Automatic Control 1

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University of Trento

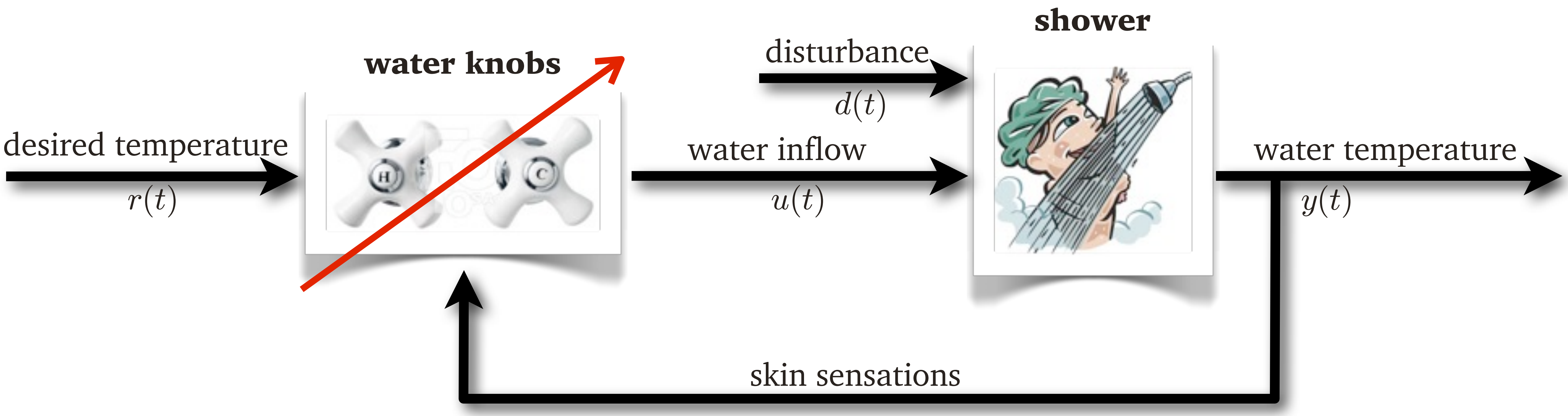
Academic year 2010-2011

Faculty of Engineering

Lecture outline

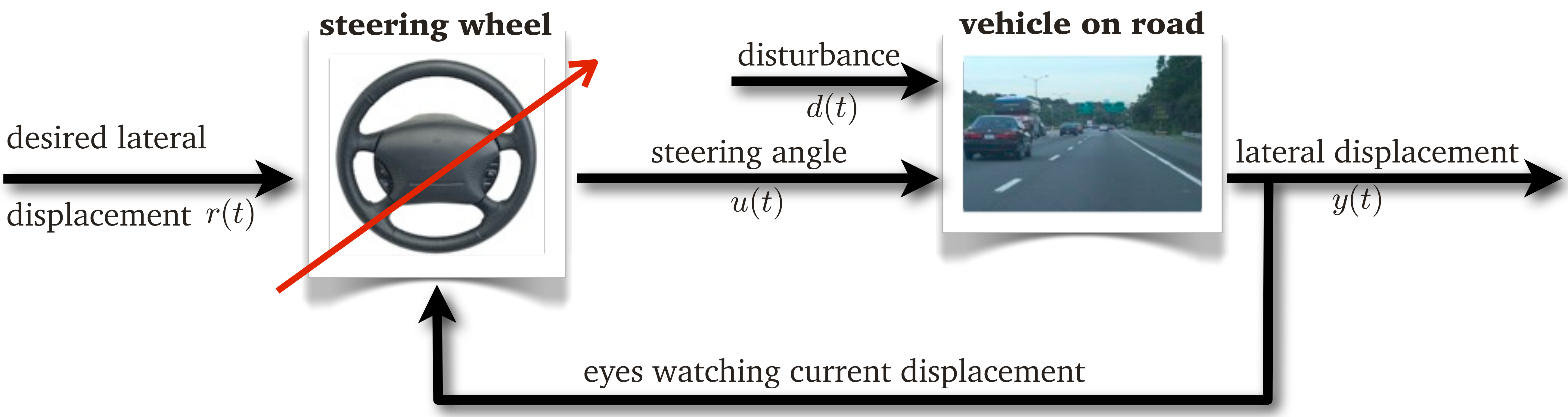
- What is *automatic control* ?
- Application examples
- Course information

What is control ? A real life example ...



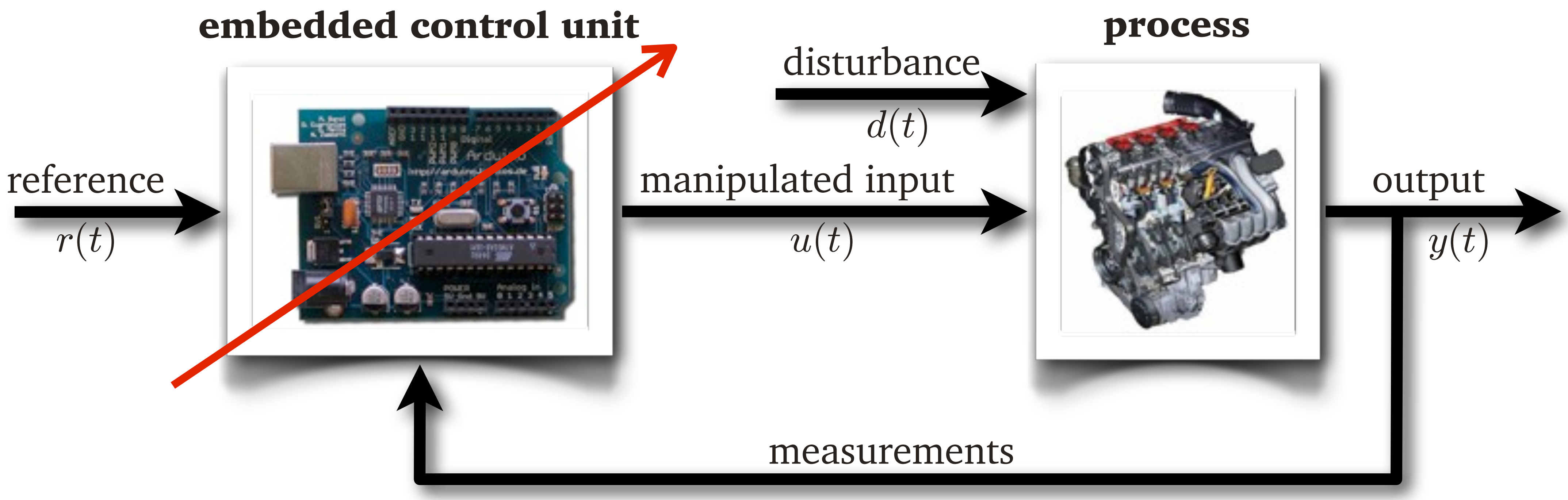
- Water inflow $u(t)$ must be **controlled** to reach and maintain the desired temperature $r(t)$
- Sensors on skin **measure** water temperature $y(t)$
- Water inflow $u(t)$ manipulated so that $y(t)\approx r(t)$ ...
- ... in spite of flow and temperature fluctuations $d(t)$

What is control ? A real life example ...



- Steering wheel must be **controlled** to reach and maintain the desired lateral displacement $r(t)$ within the lane (e.g.: staying in the middle of the lane)
- Eyes **measure** current later displacement $y(t)$
- Steering wheel $u(t)$ manipulated so that $y(t) \approx r(t)$ ...
- ... in spite of changes of road curvature and of $r(t)$

What is automatic control ?



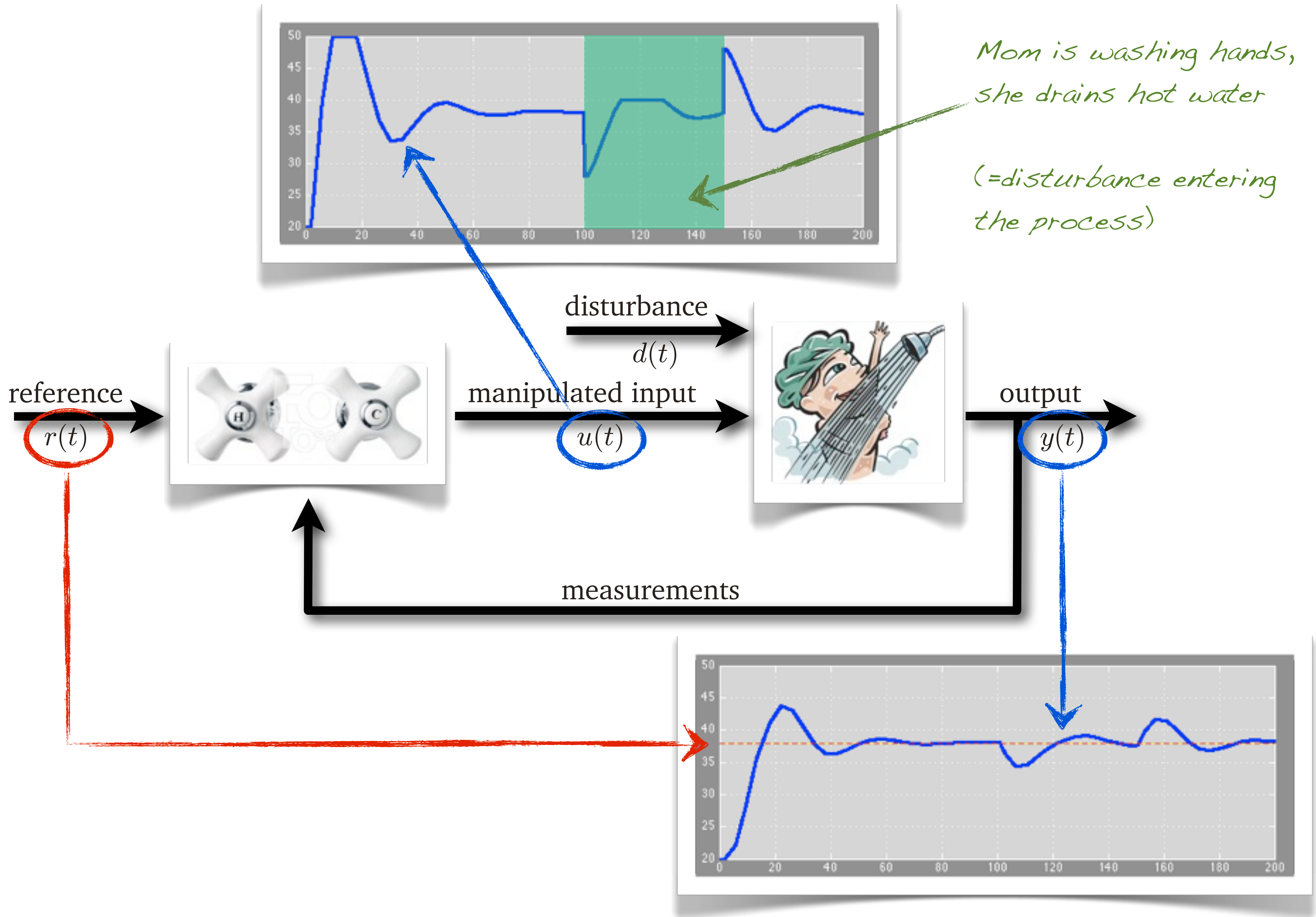
How to control the inputs $u(t)$ to the process automatically to make the output $y(t)$ *track* the given reference $r(t)$?

performance

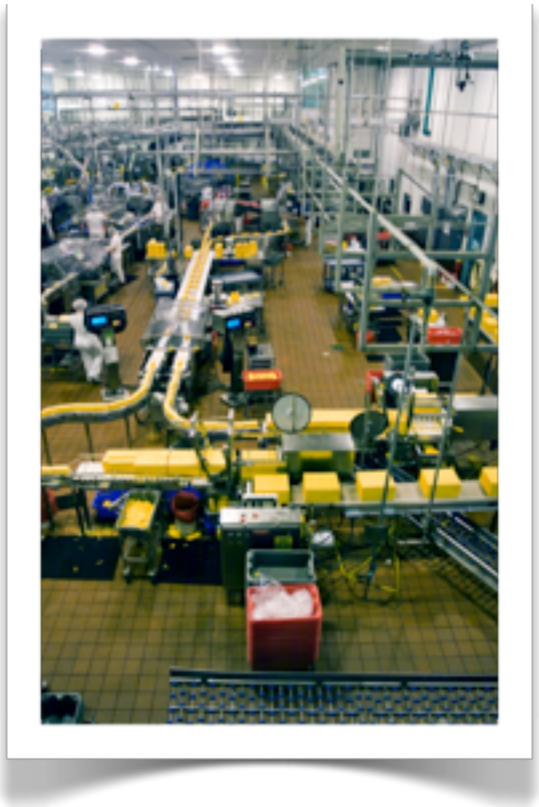
How to exploit the *measurements* of $y(t)$ to track the reference $r(t)$ in spite of *disturbances* $d(t)$ acting on the process ?

robustness

What is control ? A real life example ...



