Controls Primer
Fall 2001

Objectives

- Provide familiarity of the basic concepts in feedback control
- Survey tools in Lyapunov and optimization-based control

Proposed Schedule

4 Sep	Overview of feedback control	Richard	Tue 10 am PDT
11 Sep	Introduction to state space control and feedback	Raff	
18 Sep	Lyapunov stability and control	Lars	
25 Sep	Lyapunov, continued	Lars	
2 Oct	Optimal control theory	Reza	TBD
9 Oct	Optimal, continued	Reza	
16 Oct	Model predictive control	Bill	
12 Oct	MPC, continued	Bill	

http://www.cds.caltech.edu/~murray/courses/primer-fa01

Lecture #1
Overview of Feedback Control

Goals

- Provide engineering context for “active control technology”, through examples
- Survey some of the standard approaches and tools for feedback control
- Describe some of the future directions for the field

Lecture Outline

1. What is Control?
2. Basic Concepts in Feedback Control
3. Application Examples
    - Automotive Control
    - Flight Control
4. Future Directions

Reference: Report of the Panel On Future Directions in Control, Dynamics and Systems, 2001

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

What is Control?

Types of Control

Passive Control

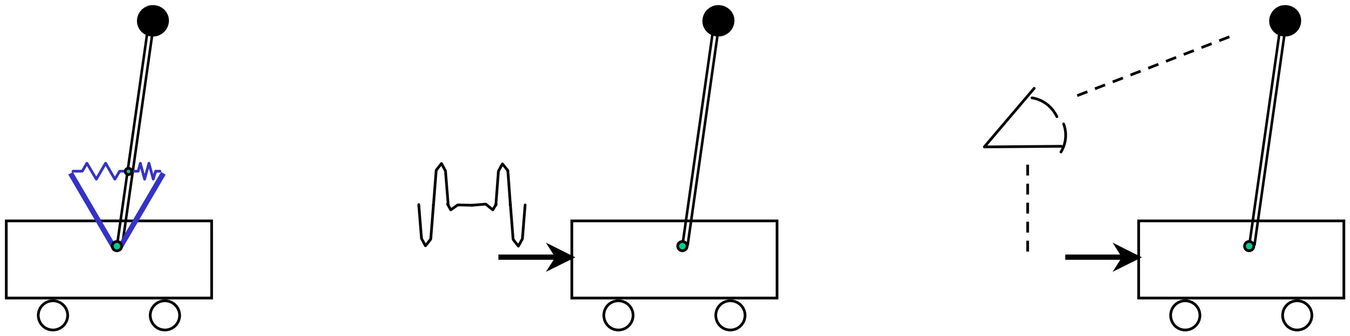
- Make structural modifications to change the plant dynamics
- Use this technique whenever it is a viable option: cheap, robust

Open Loop Control

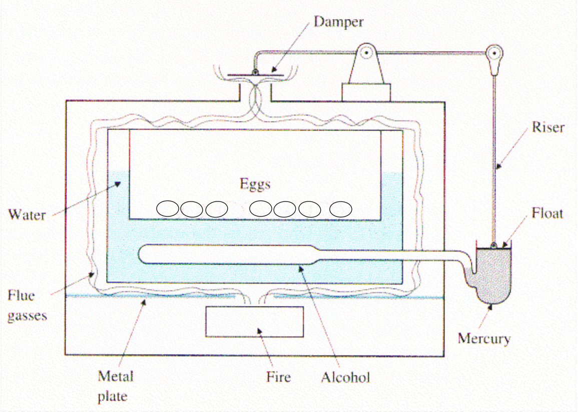
- Exploit knowledge of system dynamics to compute appropriate inputs
- Requires *very* accurate model of plant dynamics in order to work well

Active (Feedback) Control

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

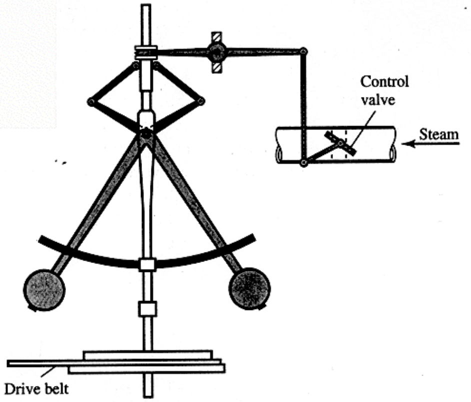


Early Uses of Feedback



Pre-1700

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



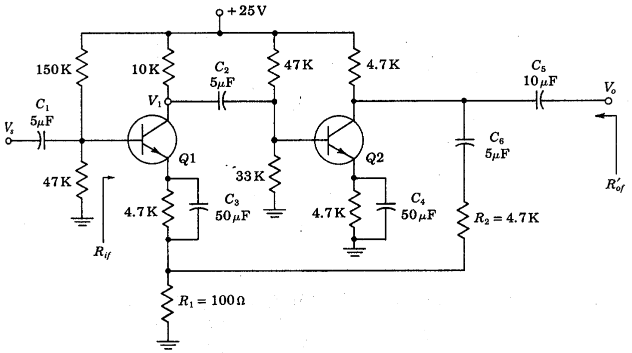
Balls fly out as speed increases, closing valve →

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
- Use feedback to reduce uncertainty (robustness)



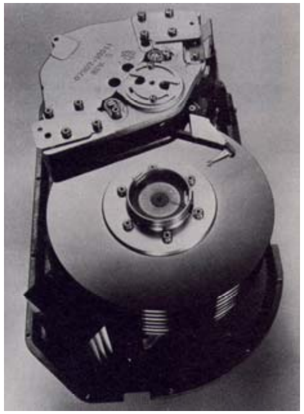
Modern Application Areas

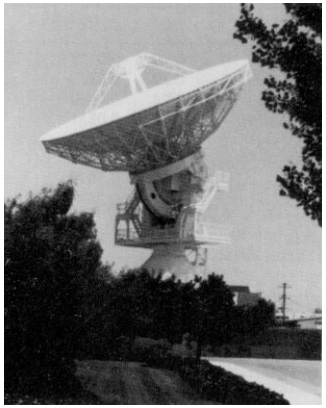
Flight Control Systems

- 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

Heating Ventilation and Air Conditioning (HVAC)

- Basic thermostatic controls to building level systems
- Very distributed system with many local control loops

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...

Emerging Application Areas

Materials Processing

- Rapid thermal processing for increased throughput
- Control of vapor deposition for special purpose materials (e.g. YPCO thin films)

Noise and Vibration Control

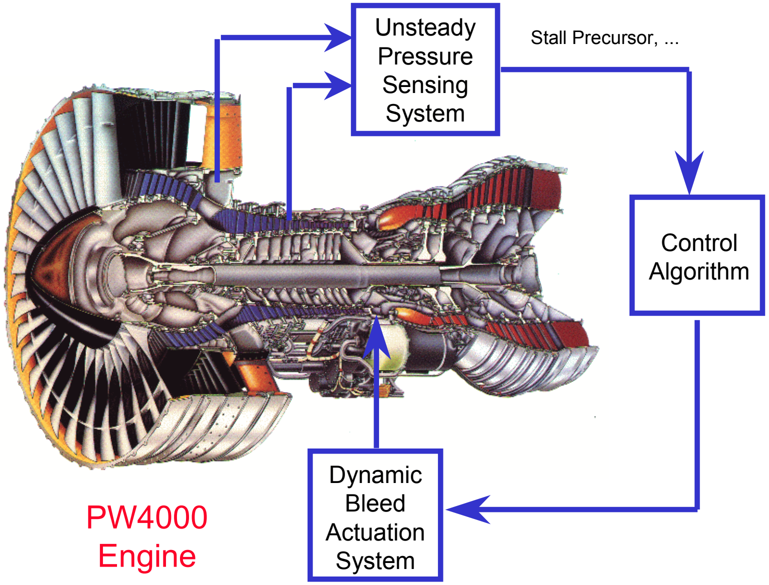
- Active mounts and speaker systems for noise and vibration reduction
- Variety of applications: cars, planes, HVAC

Intelligent Vehicle Highway Systems

- Platooning of cars for high speed, high density travel on freeways
- PATH project in California is already in test near San Diego

Smart Engines

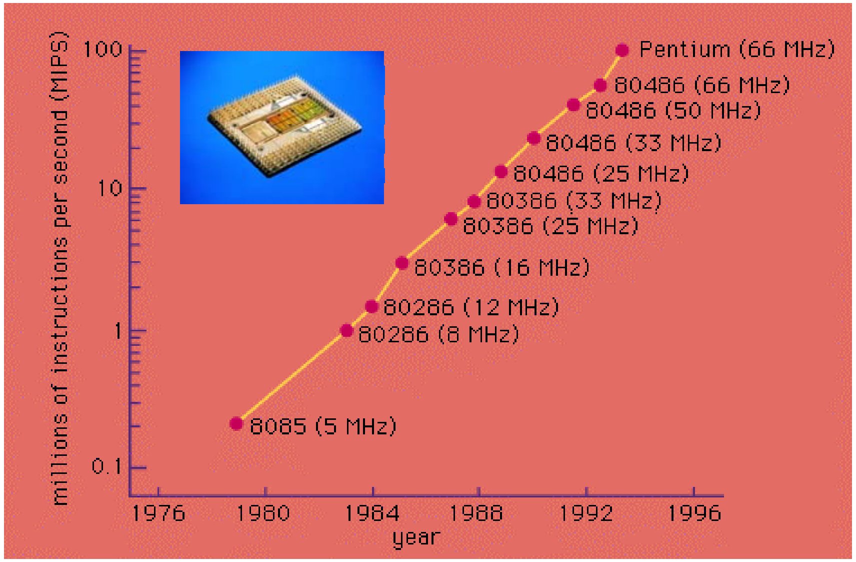
- Compression systems: stall, surge, flutter control for increased operability
- Combustion systems: operation at leaner air/fuel ratios for low emissions



Technology Trends Affecting Active Control

Computation/microprocessors

- Early controllers used analog computation Þ only simple algorithms were possible
- Development of microprocessor in 1970s opened the door to control applications
- Virtually all modern active control loops use microprocessors ⇒ rapid progress

