CDS 101: Lecture 1
Introduction to Feedback and Control

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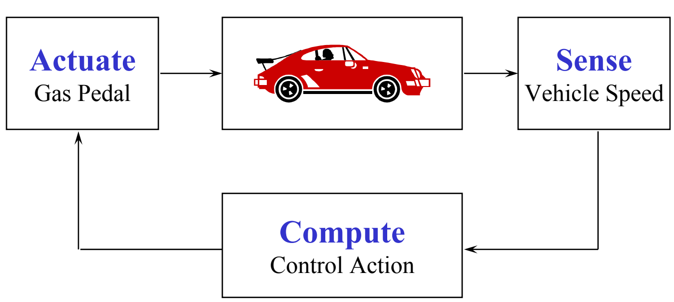
30 September 2002

Goals:
- Define what a control system is and learn how to recognize its main features
- Describe what control systems do and the primary principles of control
- Give an overview of CDS 101/110; describe course structure and administration

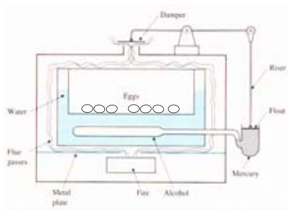
Reading (available on course web page):
- R. M. Murray (ed), *Control in an Information Rich World*, Chapter 2
- "For the Spy in the Sky, New Eyes", NY Times, June 2002.
- Optional: K. J. Astrom, *Control Systems Design*, Chapter 1

Control = Sensing + Computation + Actuation = *Feedback*



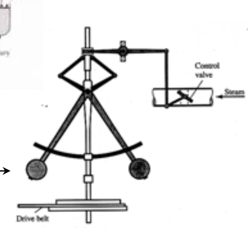
Goals: Stability, Performance, Robustness

Early Uses of Feedback and Control



Pre-1700

- Water clock (~300 BC, Alexandria), float valves
- Egg incubator (Drebbel, 1620) - control temperature



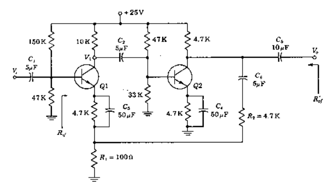
Balls fly out as speed increases, closing valve

Watt Governor (1788)

- Regulate speed of steam engine
- Reduce effects of variations in load (disturbance rejection)

Feedback Amplifiers (1920s)

- Laid mathematical foundations for classical control
- Black's use of negative feedback to reduce uncertainty (robustness)



Modern Engineering Applications

Flight Control Systems

- Modern commercial and military aircraft are "fly by wire"
- Autoland systems, unmanned aerial vehicles (UAVs) are already in place

Robotics

- High accuracy positioning for flexible manufacturing
- Remote environments: space, sea, non-invasive surgery, etc.

Chemical Process Control

- Regulation of flow rates, temperature, concentrations, etc.
- Long time scales, but only crude models of process

Communications and Networks

- Amplifiers and repeaters
- Congestion control of the Internet
- Power management for wireless communications

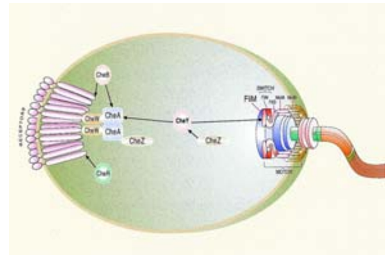
Automotive

- Engine control, transmission control, cruise control, climate control, etc
- Luxury sedans: 12 control instruments in 1976, 42 in 1988, 67 in 1991

AND *MANY* MORE...

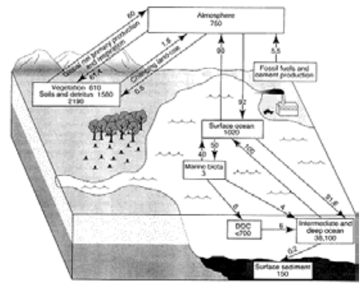
Other Applications of Feedback

Biological Systems
- Physiological regulation (homeostasis)
- Genetic regulatory networks



Environmental Systems
- Microbial ecosystems
- Global carbon cycle

Quantum Systems
- Quantum information processing
- Quantum measurement



Financial Systems
- Markets and exchanges
- Supply and service chains

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Two Main Principles of Control

Robustness to Uncertainty through Feedback
- Feedback allows high performance in the presence of uncertainty
- Example: repeatable performance of amplifiers with 5X component variation
- Key idea: accurate *sensing* to compare actual to desired, correction through *computation* and *actuation*

Design of Dynamics through Feedback
- Feedback allows the dynamics of a system to be modified
- Example: stability augmentation for highly agile, unstable aircraft
- Key idea: interconnection gives *closed loop* that modifies natural behavior

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Example #1: Balancing an Inverted Pendulum

Passive Control

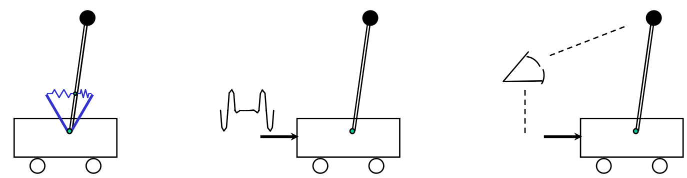
- Make structural modifications to change the plant dynamics
- Use this technique whenever it is a viable option: cheap, robust