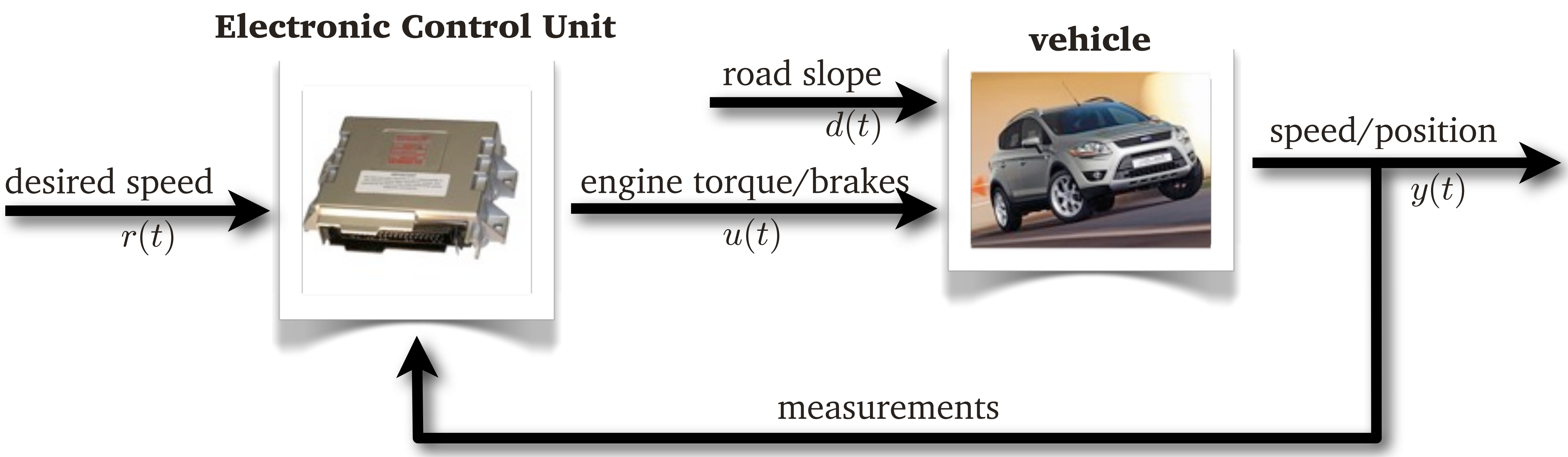
Application areas of control engineering



- Aeronautics & aerospace
- Automotive
- Manufacturing
- Process control (chemical, pharmaceutical, steel, pulp & paper, ...)
- Power electronics
- Telecommunications
- Environmental systems
- Financial engineering
- Supply chains
- Power networks
- ...

Adaptive Cruise Control (ACC)

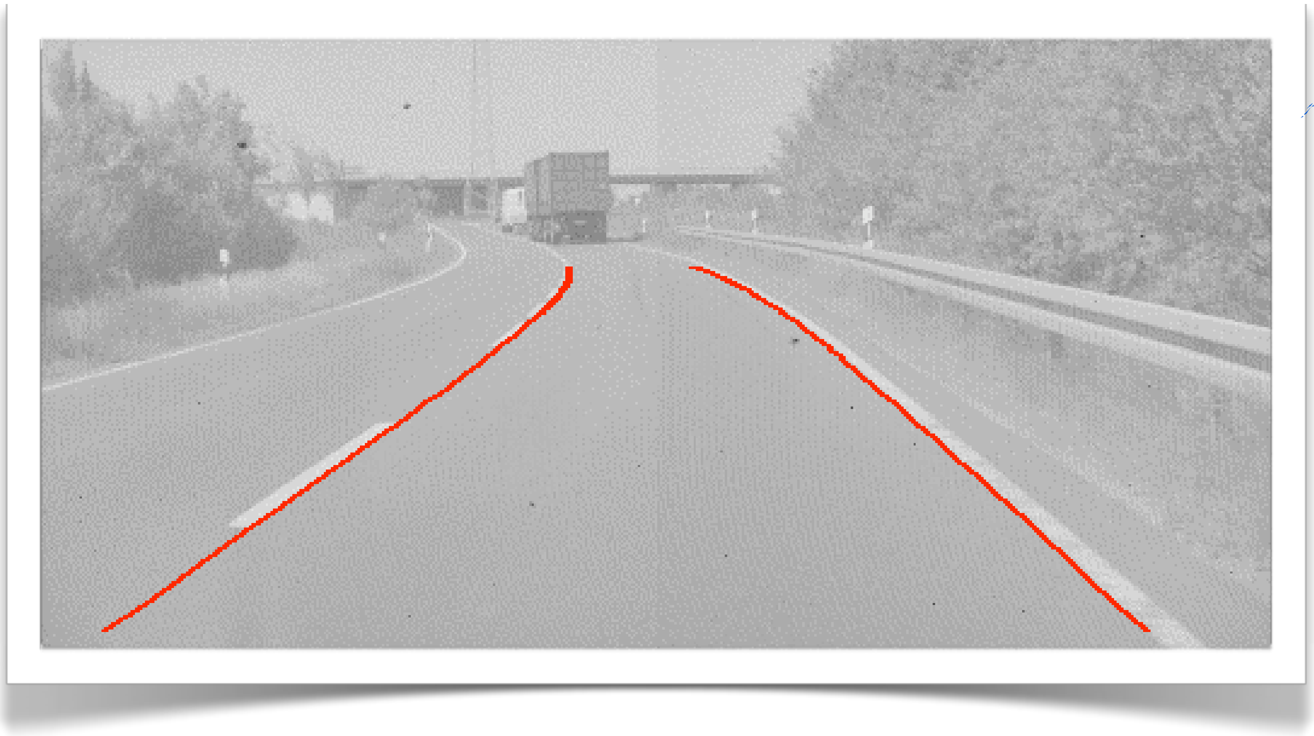
Adaptive Cruise Control (ACC)



Lane Warning

HALF - HAptical Lane Feedback

- Optical sensor detects and tracks lane markings
- Incipient lane change signalled to the driver by:
  - Haptic signal on driver seat (simulation of rumble strip)
  - Haptic feedback on steering wheel
  - Acoustic directional signals
- Lane can be automatically maintained

