your understanding of theory and test your skills gained in complementary courses. Specifically, the laboratory aims to:

1. Acquaint you with parts of a complex electromechanical system controlled by computer-based digital hardware;
2. Provide a sufficiently rich environment for you to practice and solidify your skills in modeling and approximating components of such systems;
3. Let you analyze and experimentally test different controllers to reach a variety of control objectives;
4. Expose you to real-life issues of system modeling, controller design and tuning, such as the presence of A/D and D/A conversion, noise, nonlinearities and quantization.

The Course? Experimental HW

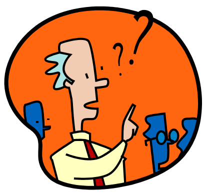






Test setups by Quanser Inc. – All components for computer control of electro-mechanical systems (Matlab-Simulink)

The Course? References…



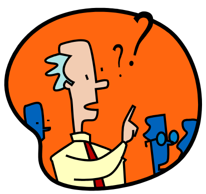
Reference Materials:

- EE406 Laboratory Experiment Sheets,
- Your EE302 and EE402 Lecture Notes,
- Quanser Inc. Hardware Manuals,
- N. S. Nise, *Control Systems Engineering*, Any recent edition.
- K. Ogata, *Modern Control Engineering*, 2009,
- K. Ogata, *Discrete-Time Control Systems*, 1995,

Online Support Materials:

- Lectures on Feedback Control Systems, Afşar Saranlı (YouTube),
- Control System Lectures, Brian Douglas (YouTube),
- Control Tutorials for MATLAB and Simulink (CTMS). http://ctms.engin.umich.edu/

The Course? Conduct



Evaluation and Grading:

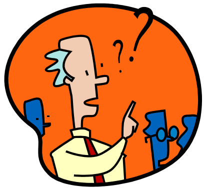
• Course+Lab Attendance & Lab Quizzes	%12
• Preliminary Works	%15
• In-Lab Performance and Reports	%35
• Midterm Exam	%13
• Final Exam	%25

Important Note I: One make-up will be granted only for students with an official excuse. Any student missing two or more Lab sessions will not be given the right to take the Final Exam and will receive NA Grade.

Preliminary Works:
Preliminary works are an important and integral part of the course work and will be prepared individually. You should cover any theoretical topics (from earlier lecture notes or from reference texts) that are required to complete the preliminary work. This will make sure that you will be able to complete the in-lab part of the experiments. The preliminary works will be pre-inspected at the beginning of the lab session for any mistakes that may compromise the in-lab experiment.

Important Note II: An acceptable preliminary work is a pre-requisite to attend the laboratory session. Any student with no (or insignificant) preliminary work will not be accepted to the lab session will receive minimum grade from the session.

The Course? Conduct



Lab Sessions:
Lab sessions will be conducted as pre-configured teams of two students. The in-lab experiment reports (one per team) will be prepared during

the execution of the lab and will be collected at the end of the lab. You should follow the Lab Assistant’s directions and instructions closely and ask whenever in doubt so as not to damage any equipment.

Midterm and Final Exams: Exams will cover the theoretical content that is covered during the lectures and in the preliminary works as well as practical aspects covered during the lab sessions. You are expected to have good knowledge of the relevant content from EE302 and EE402 lectures.

The Course? Tentative Program

	Title and Description
1	Setting up of lab groups and infrastructure. Introduction to Matlab and Simulink for dynamic systems analysis and design. **Lecture:** Introduction
2	**Lecture:** Nonlinear systems and linearization.
3	**Lecture:** Nonlinear systems and Linearization.
4	**Exp 1: Introduction.** Getting acquainted with the experiment environment, mechanical setup, hardware, and software interfaces. Explore hardware interface code fragments and implement small programs that read platform sensors and operate the actuators. (**Lecture:** Nonlinear systems and Linearization).
5	**Exp 2: Position Control.** ***Preliminary Work*** - Study the electro-mechanical system and derive the open-loop and closed-loop transfer functions from first principles. Develop a block diagram representation of the system. ***Experiment*** - Position control of DC Motor actuated linear cart through Proportional-Derivative feedback control. You will be asked to design a Proportional-Derivative controller for this plant. You will test the controller with a simulation of the plant, then apply the controller to the actual plant and analyze and compare the results. (**Lecture:** Introduction to Optimization and Least Squares),