Open Loop Control

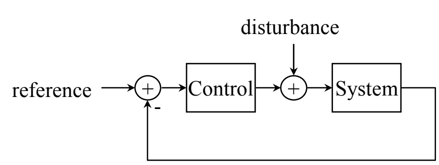
- Exploit knowledge of system dynamics to compute appropriate inputs
- Requires *very* accurate model of plant dynamics in order to work well

Active (Feedback) Control

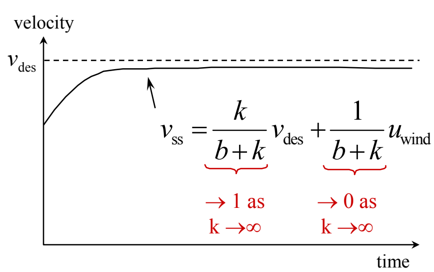
- Use sensors and actuators connected by a computer to modify dynamics
- Allows uncertainty and noise to be taken into account



Example #2: Cruise Control



$$m\dot{v} = -bv + u_{engine} + u_{hill}$$
$$u_{engine} = k(v_{des} - v)$$



$$v_{ss} = \underbrace{\frac{k}{b+k}}_{\to 1 \text{ as } k \to \infty} v_{des} + \underbrace{\frac{1}{b+k}}_{\to 0 \text{ as } k \to \infty} u_{wind}$$

Stability/performance

- Steady state velocity approaches desired velocity as k → ∞
- Smooth response; no overshoot or oscillations

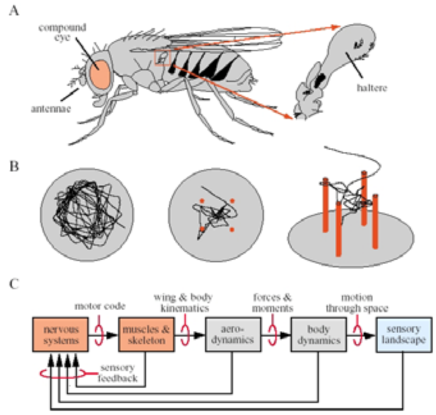
Disturbance rejection

- Effect of disturbances (hills) approaches zero as k → ∞

Robustness

- None of these results depend on the specific values of *b, m,* or *k* for *k* sufficiently large

Example #3: Insect Flight



Flight behavior in Drosophila

(a) Cartoon of the adult fruit fly showing the three major sensor strictures used in flight: eyes, antennae, and halteres (detect angular rotations)

(b) Example flight trajectories over a 1 meter circular arena, with and without internal targets.

(c) Schematic control model of the flight system

[from CDS Panel Report, Sec 3.4. Figure courtesy of Michael Dickinson, Caltech.]

Sensing:	antennae, eye, halters
Actuation:	wings, legs, body
Computation:	brain, nervous system
Effect:	robust flight in a variety of environments; fault tolerance

More information:

- M. D. Dickinson, Solving the mystery of insect flight, *Scientific American,* June 2001
- CDS 101 seminar : Friday, 11 Oct 02

Example #4: Congestion Control and the Internet

Transmission control protocol (TCP)

- Source: send packet to destination
- Source: resend packet if no ACK rec'd
- Destination: ACK received packets
- Destination: reassemble packets
- Source: Adjust rate based on loss rate

Internet router operation:

- Receive packet from input link; place at end of queue, if not full
- Transmit packet from head of queue to next router on path
- Update route table based on link status

Sensing:	data, ACK packets
Actuation:	transmit rate, router paths
Computation:	src, dst, router processors
Effect:	high speed data transmission, tolerant of link failures

More information:

- www.howstuffworks.com
- CDS 101 seminar: Friday, 25 Oct 02

Example #5: RoboCup

RoboCup competition

- 5 on 5 robot teams
- Completely autonomous
- Overhead vision system
- Centralized computer
- Radio links to robots

Movie courtesy Raff D'Andrea (Cornell)

More info at www.robocup.org

Sensing: overhead camera system, wheel angle encoders
Actuation: motor torques, kicker mechanism
Computation: central computer + vehicle microcomputers
Effect: agile motion in dynamic environment; world championship win

Control Tools

Modeling

- Input/output representations for subsystems + interconnection rules
- System identification theory and algorithms
- Theory and algorithms for reduced order modeling + model reduction

Analysis

- Stability of feedback systems, including robustness "margins"
- Performance of input/output systems (disturbance rejection, robustness)

Synthesis

- Constructive tools for design of feedback systems
- Constructive tools for signal processing and estimation

MATLAB Toolboxes

- SIMULINK
- Control System
- Neural Network
- Data Acquisition
- Optimization
- Fuzzy Logic
- Robust Control
- Instrument Control
- Signal Processing
- LMI Control
- Statistics
- Model Predictive Control
- System Identification
- μ-Analysis and Synthesis