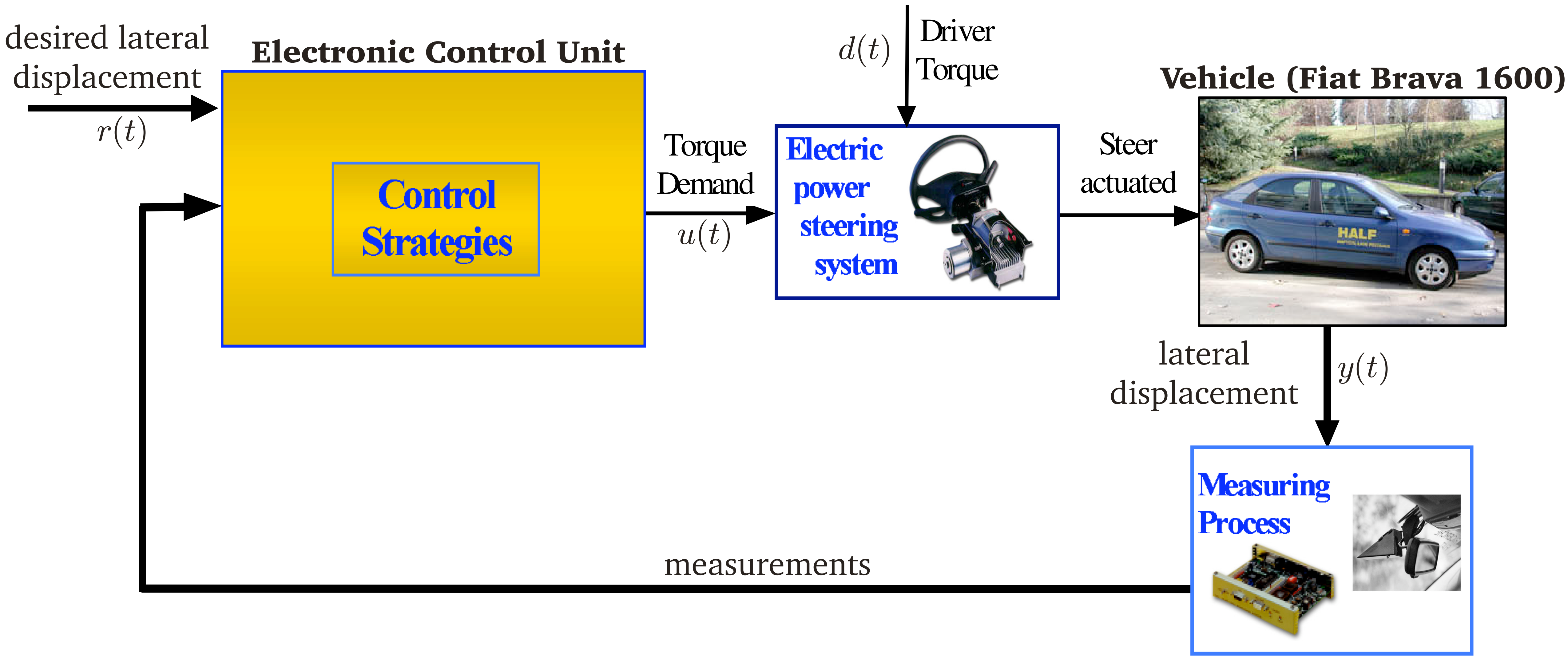


electric power steering

CENTRO RICERCHE FIAT

Lane Warning

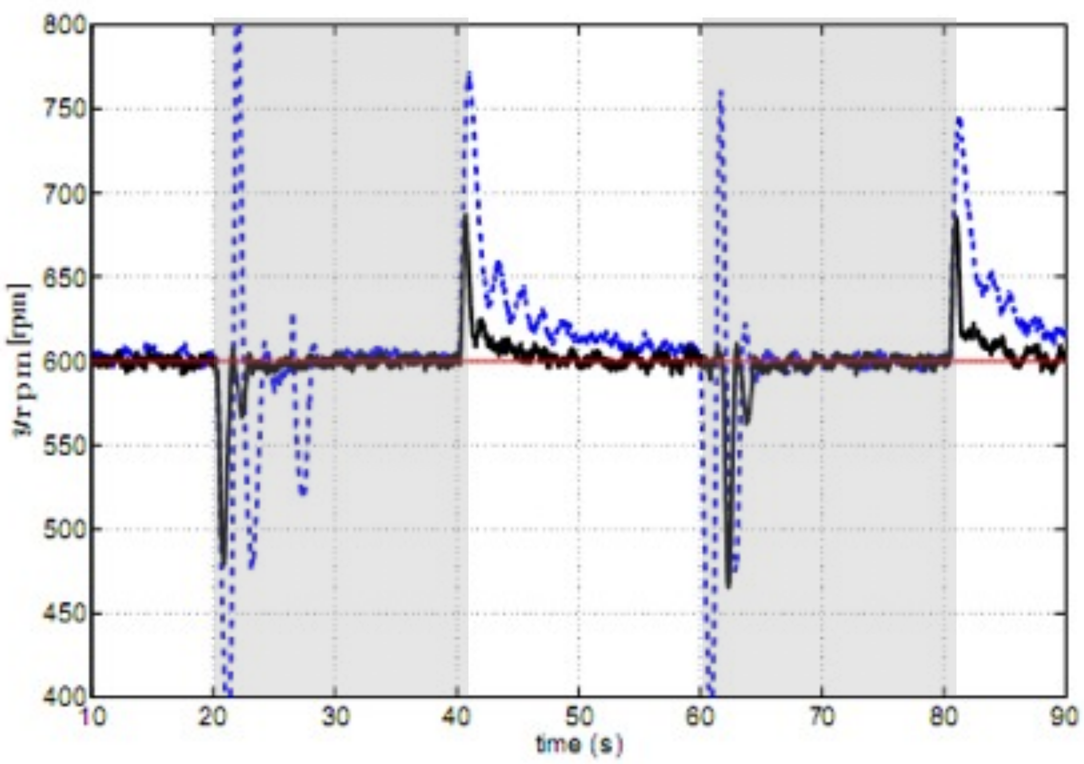
Lane Warning



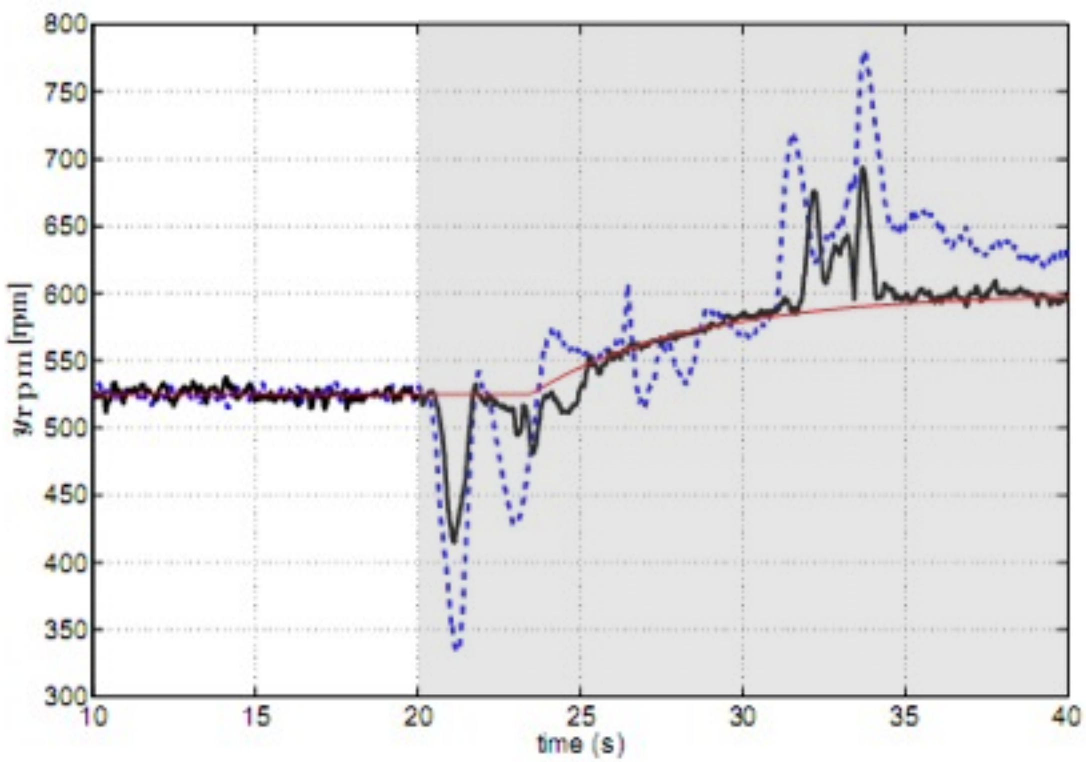
CENTRO RICERCHE FIAT

Idle speed control

Objective:
maintain the engine speed at a given rpm



Torque disturbance: power steering



Power steering + air conditioning

Active suspensions

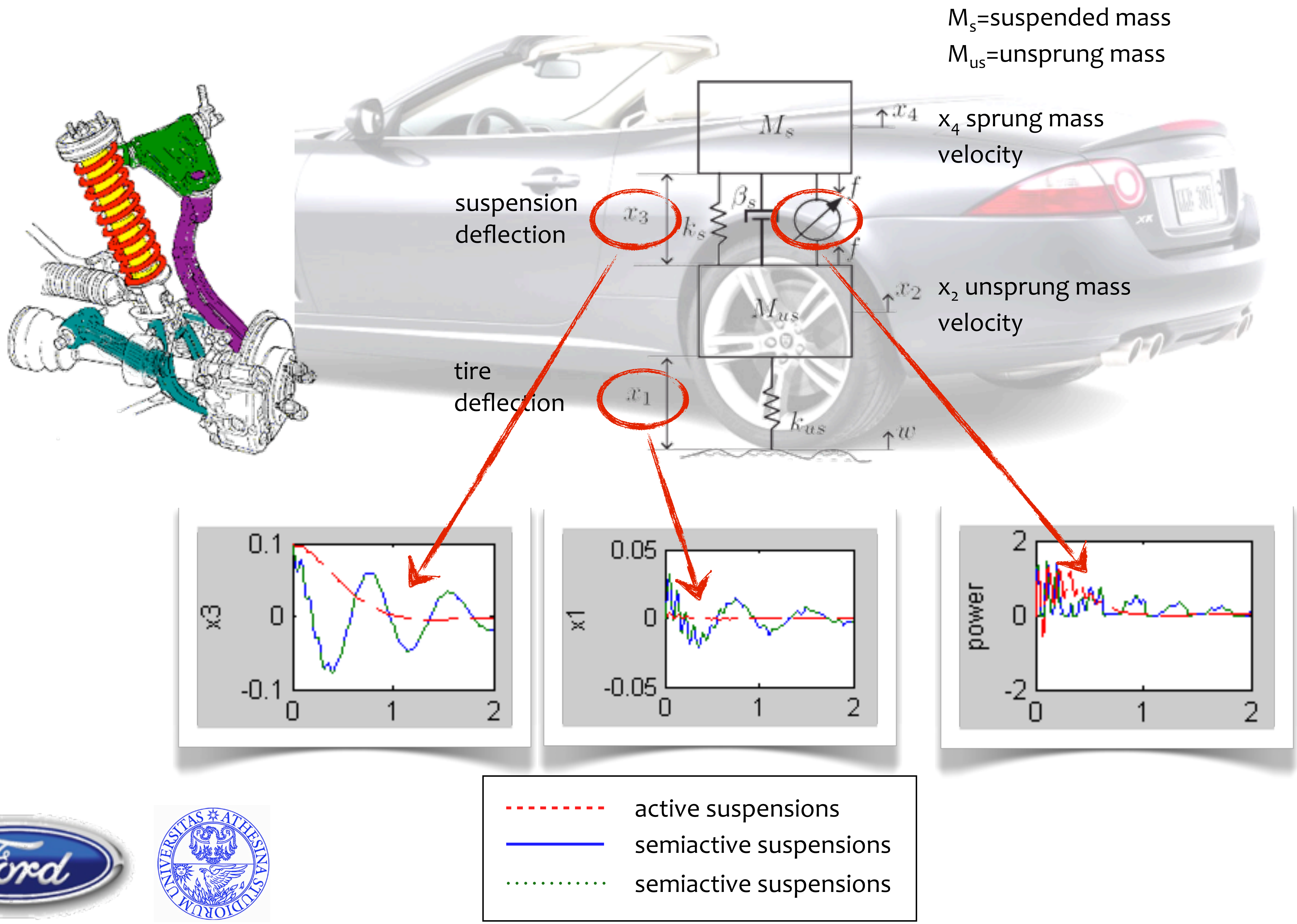
active suspensions

passive suspensions

Active Suspension System
Ford Mercur XR 40i

Ford Motor Company

(Semi)active suspensions



Traction control

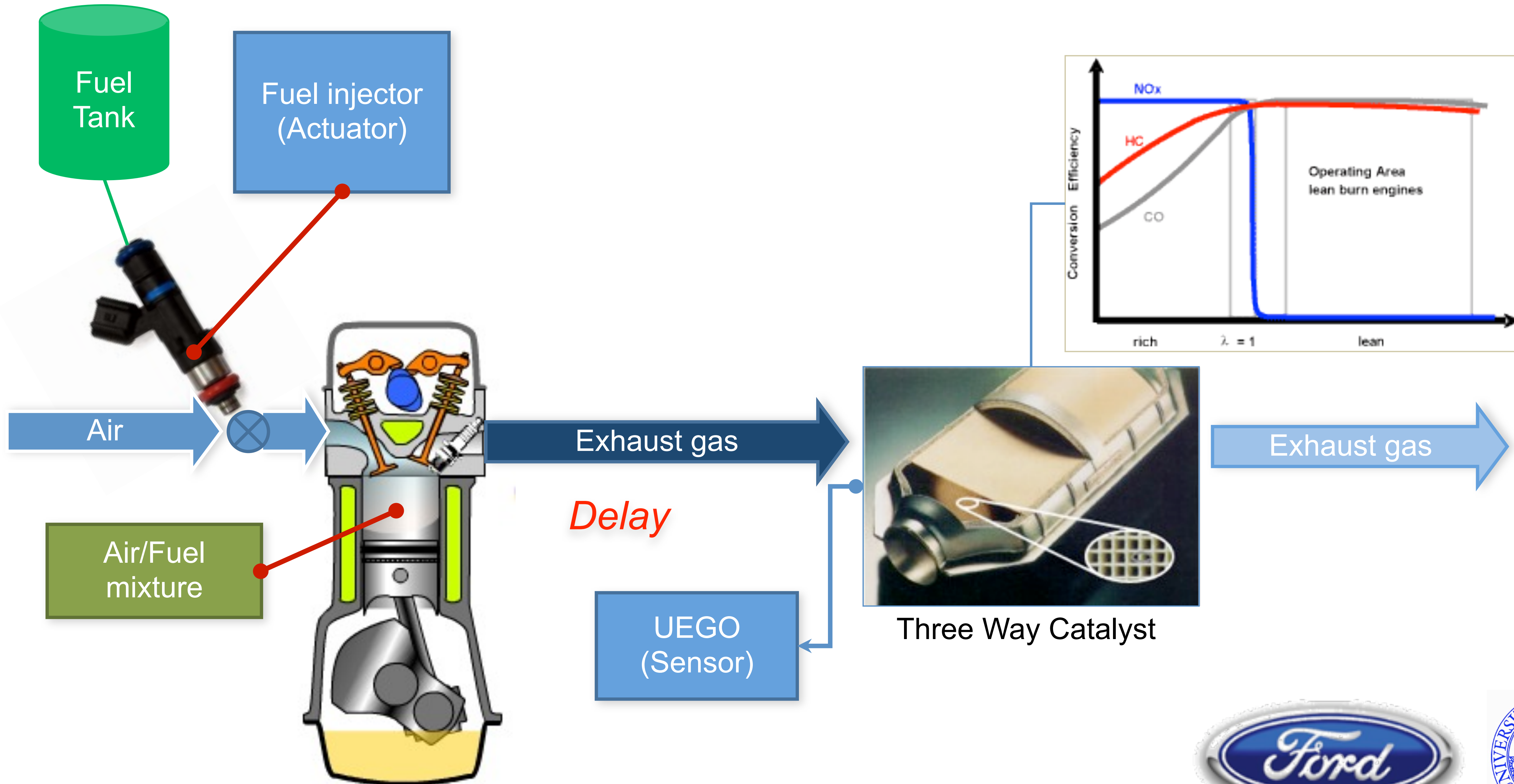
Problem: Improve driver's ability to control a vehicle under adverse external conditions (wet or icy roads)

indoor tests at ice arena ($\mu \approx 0.2$)

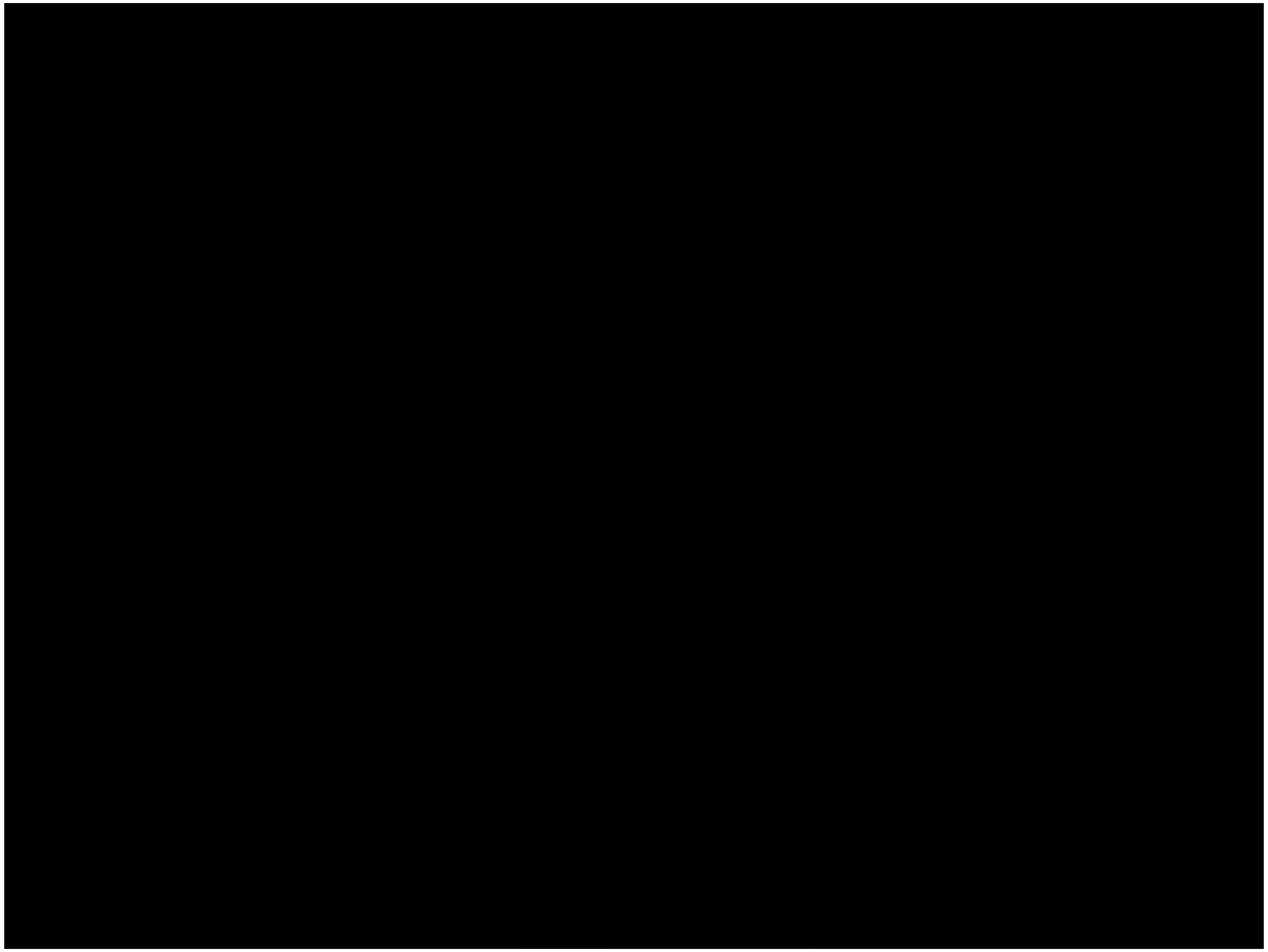
2000 Ford Focus, 2.0l 4-cyl engine
5-speed manual transmission

Air to Fuel Ratio (AFR) control

Control objectives:
Maintain the stoichiometric Air to Fuel Ratio (AFR) and avoid oxygen saturation (empty or full catalyst)



Control of suspensions



DAIMLERCHRYSLER

(Courtesy of Daimler-Chrysler)

Active steering

Courtesy of DAIMLERCHRYSLER

Segway Human Transporter

www.segway.com

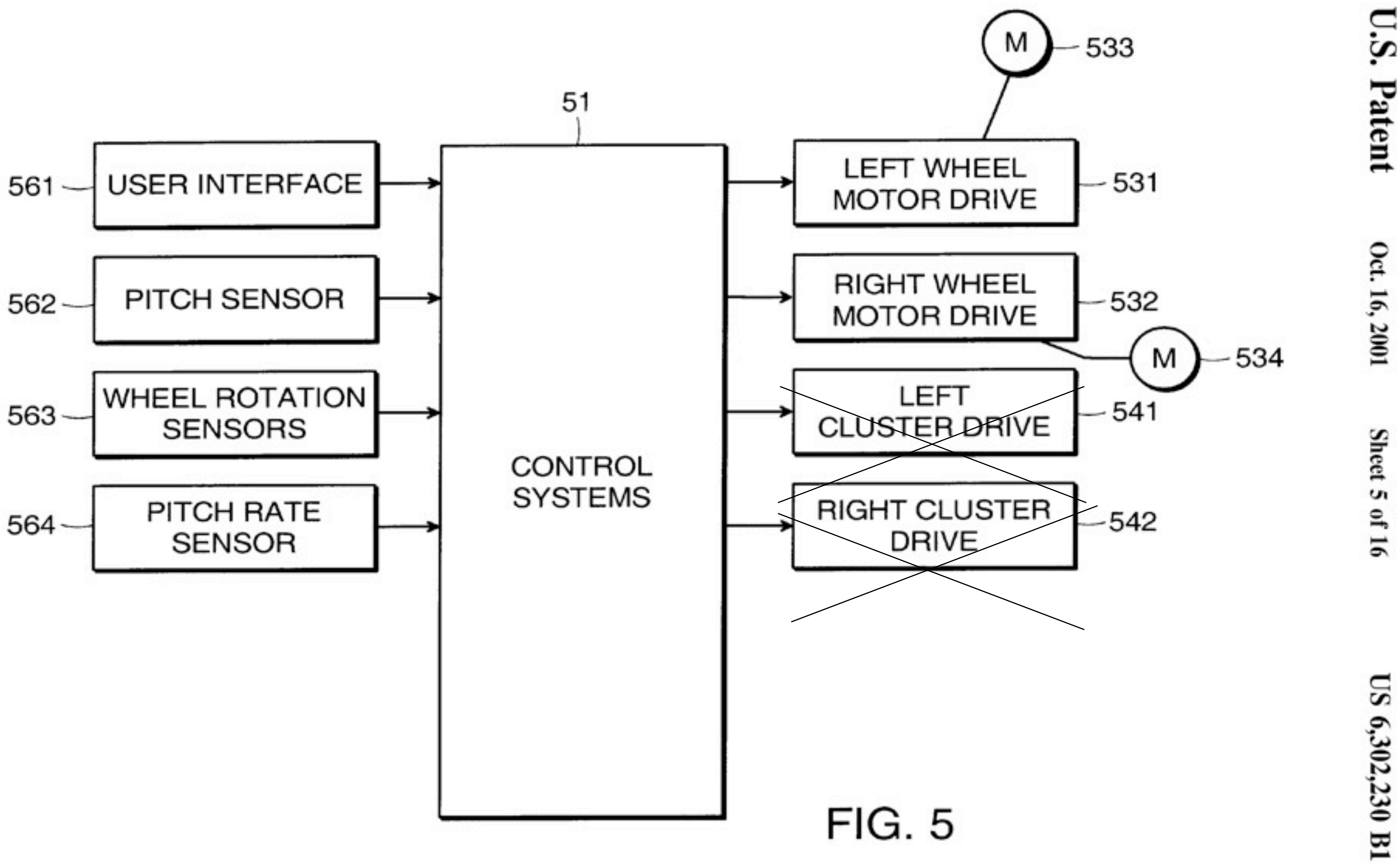
Segway Human Transporter

The Segway™ Human Transporter (HT) is the first *self-balancing*, electric-powered transportation device. With dimensions no larger than the average adult body and the ability to emulate human balance, the Segway HT uses the same space as a pedestrian, and can go wherever a person can walk.

