CDS 101/110: Lecture 1.1
Introduction to Feedback & Control

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26 September 2016

Goals:

- Give an overview of CDS 101/110: course structure & administration
  - http://robotics.caltech.edu/wiki/index.php/CDS110_2016
- Define feedback systems and their main features
- Describe what control systems do and some principles of feedback

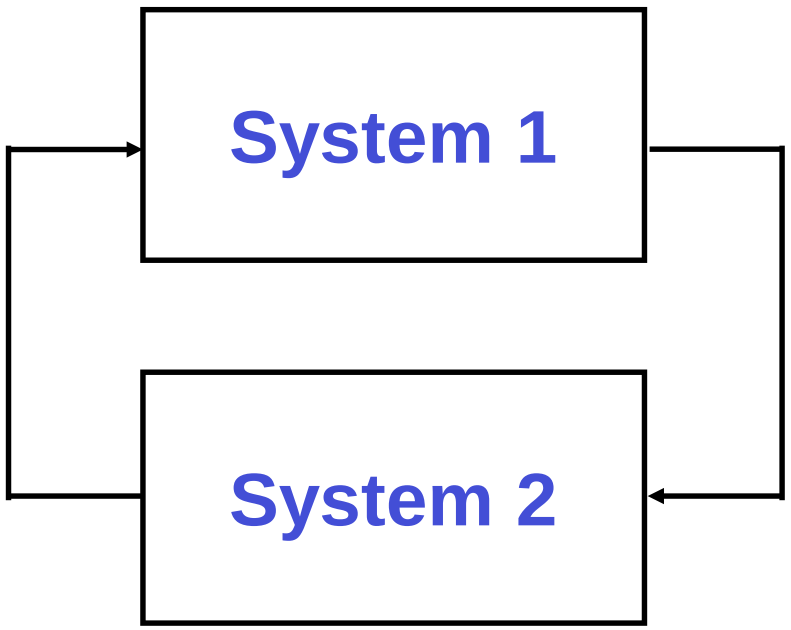
Reading:

- Åström and Murray, *Feedback Systems: An Introduction for Scientists and Engineers*, Chapter 1
- Sections 1.1-1.5
- Sections 1.6-1.9 should be *skimmed*

What is Feedback?

Merriam Webster:

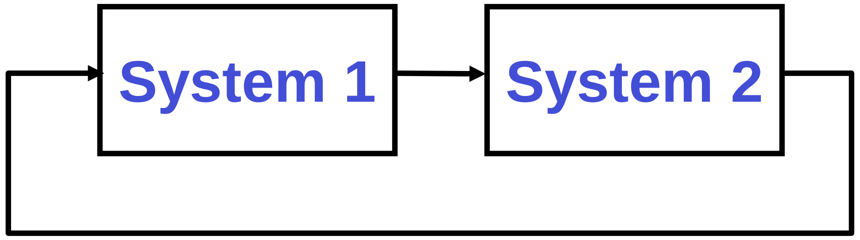
the return to the input of a part of the output of a machine, system, or process (as for producing changes in an electronic circuit that improve performance or in an automatic control device that provide self-corrective action) [1920]



Feedback = mutual interconnection of two (or more) systems

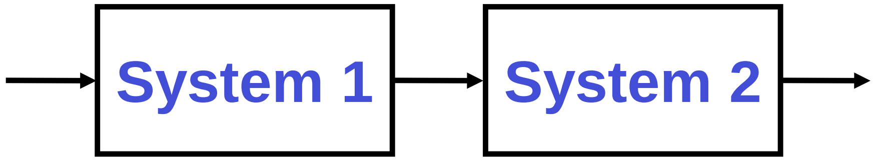
- System 1 affects system 2
- System 2 affects system 1
- Cause and effect is tricky; systems are mutually dependent

Terminology



Closed Loop

Feedback is ubiquitous in natural and engineered systems



Open Loop

CDS 101/110 Course Sequence

CDS 101 – Introduction to the *principles* and *tools* of control and feedback

- Summarize key concepts, w/ examples of fundamental principles at work
- Introduce MATLAB-based tools for modeling, simulation, and analysis

CDS 110 – Analytical understanding of key concepts in control

- Detailed description of classical control and state space concepts
- Provide knowledge to work with control engineers in a team setting

Fall

CDS 112 – Detailed design tools for control systems

- Optimization-based control (LQR, RHC/MPC, Kalman filters)

CDS 212/213 - Modern (robust) control design

- Operator-based approach to control; linear and nonlinear systems
- 212 = analysis, 213 = synthesis

Winter

CDS 140 - Introduction to Dynamical Systems

- Introduction to applied mathematical tools in dynamical systems

Spring

CDS Minor

- Undergrads: CDS 110, CDS 112, CDS 140, senior thesis
- Grad students: 54 units in CDS - usually CDS 110/112, CDS 140/240 + 2 electives

Some Related Courses

CDS 270 – Special Topics

- Changes every year. Can be taken multiple times.

ME/CS 132(a,b): Robotic Perception and Navigation

- How to robots “see,” perceive, and map their world? (uses CDS 112 ideas)
- How do they plan their motions (unique to robotics)
- Winter/Spring of this year
- This year’s focus: aerial rotorcraft vehicles.

EE 148 (a,b): Computer Vision

- Basics of image formation and image processing
- Special topics, often focusing on object identification/classification

ME 115(a,b): Introduction to Kinematics and Robotics

- Basic analysis of robot motion
- Alternates Winter/Spring with ME/CS 132(a,b)
- This year’s focus: aerial rotorcraft vehicles.

CDS 140 - Introduction to Dynamical Systems

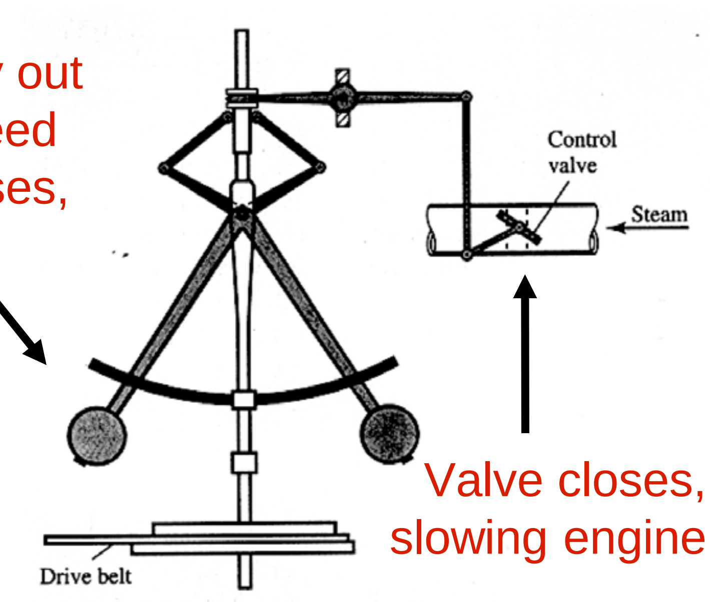
- Introduction to applied mathematical tools in dynamical systems

