CDS 110
L1.2: Introduction to Control Technology

Richard M. Murray

2 October 2002

Announcements

- Mud cards
- Lecture videos
- E-mail list
- MATLAB

Outline:

- Additional CDS 110 administration details
- Describe current and emerging applications of active control technology
- Give a basic understanding of the fundamental benefits of feedback control and the situations in which it can improve overall system performance
- Examples: automotive + aerospace engines

Reading (available on course web page):

- Suggested: K. J. Astrom, *Control Systems Design*, Chapter 1

CDS 101/110/111 Course Sequence

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

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

CDS 110a – Analytical understanding of key concepts in control

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

Fall

CDS 110b – Detailed design tools for control systems

- Estimation and robust control tools for *synthesis* of control laws

Winter

CDS 111 – Implementation of control systems for engineering applications

- Laboratory based *implementation* of computer control on flight experiment

Spring

CDS 110 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 (lead 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.

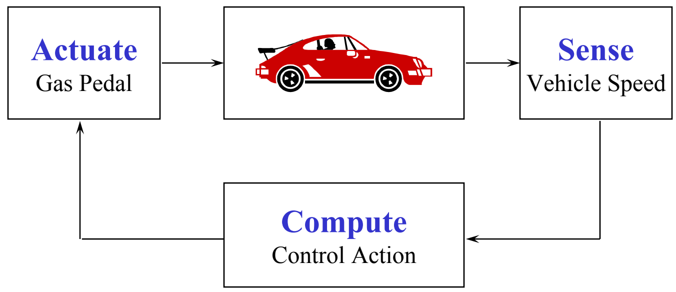
CDS 110 specific items

- Lectures on Mon *and* Wed
- Wed: 1-3 pm with break in middle
- Do *all* homework problems
- Separate reading assignments (see CDS *110* homepage)
- Please write "CDS 110" in the upper left corner of your homework

http://www.cds.caltech.edu/~murray/cds110

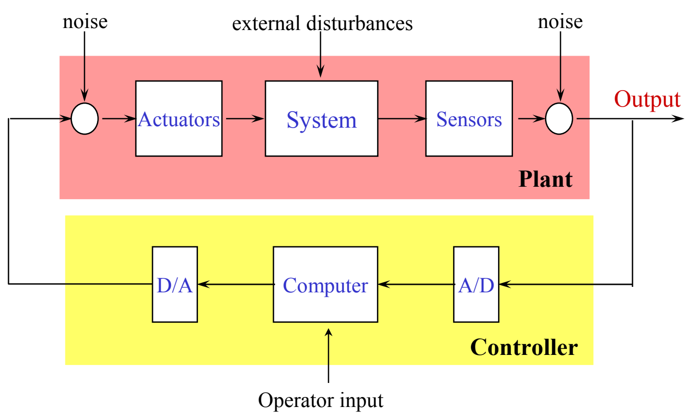
Basic Concepts in Feedback Control

Active Control = Sensing + Computation + Actuation



Goals: Stability, Performance, Robustness

Modern Control System Components

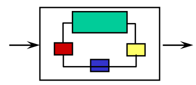


Plant	Physical system, actuation, sensing
Controller	Microprocessor plus conversion hardware (single chip)
Feedback	Interconnection between plant output, controller input

Active Control Methodologies

Black box methods

- Basic idea: Learn by observation or training
- Examples:
  - Auto-tuning regulators
  - Adaptive neural nets
  - Fuzzy logic



Model-based methods

- Use a detailed model (PDEs, ODEs) for analysis/design
- Examples:
  - Optimal regulators
  - H_∞ control
  - Feedback linearization

Advantages:

- No need for complex modeling or detailed understanding of physics
- Works well for controllers replacing human experts

Disadvantages:

- No formal tools for investigating robustness and performance
- Don't work well for high performance systems with complicated dynamics

Advantages:

- Works well for highly coupled, multivariable systems
- Rigorous tools for investigating robustness and performance (using models)

Disadvantages:

- Tools available only for restricted class of systems (e.g., linear, time-invariant)
- Requires control-oriented physical models; these are not always easy to obtain

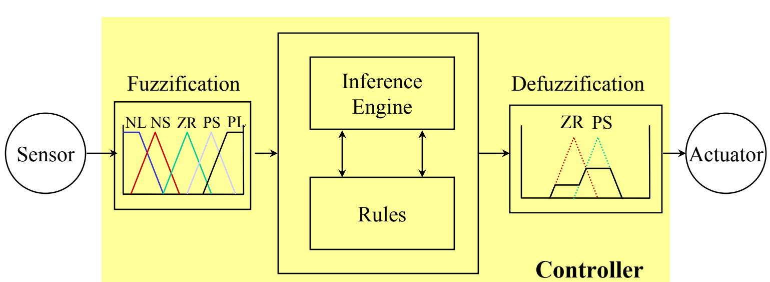
Control Using Fuzzy Logic

Basic idea: write control actions as *fuzzy logic* rules:

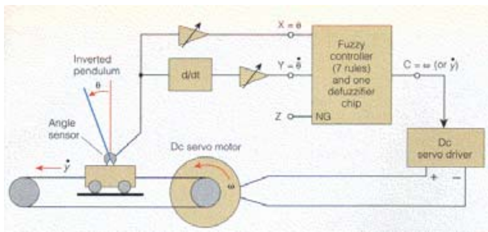
Standard logic:	Fuzzy logic:
If T < 68° **then** turn heater on	**If** very cold **then** more heat

Fuzzy logic allows:

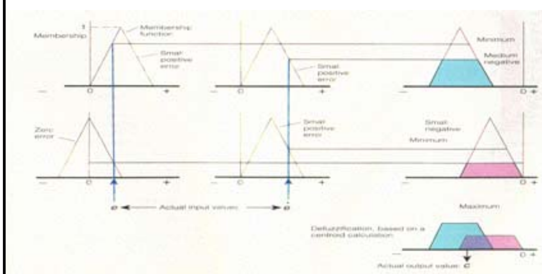
- Easy specification of control actions as rules
- Allows conflicting rules
- Smoothing of control actions



Example: Fuzzy Control of an Inverted Pendulum



$\dot{\theta}$ \ θ	NL	NM	NS	ZR	PS	PM	PL
PL							
PM							
PS			ZR		PS		
ZR		NM		ZR		PM	
NS			NS		ZR		
NM							
NL							



- Basic control structure unchanged: sense, compute, actuate
- Use simple (and overlapping) rules to specify control action
- Gives satisfactory performance with very simple control specification

Source: Yamakawa, *Fuzzy Sets and Systems, 1989*

Additional Applications of Fuzzy Logic

Pilotless, voice-controlled helicopter (Sugeno)
- System in operation since 1992
- Responds to “hover”, “forward”, “left”, etc
- Motivated by automated crop dusting

Elevator scheduling (Kim et al)
- Simulated 3 car system; multiple scenarios
- Improvement over “conventional” algorithm
  - 9% decrease in avg waiting time
  - 20% decrease in long waiting periods
  - 4% decrease in power consumption

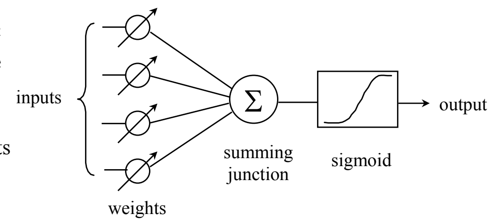
Other applications
- Sendai railway systems (1987)
- Autofocus cameras (Panasonic)
- Air conditioning (Mitsubishi)

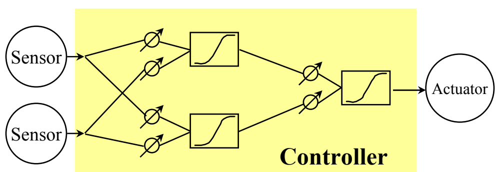
Common features that fuzzy exploits
- Feedback able to improve performance
- Lack of high-fidelity, control oriented models
- Good human expertise available
- Relatively low performance requirements (non-catastrophic failure modes)

Control using Artificial Neural Networks

Basic idea: encode controller logic using neural network architecture

- Train weights based on learning, gradient search ,etc
- Controller "figures out" proper inputs to get desired response





Advantages:

- Does not require explicit model of plant; learns from observing
- Structure allows complex, nonlinear control actions

Disadvantages:

- Can require long training periods
- Applications appear limited compared to other methods

Model-Based Control

Classical control

- Frequency domain based tools; stability via gain and phase margins
- Mainly useful for single-input, single output (SISO) systems
- Still one of the main tools for the practicing engineer

Modern control

- "State space" approach to linear control theory
- Works for SISO and multi-input, multi-output (MIMO) systems
- Performance and robustness measures are often not made explicit

Optimal control

- Find the input that minimizes some objective function (e.g., fuel, time)
- Can be used for open loop or closed loop control (min-time, LQG)

Robust control

- Generalizes ideas in classical control to MIMO context
- Uses operator theory at its core, but can be easily interpreted in frequency domain

Nonlinear control, adaptive control, hybrid control ...

Representations of Systems

Ordinary Differential Equations

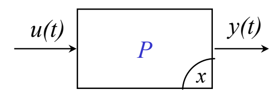
$$\dot{x} = f(x, u)$$
$$y = h(x, u)$$

Linearization around x_0=0

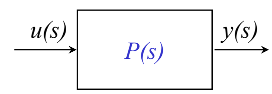
$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

Laplace transform

Block diagrams



Linearization around x_0=0

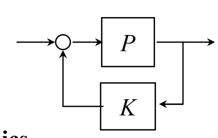


$$P(s) = \frac{a_{n-1}s^{n-1} + \cdots + a_0}{s^n + b_{n-1}s^{n-1} + \cdots + b_0}$$

Stability and Robustness

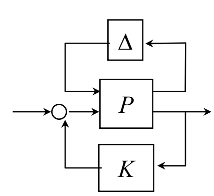
Stability: bounded inputs produce bounded outputs

- Necessary and sufficient condition: check for nonzero solutions around feedback loop
- Basic problem: positive feedback (internal or external)



Robustness: stability in the presence of unknown dynamics

- Check for stability in presence of uncertainty
- Need to check stability for *set* of systems
- "Small gain theorem" gives tight conditions based on bounds of uncertainty operator