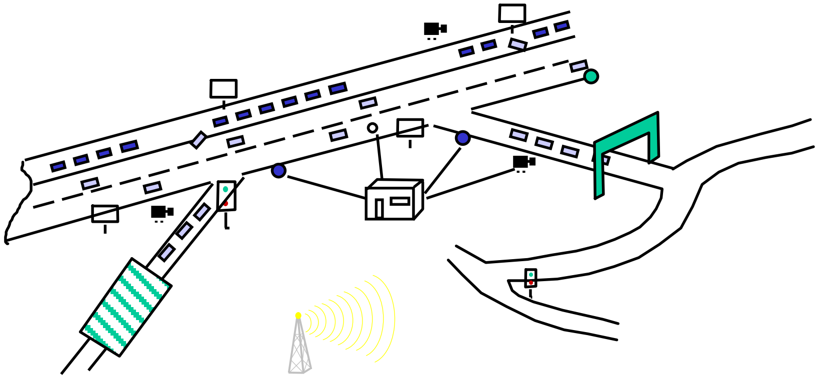


Sensors and Actuators

- Sensors are getting cheaper, faster, smaller
- Macro-scale actuation evolves slowly; power electronics getting cheaper
- Micro-scale actuation is changing rapidly

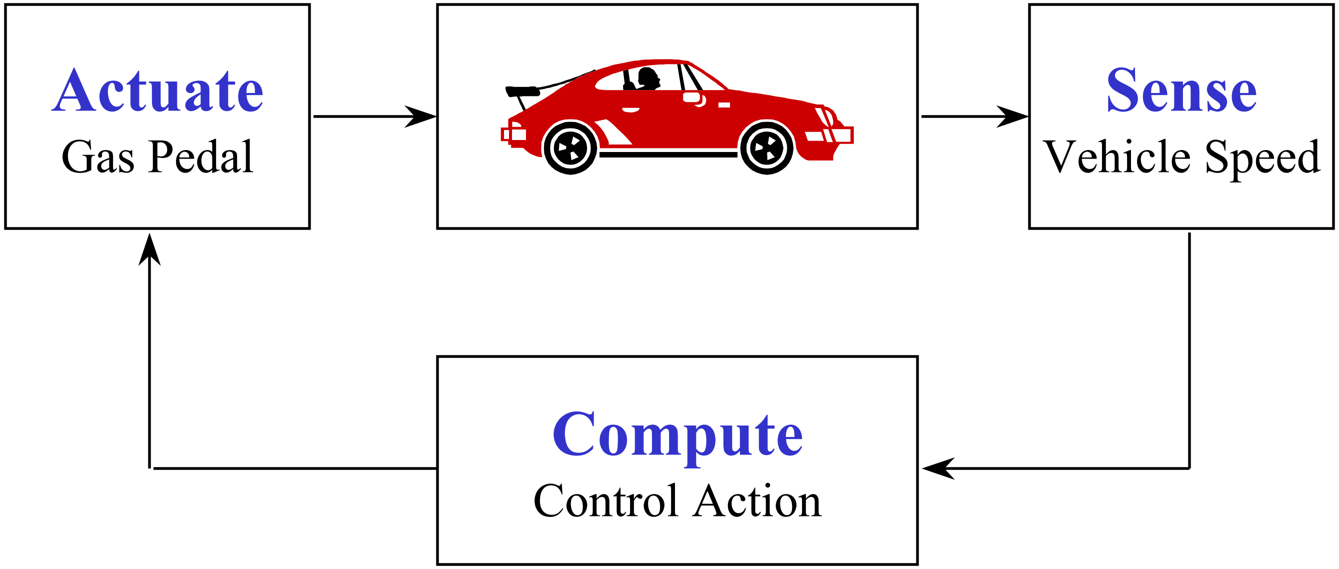
Communications and Networking

- Increased use of sensing and actuation across networks
- Examples: IVHS, ATC, UAVs



Basic Concepts in Feedback Control

Active Control = Sensing + Computation + Actuation



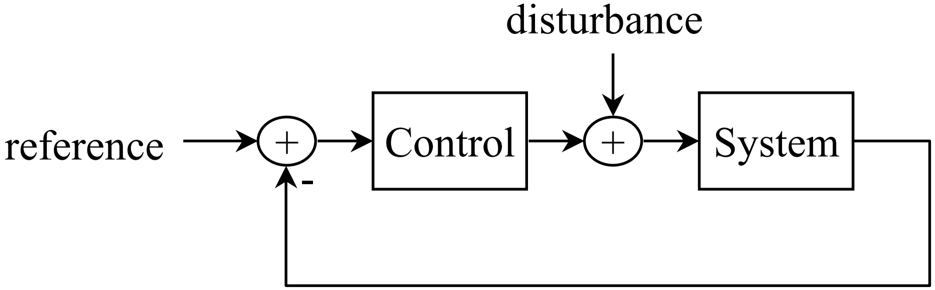
Actuate
Gas Pedal

Sense
Vehicle Speed

Compute
Control Action

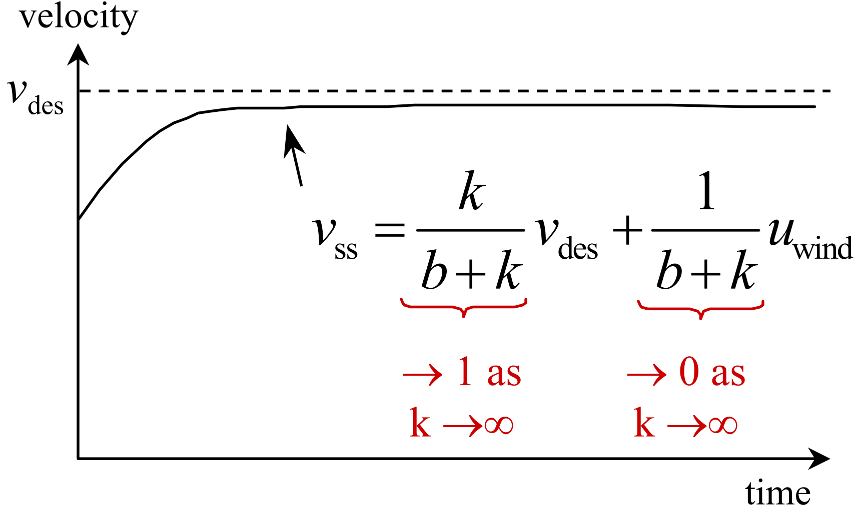
Goals: Stability, Performance, Robustness

Benefits of Feedback: Disturbance Rejection & Robustness



$$m\dot{v} = -bv + u_{\text{engine}} + u_{\text{wind}}$$

$$u_{\text{engine}} = k(v_{\text{des}} - v)$$



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

Stability/performance

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

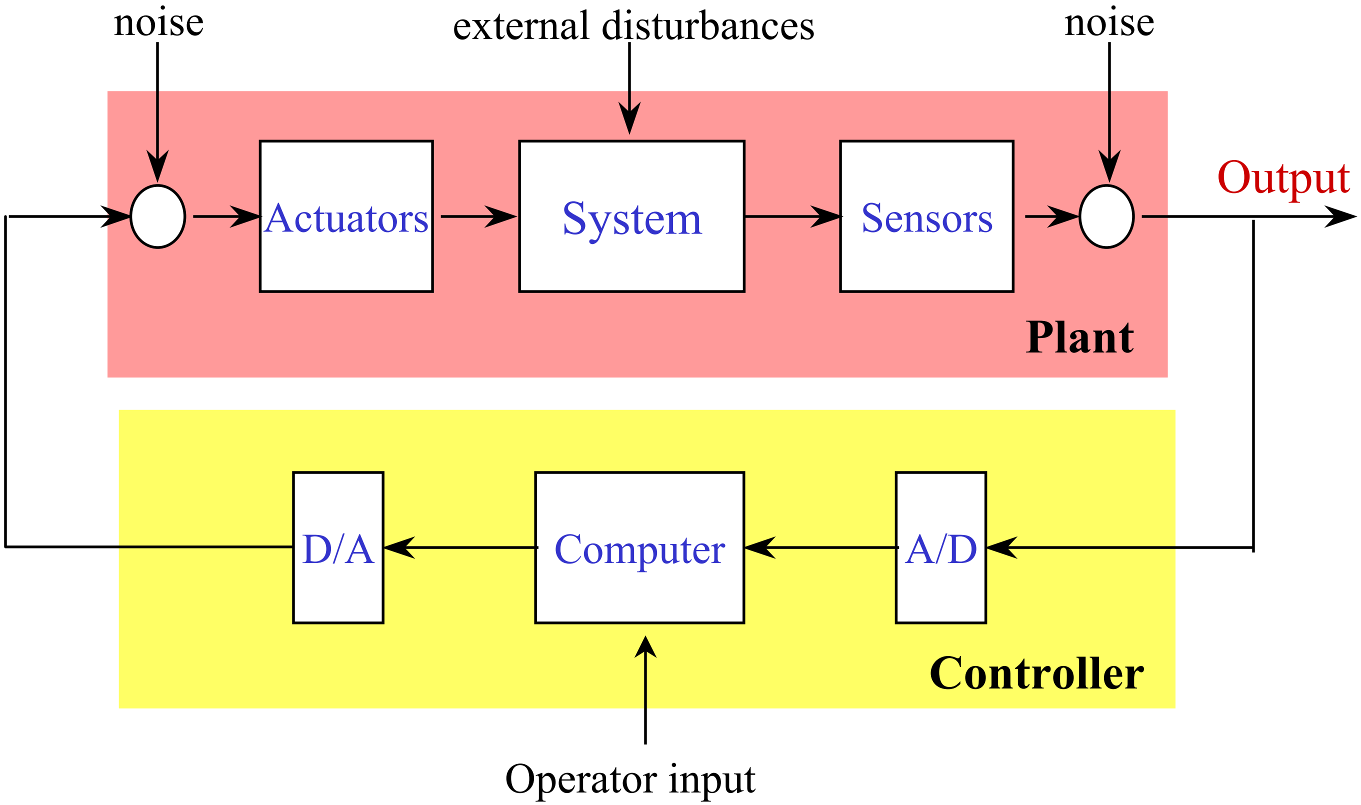
Disturbance rejection

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

Robustness

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

Modern Control System Components

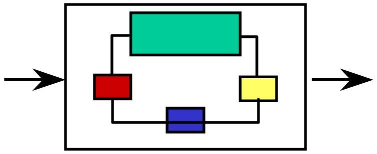


Plant	Physical system, actuation, sensing
Controller	Microprocessor plus conversion hardware (single chip)
Feedback	Interconnection between plant output, controller input

