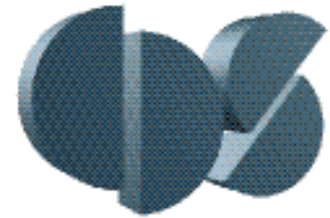




# CDS 101/110a: Lecture 1.1

## Introduction to Feedback & Control



**Richard M. Murray**

**29 September 2008**


### **Goals:**

- Give an overview of CDS 101/110/210: course structure & administration
- Define feedback systems and learn how to recognize main features
- Describe what control systems do and the primary principles of feedback

### **Reading:**

- Åström and Murray, *Feedback Systems: An Introduction for Scientists and Engineers*, Chapter 1 [30 min]

# Course Administration



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## CDS 101/110a, Fall 2008

CDS 101/110a Schedule

This is the homepage for CDS 101 (Analysis and Design of Feedback Systems) and CDS 110 (Introduction to Control Theory) for Fall 2008.

**Instructor**

- Richard Murray, murray@cds.caltech.edu
- Doug MacMynowski, macmardg@cds.caltech.edu
- Lectures: MWF, 2-3 pm, 74 JRG
- Office hours: Fridays, 3-4 pm (by appt)
- Prior years: [FA03](#), [FA04](#), [FA06](#), [FA07](#)

**Teaching Assistants**

- Julia Bromberg
- Luis Soto + TBD
- Office hours: 11-12:30 pm, 74 JRG

**Course Ombuds**

- TBD

**Announcements**

- 21 Aug 08: created course homepage

**Course Syllabus**

CDS 101/110 provides an introduction to feedback and control. Basic principles of feedback and its use as a tool for altering the dynamics of systems and managing uncertainty. Key themes throughout the course will include input/output response, model versus global behavior.

CDS 101 is a 6 unit (2-0-4) class intended for advanced students in engineering and applied sciences. CDS 110 is a 3 unit (3-0-6) class that provides a traditional first course in control theory for engineers and applied scientists. A strong mathematical background, including working knowledge of linear algebra and differential equations (Laplace transforms, residue theory) is helpful but not required.

### Course syllabus

- CDS 101 vs 110a vs 210
- Lectures, recitations
- Office hours
- Grading
- Homework policy (+ grace period)
- Course text and references
- Class homepage
- Software
- Course outline
- Signup sheet, mailing list
- Lecture MP3s
- Course load: keep track of hours
- Course ombuds: send e-mail by Tue evening to volunteer

# CDS 101/110 Instructional Staff

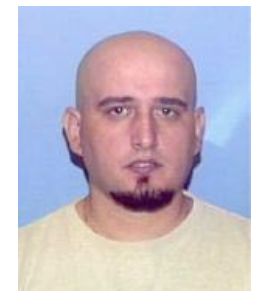
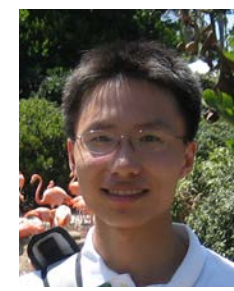
## Lecturer: Richard Murray (CDS)

- Professor of Control & Dynamical Systems
- Research in networked control systems, autonomous systems, biological systems



## Lecturer Doug MacMynowski (CDS)

- Senior Research Associated in CDS
- Research in climate modeling, fluid dynamics, and telescope control



## Head TA: Julia Braman

- ME, fault-tolerant control and verification

## TAs

- Shuo Han (EE) - bio-inspired flight control
- Gentian Buzi (CDS) - biological dynamics
- Max Merfeld (ME) - undergraduate
- Luis Soto (CDS) - ecosystems



# Mud Cards

## Mud cards

- 3 x 5 cards passed out at beginning of each lecture
- Describe “muddiest” part of the lecture (or other questions)
- 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!)

## Class FAQ list

- Responses to mud cards and other frequently asked questions in the class
- Previous FAQs available on AM wiki

## AMwiki

- Additional exercises, FAQs, examples

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

article discussion edit history

Create an account or log in

### CDS 101/110a, Fall 2006

CDS 101/110a Schedule Recitations **FAQ** **AM08**

This is the homepage for CDS 101 (Analysis and Design of Feedback Systems) and CDS 110 (Introduction to Control Theory) for Fall 2006.