Example #1: Flyball Governor

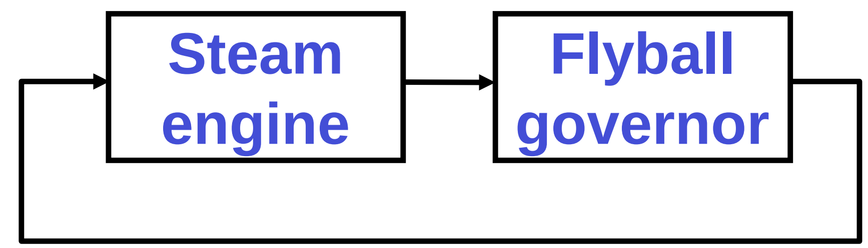
“Flyball” Governor (1788)

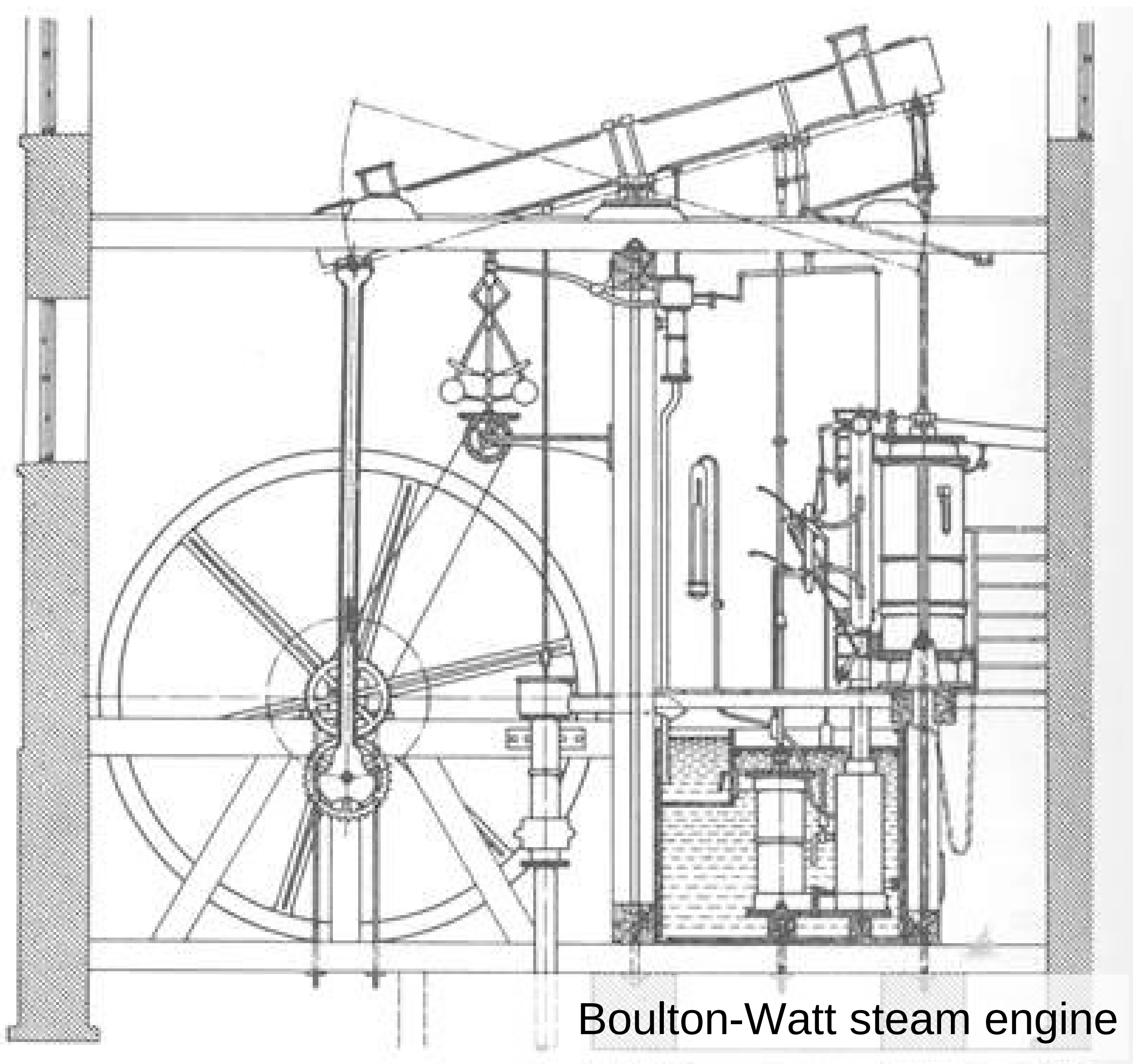
- Regulate speed of steam engine
- Reduce effects of variations in load (disturbance rejection)
- Major advance of industrial revolution

Balls fly out as speed increases,



Valve closes, slowing engine





Boulton-Watt steam engine

Other Examples of Feedback

Biological Systems

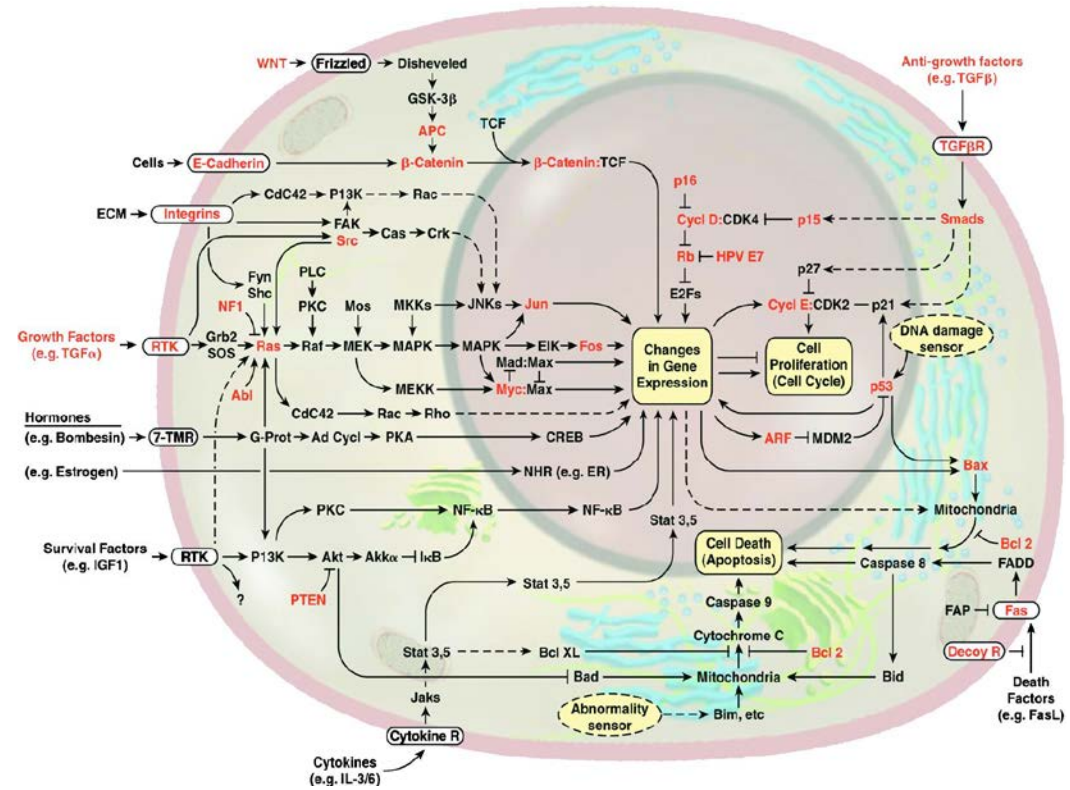
- Physiological regulation (homeostasis)
- Bio-molecular regulatory networks