No uncertainty ⇒ No need for control

Modeling Uncertainty

Noise and disturbances

- Model the amount of noise by its signal strength in different frequency bands
- Can model signal strength by peak amplitude, average energy, and other norms
- Typical example: Dryden gust models (filtered white noise)

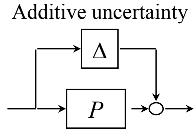
Parametric uncertainty

- Unknown parameters or parameters that vary from plant to plant
- Typically specified as tolerances on the basic parameters that describe system

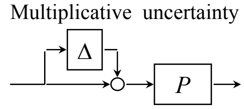
Unmodeled *dynamics*

- High frequency dynamics (modes, etc) can be excited by control loops
- Use bounded operators to account for effects of unmodelled modes:

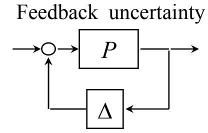
Additive uncertainty



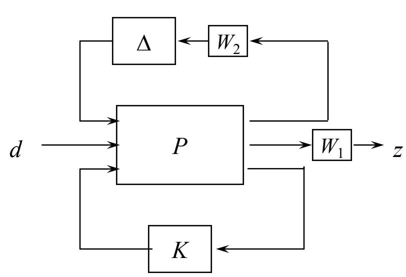
Multiplicative uncertainty



Feedback uncertainty



Robust Performance



d	disturbance signal
z	output signal
Δ	uncertainty block
W_2	performance weight
W_2	uncertainty weight

Goal: guaranteed performance in presence of uncertainty

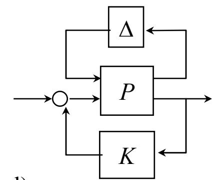
$$\|z\|_2 \le \gamma \|d\|_2 \quad \text{for all} \quad \|\Delta\| \le 1$$

- Compare energy in disturbances to energy in outputs
- Use frequency weights to change performance/uncertainty descriptions
- "Can I get X level of performance even with Y level of uncertainty?"

Tools for Analyzing and Synthesizing Controllers

(Post-) Modern Control Theory

- Generalizes gain/phase margin to MIMO systems
- Uses operator theory to handle uncertainty, performance
- Uses state space theory to performance computations



Analysis Tools

- gains for multi-input, multi-output systems
- μ H_∞ analysis software
  - Allow structured uncertainty descriptions (fairly general)
  - Computes upper and lower bounds on performance
  - Wide usage in aerospace industry

Synthesis Tools

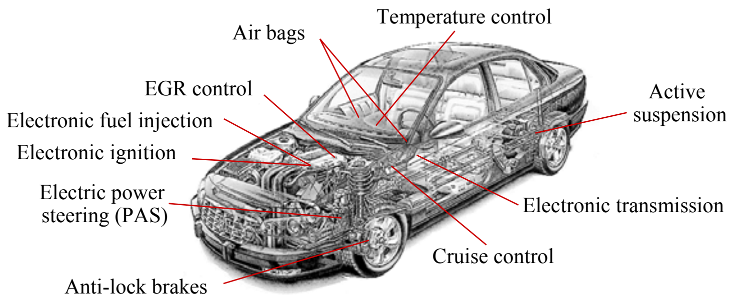
- LQR/LQG + "loop shaping"; modern tools for control engineers
- μ synthesis H_∞ software; tends to generate high order controllers
- Model reduction software for reducing order of plants, controllers