**Instructor**

- Richard Murray, murray@cds.caltech.edu
- Lectures: MWF, 2-3 pm, 74 JRG
- Office hours: Fri, 3-4 pm (110 STL) & Sun, 6-8 pm (114 STL), TA Schedule
- Prior years: [FA03](#), [FA04](#)

**Teaching Assistants** (cds110-tas@cds)

- Mary Dunlop (head TA)
- Melvin Flores, Elisa Franco, Laura Lindzey, Ling Shi
- [Recitation schedule](#)

**Announcements**

- 27 Aug 06: web page created

**Course Syllabus**

CDS 101/110 provides an introduction to feedback and control in physical, biological, engineering, and information sciences. Basic principles of feedback and its use as a tool for altering the dynamics of systems and managing uncertainty. Key themes throughout the course will include input/output response, modeling and model reduction, linear versus nonlinear models, and local versus global behavior.

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

# What is Feedback?

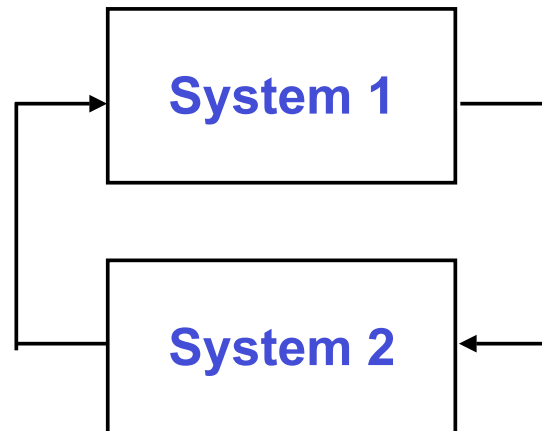
## Merriam Webster:

the return to the input of a part of the output of a machine, system, or process (as for producing changes in an electronic circuit that improve performance or in an automatic control device that provide self-corrective action) [1920]

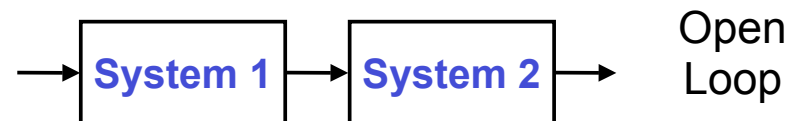
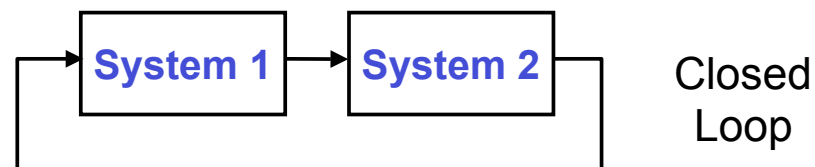
## Feedback = mutual interconnection of two (or more) systems

- System 1 affects system 2
- System 2 affects system 1
- Cause and effect is tricky; systems are mutually dependent