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

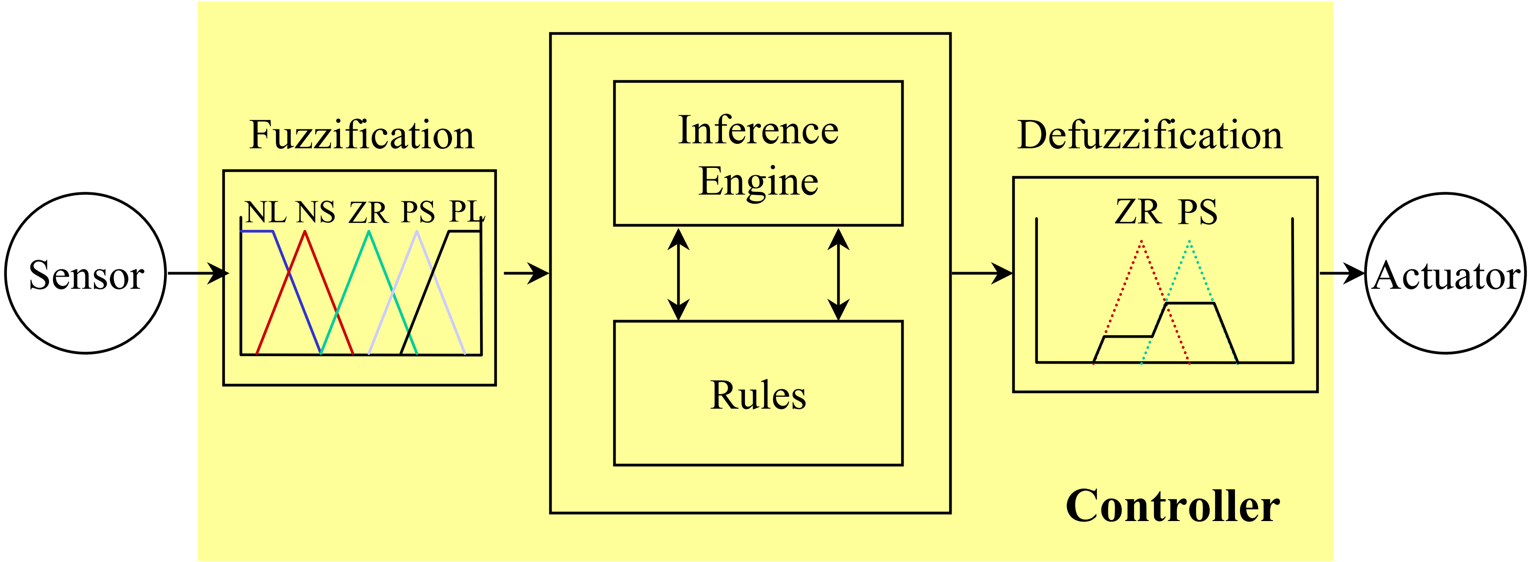
Basic idea: write control actions as *fuzzy logic* rules:

Standard logic:
If T < 68° **then**
turn heater on

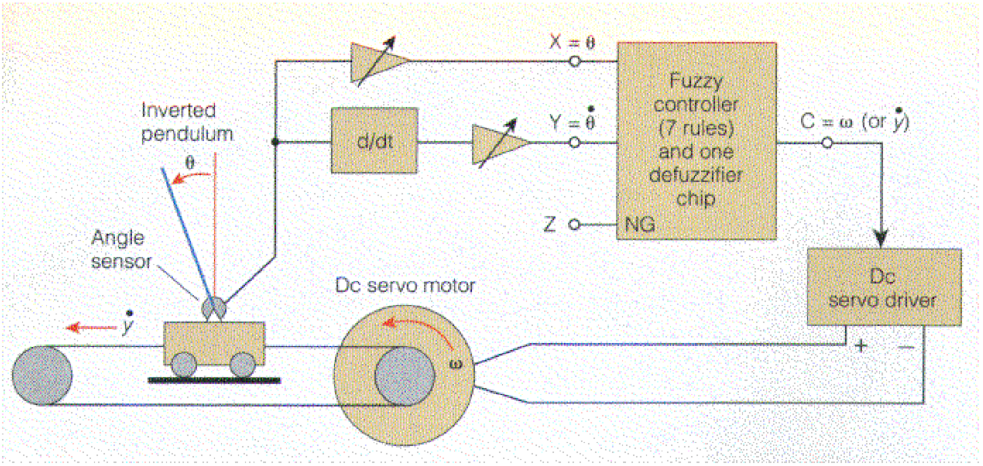
Fuzzy logic:
If very cold **then**
more heat

Fuzzy logic allows:

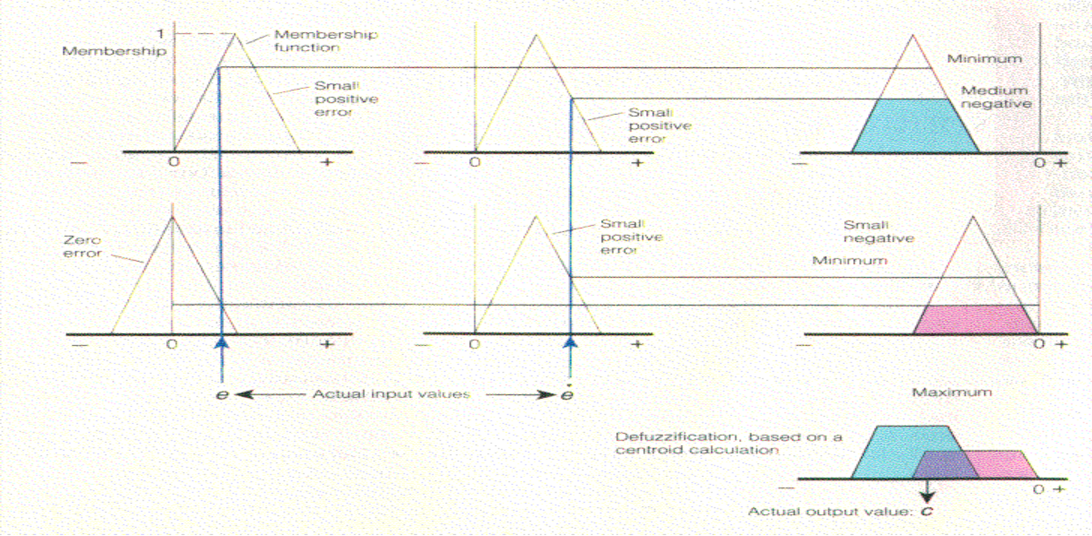
- Easy specification of control actions as rules
- Partially conflicting rules
- Smoothing of control actions



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)

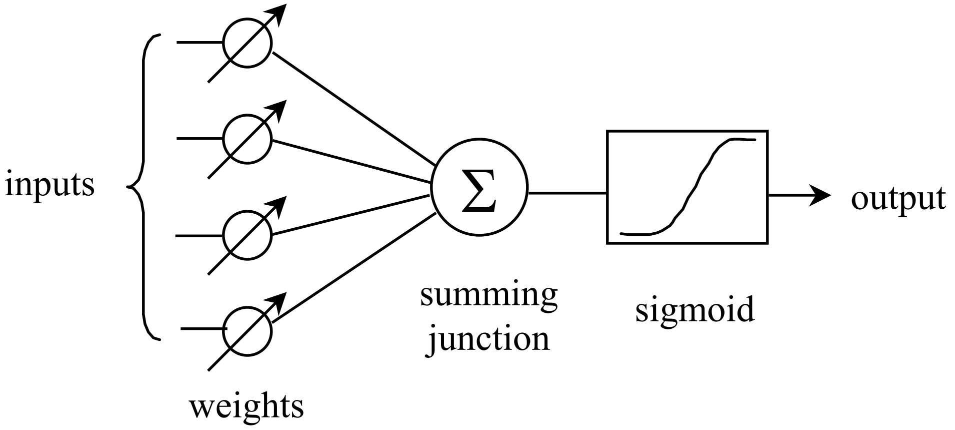
Common features that fuzzy exploits

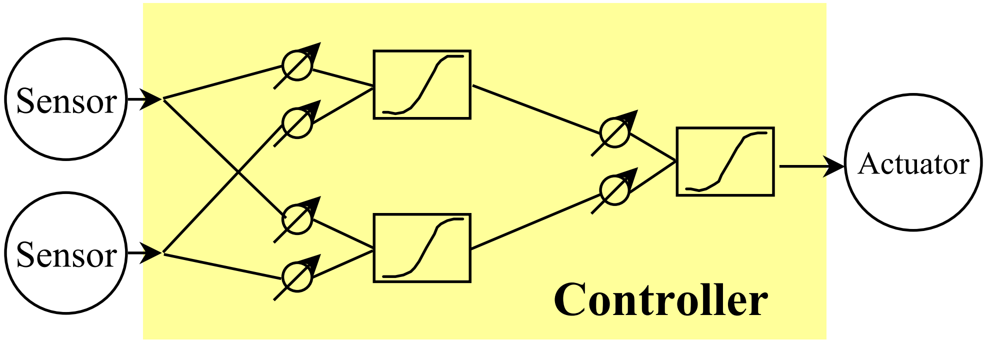
- Feedback able to improve performance
- Lack of high-fidelity, control oriented models
- Good human expertise available
- Relatively low performance requirements (non-catastrophic failure modes)

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

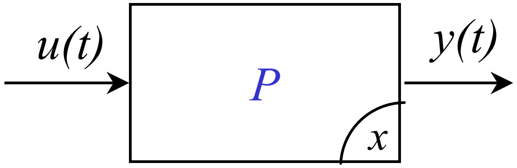
$$\dot{x} = f(x, u)$$
$$y = h(x, u)$$

Linearization around x_0=0

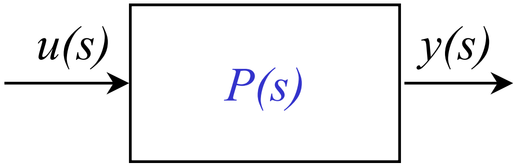
$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

Laplace transform

Block diagrams (Operators)



Linearization around x_0 =0

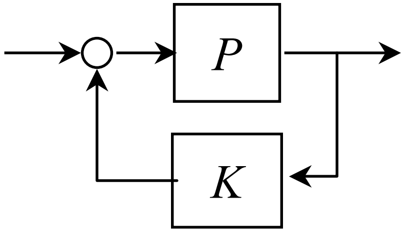


$$P(s) = \frac{a_{n-1}s^{n-1} + \cdots + a_0}{s^n + b_{n-1}s^{n-1} + \cdots + b_0}$$

Stability and Robustness

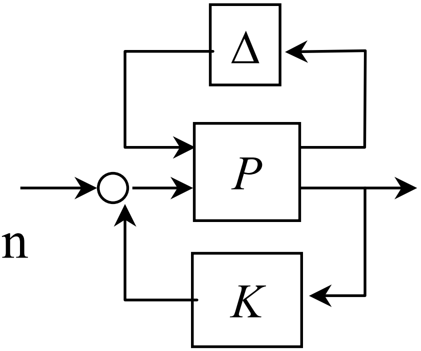
Stability: bounded inputs produce bounded outputs