Dynamic stabilization is the essence of the Segway Human Transporter (HT). Dynamic stabilization enables Segway HT to work seamlessly with the body's movements.

Gyroscopes and tilt *sensors* in Segway HT monitor a user's center of gravity at about 100 times a second. When a person leans slightly forward, Segway HT moves forward. When leaning back, Segway HT moves back.

Segway Human Transporter



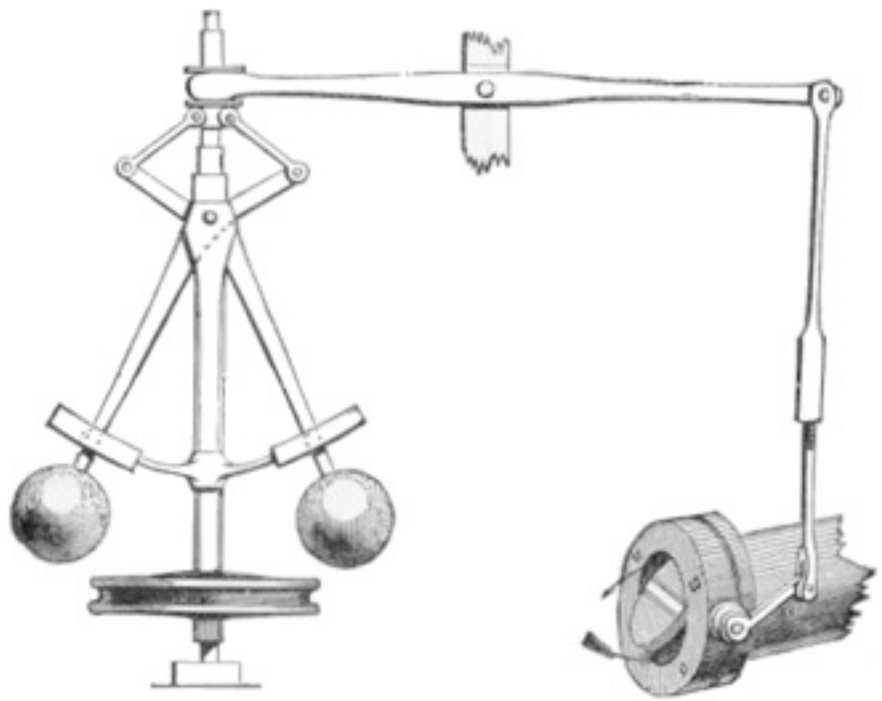
Short historical notes

- Water level controllers date back to ancient Greece
  (Ktesibios of Alexandria, water clock*, 270 B.C.), (Philon of Byzantium, 250 B.C.)*
  (Heron of Alexandria, ≈100 A.D.)

- Other examples in the 17th-18th century
  (Cornelis Drebbel's incubator*, 1620), (Edmund Lee's* self-regulating wind machine*, 1745)*
  (Thomas Mead's lift tenter and speed controller*, 1787)*

- James Watt's flyball governor (1788)

  Used to regulate the speed of steam engines.
  If speed increases, flyballs spread apart and
  the steam flow through the throttle is reduced.
  And vice versa.



- Frequency domain (1930-1950)
  (H. Nyquist, H.W. Bode, N.B. Nichols)

- State-space and optimal control (1950-1980)
  (R. Kalman, R. Bellman)

- Nonlinear, robust, adaptive, optimization-based, (...) control (1980-today)

Is control needed after all ?

Friday November 7, 1997

Baby Benz falls foul of a moose

"Mercedes is recalling 3,000 brand-new A Class mini cars to correct stability problems revealed in Scandinavian tests."

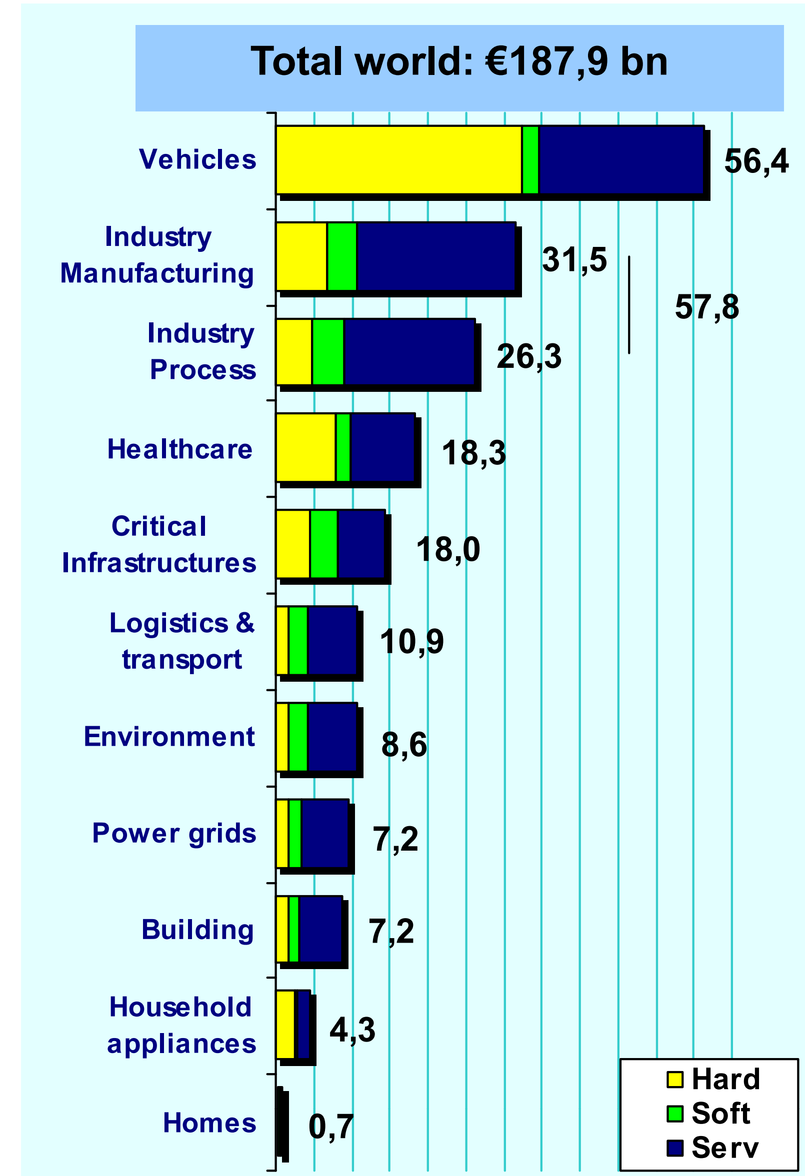
A Class failed the "moose test", simulating a sudden swerve to avoid a moose on the road.

The recall of about 3,000 cars followed motoring press reports which indicated the A Class is *unstable*, and likely to roll over, in extreme lane-changing tests.

Problem solved by introducing the Electronic Stability Program (ESP), which *automatically manipulates* brakes (and engine torque) to keep skid under control.

Is control needed after all ?

- Worldwide Monitoring & Control market (=188 billions euro)
- Monitoring & control ≈ semiconductor industry ≈ 2 x mobile phone industry
- Still growing, young areas with great potentials (power grids, building automation, environment)



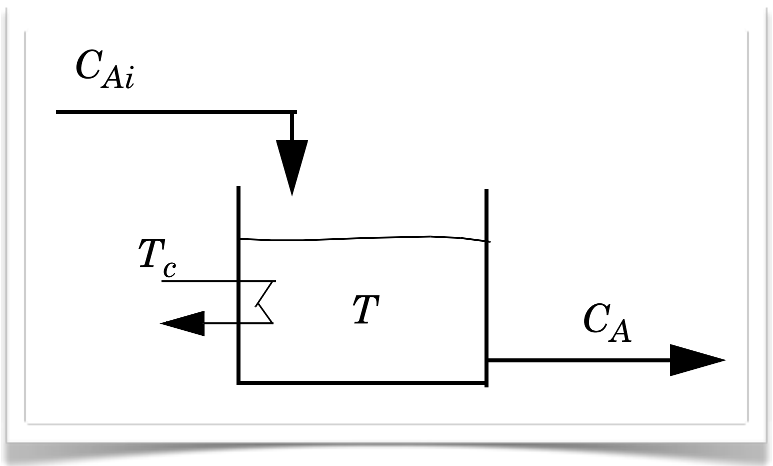
A report & a presentation prepared by:
DECISION Etudes & Conseil
RPA

Available for download: http://www.decision.eu/smart2007.htm

Process control

- Control is heavily used in the process industries
- Usually slow processes (heat transfer, chemical reactions, distillation, etc.)
- Usually several input and output variables

Example: Continuous stirred-tank reactor



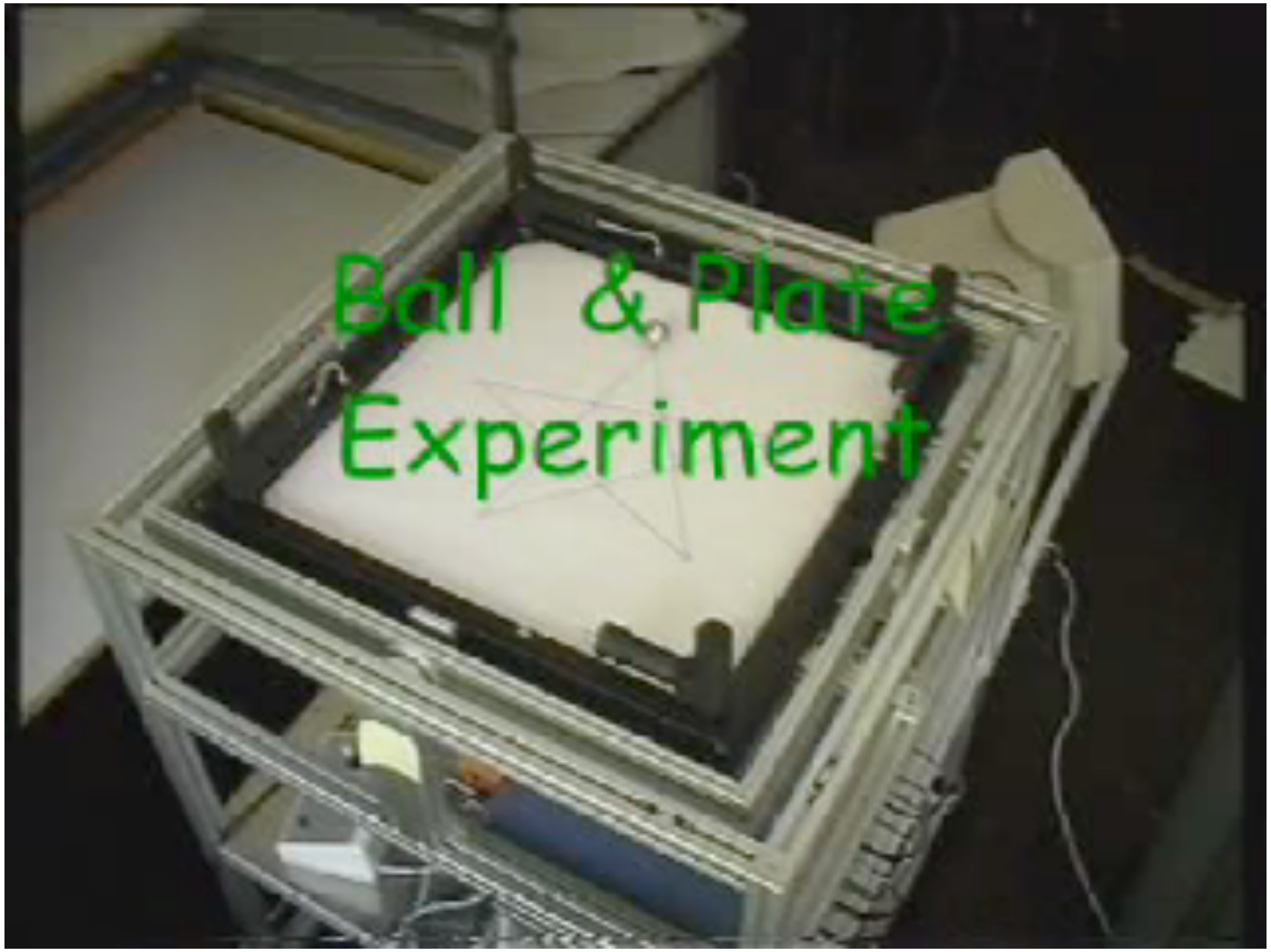
Manipulated inputs:
- reactant concentration C_{Ai} in feed
- coolant temperature T_c