## Feedback is ubiquitous in natural and engineered systems



## Terminology

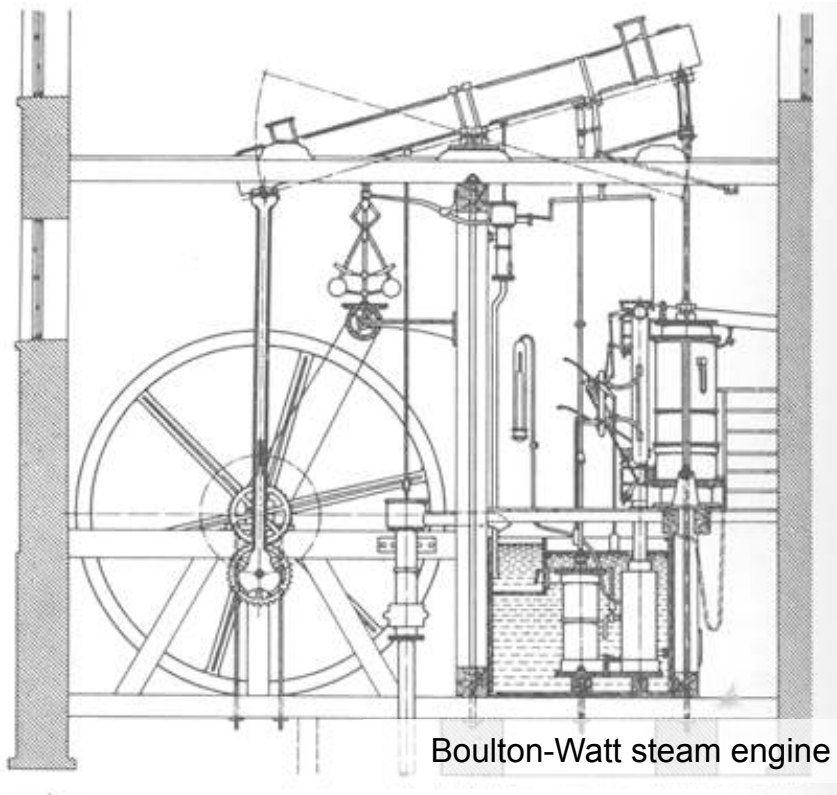




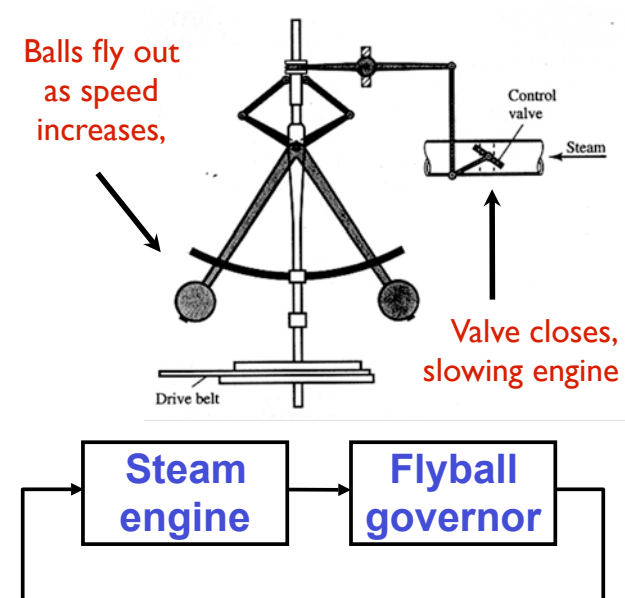
# Example #1: Flyball Governor

## “Flyball” Governor (1788)

- Regulate speed of steam engine
- Reduce effects of variations in load (disturbance rejection)
- Major advance of industrial revolution



Boulton-Watt steam engine



Courtesy Eric Klavins, U. Washington (2008)