- 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)

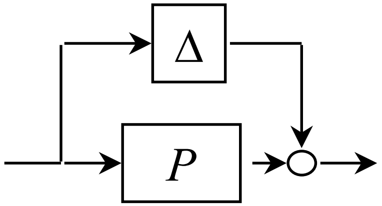
Parametric uncertainty

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

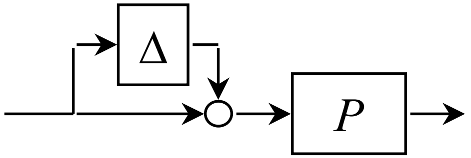
Unmodeled *dynamics*

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

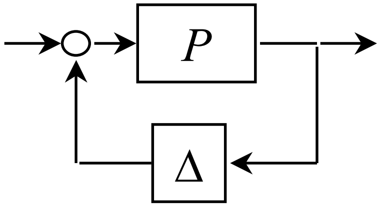
Additive uncertainty



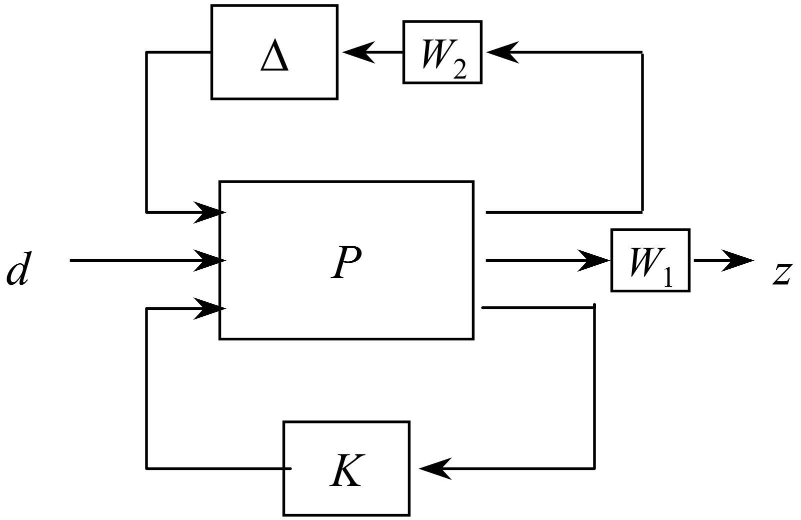
Multiplicative uncertainty



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

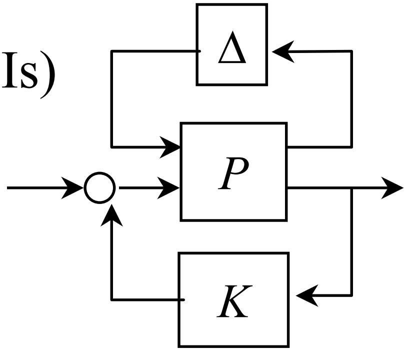
$$\|z\|_2 \le \gamma \|d\|_2 \quad \text{for all} \quad \|\Delta\| \le 1$$

- 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 (LMIs)



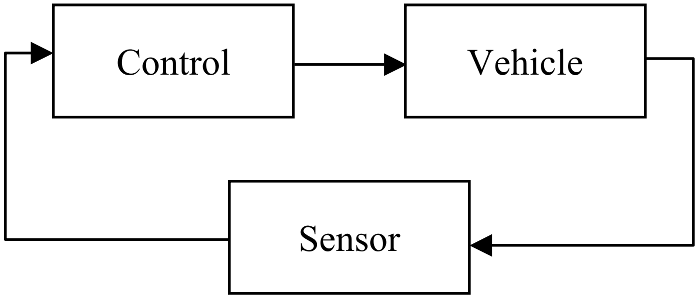
Analysis Tools

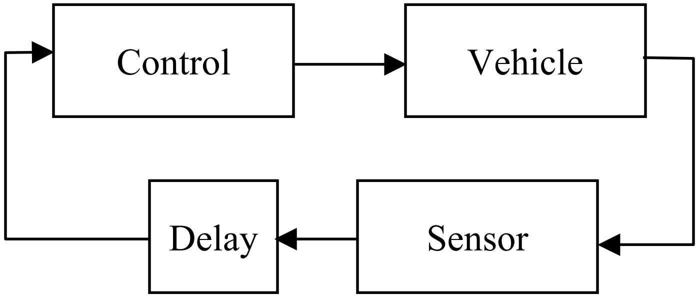
- H_∞ gains for multi-input, multi-output systems
- μ analysis software
  - Allow structured uncertainty descriptions (fairly general)
  - Computes *upper and lower bounds* on performance
  - Wide usage in aerospace industry

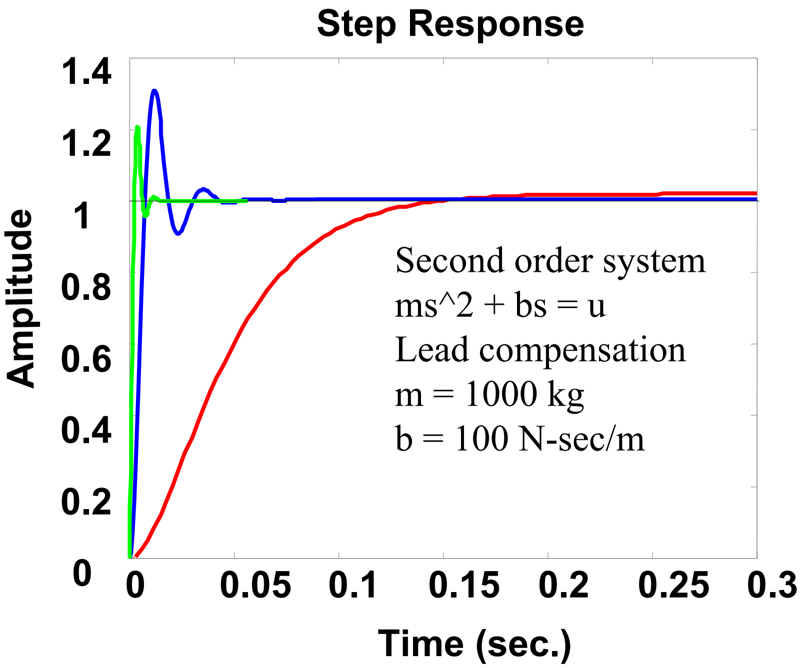
Synthesis Tools

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

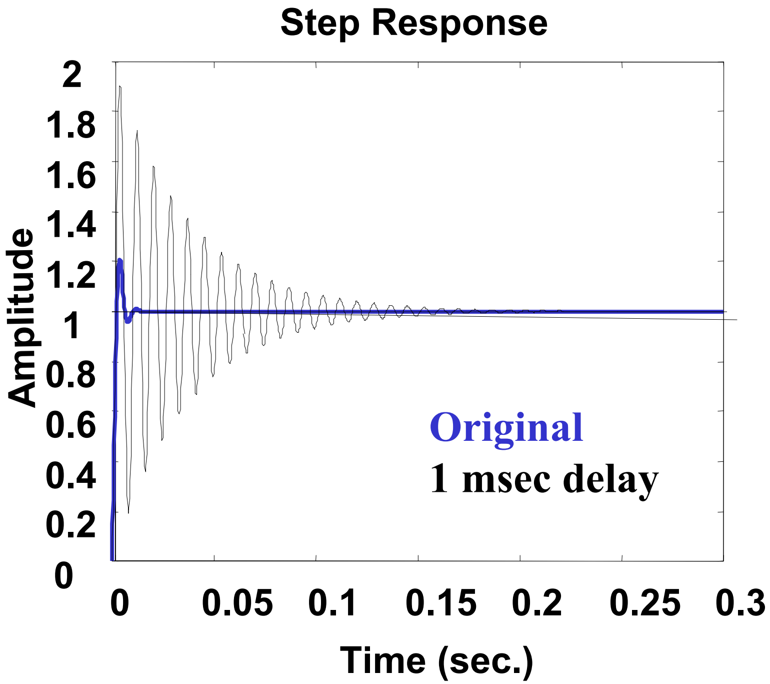
Achilles Heel: Effects of Time Delay on Performance







Second order system
ms^2 + bs = u
Lead compensation
m = 1000 kg
b = 100 N-sec/m



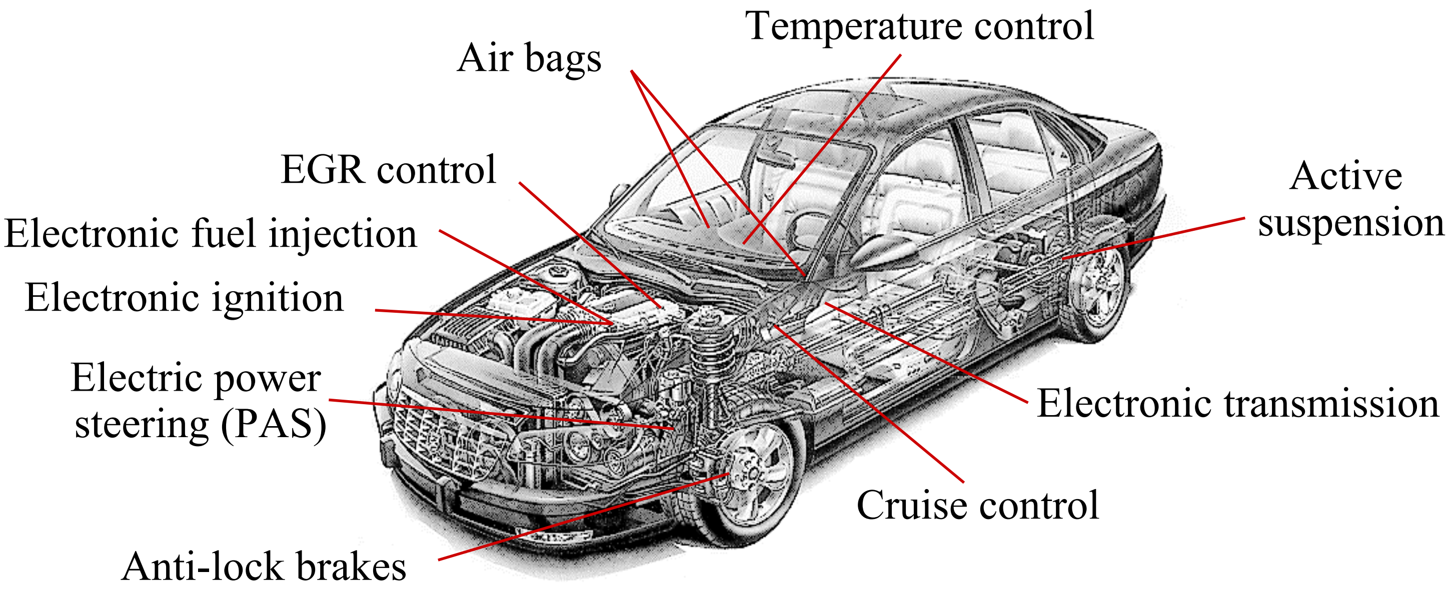
Communications delays and uncertainty can have a major effect on high performance systems