Controlled outputs:
- reactant concentration C_{Ai} in vessel
- vessel temperature T

www.abacusengg.in

Control systems example: Ball and plate

Control systems example: Ball and plate



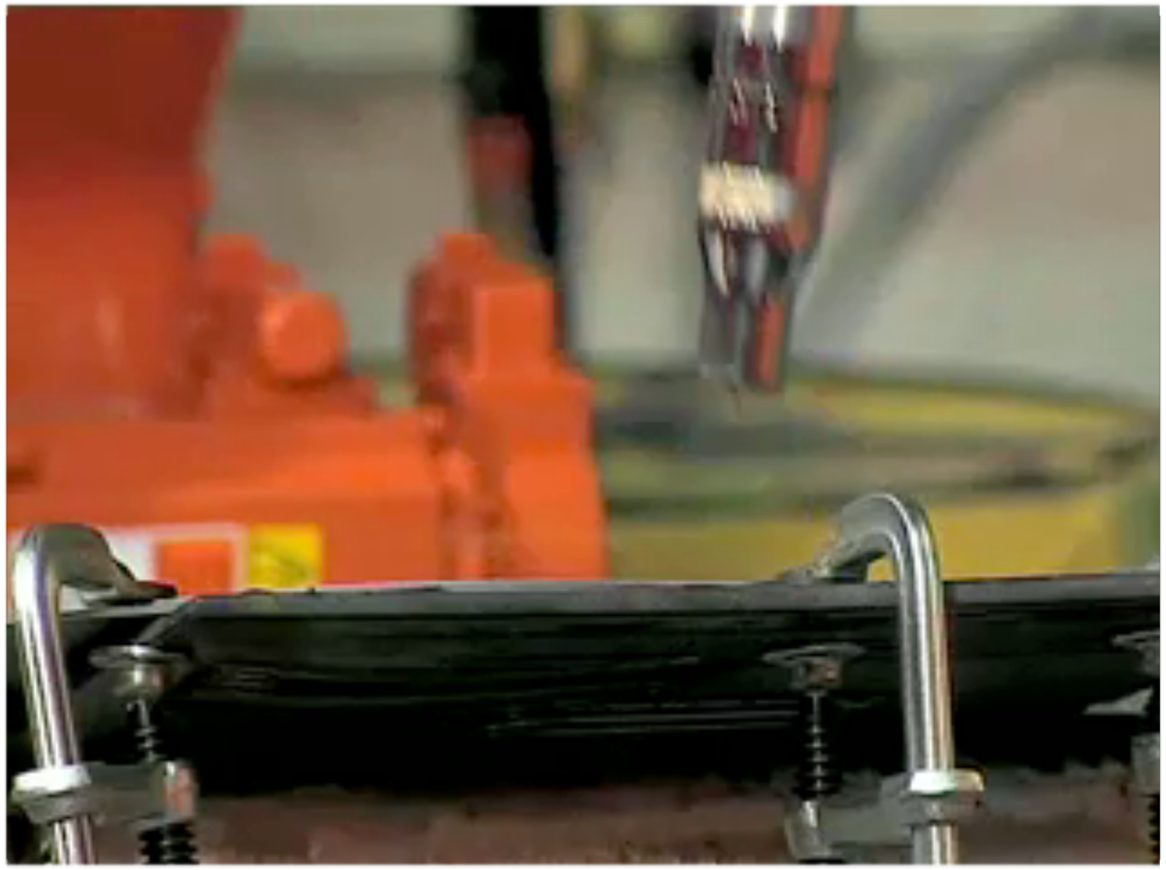
control station

commands →

← measurements

ball & plate

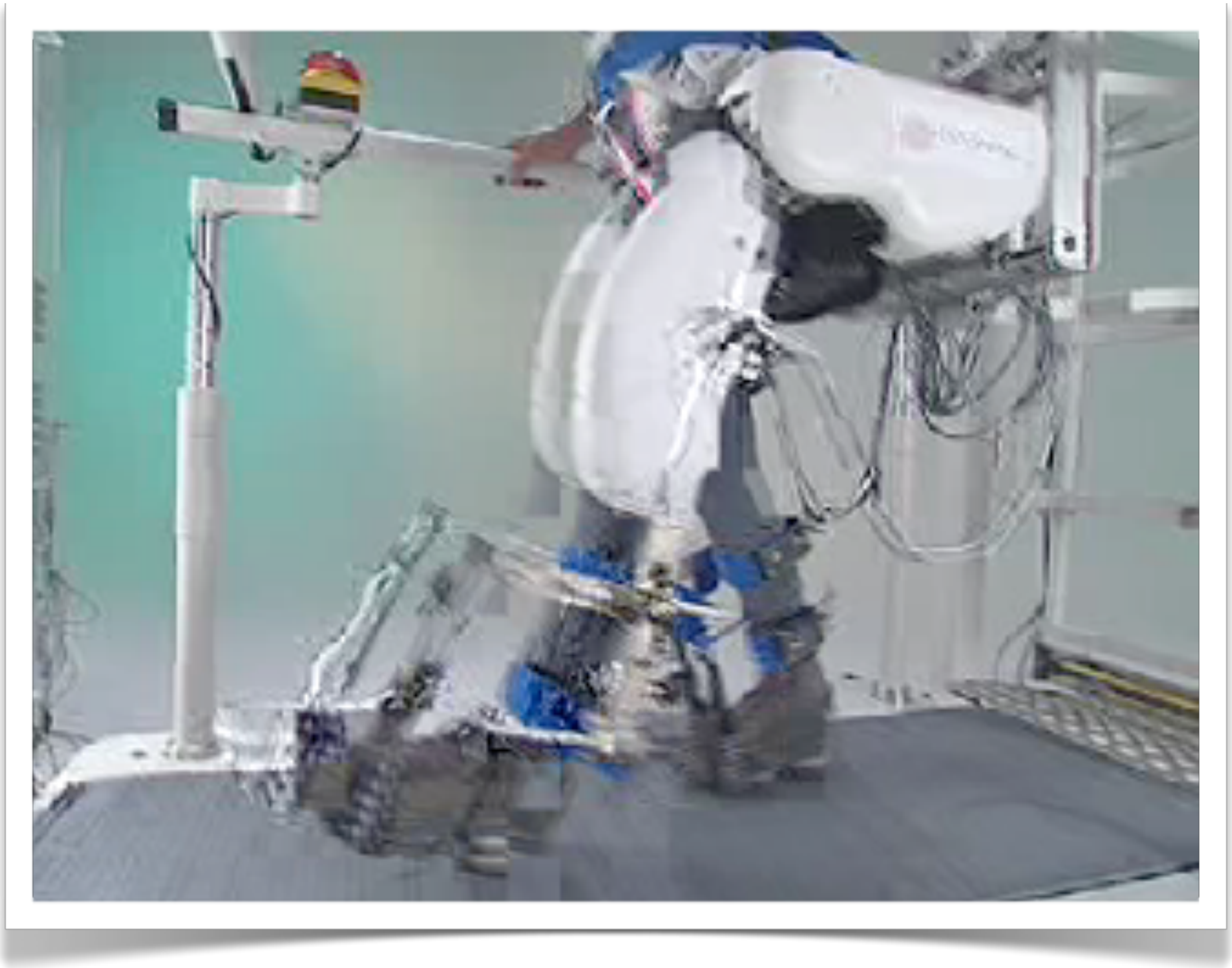
Robotics



Robotics

- Snake Robot (Biorobotics and Biomechanics Lab, Technion, Israel)

Functional electrical stimulation



Aeronautics and aerospace

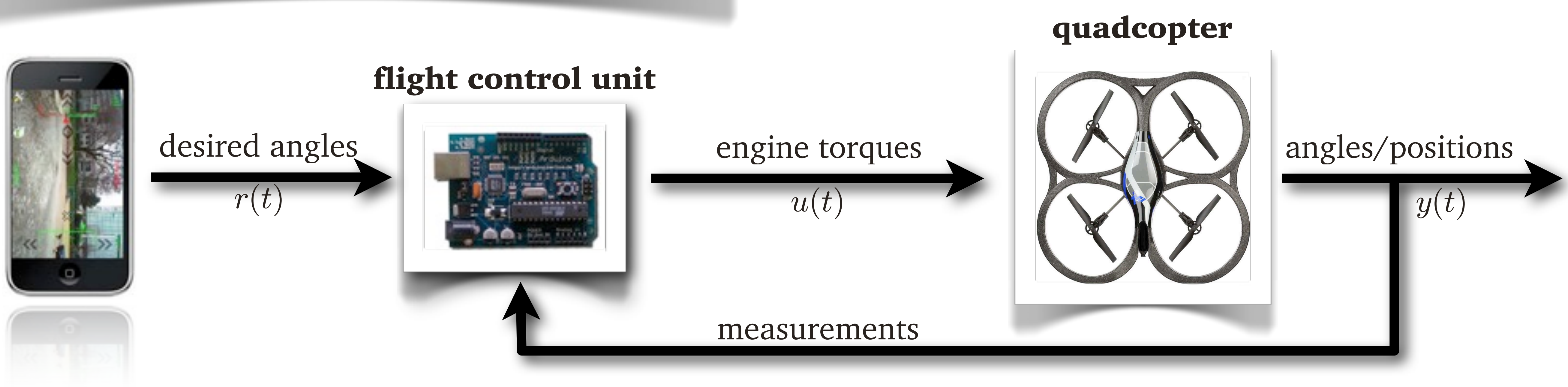
Control systems heavily used in:

- Aircrafts (roll, pitch, yaw)
- Helicopters
- Satellites
- ...

Aeronautics and aerospace. Quadcopter example

Parrot AR Drone

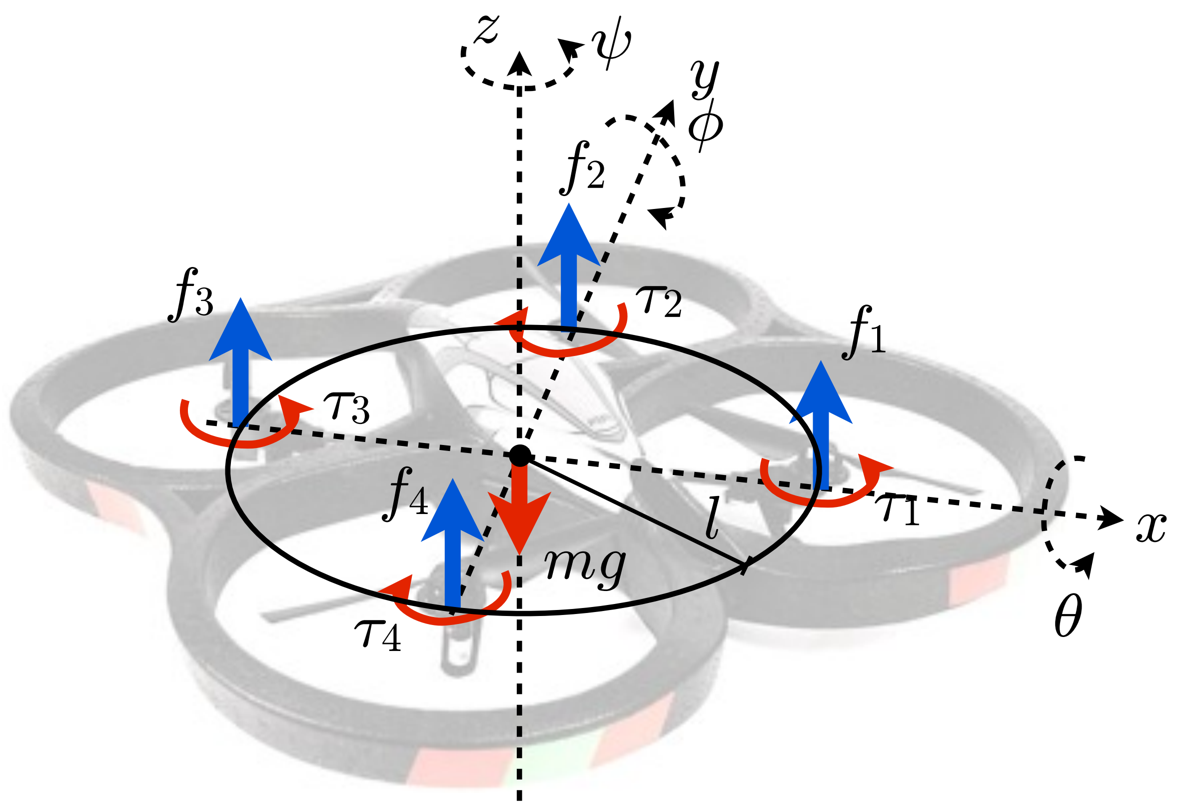
- 6 DoF Inertial Measurement Unit (3 accelerometers, 3 gyros)
- 468MHz ARM9 CPU running Linux
- Ultrasound altimeter/ground detector
- Two cameras:
  - Vision-based stabilization (176x144)
  - Wifi streaming (640x480)



Aeronautics and aerospace. Quadcopter example

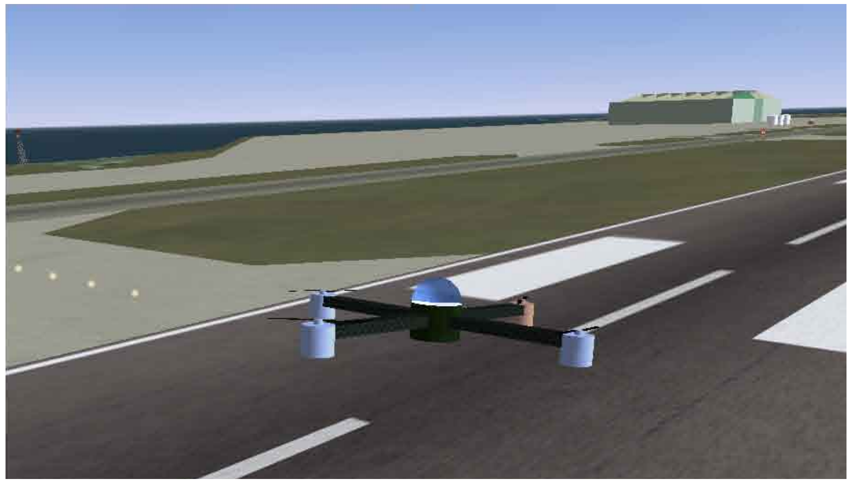
- Manipulated inputs
  - total force u
  - torques $\tilde{\tau}_\theta,\ \tilde{\tau}_\phi,\ \tilde{\tau}_\psi$
- Outputs to regulate

$$x,\ y,\ z,\ \theta,\ \phi,\ \psi,\ \dot{x},\ \dot{y},\ \dot{z},\ \dot{\theta},\ \dot{\phi},\ \dot{\psi}$$