# Other Examples of Feedback

## Biological Systems

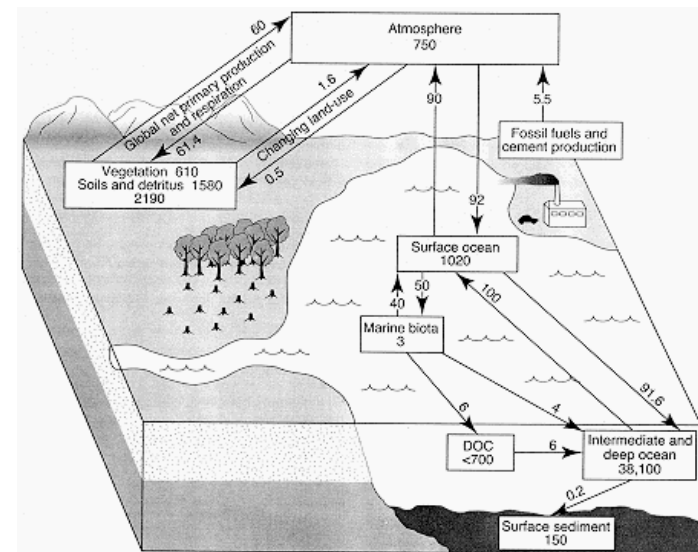
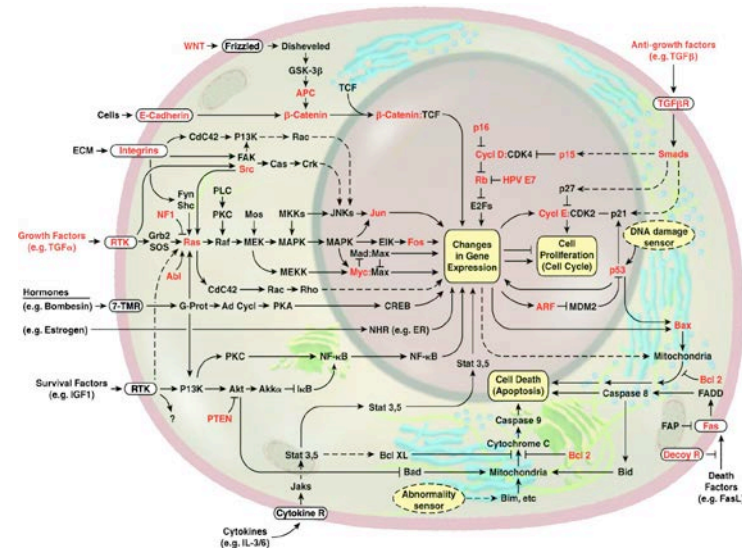
- Physiological regulation (homeostasis)
- Bio-molecular regulatory networks

## Environmental Systems

- Microbial ecosystems
- Global carbon cycle

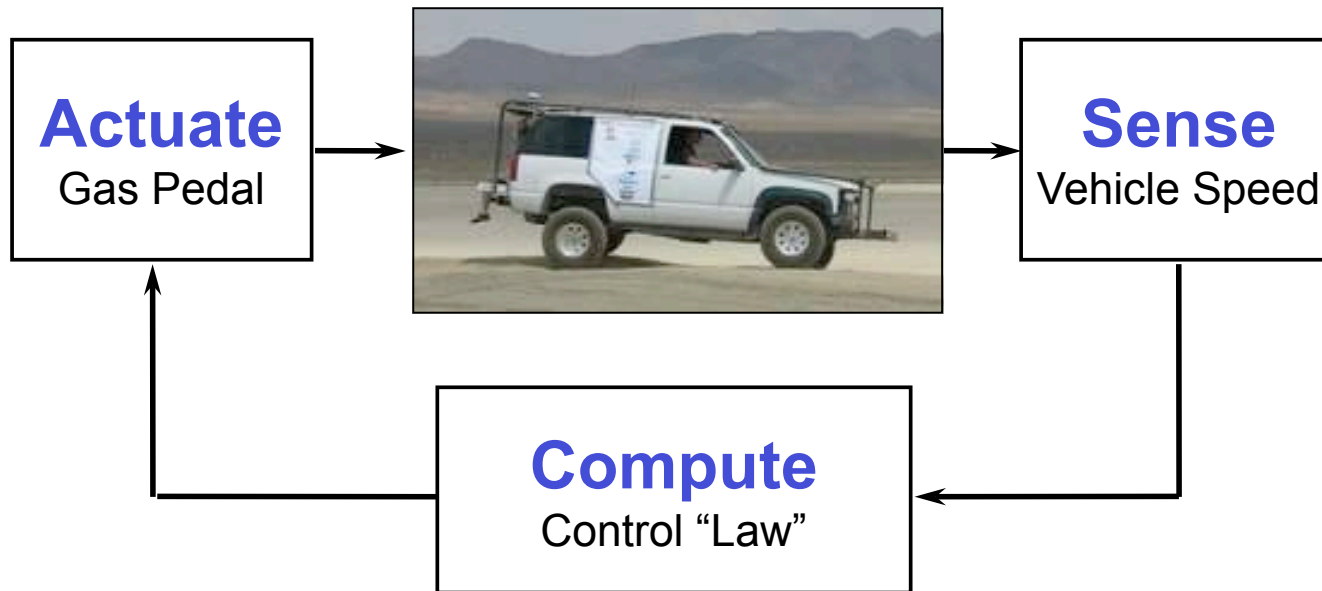
## Financial Systems

- Markets and exchanges
- Supply and service chains



# ***Control = Sensing + Computation + Actuation***

In Feedback “Loop”