Application Examples

Smart cars and intelligent highways

Flight Control

Feedback Control in Automobiles



Air bags

Temperature control

EGR control

Electronic fuel injection

Electronic ignition

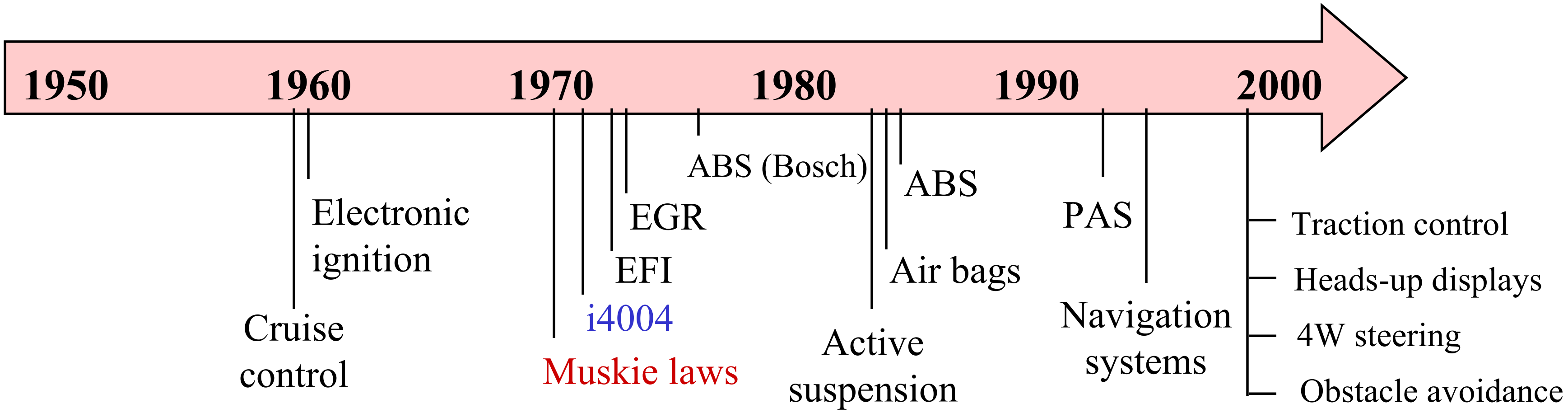
Electric power steering (PAS)

Anti-lock brakes

Active suspension

Electronic transmission

Cruise control



1950 1960 1970 1980 1990 2000

Cruise control

Electronic ignition

Muskie laws

i4004

EFI

EGR

ABS (Bosch)

Active suspension

Air bags

ABS

PAS

Navigation systems

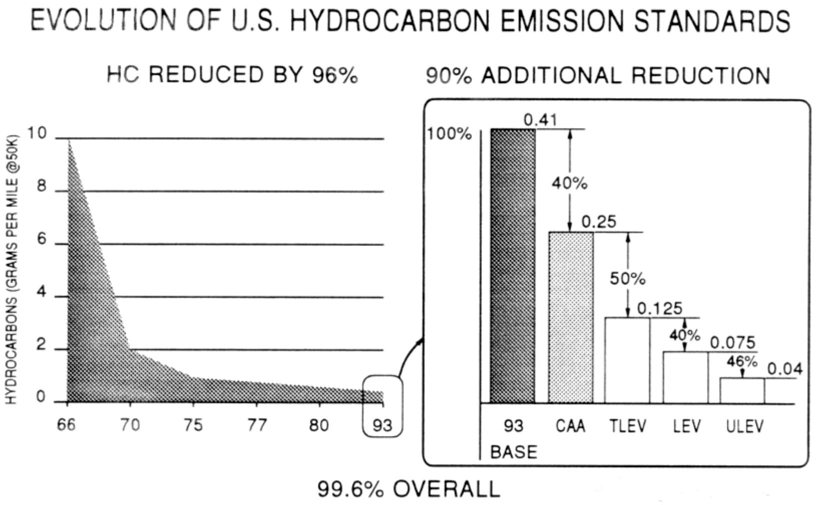
Traction control

Heads-up displays

4W steering

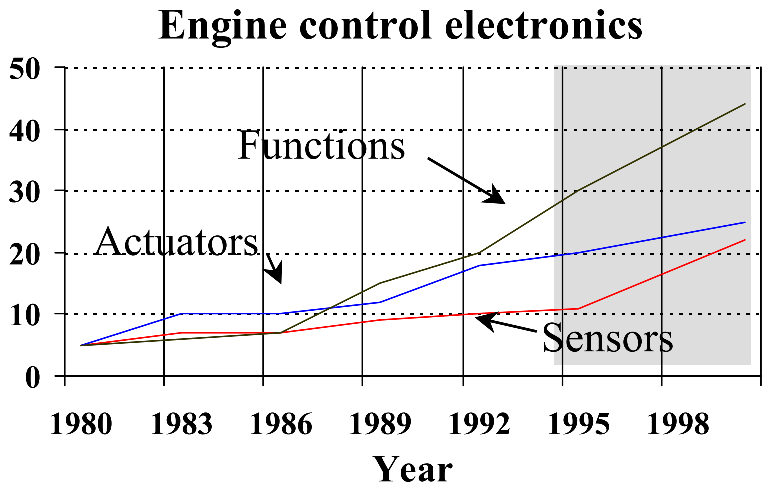
Obstacle avoidance

Engine Control

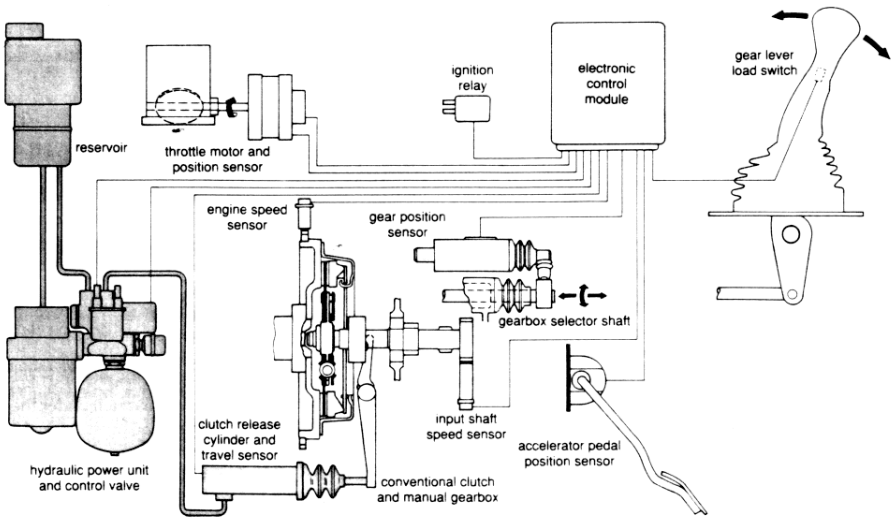


Reliance on active control is increasing

- 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



Trends and Lessons in Automotive Control

Advances often driven by gov't 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

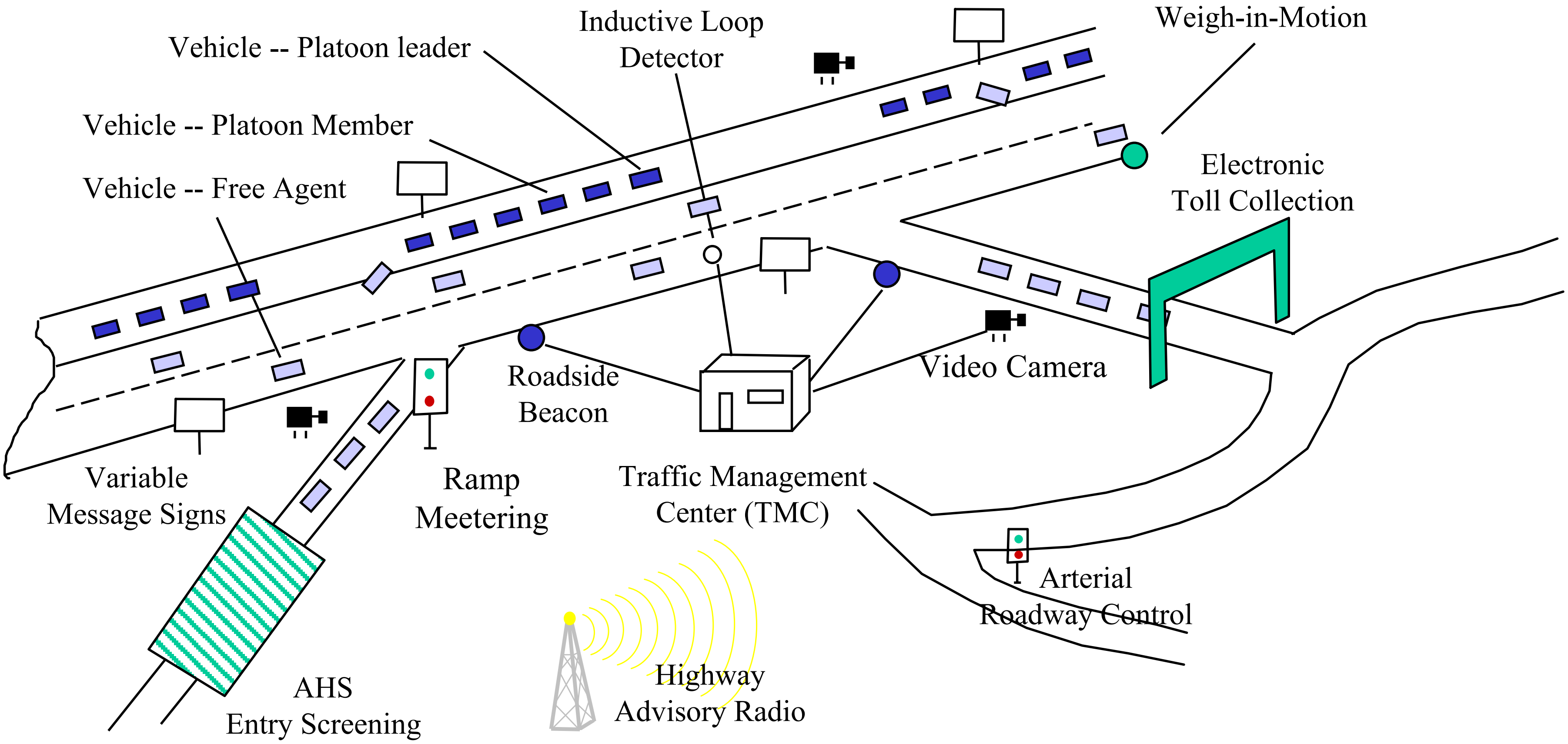
Additional benefits

- 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

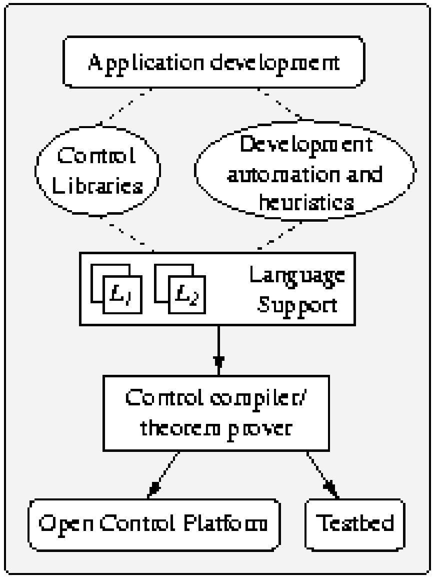
Intelligent Vehicle Highway Systems (IVHS)