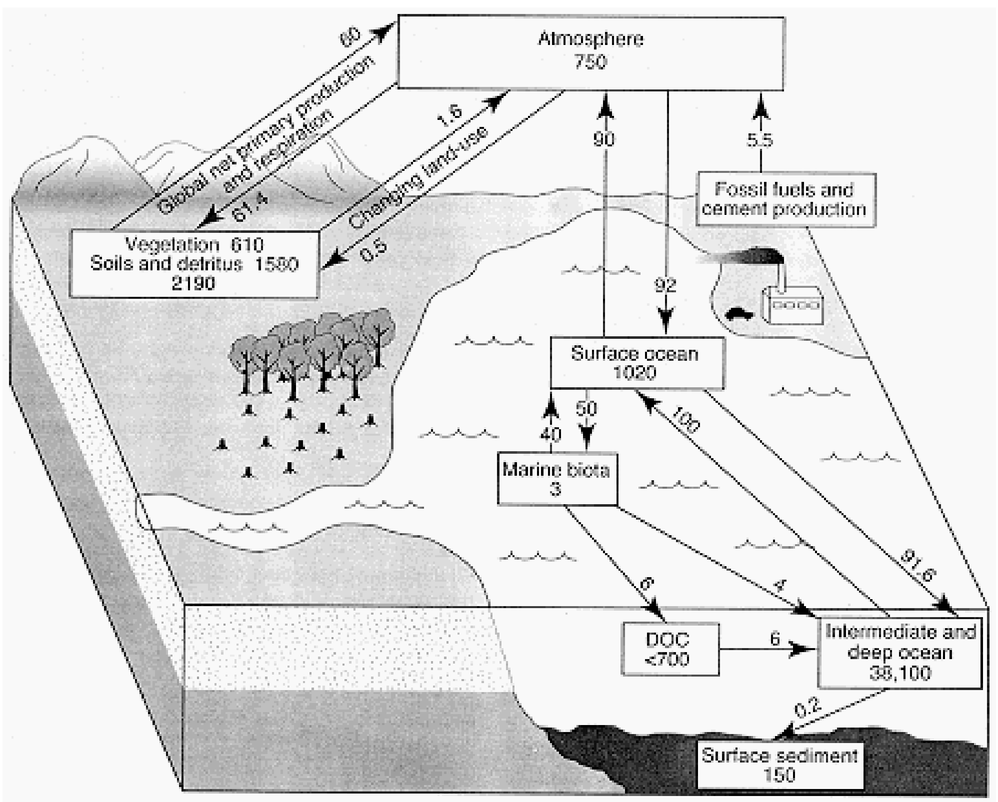
Environmental Systems

- Microbial ecosystems
- Global carbon cycle

Financial Systems

- Markets and exchanges
- Supply and service chains





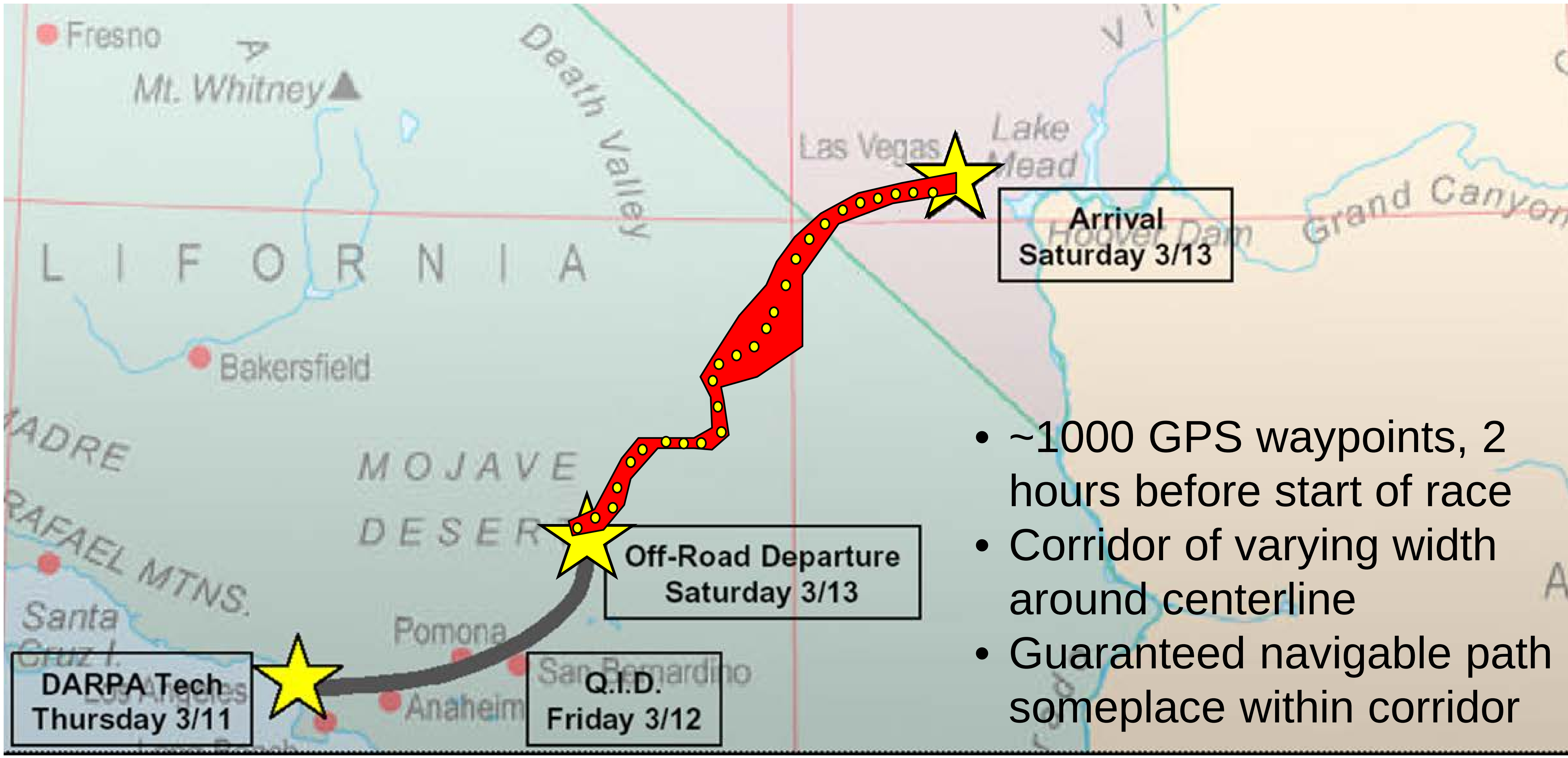
Control = Sensing + Computation + Actuation

$\underbrace{\text{Sensing + Computation + Actuation}}_{\text{In Feedback "Loop"}}$

Goals

- Sta
- Per
- Rob

DARPA Grand Challenge #1: Los Angeles to Las Vegas in 10 Hours or Less, No Humans Allowed