## **Goals**

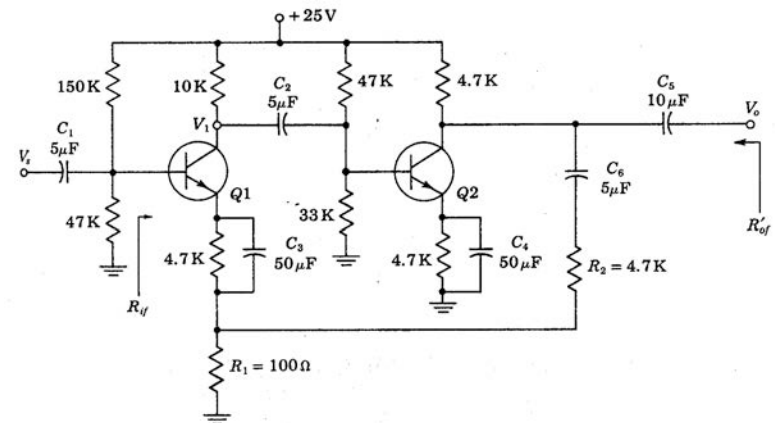
- Stability: system maintains desired operating point (hold steady speed)
- Performance: system responds rapidly to changes (accelerate to 6 m/sec)
- Robustness: system tolerates perturbations in dynamics (mass, drag, etc)



# Two Main Principles of Feedback

## 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 (behavior) of a system to be modified
- Example: stability augmentation for highly agile, unstable aircraft
- Key idea: interconnection gives *closed loop* that modifies natural behavior

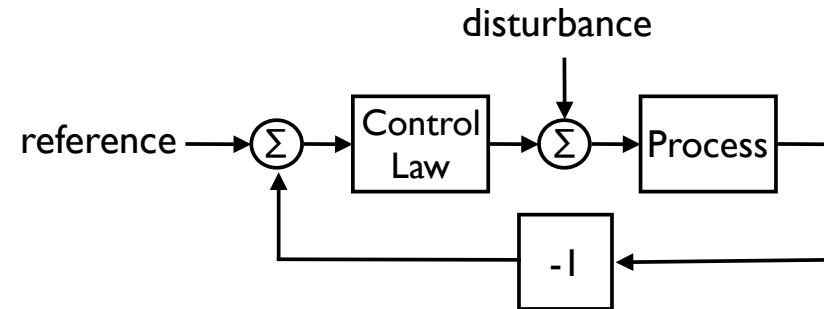
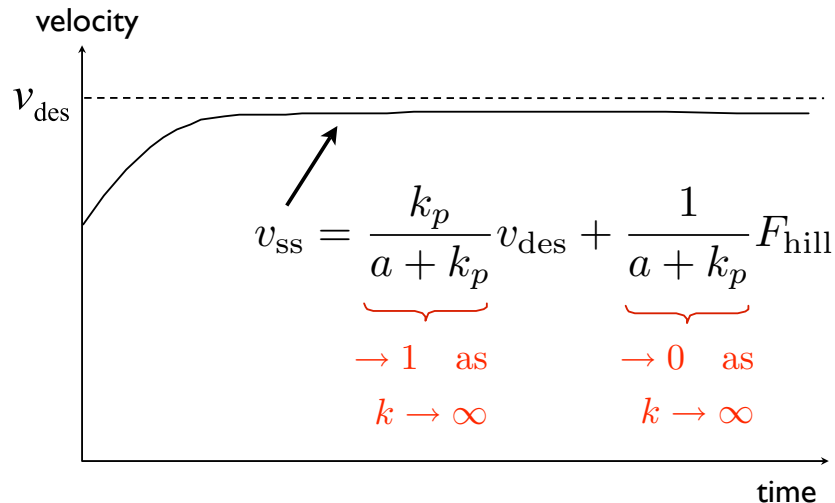