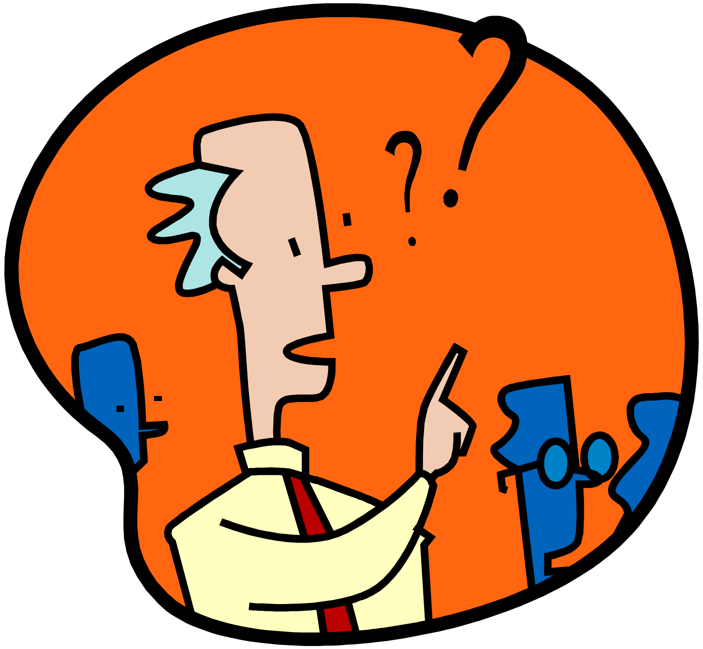
The Course? Tentative Program

6	**Exp 3: Velocity Control using Lead Compensator.** ***Preliminary Work*** **-** You will have already derived the open-loop transfer function of the servo plant. You will now design a phase-lead type compensator from supplied controller performance specifications. ***Experiment*** **-** You will first test the performance of your controller in simulation for regulating the speed of the servo plant. You will tune your controller in simulation and then apply the controller to the actual servo plant. Finally you will compare and contrast the results. (**Lecture:** Introduction to Optimization and Least Squares),
7	**Exp 4: Single Pendulum Gantry Control using Pole Placement** ***Preliminary Work*** **-** You will derive the open-loop system block diagram and state-space representation of the gantry-pendulum system. You will linearize the model to obtain the small angle transfer function. You will then design the state-feedback controller to meet the controller performance specifications. ***Experiment*** **-** You will construct the system and test your controller first in simulation and then with the actual cart-pendulum plant. You will fine-tune your controller, compare and contrast your results. You will then observe the disturbance rejection of tapped pendulum. (**Lecture:** Optimal state-space control using the Linear Quadratic Regulator)
8	**Lecture:** Optimal state-space control using the Linear Quadratic Regulator
9	**Lecture:** Optimal state-space control using the Linear Quadratic Regulator

The Course? Tentative Program

10	**Exp 5: Flexible Joint Position Control using LQR.** ***Preliminary Work*** **-** You will write down the equations of motion and derive the open-loop system model. The state-space model is also to be derived. You will review the given controller performance specifications. ***Experiment*** **-** Position control of an unactuated cart connected to an actuated cart through a linear spring system. You will use the Matlab LQR design function to design an LQR controller for the given specifications and manually tune the weighting matrices. You will evaluate the system performance against controller performance specifications through simulations and with the actual hardware. **(Lecture**: Some key results from discrete-time systems)
11	**Exp 6: Simple Inverted Pendulum using LQR Control** ***Preliminary Work*** **-** You will derive the equations of motion and system model for the inverted pendulum, derive the linear approximation through small angle assumption, and review the given controller performance specifications. ***Experiment*** **-** The concurrent control of the cart-mounted simple inverted pendulum together with cart position. You will design the required LQR through the derived linear approximation to the system and the Matlab LQR design function. You will then test your design in simulation and with actual hardware. (**Lecture**: Some key results from discrete-time systems)
12	**Exp 7: Discrete-Time Controller Design** In this lab, the effects of reduced sampling rates on a continuous-time design will be investigated and will be compared with the performance of a proper discrete-time controller design. The details of the preliminary and laboratory work will be made available. (**Lecture**: TBD)
13	**DEMO: Advanced Control System Demo (Self Erecting Inverted Pendulum and/or 3DOF Helicopter Setup).** Advanced nonlinear control system examples are demonstrated: The self-erecting inverted pendulum is a hybrid control system that first erects the pendulum using an energy pumping strategy and then dynamically switches to LQR. Also a helicopter flight control demo is performed. (**Lecture**: TBD)