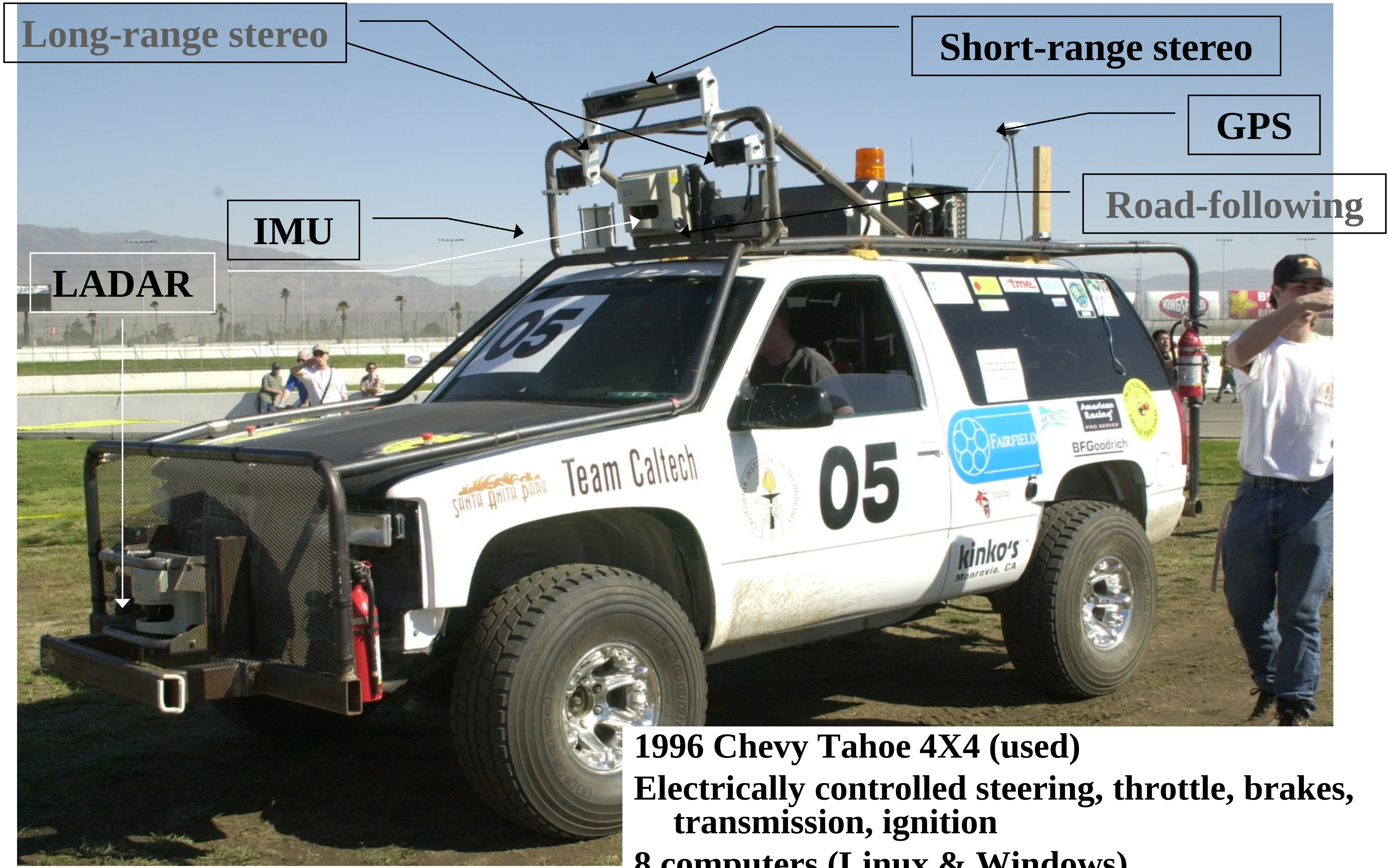


- ~1000 GPS waypoints, 2 hours before start of race
- Corridor of varying width around centerline
- Guaranteed navigable path someplace within corridor

- Vehicle must be completely autonomous; no remote control
- Vehicle must be able to avoid obstacles, including other vehicles.
- First vehicle to reach Las Vegas (~250 miles) in <10 hours wins **$1M**

“Bob” & Team Caltech

(organized by Prof. Richard Murray)



1996 Chevy Tahoe 4X4 (used)

Electrically controlled steering, throttle, brakes, transmission, ignition

8 computers (Linux & Windows)

30 Sensors

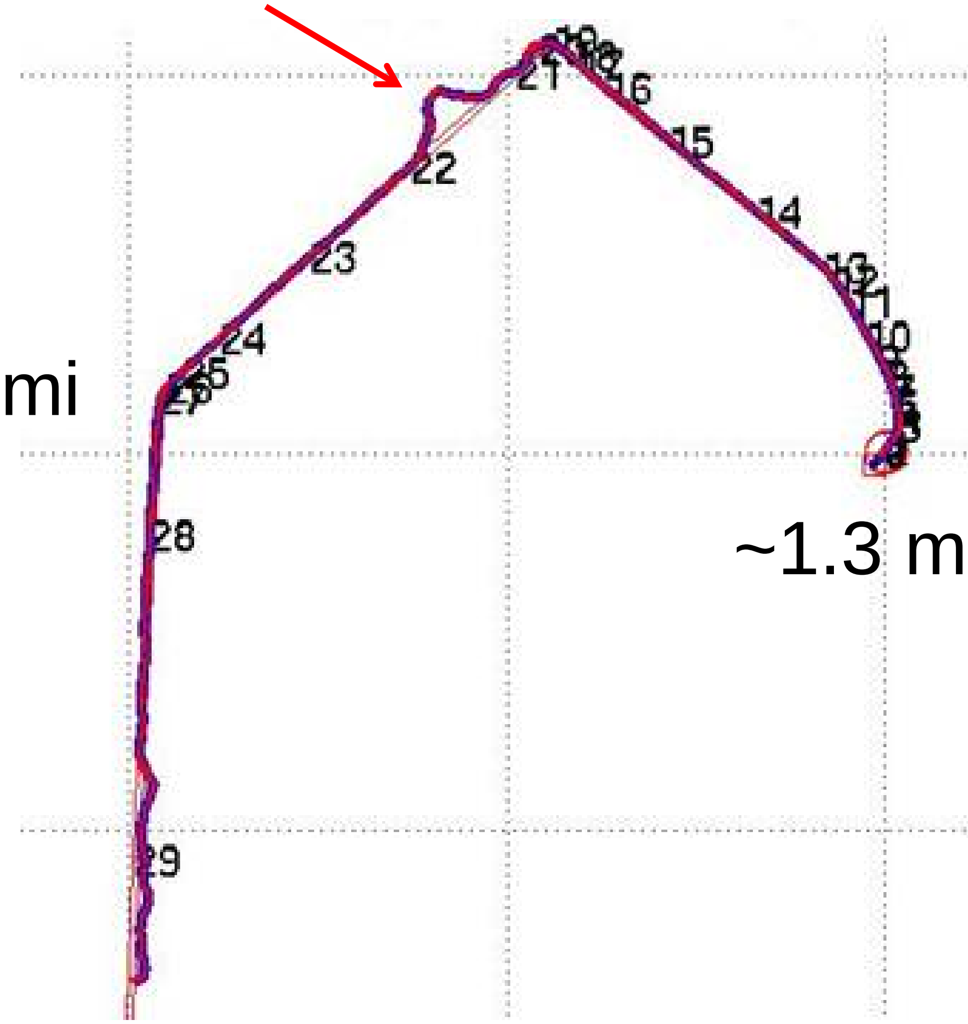
$500K, > 20,000 person-hours (25-55 undergrads)