## Example #2: Speed Control



$$m\dot{v} = -av + F_{\text{eng}} + F_{\text{hill}}$$

$$F_{\text{eng}} = k_p(v_{\text{des}} - v)$$



### Stability/performance

- Steady state velocity approaches desired velocity as  $k \rightarrow \infty$
- Smooth response; no overshoot or oscillations

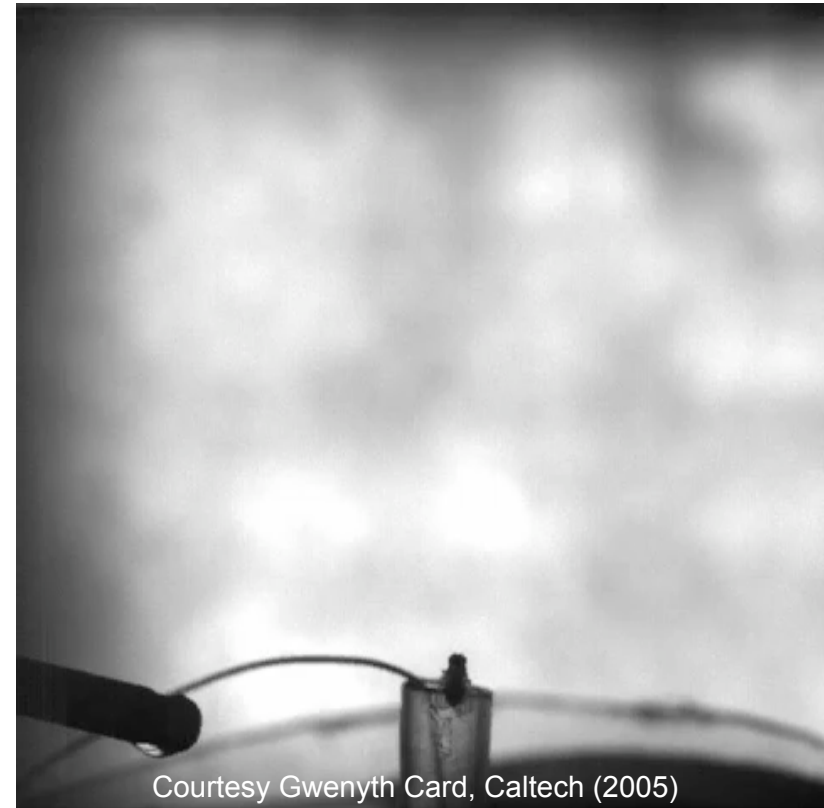
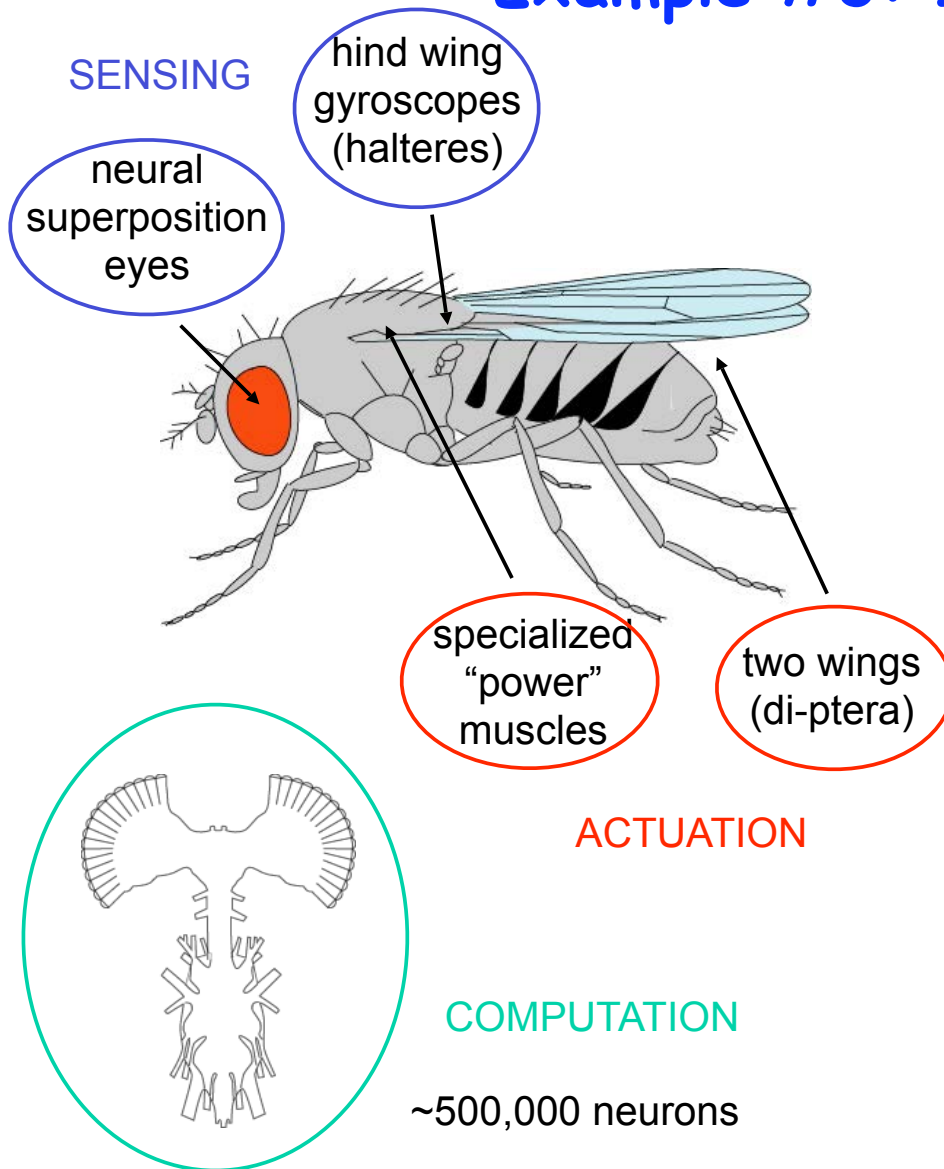
### Disturbance rejection