Feedback Control In Practice?

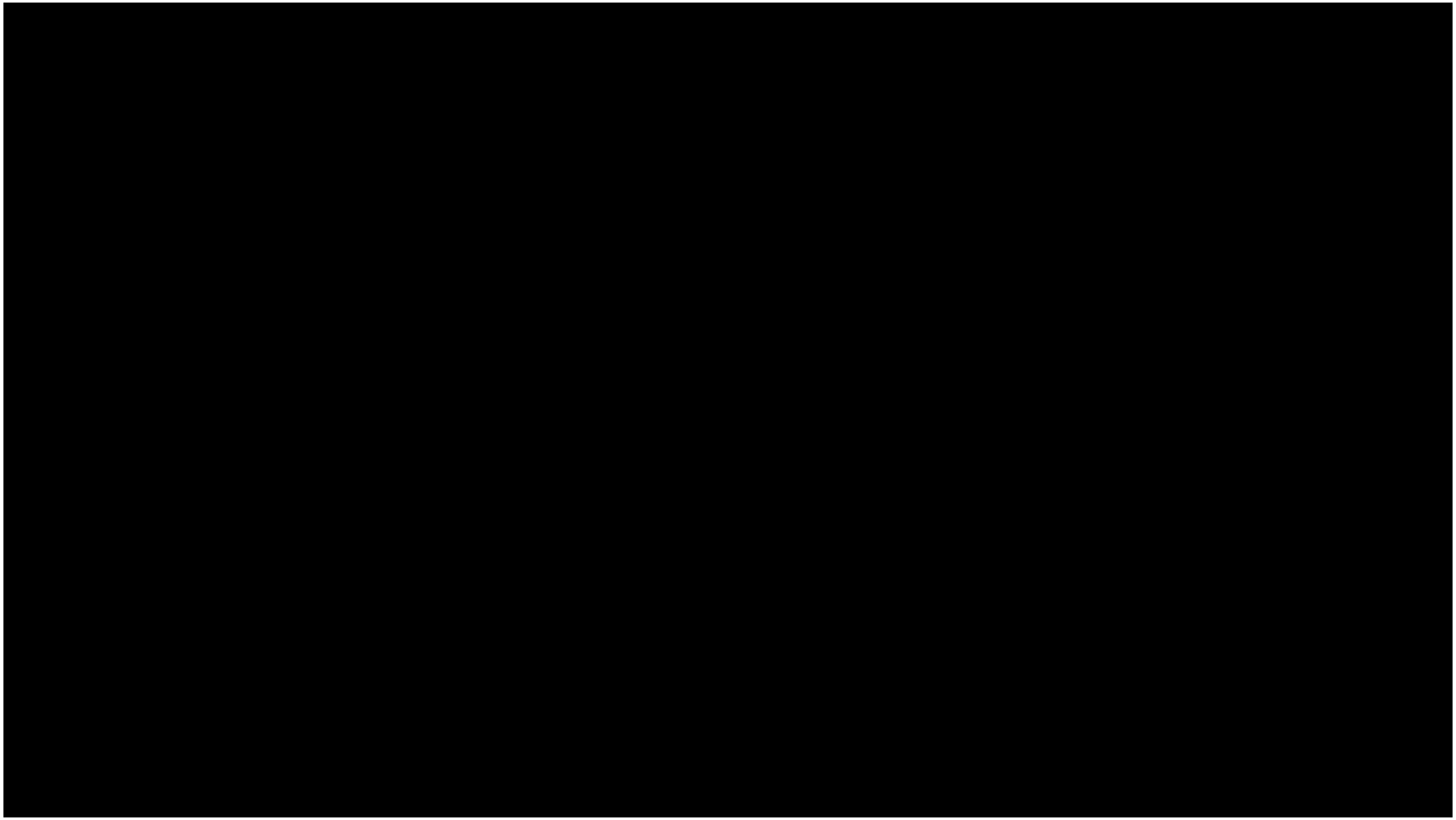


Some Interesting Examples…

Feedback Control In Practice?