Use Feedback Control to Regulate and Optimize Traffic Control

High Confidence, Reconfigurable, Distributed Control

(Hickey, Murray, Chandy, Doyle)



Application development

Control Libraries

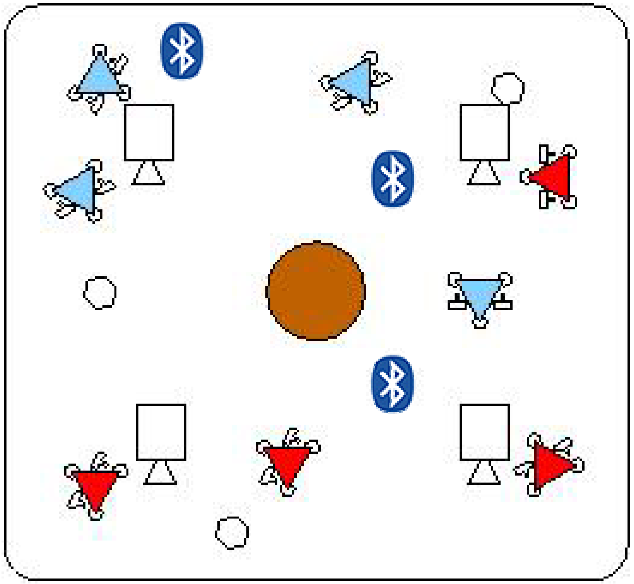
Development automation and heuristics

L_1 L_2 Language Support

Control compiler/theorem prover

Open Control Platform

Testbed



Optimization-Based Control

- Real-time model predictive control for online control customization: theory + software
- Online implementation on Caltech Ducted Fan

Software Environments

- Logical programming environments for embedded control systems design
- "On-the-fly", correct by construction techniques

Multi-Vehicle Testbed

- Implementation on multi-vehicle, wireless testbed using Open Control Platform
- Bluetooth-based point to point communications with ad-hoc networking

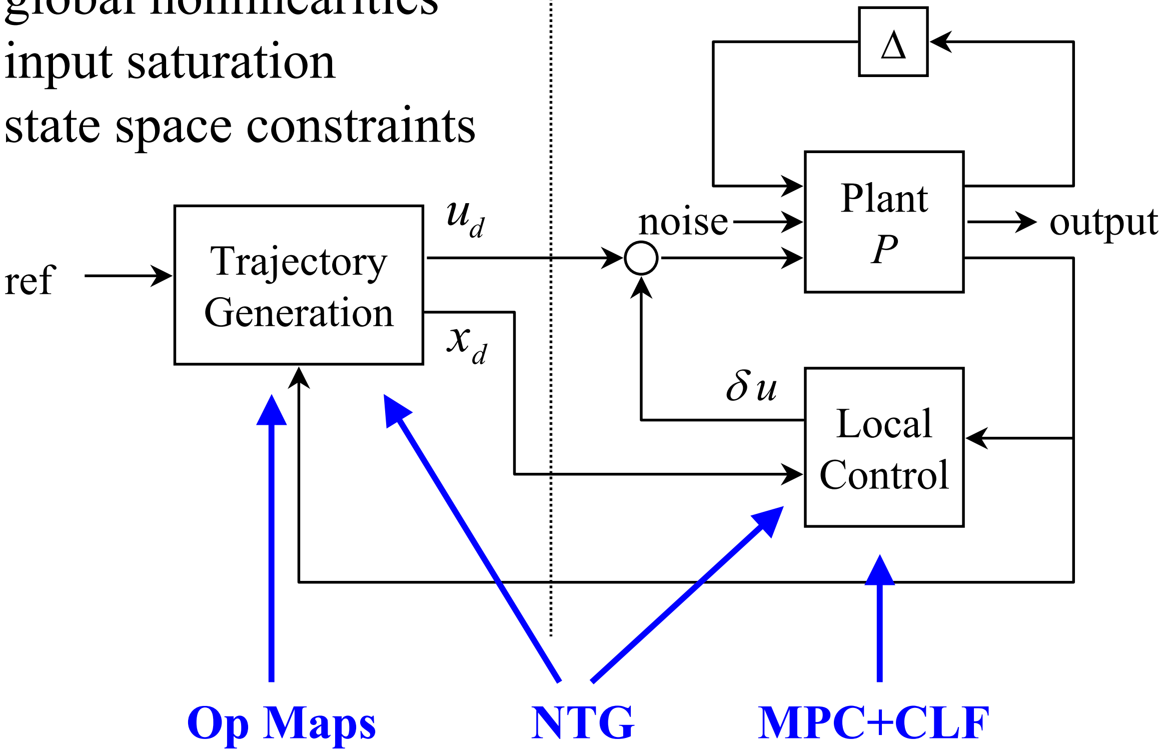
Output: Framework and Prototype Environment for Robust, Software Enabled Control Systems

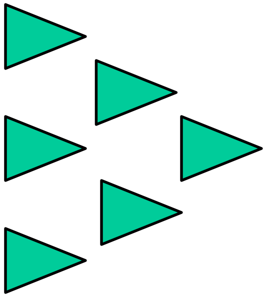
Overview: Optimization-Based Control

Nonlinear design

- global nonlinearities
- input saturation
- state space constraints

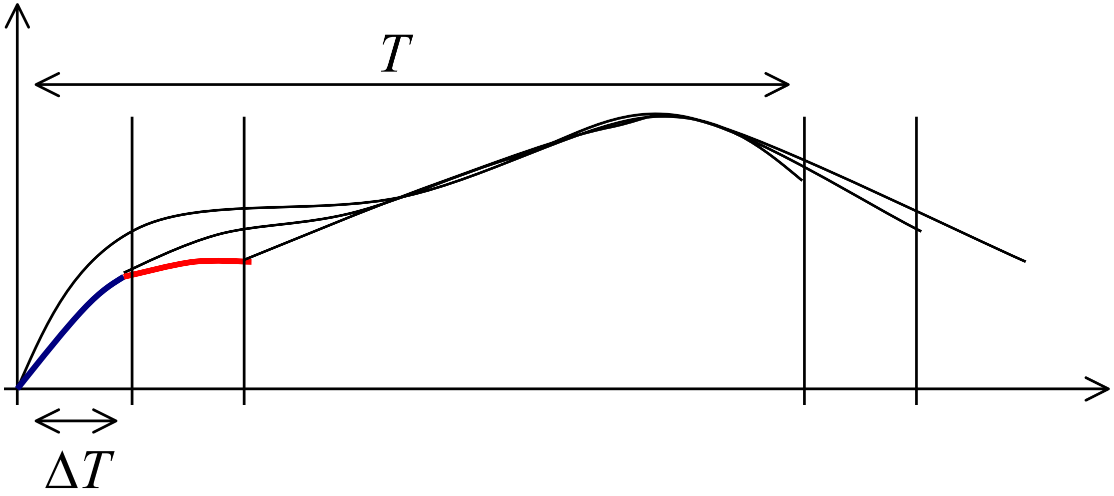
Local design





- Use *real-time* trajectory generation to construct (suboptimal) feasible trajectories
- Use model predictive control for *reconfigurable* tracking & robust performance
- Extension to multi-vehicle systems performing cooperative tasks (ongoing)

Overview: Optimization-Based Control



$$u_{[t,t+\Delta T]} = \arg\min \int_t^{t+T} L(x(\tau),u(\tau))\,d\tau + V(x(t+T))$$

$$x_0 = x(t) \quad x_f = x_d(t+T)$$

$$\dot{x} = f(x,u) \quad g(x,u) \le 0$$

Online control customization

- System: f(x,u)
- Constraints/environment: g(x,u)
- Misssion: L(x,u)

Update in real-time to achieve *reconfigurable* operation

Theory: MPC + CLF Approach

$$J_T^*(x_0) = \min_{u(\cdot)} \int_0^T q(x(\tau), u(\tau))\, d\tau + V(x(T))$$

Finite horizon

CLF
≈ "cost to go"

$$\inf_u \, (\dot{V} + q)(x,u) \le 0$$

Basic Idea

- Use online models to compute receding horizon optimal control
- CLF-based terminal cost gives stability + short time horizons

Properties

- Can prove stability (in absence of constraints)
- Incremental improvement property ⇒ finite iterations OK
- Increased horizon ⇒ larger region of attraction