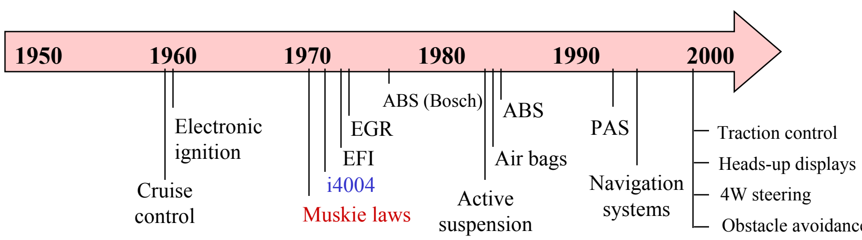
Application Examples

Smart cars and intelligent highways

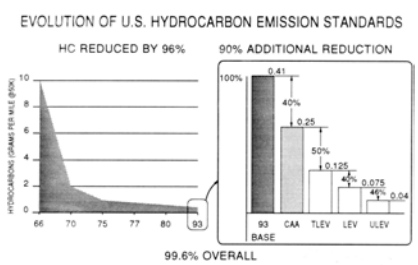
Active control of gas turbine engines

Application #1: Feedback Control in Automobiles



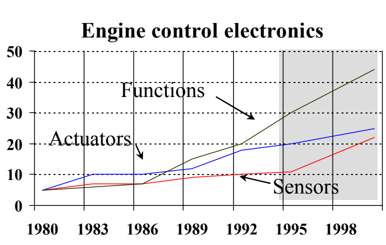


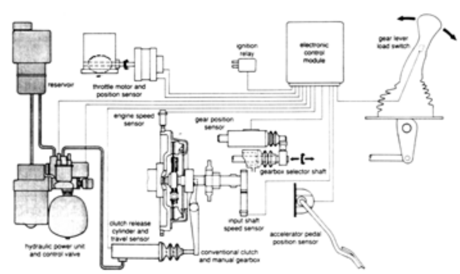
Engine Control



Reliance on active control is increasing

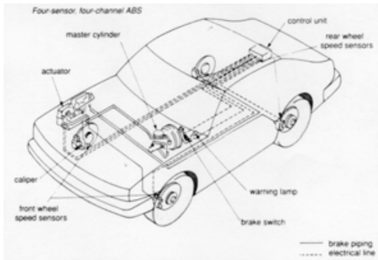
- Increasingly strict emissions and fuel efficiency requirements
- Continued Improvements in sensing, actuation, electronics, microprocessors
- Main bottlenecks are uncertainty, complexity, and sensing capability
- Integration of control functions becoming more difficult due to increased reliance on outside suppliers

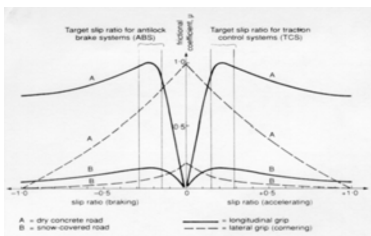




Source: Barron & Powers, *IEEE/ASME T. Mechatronics*, Mar 96

Antilock Brakes





History of ABS technology

- Developed in 1950s for aircraft (mechanical)
- 1965: mechanical ABS developed by Dunlop
- 1968: Ford demonstrates electronic ABS
- 1978: Bosch Anti-Blockier System
  - resolved problems w/ harsh environment electronics + connectors, solder joints
- Currently used on 50% of new cars, 90% of light trucks

System description

- Try to hold “slip ratio” at 0.15 - 0.30
- Releases brake when excessive slip is detected
- Gives max braking + good lateral traction

Performance

- Stopping distances reduced by 15% on dry road, 40% on wet road
- Safety self-check on startup; static + dynamic
- No difference in fatality rate w/ ABS (!)

Trends and Lessons in Automotive Control

Advances often driven by regulations

- Muskie laws (1970) for emissions
- Restraint laws in 1980s → air bags
- CAFE → electric power steering systems

Electronics + control provided solution

- Feedback was needed to get reliable performance in multiple operating conditions, with variations in parts

Strict reliability and cost requirements

- Control solutions must show demonstrated benefit and have low cost
- Reliability has improved steadily in past 20 years

These issues are common to many emerging applications areas that make use of active control technology

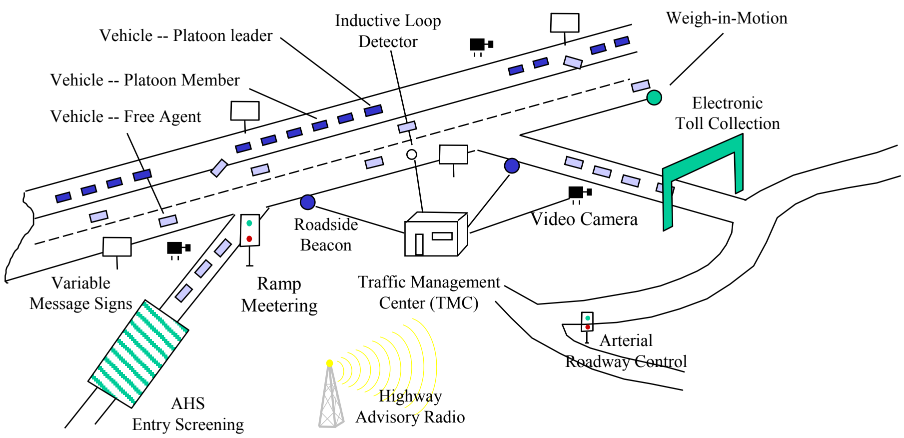
Additional benefits

- Increasing use of controls for non-regulated functions
  - Anti-lock brakes
  - Active suspension
- Increased sensing allows improved diagnostics and prognostics (not used?)

Emerging Trends

- Networking: car is no longer an isolated
  - Security systems: lo-jack, etc
  - GPS-based navigation
  - Diagnostics? IVHS?
- Distributed control
  - Increased reliance on suppliers for (smart) components
  - Presents integration challenges

Intelligent Vehicle Highway Systems (IVHS)



Use Feedback Control to Regulate and Optimize Traffic Control

Applications #2: Gas Turbine Engines

Military Applications

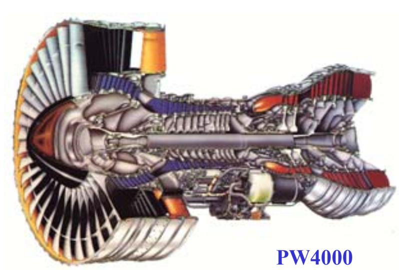
- Military aircraft engines: distorted inlets, high power/weight requirements
- Tank and helicopter engines: no outer fan, high power/weight requirements