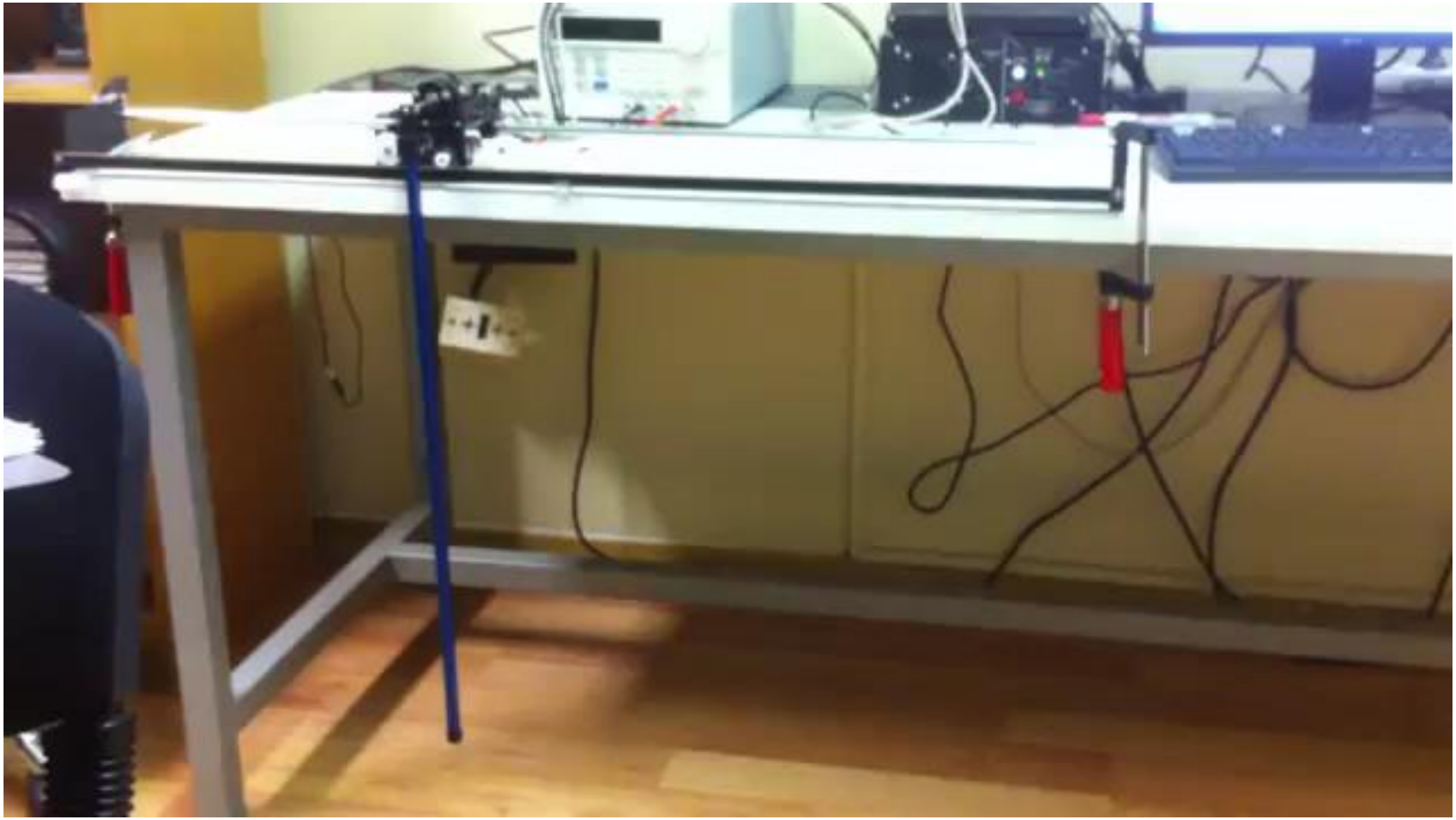
"An example from nature" – Youtube "Smarter Every Day"

Feedback Control In Practice?