Inside Bob

Team Caltech: Race Results

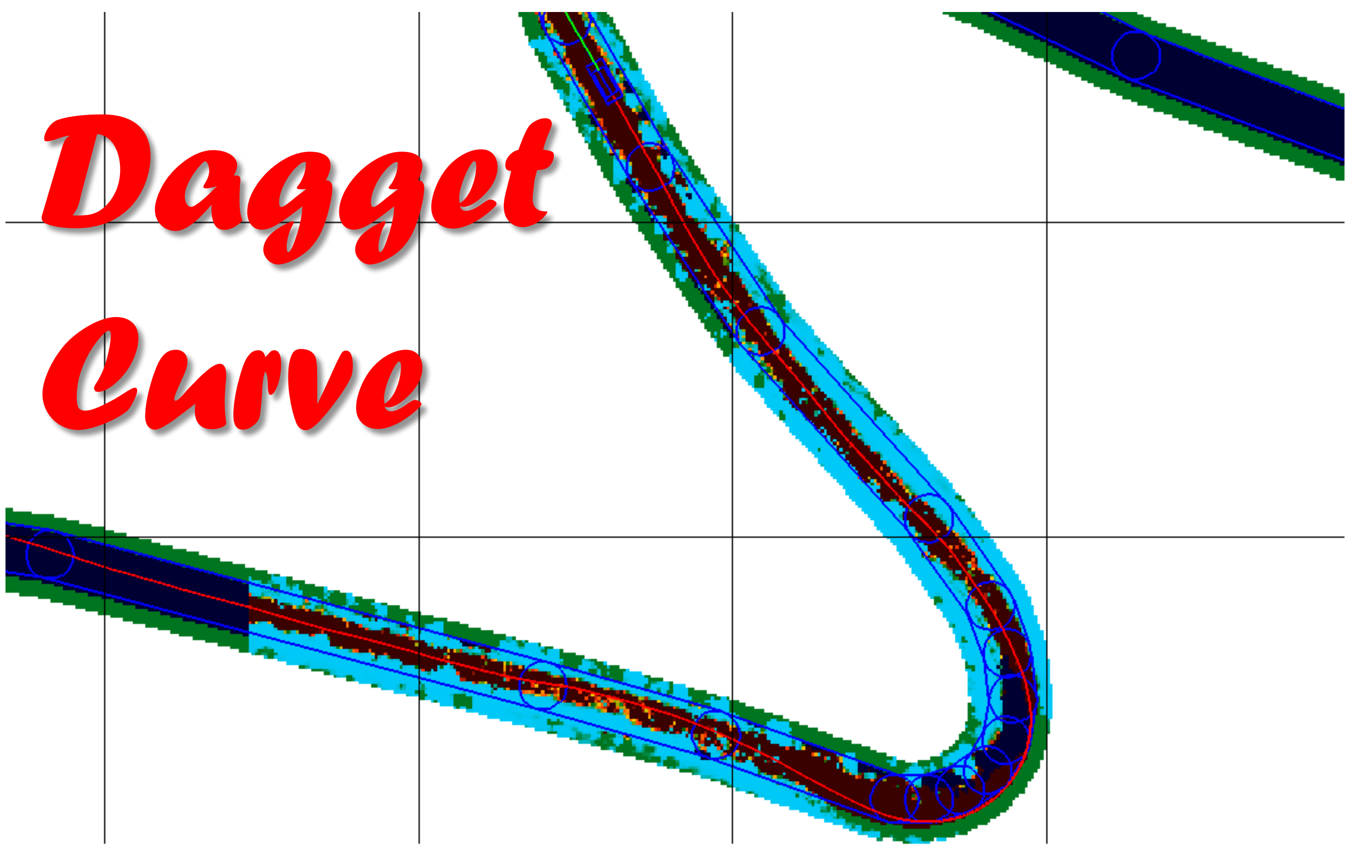
~1 mi: went off dirt road

~0.5 mi



~1.3 mi: Logical Error

Start



Results:

- 15 teams deemed “safe”
- Caltech placed 5th
- Caltech alums Golem Group placed 4th
- No team covered more than 5% of the distance
- Many important lessons

- A ***PR DISASTER*** for DARPA

DARPA Grand Challenge #2: The Mulligan

Race Day: 8 October 2005

- 198 teams submitted application video
- 118 teams selected for site visit
- 43 teams selected for qualifying event
- 21 qualified for final race
  - Team Caltech in 19th start
  - New Vehicle "Alice"

Alice Overview

Team Caltech

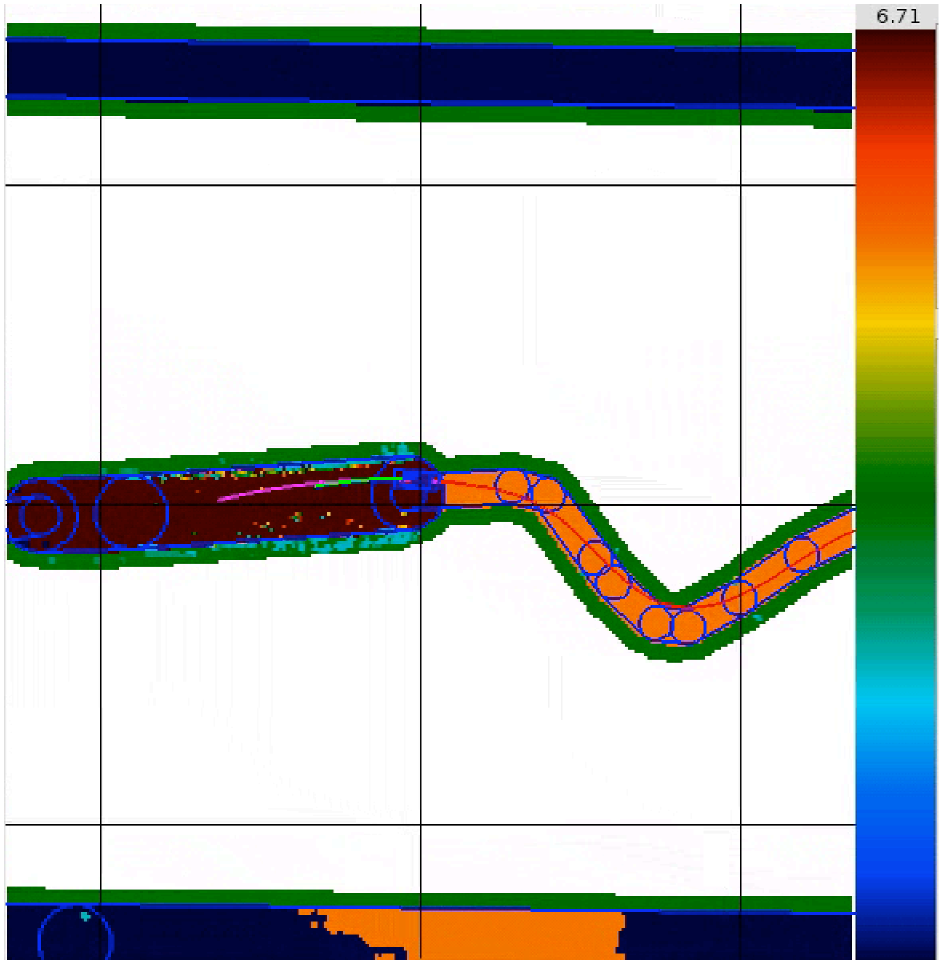
- 50 students worked on Alice over 1 year
- Course credit through CS/EE/ME 75
- Summer team: 20 SURFs + 10 others