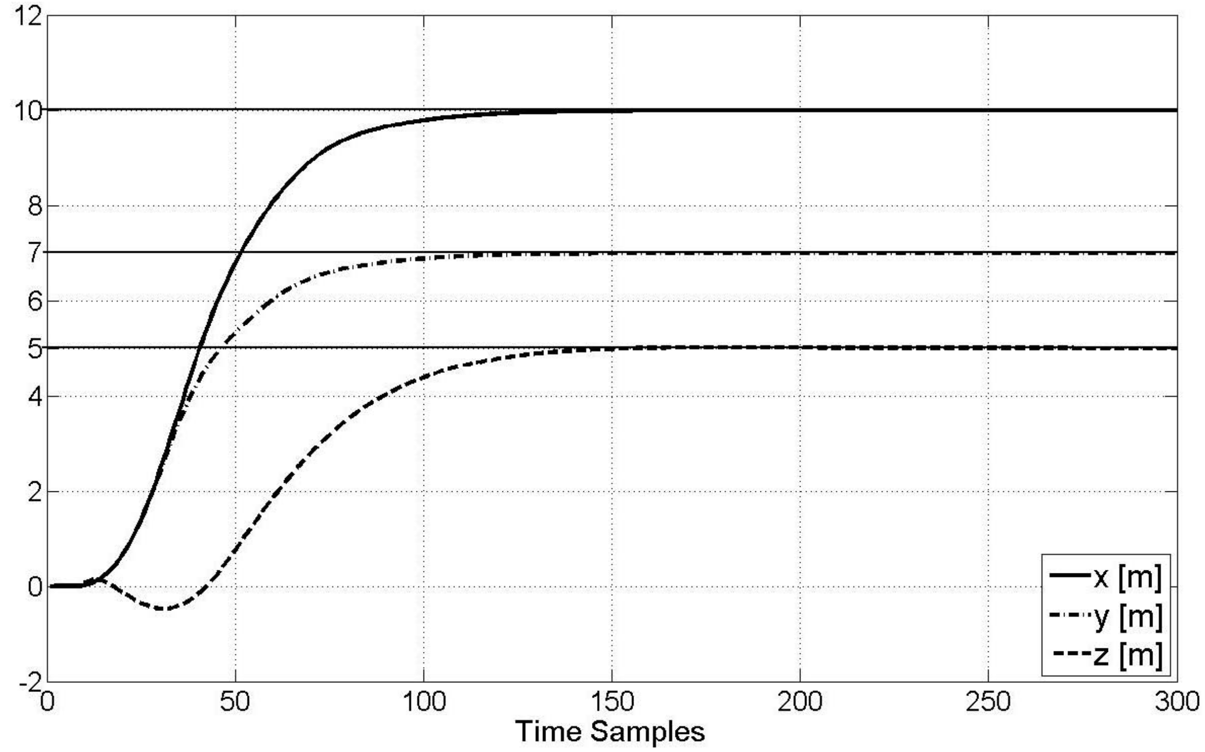


$$\begin{aligned}
m\ddot{x} &= -u\sin\theta - \beta\dot{x}\\
m\ddot{y} &= u\cos\theta\sin\phi - \beta\dot{y}\\
m\ddot{z} &= u\cos\theta\cos\phi - mg - \beta\dot{z}\\
\ddot{\theta} &= \tilde{\tau}_\theta\\
\ddot{\phi} &= \tilde{\tau}_\phi\\
\ddot{\psi} &= \tilde{\tau}_\psi
\end{aligned}$$

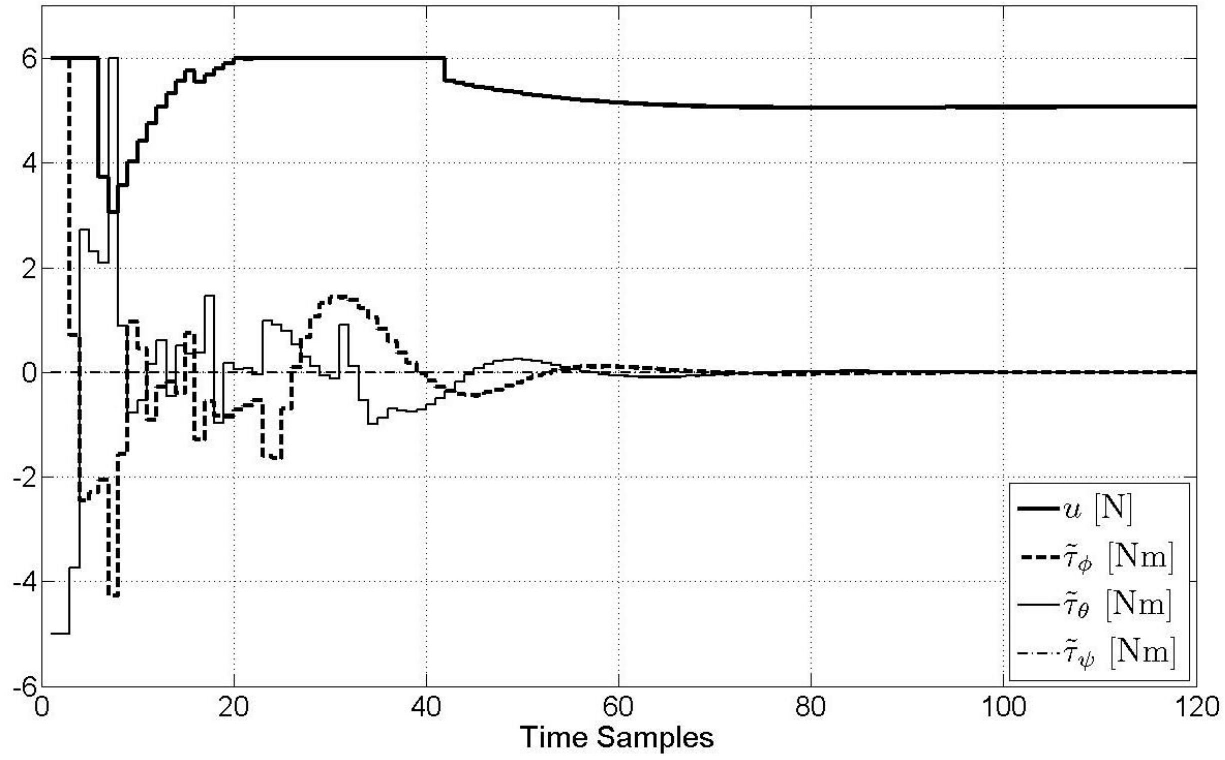
Aeronautics and aerospace. Quadcopter example



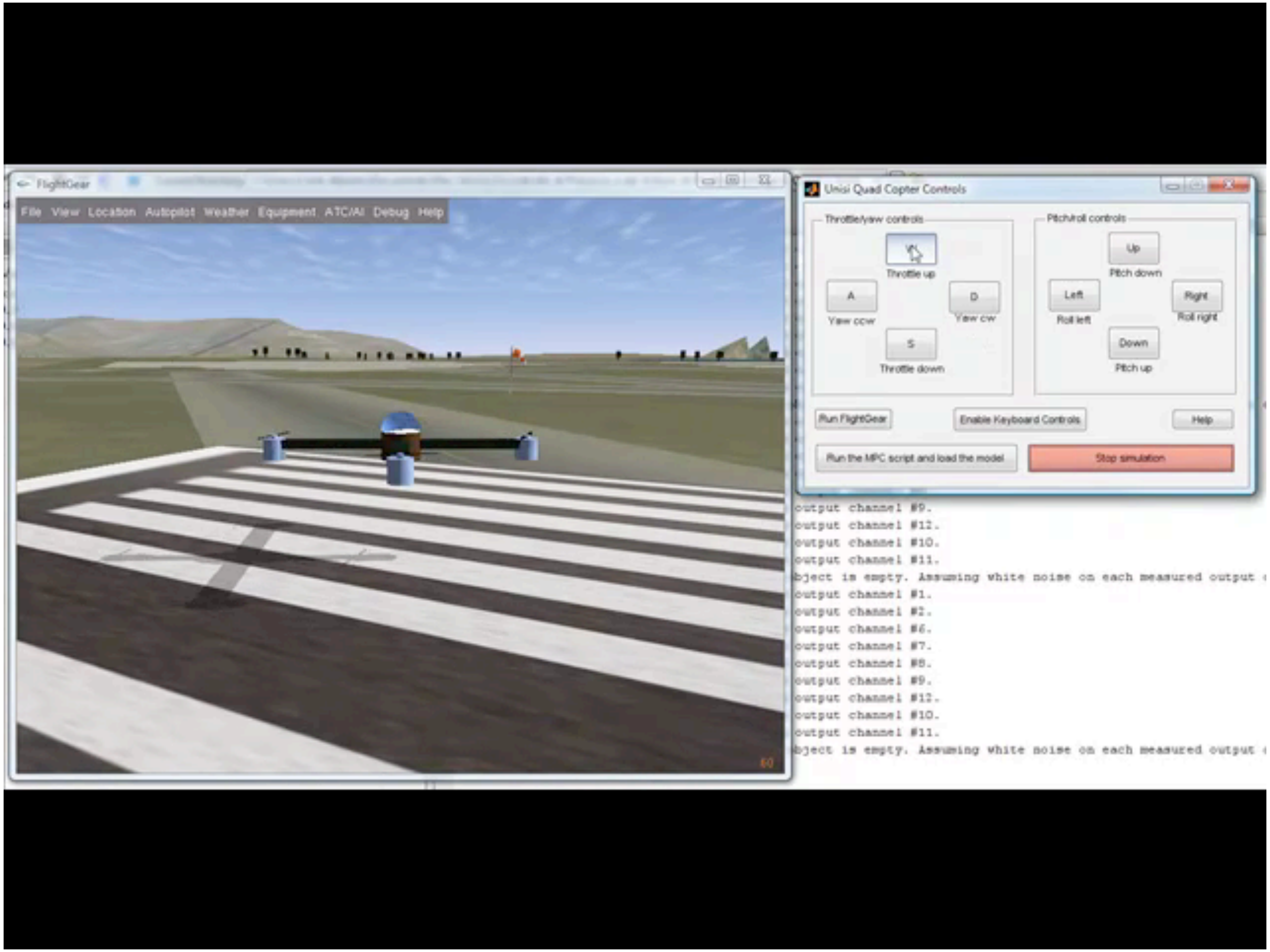
Outputs: position (x,y,z)