Application: Camera Stabilization on Drones and Robots

Feedback Control In Practice?



Experiment: the pendulum swing stabilization

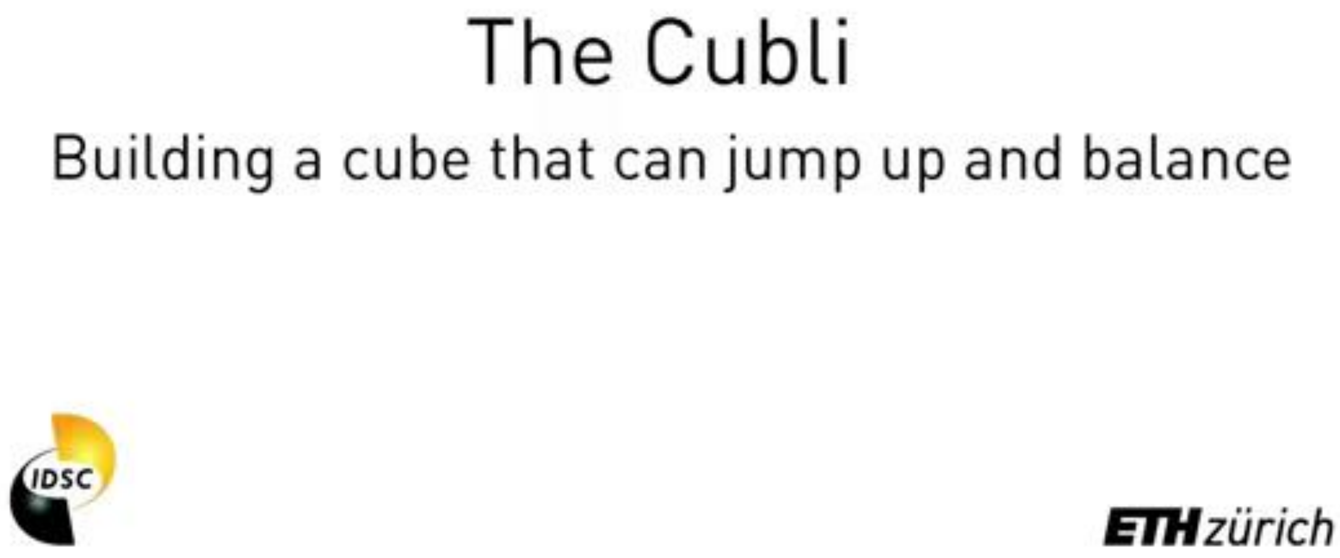
Feedback Control In Practice?

Application: Crane swing stabilization

Feedback Control In Practice?