Commercial Applications

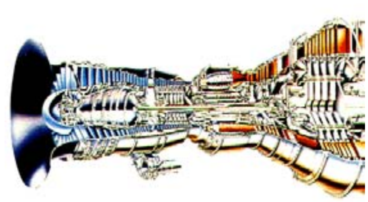
- Commercial aircraft engines: high bypass ratio, efficiency and noise requirements
- Supersonic transport engines: strict emissions requirements (ozone layer)
- Power generation: no outer fan; low emissions req's, low maintenance

Trends and Challenges

- Constant need for higher efficiency, lower weight, longer life
- Increasing concern with lower emissions (power & HSCT)

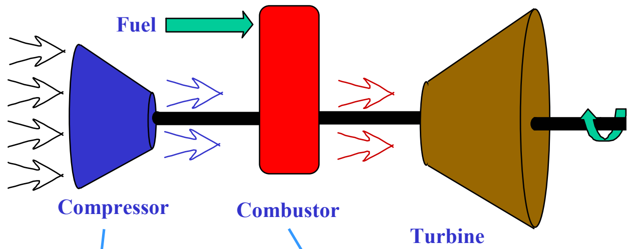


PW4000

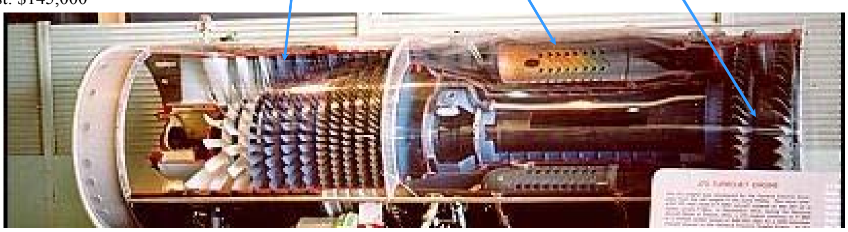


FT8

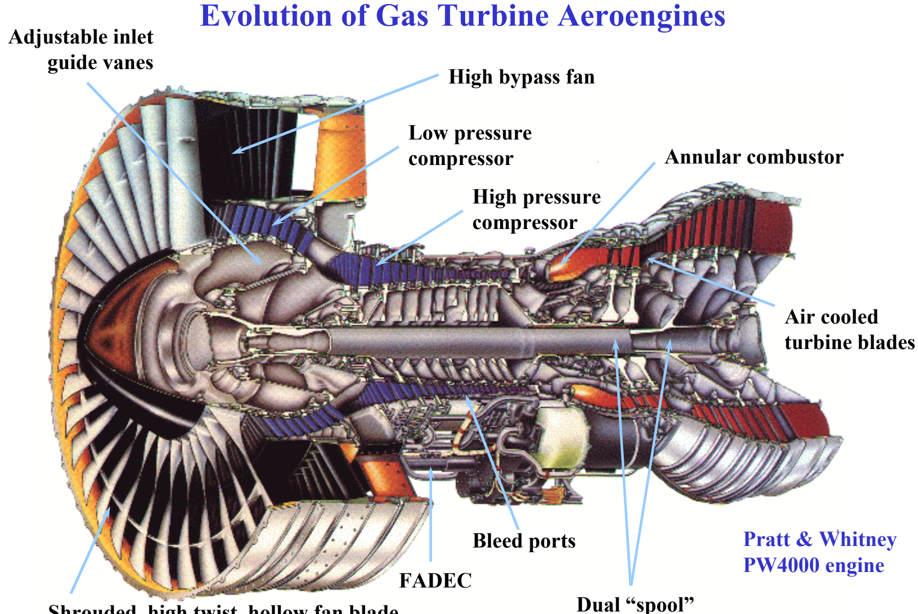
Principles of Operation



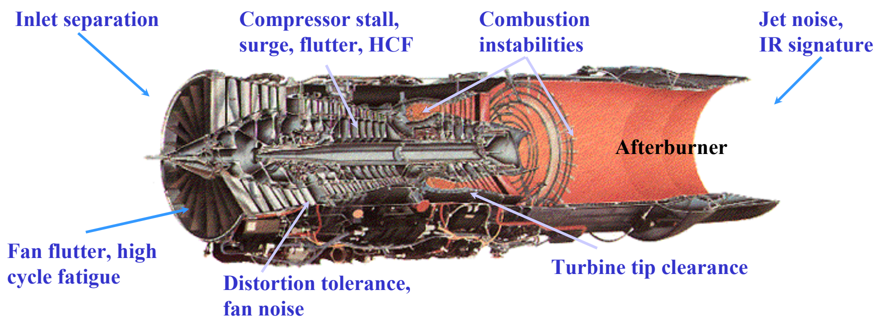
GE J-73 (1950s)
12-stage axial compressor
Two-stage axial turbine
8,920 lbs. max. thrust
Weight: 3,650 lbs.
Cost: $145,000



Evolution of Gas Turbine Aeroengines



Performance Limitations in Aircraft Engines



Inlet separation
- Separation of flow from surface
- Possible use of flow control to modify

Distortion
- Major cause of compressor disturbances

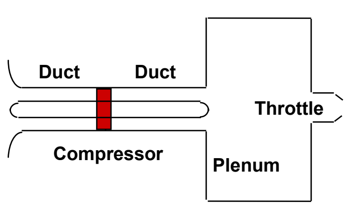
Rotating stall and surge
- Control using BV, AI, IGVs demonstrated
- Increase pressure ration ⇒ reduce stages