Real-Time Trajectory Generation / Optimization

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

Collocation

$$(x,u) = \sum \alpha_i \psi^i(t)$$

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

Flatness

$$z = z(x, u, \dot{u}, \ldots, u^{(p)})$$

$$x = x(z, \dot{z}, \ldots, z^{(q)})$$

$$u = u(z, \dot{z}, \ldots, z^{(q)})$$

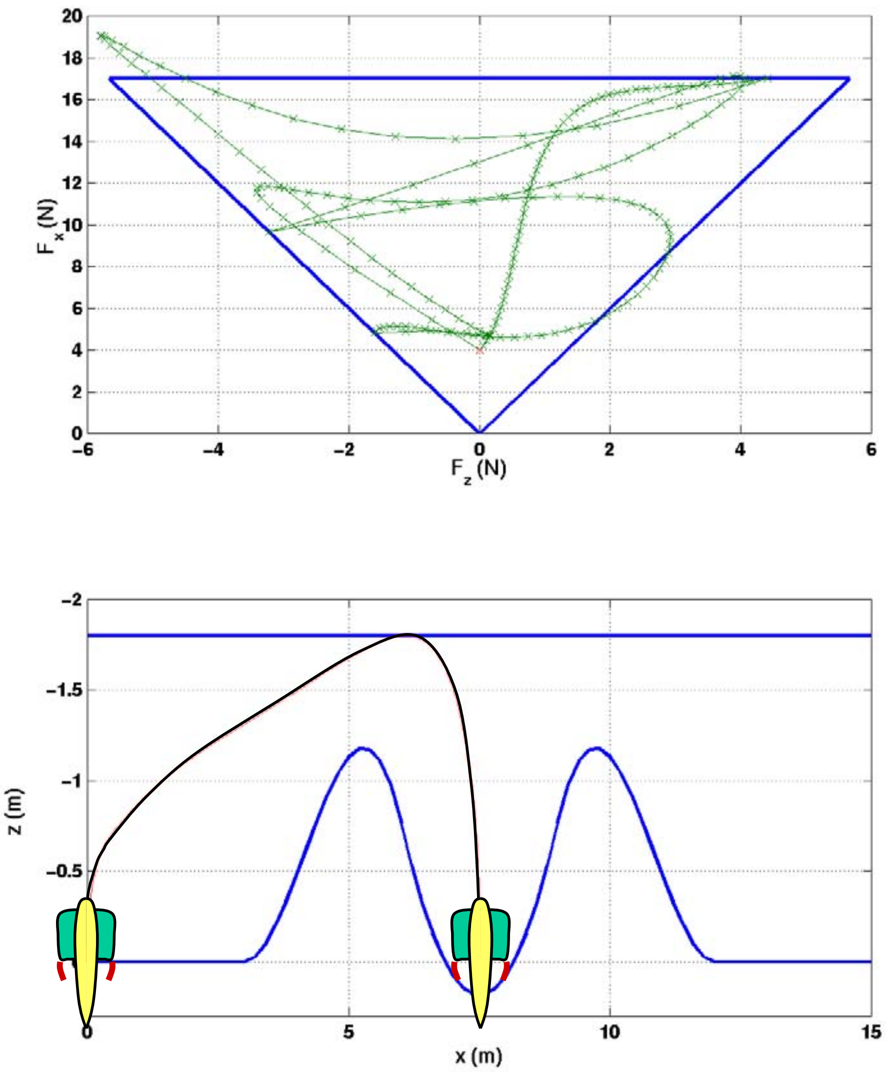
$$z = \sum \alpha_i \psi^i(t)$$

Quasi-collocation

$$y = h(x)$$

$$(x,u) = \Gamma(y, \dot{y}, \ldots, y^{(q)})$$

$$0 = \Phi(y, \dot{y}, \ldots, y^{(p)})$$



Ducted Fan Terrain Avoidance

Experimental Results: Caltech Ducted Fan

NTG +
MPC +
CLF

Pitch
Control

dSPACE
RTOS

Multi-Vehicle Optimization-Based Control

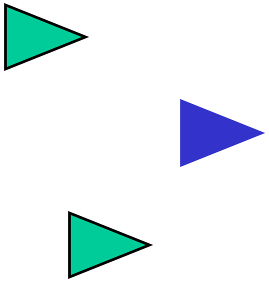
Assume we have real-time, finite horizon optimal control as a *primitive*

$$\left.\begin{aligned} u_{[t,t+\Delta T]} &= \arg\min \int_t^{t+T} L(x,u)\,dt + V(x(t+T)) \\ x_0 &= x(t) \quad x_f = x_d(t+T) \\ \dot{x} &= f(x,u) \quad g(x,u) \le 0 \end{aligned}\right\}$$

Choose f, g, L to represent the *coupling* between the various subsystems

Cooperation depends on how we model “rest of the world”

$$\ddot{q}_1 = 0 \quad |u_1| \le L$$

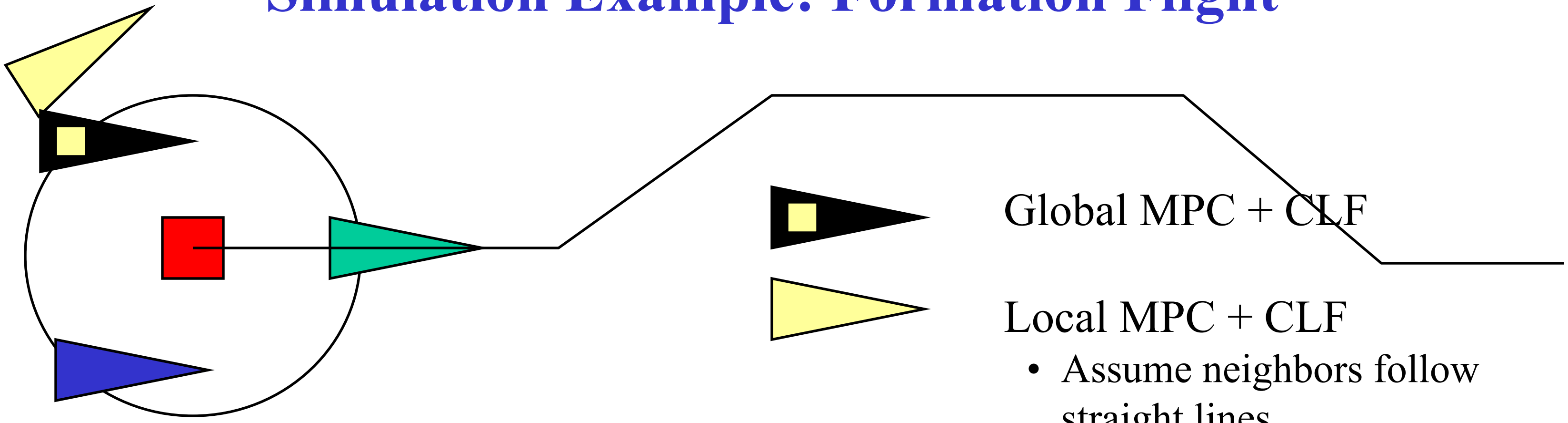


$$\boxed{\begin{aligned} u_{2,[t,t+\Delta T]} &= \arg\min \int_t^{t+T} L(q_{1,}x_2,q_3,u_2)\,dt + V \\ \dot{x}_2 &= f(x_2,u_2) \quad g(x_2,u_2) \le 0 \end{aligned}}$$

$$\ddot{q}_3 = 0 \quad |u_3| \le L$$

Reconfigurable based on condition, mission, environment

Simulation Example: Formation Flight



Global MPC + CLF

Local MPC + CLF

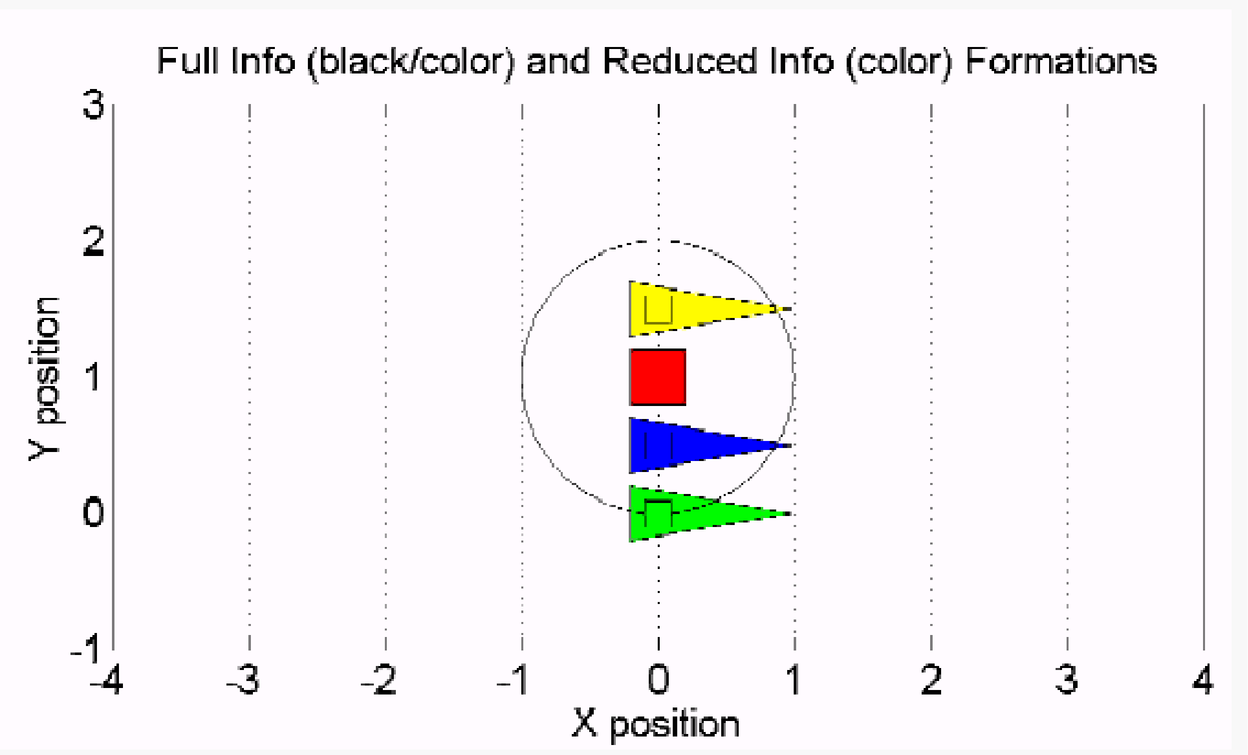
- Assume neighbors follow straight lines

Task:

- Maintain equal spacing of vehicles around circle
- Follow desired trajectory for center of mass