Inputs: torques and force

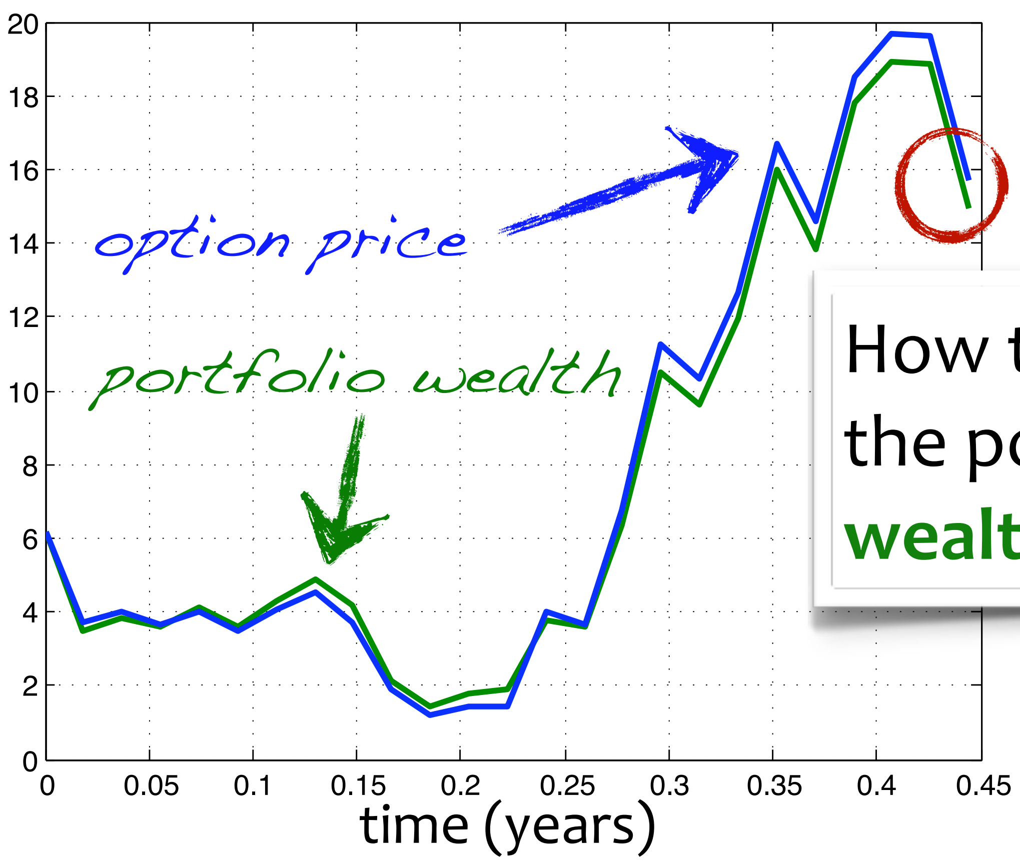


Aeronautics and aerospace. Quadcopter example

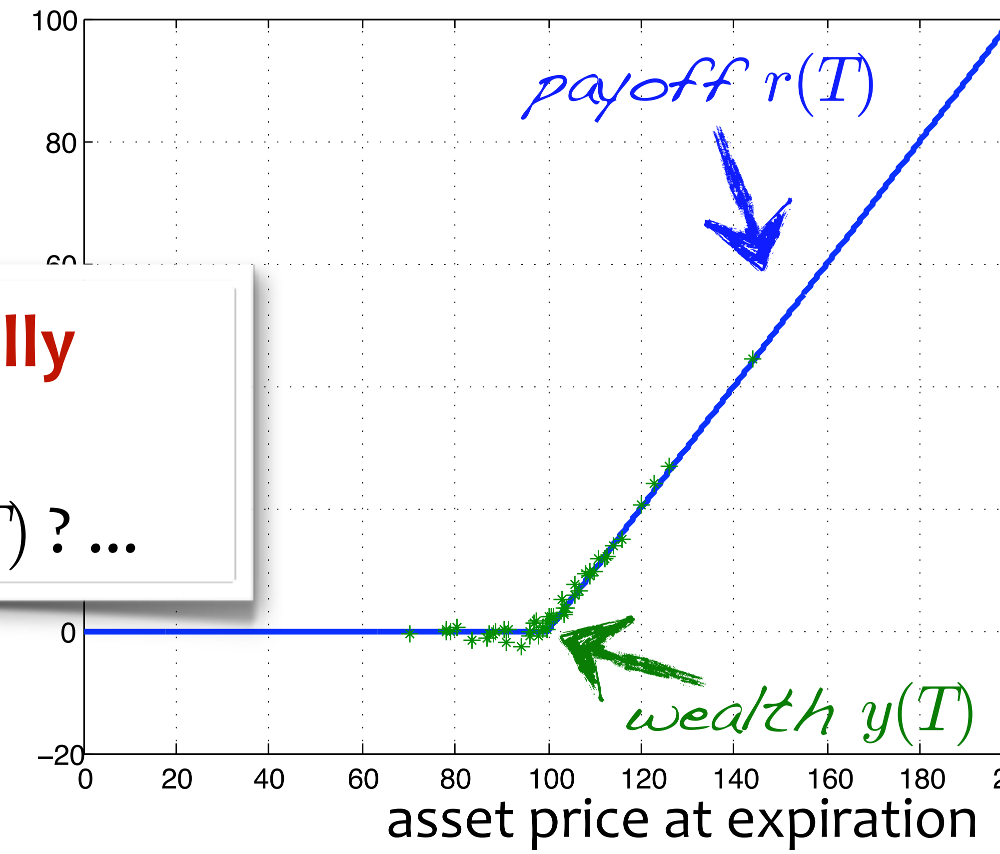


Financial engineering. Example: Option hedging

- The financial institution sells a synthetic option to a customer and gets $y(0)$ (€)
- Such money is used to create a portfolio $y(t)$ of underlying assets (e.g. stocks) whose quantities at time t are $u_1(t)$, $u_2(t)$, ..., $u_n(t)$
- At the expiration date T, the option is worth the payoff $r(T)$ = wealth (€) to be returned to the customer

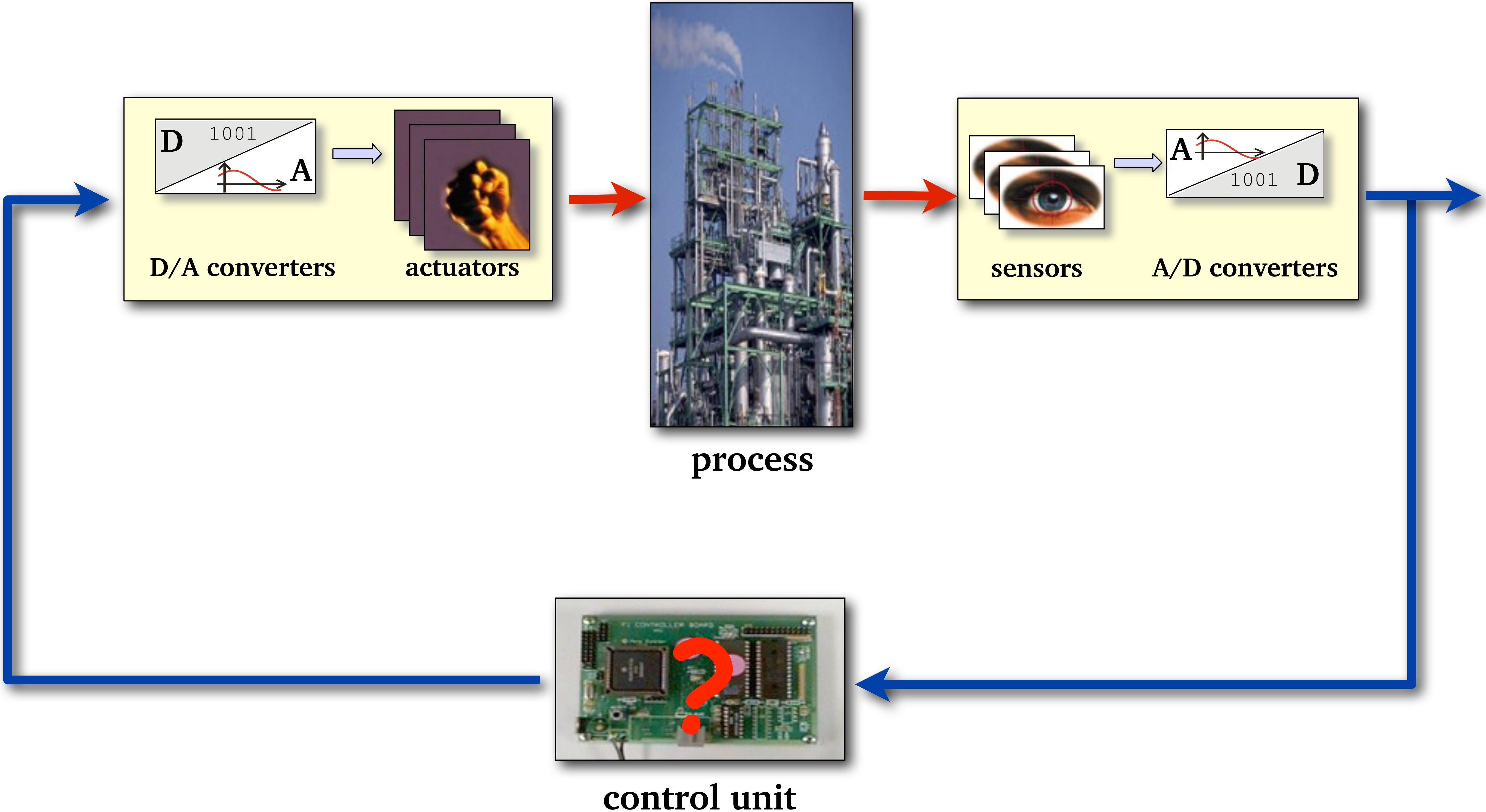


How to **adjust dynamically** the portfolio so that **wealth** $y(T) =$ **payoff** $r(T)$? ...



MPS CAPITAL SERVICES

A typical control system



Most used sensors and actuators in control systems

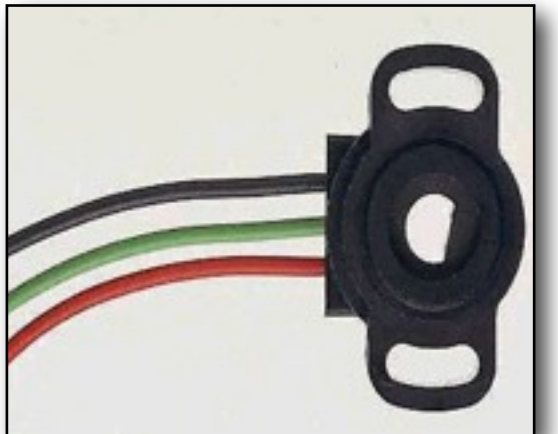
Sensors

- temperature
- pressure
- flow
- level
- velocity, position
- acceleration
- force (strain) / deformation

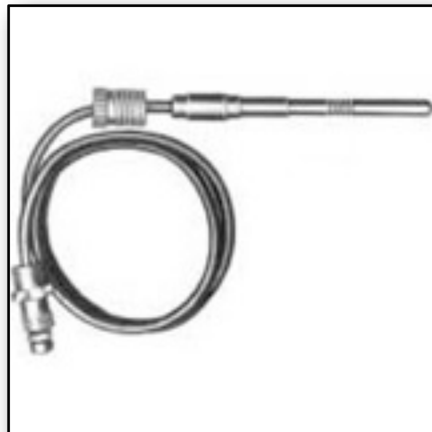
Actuators

- electrical motors (DC, brushless, step)
- pumps
- valves
- heaters

Sensors and actuators in control systems

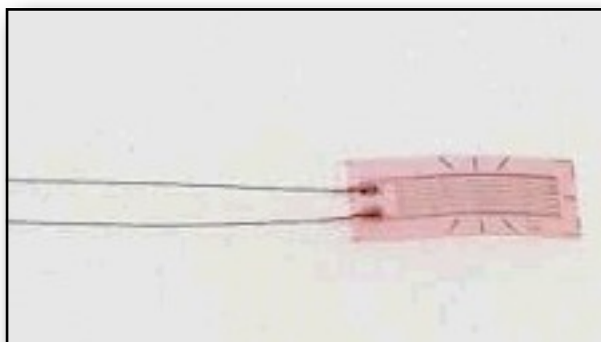


angular position



thermocouple

pressure sensor

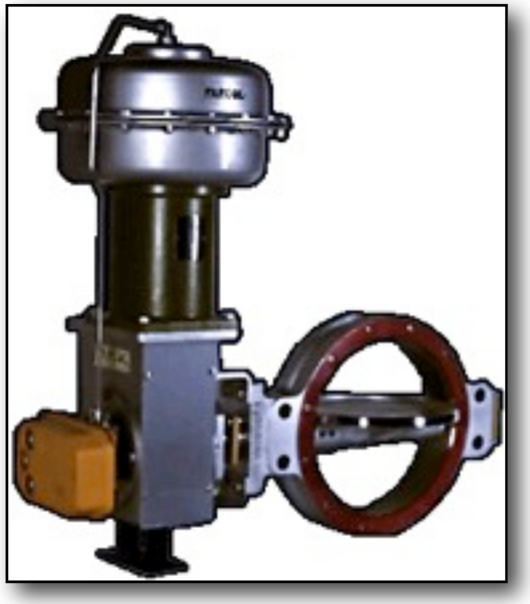


strain gage

liquid flow sensor

brushless motor

pump

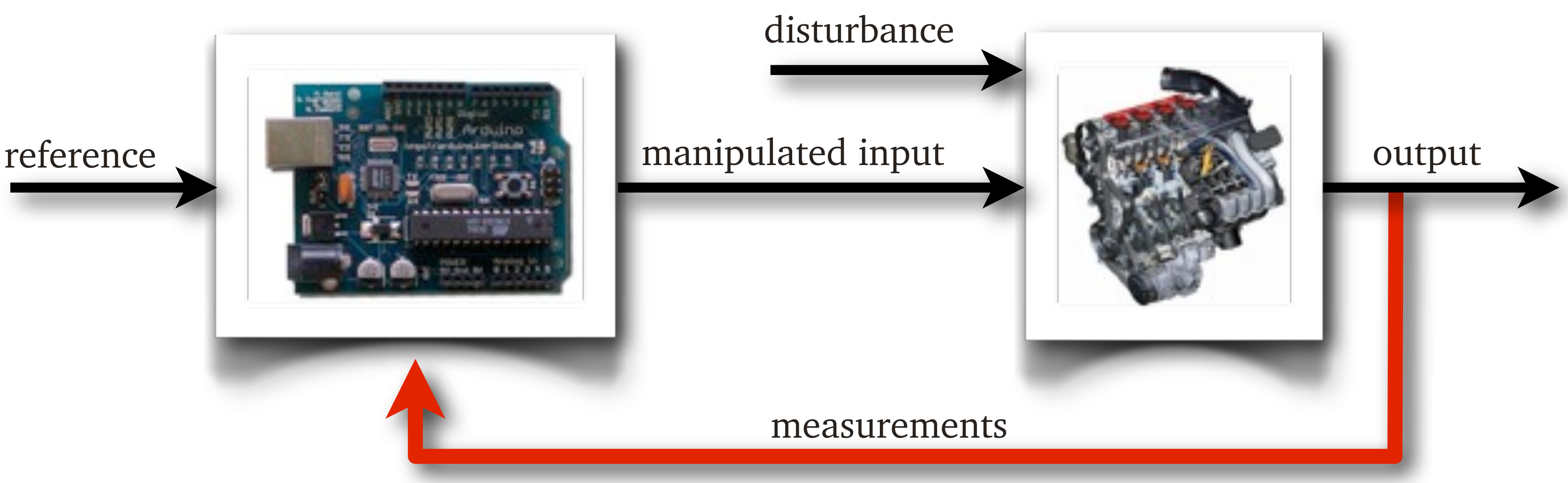


valve

Open-loop vs. closed-loop control

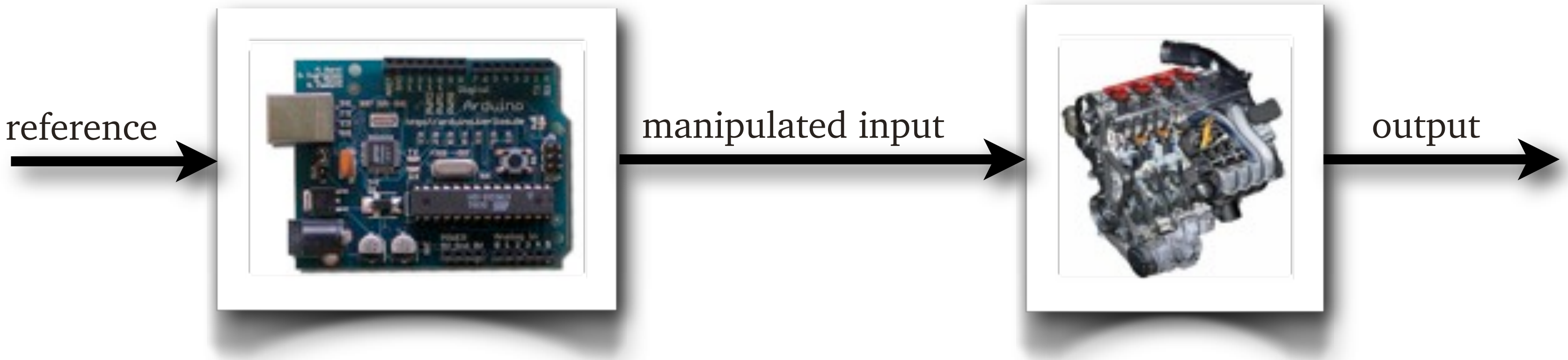
Closed-loop control ***(feedback control)***