Course Administration


CALIFORNIA INSTITUTE OF TECHNOLOGY
Control and Dynamical Systems

CDS 101 - Principles of Feedback and Control
CDS 110 - Introductory Control Theory
ChE 105 - Process Control
Fall 2002

Instructor
R. Murray, 107 Steele
murray@cds.caltech.edu

Co-instructors
M. Dickinson
E. Klavins
H. Mabuchi
D. MacMartin

Teaching Assistants
Sean Humbert (head TA), jshumber@cds
Tim Chung, Lars Cremean,
Zhipu Jin, Shreesh Mysore
Office hours: Fridays, 3-5 pm, 135 Steele

Lectures
M2-3, W1-3; 102 Steele
F2-3, 102 Steele (optional)

CDS 101 vs CDS110a/ChE 105 CDS 101 is a 6 unit (2-0-4) class intended for advanced students in science and engineering who are interested in the principles and tools of feedback control, but not the analytical techniques for design and synthesis of control systems.

CDS 110a/Che 105 is a 9 unit class (3-0-6) that provide a traditional first course in control for engineers and applied scientists. It assumes a stronger mathematical background, including working knowledge of linear algebra, ODEs. Familiarity with complex variables (Laplace transforms, residue theory) is helpful but not required.

Lectures The main course lectures are on Mondays from 2-3 pm and Wednesdays from 1-3 pm in 102 Steele. CDS 101 students are not required to attend the Wednesday lectures, although they are welcome to do so. In addition, optional lectures will be held on Fridays from 2-3 pm in 102 Steele on supplemental topics. The schedule for these optional lectures is given below.

Grading The final grade will be based on homework sets, a midterm exam and a final exam.

- Homework: 50%
  Homework sets will be handed out weekly and due on Mondays by 5 pm to the box outside of 102 Steele. *Late homework will not be accepted without* **prior** *permission from the instructor.*
- Midterm exam: 20%
  A midterm exam will be handed out at the beginning of midterms week (30 Oct) and due at the end of the midterm examination period (5 Nov). The midterm exam will be open book and computers will be allowed (though not required).
- Final exam: 30%
  The final exam will be handed out on the last day of class due at the end of finals week. It will be an open book exam and computers will be allowed (though not required).

  For all students who attend the office hours at least once in the first three weeks of class, if your grade on the final is higher than your homework and midterm average, the final will be used to determine your course grade.

Homework policy Collaboration on homework assignments is encouraged. You may consult outside reference materials, other students, the TA, or the instructor. All solutions that are handed in should reflect your understanding of the subject matter at the time of writing.

Course syllabus
- Instructional staff
- CDS 101 vs CDS 110ab/ChE 105
- Lectures
- Grading
- Homework policy
- Course text and references
- Office and library hours
- Class homepage
- Software
- Course outline

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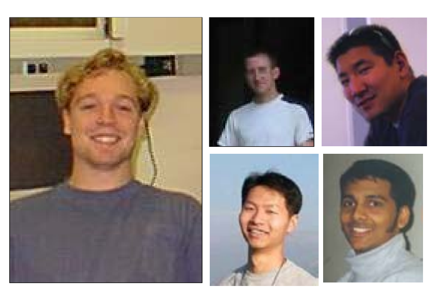
Instructional Staff

Lecturer: Richard Murray (CDS)
- Overall course management

Co-Instructors
- Michael Dickinson (BE)
- Eric Klavins (CS)
- Hideo Mabuchi (Ph)
- Doug MacMartin (CDS)

Head TA: Sean Humbert (CDS)
- Coordinate course infrastructure + TAs

TAs
- Lars Cremean (ME)
- Tim Chung (ME)
- Zhipu Jin (EE)
- Shreesh Mysore (CDS)



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Mud Cards

Mud cards
- 3 x 5 cards distributed at each lecture
- Describe "muddiest" part of the lecture
- Turn in cards at end of class
- Responses posted on FAQ list by **8 pm** on the day of the lecture (make sure to look!)

What does closed loop mean? You used this term without defining it.

Class FAQ list
- Searchable database of responses to mud cards and other frequently asked questions in the class

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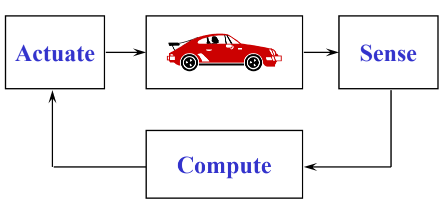
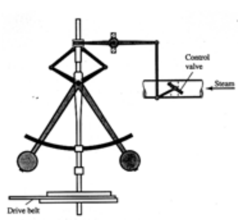
Summary: Introduction to Feedback and Control

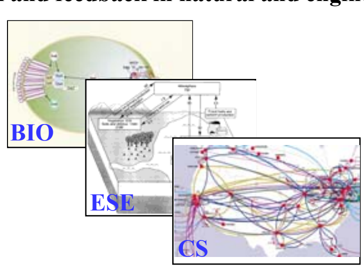


Control =
Sensing + Computation + Actuation

Feedback Principles
- Robustness to Uncertainty
- Design of Dynamics

Many examples of control and feedback in natural and engineered systems:





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