- Effect of disturbances (eg, hills) approaches zero as  $k \rightarrow \infty$

### Robustness

- Results don't depend on the specific values of  $a$ ,  $m$  or  $k_p$ , for  $k_p$  sufficiently large

## Example #3: Insect Flight



### More information:

- M. H. Dickinson, Solving the mystery of insect flight, *Scientific American*, June 2001

# 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

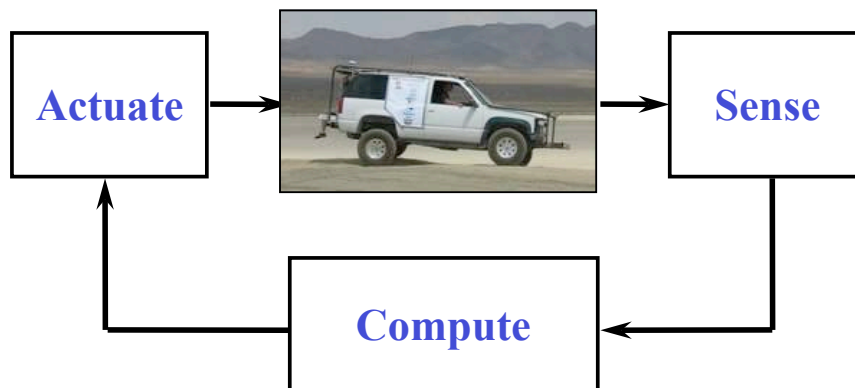
- Constructive tools for design of feedback systems
- Constructive tools for signal processing and estimation (Kalman filters)

## 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
- $\mu$ -Analysis and Synthesis
- Systems biology (SBML)



# Summary: Introduction to Feedback and Control



**Control =**

Sensing + Computation +  
Actuation

## Feedback Principles

- Robustness to Uncertainty
- Design of Dynamics

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