Alice

- 2005 Ford E-350 Van
- Sportsmobile 4x4 offroad package
- 5 cameras: 2 stereo pairs + roadfinding
- 5 LADAR : long, medium*2, short, bumper
- 2 GPS units + 1 IMU (LN 200)
- 6 Dell 750 PowerEdge Servers
- 1 IBM Quad Core AMD64 (fast!)
- 1 Gb/s switched ethernet

Software

- 15 programs with ~50 execution threads
- FusionMapper: integrate all sensor data into a speed map for planning
- PlannerModule: optimization-based planning over a 10-20 second horizon



Alice’s Media Debut

Alice’s Media Debut

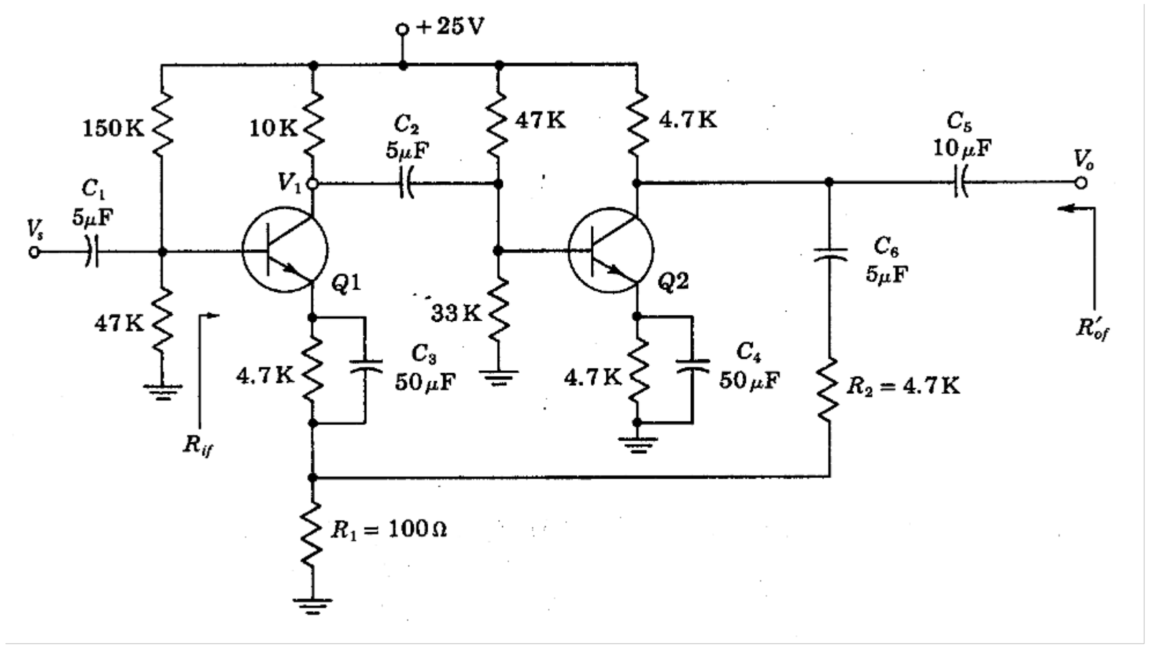
Slashdot | DARPA GC Updates, 8 Oct 05. 2:45 pm

Most interesting one so far is … Caltech's Alice

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*

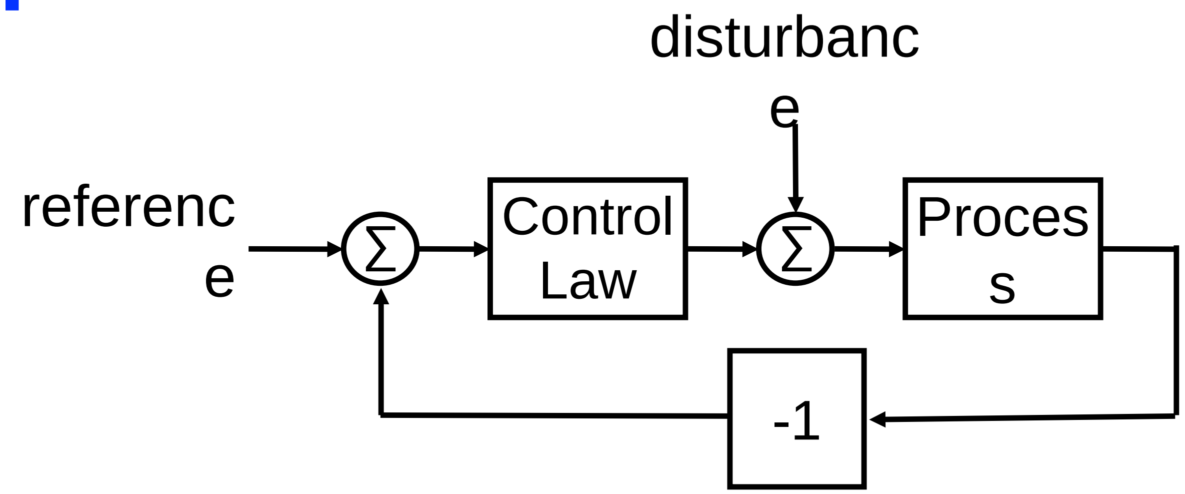


Design of Dynamics through Feedback

- 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

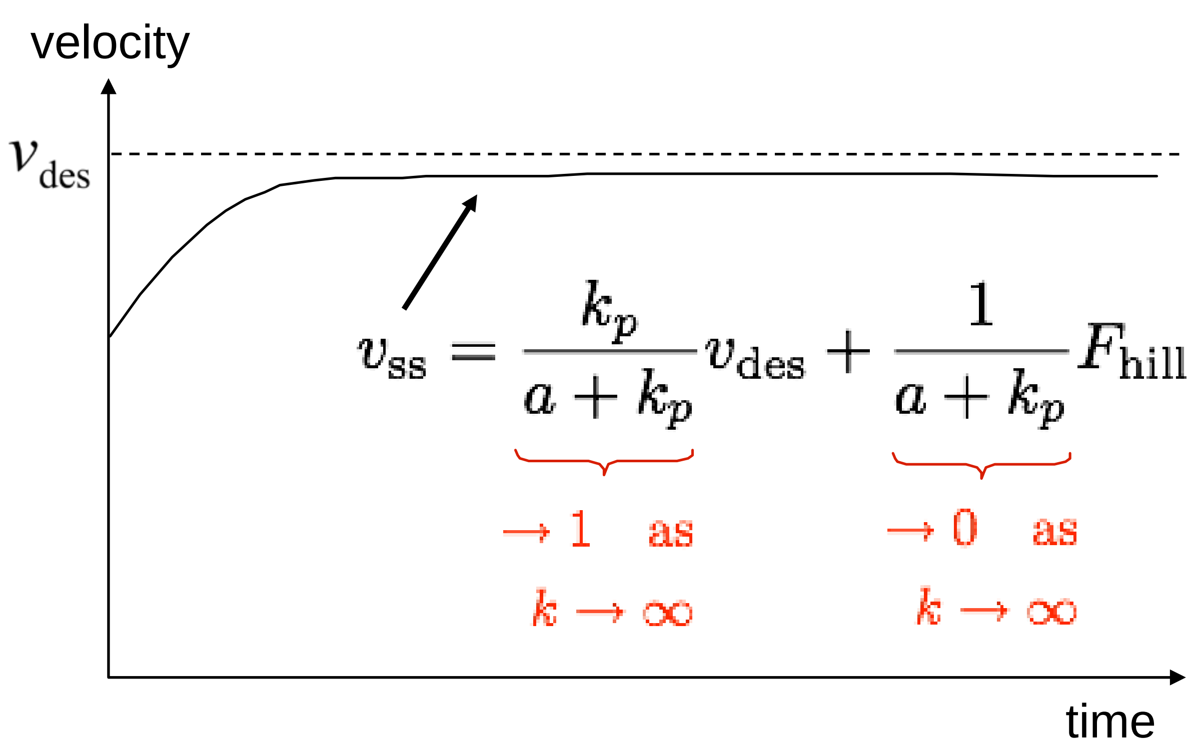

X-29 experimental aircraft (NASA)