Measurements of the output variables are *fed back* to the process through the controller



Open-loop control ***(feedforward control)***

The manipulated input variable is generated without measuring the output variable



How to design a (modern) control system

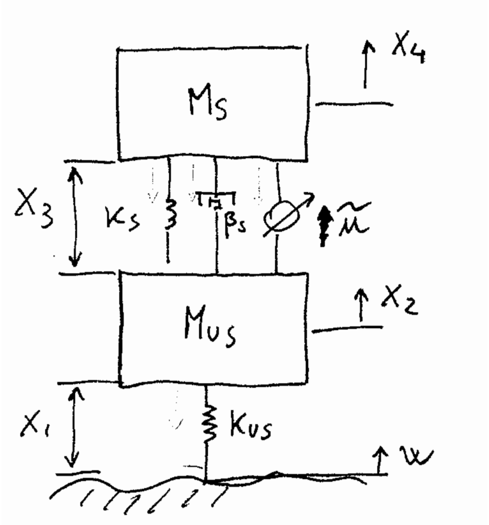
- Understand the **automation problem**:
  - Which variables can be *manipulated* by actuators ?
  - What are the *output* variables of interest ?
  - What should we *measure* ?
  - Which are the *disturbances* ?
- Get a reliable **simulation model**
- Get a simplified **mathematical model** of the main process dynamics
- Use design techniques to synthesize the **control algorithm**
- **Test** in simulation, **validate** on real process

Control design requires a *dynamical model* of the open-loop process

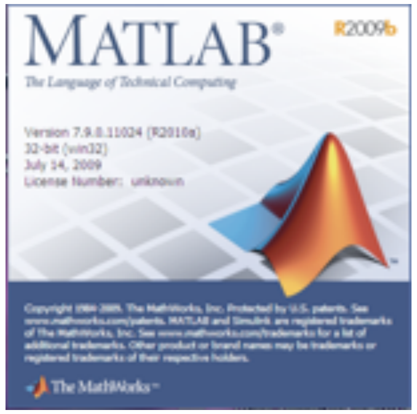
What you will learn in this course

- The tools to study the mathematical properties of dynamical systems (control theory is often called "*systems theory*")

- Building simple dynamical models of common physical processes



- Computer-aided tools for analysis, simulation, and control of dynamical systems (in MATLAB™)



What you will learn in this course

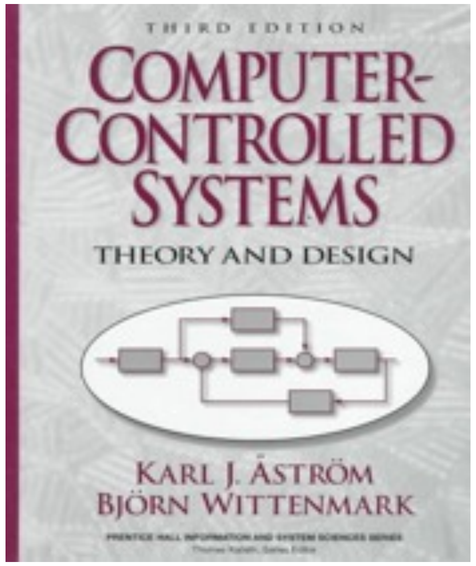
- Analysis of dynamical systems in continuous time (differential equations, Laplace transform, stability)
- Models of dynamical systems (electrical, mechanical, hydraulic,...)
- Analysis of dynamical systems in discrete-time (difference equations, Zeta transform)
- State-feedback control synthesis in the time domain (pole-placement)
- State estimation
- Output feedback control (dynamic compensator)
- Integral action

Automatic Control 2: Frequency-domain analysis and synthesis (loop shaping) and more advanced control techniques (optimal, nonlinear, predictive, ...)

Suggested references

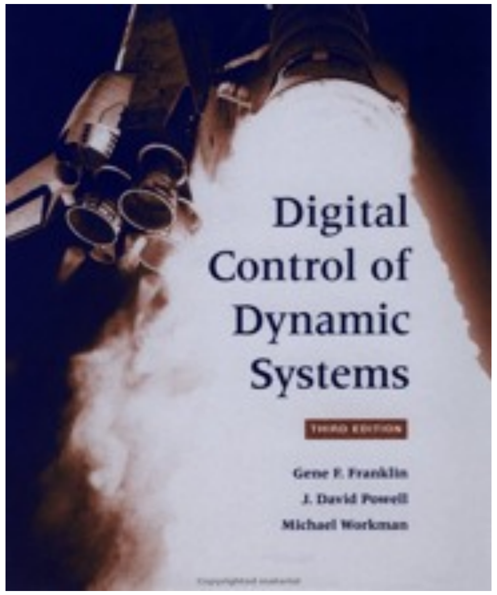
- A. Bemporad - Lecture notes (what you're looking at right now ...)

(maybe enough ...)



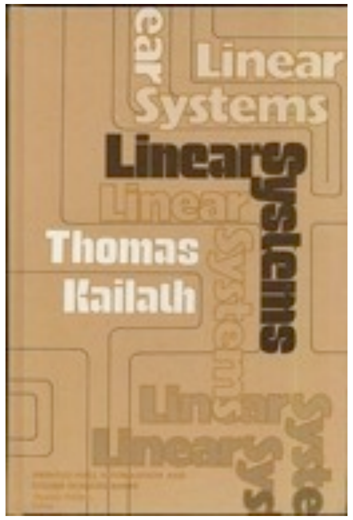
- K.J. Åström, B. Wittenmark, Computer-controlled Systems, Theory and Design, Prentice-Hall

(good classical textbook on digital control)



- G.F. Franklin, J.D. Powell, M. Workman "Digital Control of Dynamic Systems", Addison-Wesley Longman.

(good classical textbook on digital control)



- T. Kailath, "Linear Systems", Prentice-Hall

(advanced textbook for state-space concepts)

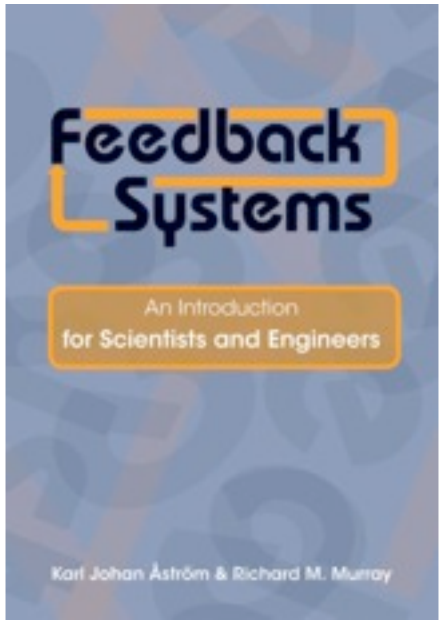
Suggested references

- E. Fornasini, G. Marchesini, "Appunti di Teoria dei Sistemi" , Edizioni Libreria Progetto (in Italian)

(advanced textbook for state-space concepts)

- P. Bolzern, R. Scattolini, N. Schiavoni, "Fondamenti di controlli automatici" (in Italian)

(good textbook for frequency-domain)



- K.J. Åström, R.M. Murray, "Feedback Systems: An Introduction for Scientists and Engineers", (available on-line for download)

(new textbook, plenty of examples)

Logistics

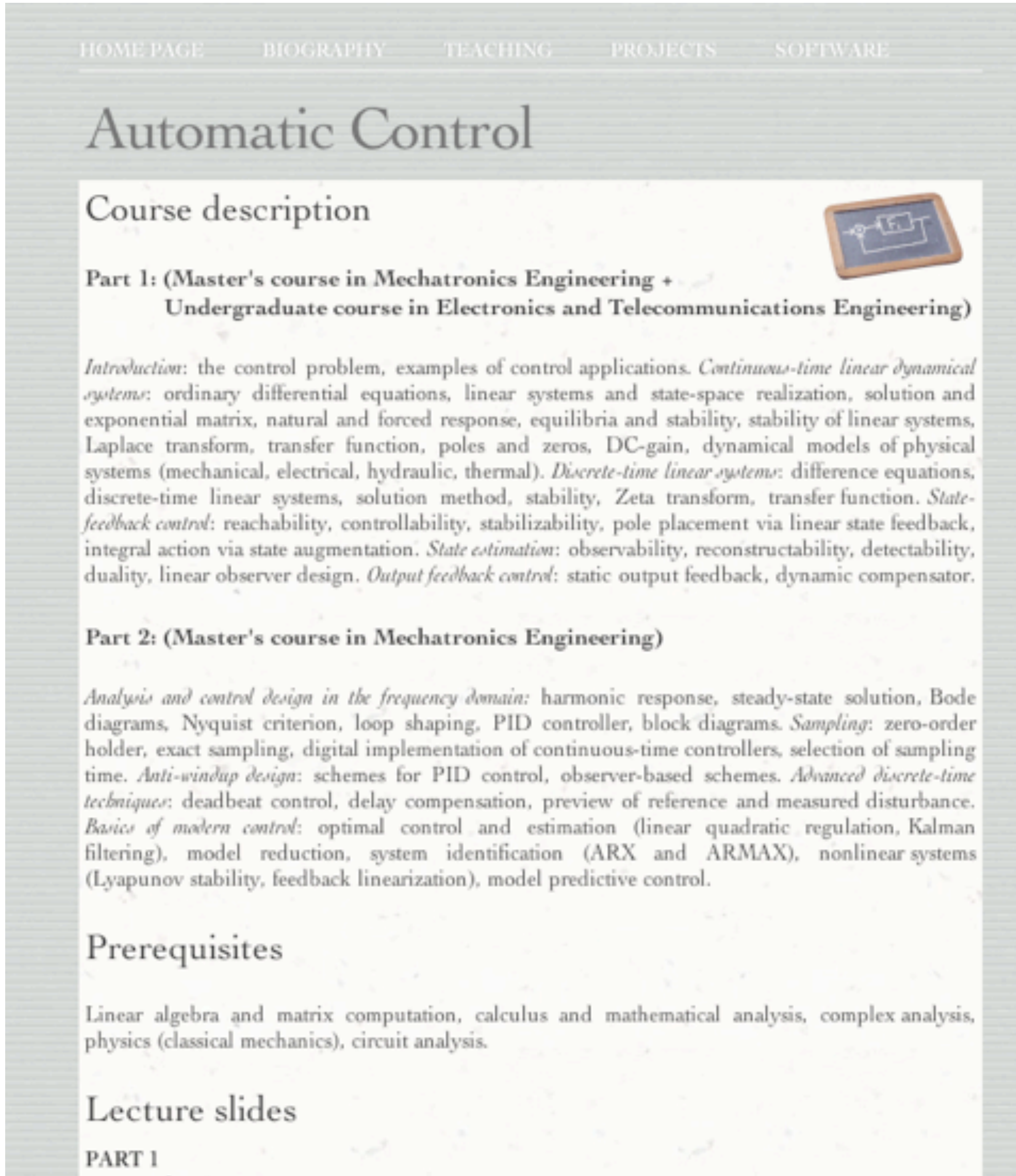
- Midterm exam: **April 21, 2011**. No expiration date.
  = Final exam of Automatic Control 1 (TLC)
  = Exam of AC2 for those elder mechatronic students that already passed AC1.

- Final exam: sometimes in June 2011 (AC1 + AC2).
  <u>Note</u>: *Submitting a new AC1 test automatically kills the midterm test* !

- Classroom exercises

- Classroom exercises in MATLAB™

Web site



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Automatic Control

Course description

Part 1: (Master's course in Mechatronics Engineering + Undergraduate course in Electronics and Telecommunications Engineering)

Introduction: the control problem, examples of control applications. *Continuous-time linear dynamical systems*: ordinary differential equations, linear systems and state-space realization, solution and exponential matrix, natural and forced response, equilibria and stability, stability of linear systems, Laplace transform, transfer function, poles and zeros, DC-gain, dynamical models of physical systems (mechanical, electrical, hydraulic, thermal). *Discrete-time linear systems*: difference equations, discrete-time linear systems, solution method, stability, Zeta transform, transfer function. *State-feedback control*: reachability, controllability, stabilizability, pole placement via linear state feedback, integral action via state augmentation. *State estimation*: observability, reconstructability, detectability, duality, linear observer design. *Output feedback control*: static output feedback, dynamic compensator.

Part 2: (Master's course in Mechatronics Engineering)

Analysis and control design in the frequency domain: harmonic response, steady-state solution, Bode diagrams, Nyquist criterion, loop shaping, PID controller, block diagrams. *Sampling*: zero-order holder, exact sampling, digital implementation of continuous-time controllers, selection of sampling time. *Anti-windup design*: schemes for PID control, observer-based schemes. *Advanced discrete-time techniques*: deadbeat control, delay compensation, preview of reference and measured disturbance. *Basics of modern control*: optimal control and estimation (linear quadratic regulation, Kalman filtering), model reduction, system identification (ARX and ARMAX), nonlinear systems (Lyapunov stability, feedback linearization), model predictive control.

Prerequisites

Linear algebra and matrix computation, calculus and mathematical analysis, complex analysis, physics (classical mechanics), circuit analysis.

Lecture slides

PART 1

Introduction

http://www.ing.unitn.it/~bemporad/teaching/ac

Logistics

- Lectures

Wednesday	10.30	13.00	Room A102
Thursday	10.30	13.00	Room A102
Friday	10.30	13.00	Room A102

- Appointments for questions & explanations: send an email

Teaching assistants:

Matteo Rubagotti http://www.ing.unitn.it/~rubagott
Sergio Trimboli http://www.ing.unitn.it/~trimboli

Questions ???