Flutter and high cycle fatigue
- Aeromechanical instability
- Linear control using BVs

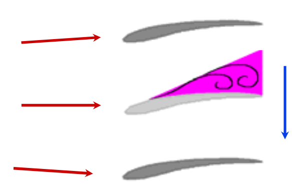
Combustion instabilities
- Large oscillations cannot be tolerated
- Typically discovered late in development

Jet noise and shear layer instabilities
- Gov't regulations driving new innovation

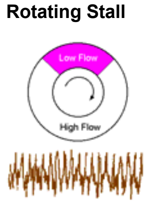
Rotating Stall and Surge



Emmons model (1952)

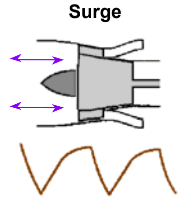


Rotating Stall

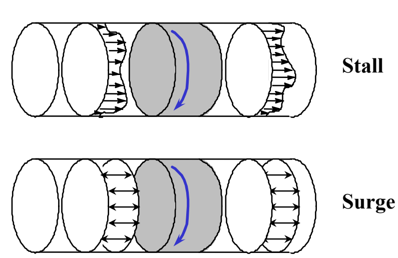


Approx. 0.5E Frequency

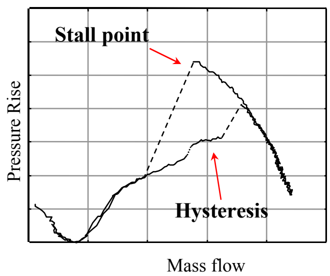
Surge

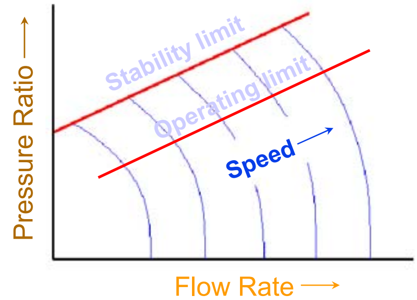


Approx. 0.3E Frequency



Impact of Stall and Surge on Engine Performance





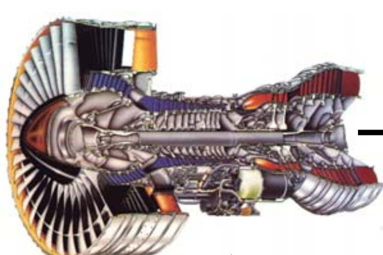
System performance limited by instability

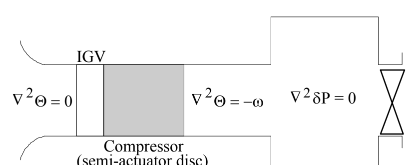
- Number of rotors/stators required to deliver pressure set by instability limit
- Hysteresis loop forces operation away from peak pressure rise

Benefits of active control of stall/surge

- 10% decrease in stalling mass flow can lead to 2% increase in fuel efficiency (!)
- Requires system redesign, not retrofit
- Complexity, weight, reliability are important (mostly unaddressed) issues

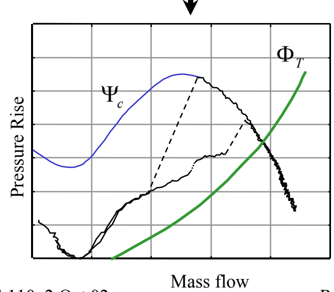
Moore-Greitzer Model (1986)





$$\Psi = \Psi_c(\Phi + \delta\phi) - l_c \frac{d\Phi}{d\xi} - \lambda \frac{\partial \delta\phi}{\partial \theta} - (\mu + m)\frac{\partial \delta\phi}{\partial \xi}$$

One mode expansion
+ Galerkin projection

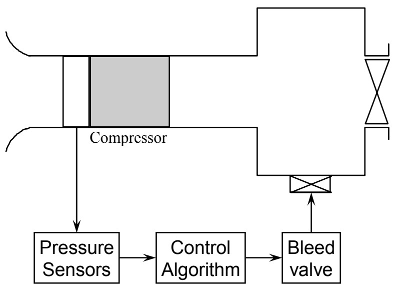


$$\dot{\psi} = \frac{1}{4B^2 l_c}\left(\phi - \Phi_T(\psi)\right)$$

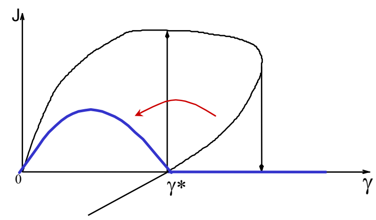
$$\dot{\phi} = \frac{1}{l_c}\left(\Psi_c(\phi) - \psi + \frac{J}{8}\frac{\partial^2 \Psi_c}{\partial \phi^2}\right)$$

$$\dot{J} = \frac{2}{\mu + m}\left(\frac{\partial \Psi_c}{\partial \phi} + \frac{J}{8}\frac{\partial^3 \Psi_c}{\partial \phi^3}\right)J$$