Example #2: Speed Control



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

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



$$v_{ss} = \underbrace{\frac{k_p}{a + k_p}}_{\substack{\to 1 \quad \text{as} \\ k \to \infty}} v_{\text{des}} + \underbrace{\frac{1}{a + k_p}}_{\substack{\to 0 \quad \text{as} \\ k \to \infty}} F_{\text{hill}}$$

Stability/performance

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

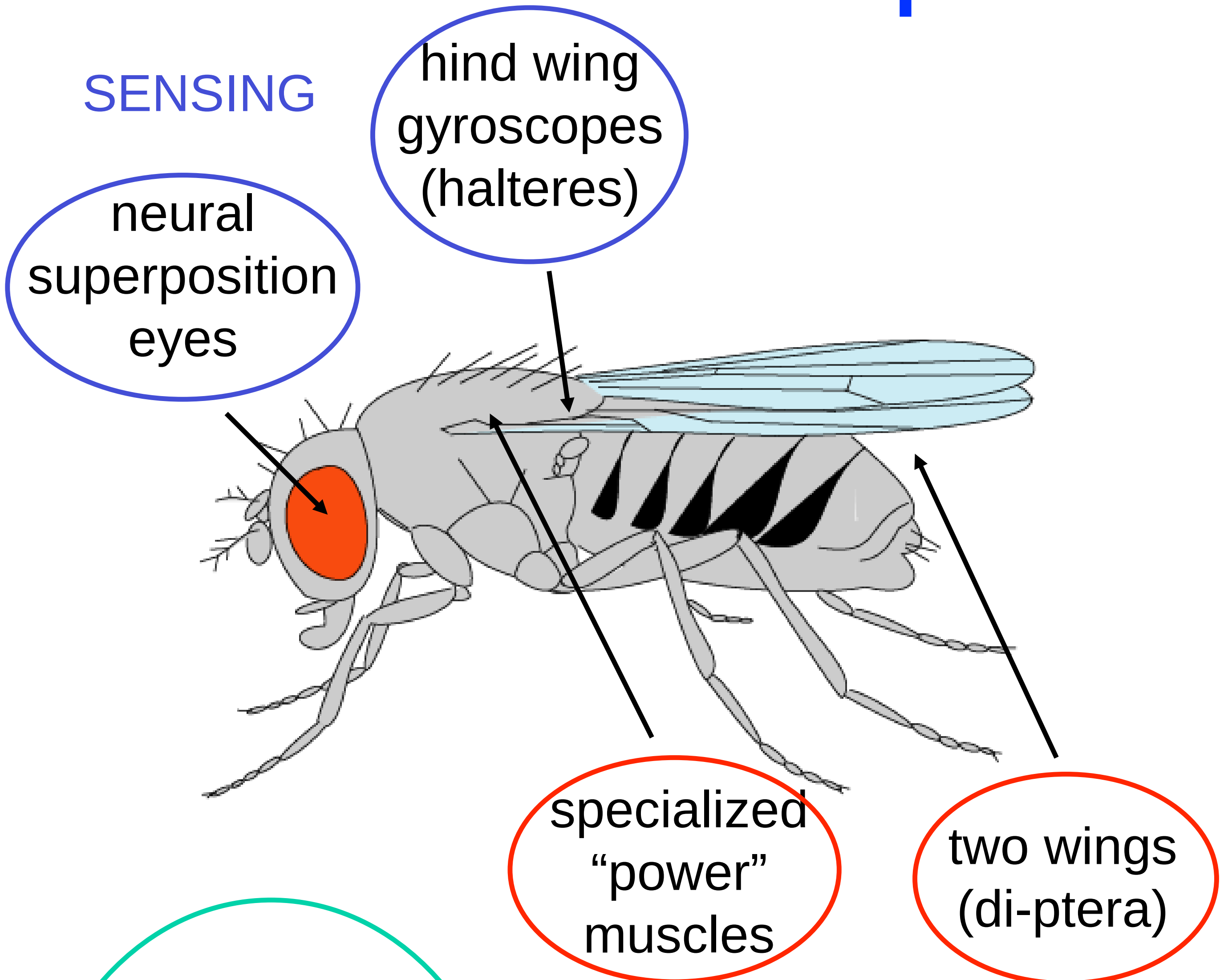
Disturbance rejection

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

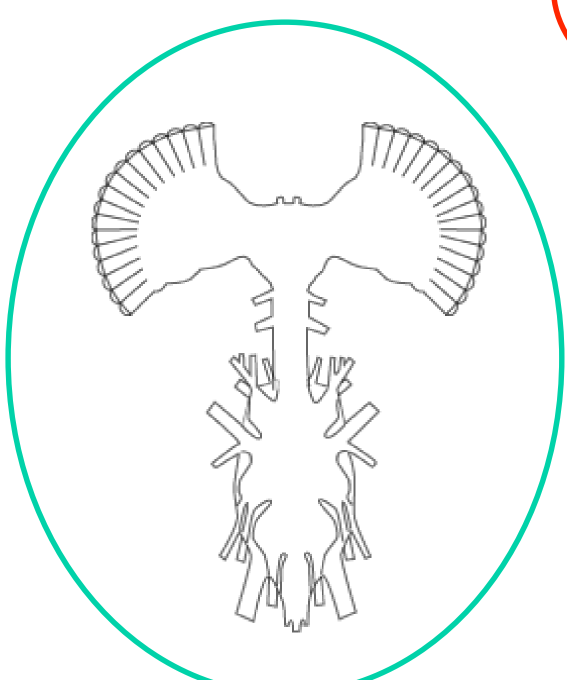
Robustness

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

Example #3: Insect Flight



ACTUATION



COMPUTATION

~500,000 neurons

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
- *Linear Time Invariant Systems (LTI),* mainly
- System identification theory and algorithms

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 (e.g., Kalman filters) needed for control