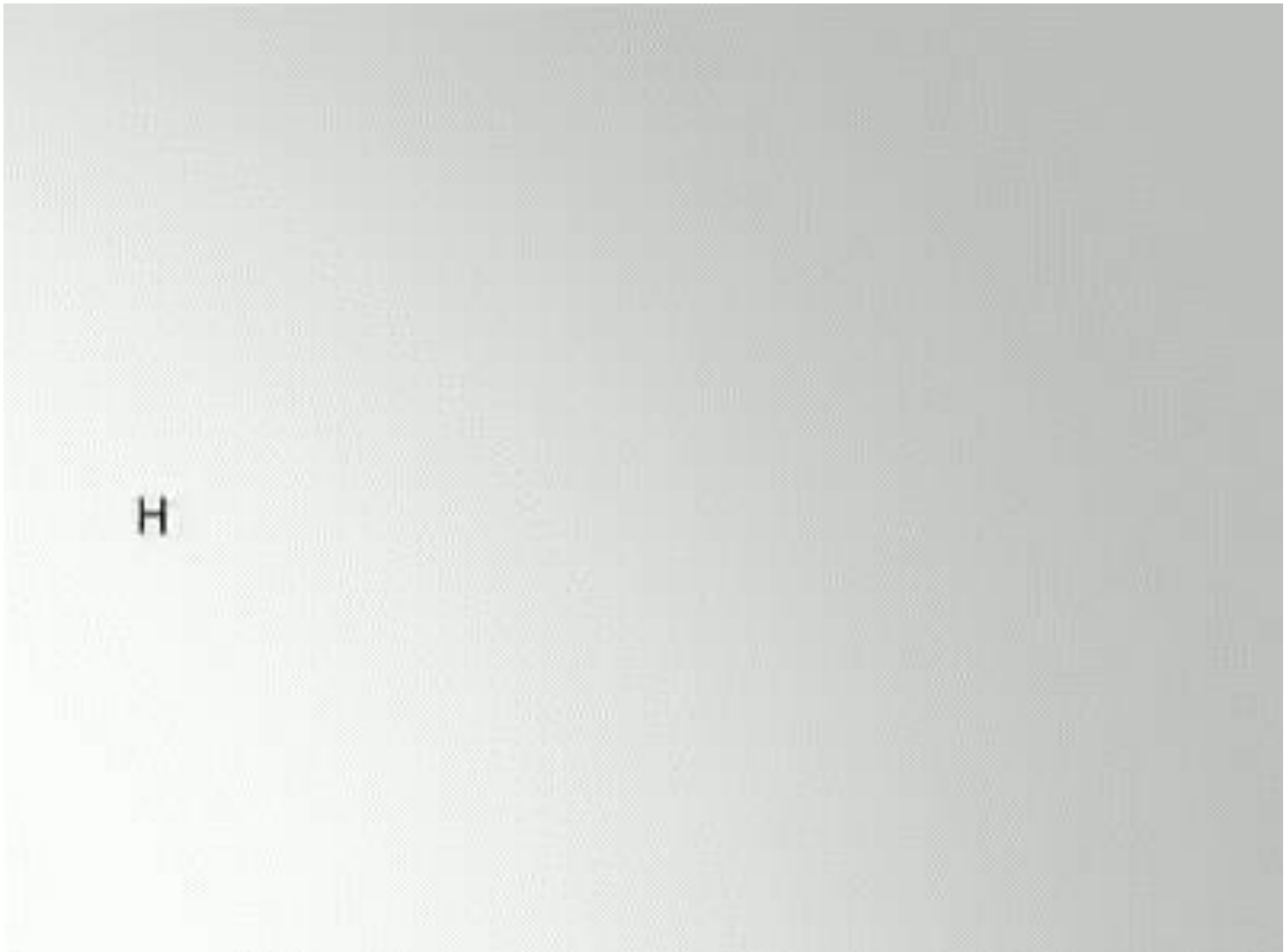
Experiment: The Inverted Pendulum

Feedback Control In Practice?



Application: The Cubli prototype (and Satellite control in space)

Feedback Control In Practice?



Application: The Segway transporter

Feedback Control In Practice?

Extreme Inverted pendulums: Dynamically balanced legged robots
Boston Dynamics Atlas robot - 2017

Feedback Control In Practice?

Extreme Inverted pendulums: Dynamically balanced legged robots
Boston Dynamics Spot Mini robot - 2018

Feedback Control In Practice?

Extreme Inverted pendulums: SpaceX Falcon 9 Reusable rocket - 2017

Feedback Control In Practice?

Extreme Inverted pendulums: SpaceX Falcon 9 Reusable rocket – 2017 (Development)

Feedback Control In Practice?

Lab Demo: The see-saw platform

Feedback Control In Practice?

Application: Ship platform stabilization

Feedback Control In Practice?

Application: Active Car Suspension (Car stabilization)

Feedback Control Failures

Systems can fail: SpaceX – Starship fails on Landing

Feedback Control Failures

Systems can fail: Segway fails compilation

Good Wishes…

Control Theory is an exciting field and we hope that this laboratory will give you a chance to experience and enjoy it in practice. Good Luck and have fun.