Bifurcation Control Using 1D Bleed Valves



$$\dot{\psi} = \frac{1}{4B^2 l_c}\left(\phi - (\gamma + \underline{KJ})\sqrt{\psi}\right)$$



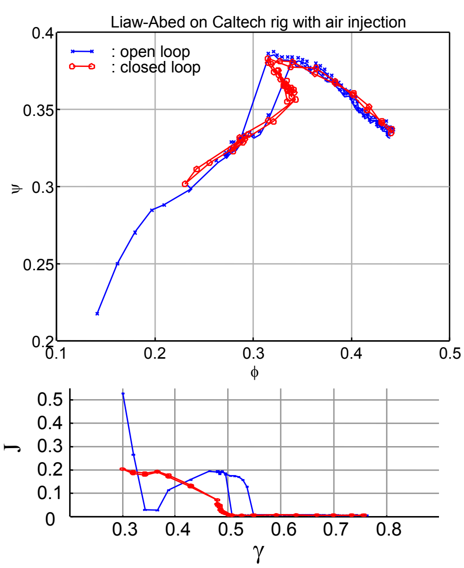
(Liaw and Abed, 1992)

$$K_{\min} = -\frac{\phi^* \Psi_c'''(\phi^*)}{8\gamma^* \psi^* \Psi_c''(\phi^*)} - \frac{\gamma^* \Psi_c''(\phi^*)}{8\psi^*}$$

Remarks:

- Can show system is not stabilizable ⇒ can only achieve operability enhancement
- Achieve performance benefit by engine redesign; operate closer to peak pressure
- 2D actuation (IGV, BV, or AI) gives stability extension, but more complex (?)

Experimental Results Using Modified Ψ_c



Use steady air injection to shift Ψ_c

- Changes shape of Ψ_c to give lower rate requirements
- Implication: actuator requirements strongly affected by system design

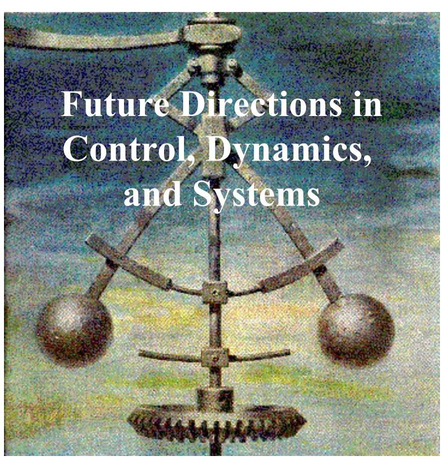
Other shifting mechanisms possible

- Blade redesign
- Casing treatments

> Lesson Learned:
>
> Must consider controllability in the design process

Yeung & Murray, JPC'97

Future Trends and Emerging Opportunities



Panel on Future Directions in Control, Dynamics, and Systems

Richard M. Murray (chair)
Caltech

Outline

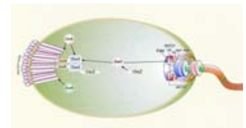
- Overview of Panel
- Summary of Panel Findings
- Themes & Recommendations
- Next Steps & Timeline

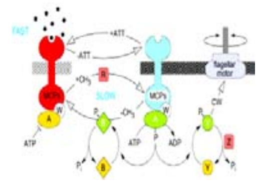
http://www.cds.caltech.edu/~murray/cdspanel

Biological Engineering

"Systems Biology"

- Many molecular mechanisms for biological organisms are characterized
- Missing piece: understanding of how network interconnection creates robust behavior from uncertain components in an uncertain environment
- Transition from organisms as genes, to organisms as networks of integrated chemical, electrical, fluid, and structural elements



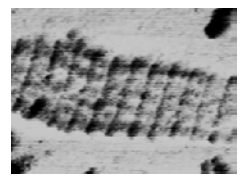


Key features of biological systems

- Integrated control, communications, computing
- Reconfigurable, distributed control, built at molecular level

Design and analysis of biological systems

- Apply engineering principles to biological systems
- Systems level analysis is required
- Processing and flow information is key



Complex, Multi-Scale Networks and Systems

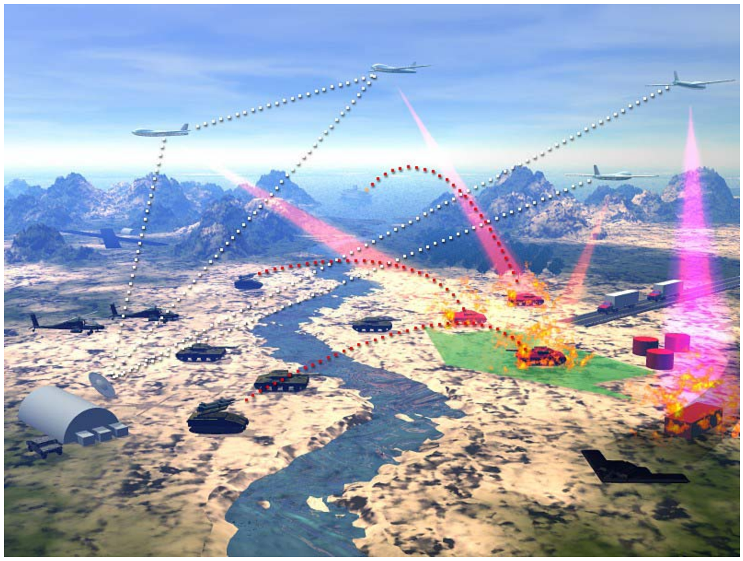
Pervasive, ubiquitous, convergent networking