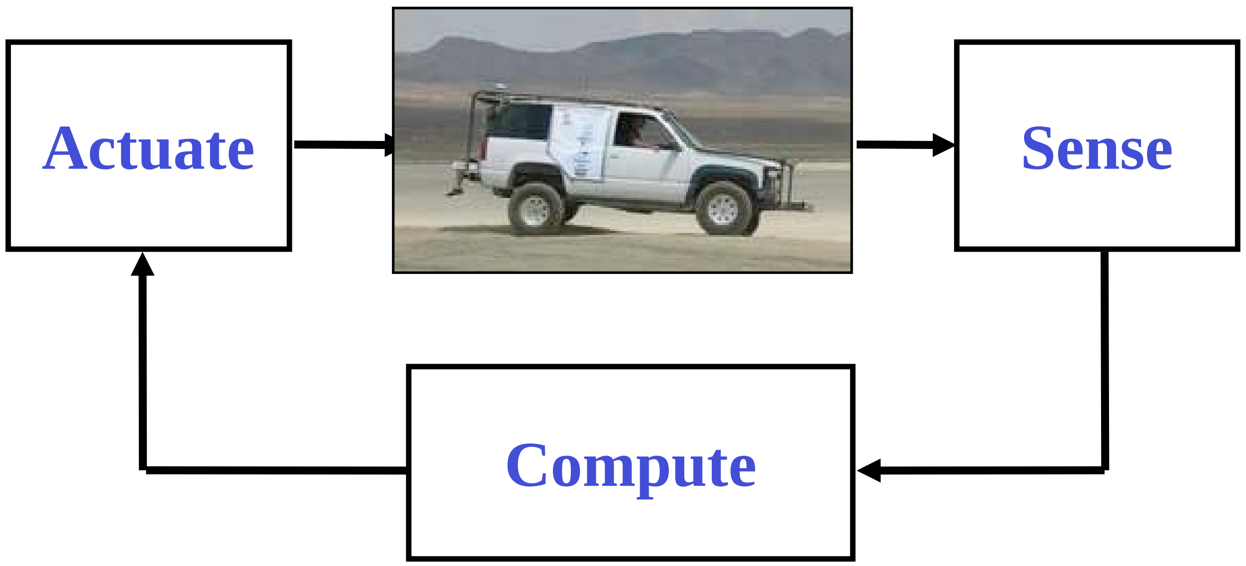
MATLAB Toolboxes

- 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
- Systems biology (SBML)

Python Toolboxes

- scipy/numpy
- python-control

Summary: Introduction to Feedback and Control



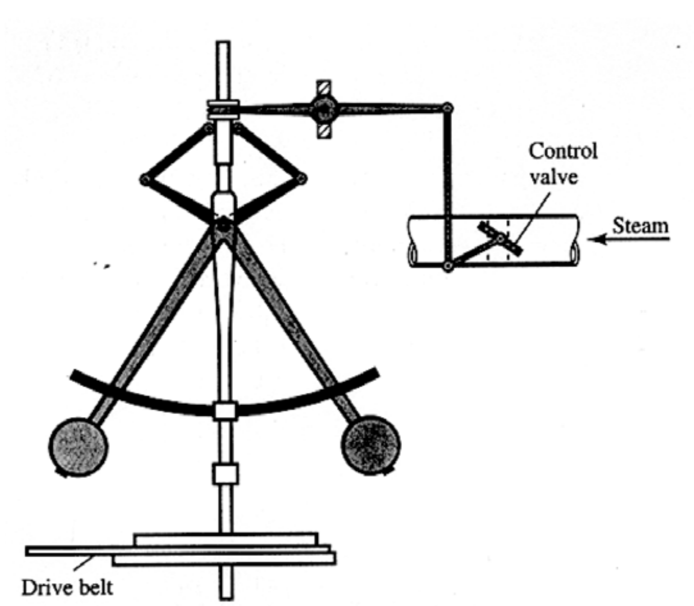
Control =

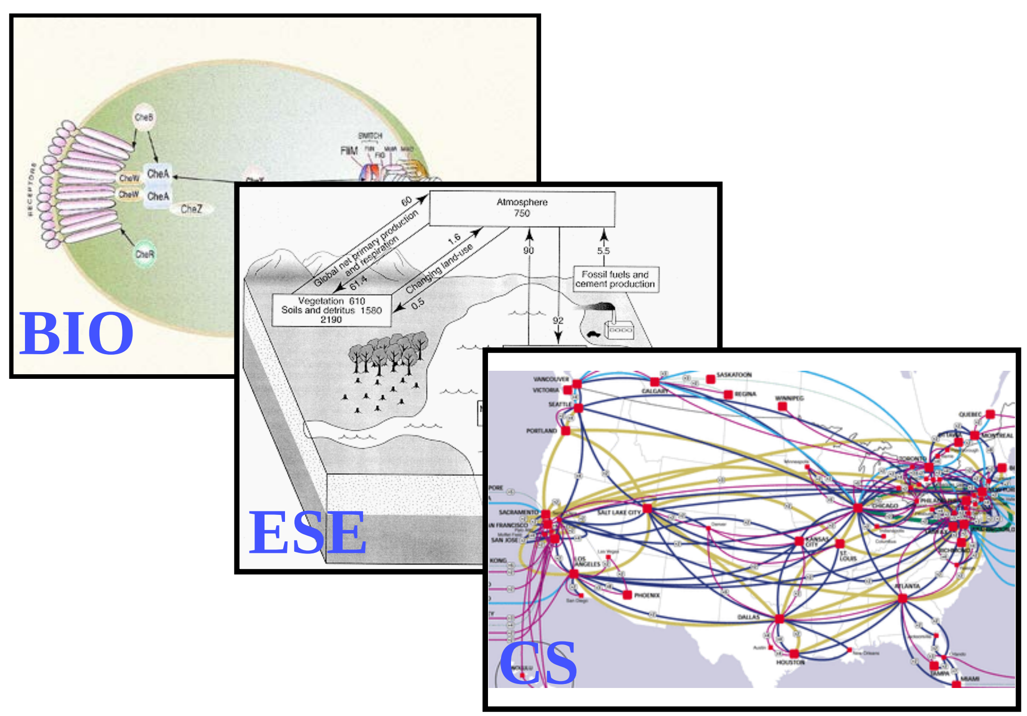
Sensing + Computation + Actuation

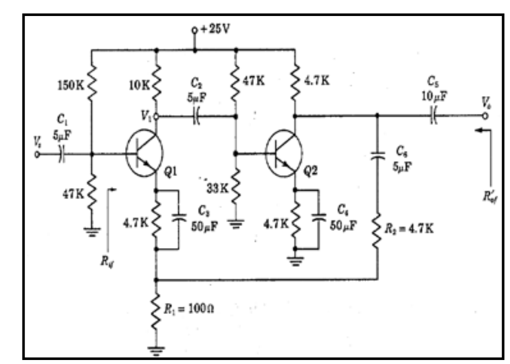
Feedback Principles

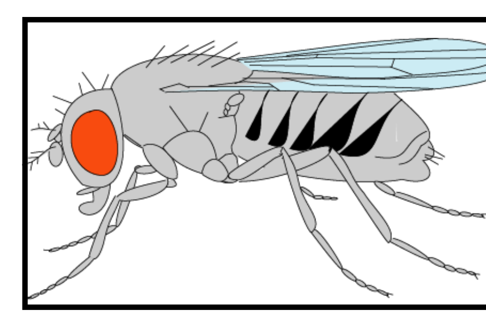
- Robustness to Uncertainty
- Design of Dynamics

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









Plans for the Week

Monday (26 Sept)

- Introductory lecture, course logistics
- Fill out signup sheet (to get on Piazza and mailing list)
- Pick up background survey (turn in if you are done with it)
- Homework set #1 will be posted to web page tonight (due 7 Oct)

Wednesday (28 Sept)

- Review of differential equations and some linear algebra (Ma 1 and Ma 2/102)

Friday (2 Oct)

- Feedback principles - basic ideas of the class via simple examples
- Course ombuds announced

Homework #1 handout, due next week