- Heterogeneous networks merging communications, computing, transportation, finance, utilities, manufacturing, health, consumer, entertainment, ...
- Robustness and reliability are the dominant challenges
- Need "unified field theory" of communications, computing, and control

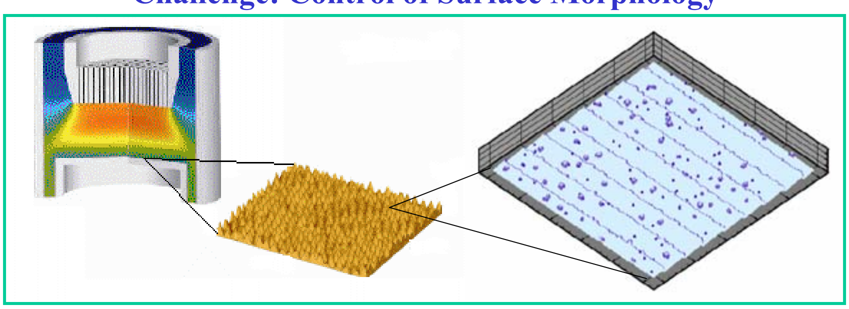
Many applications

- Congestion control on the internet
- Power and transportation systems
- Financial and economic systems
- Quantum networks and computation
- Biological regulatory networks and evolution
- Ecosystems and global change

Future Battlespace Systems



Challenge: Control of Surface Morphology



Question: can control be used to modify surface morphology?

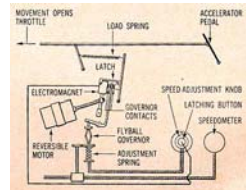
- Use unsteady processing conditions and *in situ* diagnostics to alter growth
- Provide more structured approach than existing techniques
- Can also be used to understand actuation of domain walls

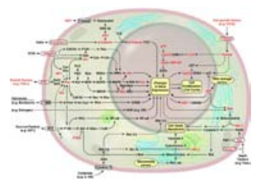
Challenges

- Sensing of relevant characteristics
  - Nucleation events
  - Grain boundary features
  - Surface roughness
- Coupling between macro-scale actuation and micro-scale physics
- Models suitable for controllability analysis and control design

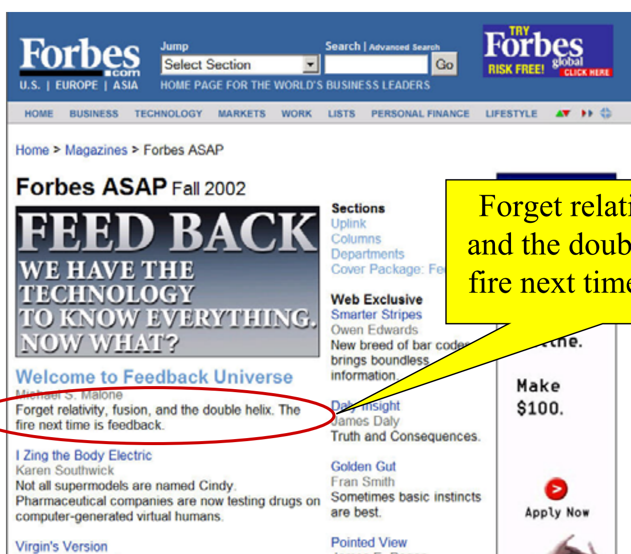
Report: Control in an Information Rich World

1. **Executive Summary**
2. **Overview of the Field**
   - What is Control?
   - Control System Examples
   - The Increasing Role of Information-Based Systems
   - Opportunities and Challenges Now Facing Us
3. **Applications, Opportunities and Challenges**
   - Aerospace and Transportation
   - Information and Networks
   - Robotics and Intelligent Machines
   - Biology and Medicine
   - Materials and Processing
   - Other Applications
4. **Education and Outreach**
5. **Recommendations**



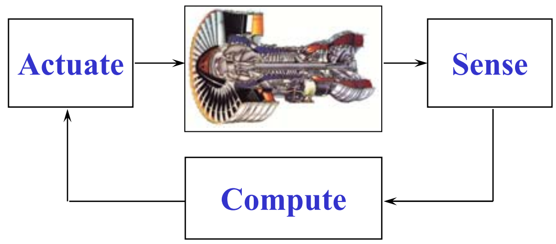


Feedback is "hot"



Forget relativity, fusion, and the double helix. The fire next time is feedback.

Summary



Feedback enables performance in the presence of uncertainty

- Uncertainty management requires clever and appropriate use of feedback
- Model-based control and black box controllers can both enhance performance

Rapid improvements in sensing, computation, communication drives control

- All of these are becoming cheaper and more ubiquitous; networking will have a large impact on control, diagnostics, prognostics, maintainence, etc
- Actuation still remains a bottleneck; control configured design is key