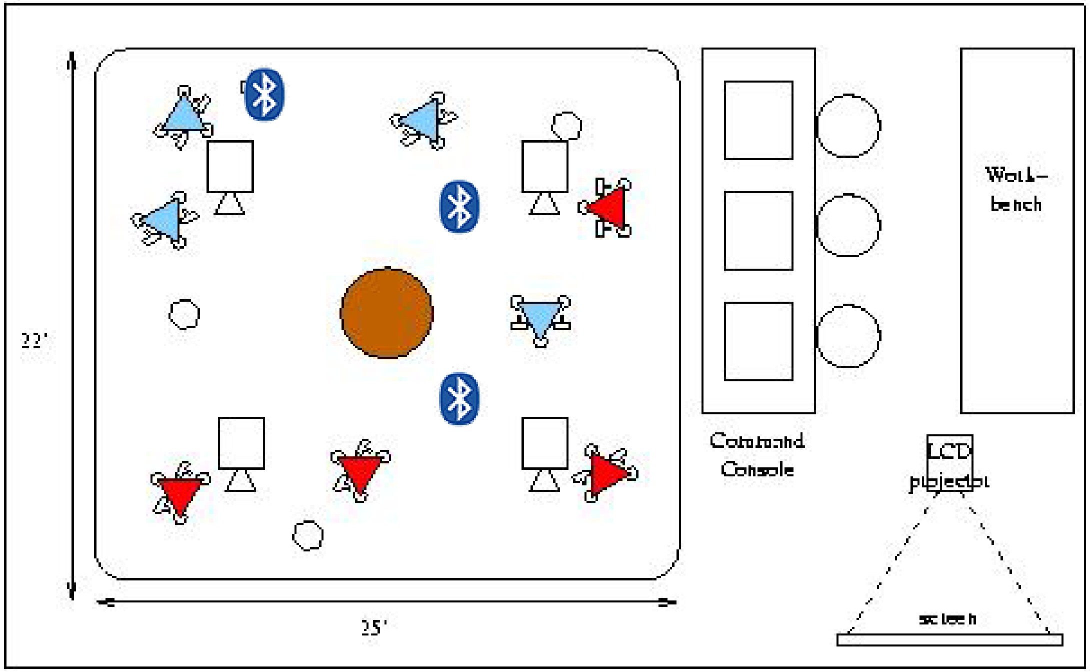
Parameters:

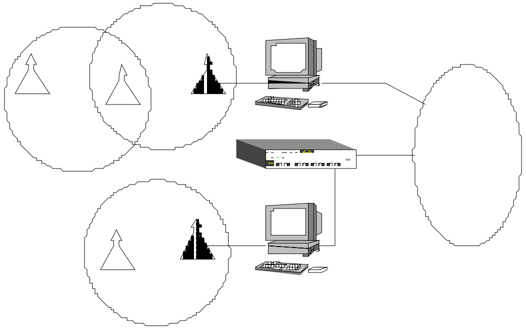
- Horizon: 2 sec
- Update: 0.5 sec
- **High damping**

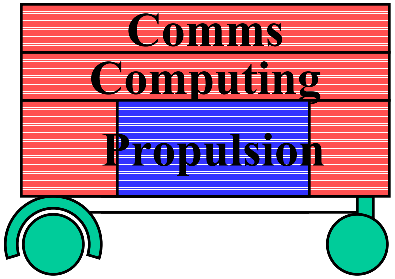


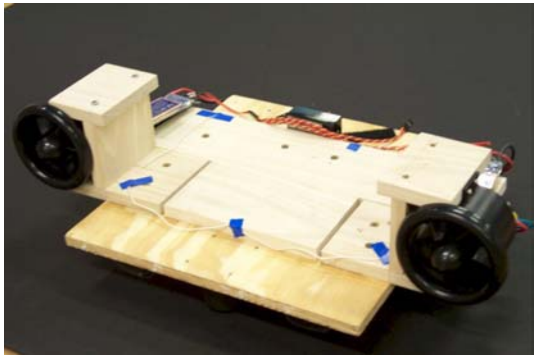
Multi-Vehicle Wireless Testbed for Integrated Control, Communications and Computation

(Hickey, Low, Murray, Doyle, Effros + 8 undergrads)







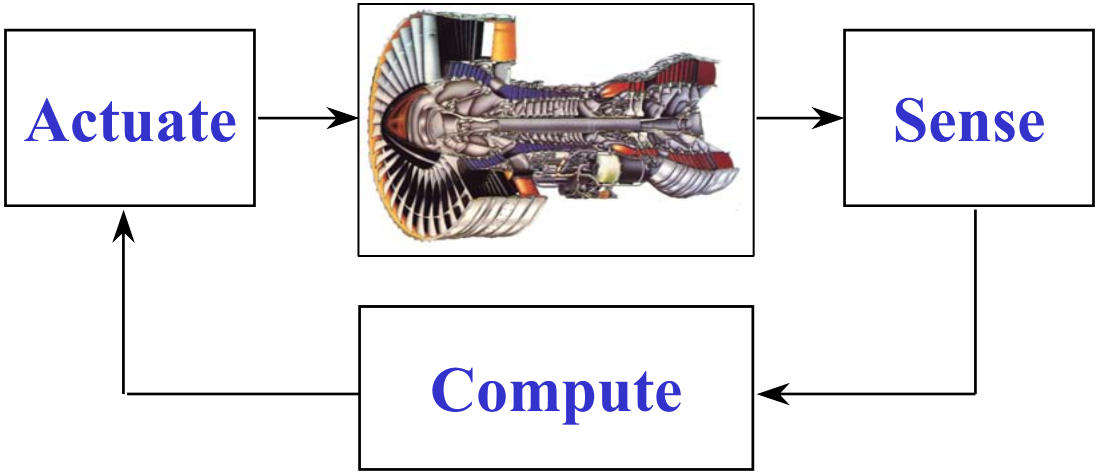


Testbed features

- Distributed computation on individual vehicles + command and control console
- Point to point, ad-hoc networking (bluetooth) + local area networking (802.11)
- Cooperative control in dynamic, uncertain, and adversarial environments

RoboCup Video (Raff D'Andrea [Cornell], CIT `96)

Summary


Actuate

Sense

Compute

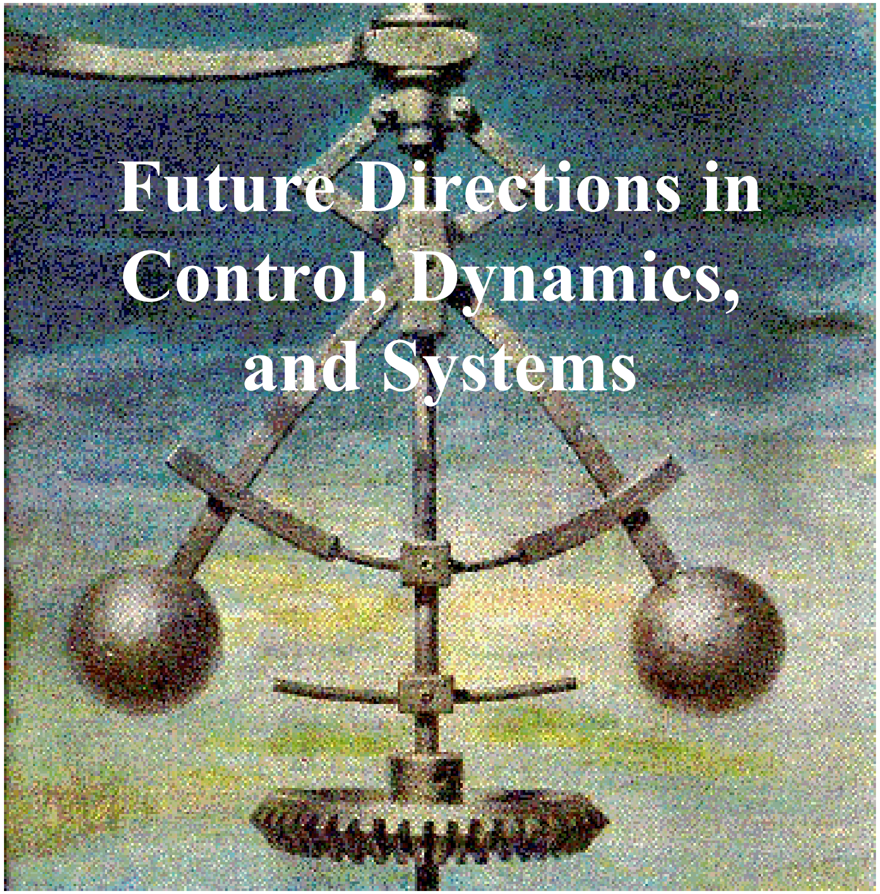
Feedback enables performance in the presence of uncertainty

- 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

Future Directions



Panel on Future Directions in Control, Dynamics, and Systems

Richard M. Murray (chair)
Caltech

Outline

- Review of Panel Activities
- Overview of Panel Report
- Next Steps & Timeline

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

Motivation for the Panel

Articulate the challenges and opportunities for the field

- Present a vision that can be used to inform high level decision makers of the importance of the field to future technological advances
- Identify possible changes in the way that research is funded and organized that may be needed to realize new opportunities
- Provide a compelling view of the field that continues to attract the brightest scientists, engineers, and mathematicians to the field

Respond to the changing nature of control, dynamics, and systems research

- Many new application areas where controls tools are playing a stronger role: biology, environment, materials, information, networks, …
- Controls engineers taking on a much broader, systems-oriented role, while maintaining a rigorous approach and practical toolset

Panel Composition

Karl Astrom
Lund Institute of Technology

Siva Banda
Air Force Research Lab

Stephen Boyd
Stanford

Roger Brockett
Harvard

John Burns
Virginia Tech

Munther Dahleh
MIT

John Doyle
Caltech

John Guckenheimer
Cornell

Charles Holland
DDR&E

Pramod Khargonekar
U. Michigan

P. S. Krishnaprasad
U. Maryland

P. R. Kumar
U. Illinois, Champagne-Urbana

Jerrold Marsden
Caltech

Greg McRae
MIT

George Meyer
NASA Ames

Richard Murray
Caltech

William Powers
Ford

Gunter Stein
Honeywell

Pravin Varaiya
UC Berkeley

Panel Activities

Panel Meeting: 16-17 June 00

- 47 attendees representing academia, industry, government
- Subpanels in 5 application areas
- Basis for report findings

Writing Committee Meetings

- Boyd, Brockett, Burns, Dahleh, Doyle, Laub, Murray, Stein
- Meetings in Oct 00, Mar 01
- Generated outline + drafts

Panel Presentations

- AFOSR Contractors Meeting, 8/00
- Gov't Program Managers, 2/01
- DARPA UAV workshop, 3/01
- IFAC NOLCOS, 6/01

Announcements

- Control Systems Magazine, 6/00
- Systems and Control E-Letter, 6/00
- Systems and Control E-Letter, 9/00

Communication

- CDS Panel web site
  - Draft copies of report
  - Links to related activities/reports
- Mailing list (150+ people)
- Bulletin board

Linkages

- European Commission Workshop, 6/00

Control in an Information Rich World

Report of the Panel on Future Directions in Control, Dynamics, and Systems (v2.0, 27 Jul 01)

1. Executive Summary (5 pages)
- What is Feedback Control?
- Why Does it Matter?
- Control Will Be Even More Important in the Future
- …But It Won't Be Easy
- What Needs to be Done

2. Overview (20 pages)
- What is Control?
- Control System Examples
- The Shift to Information-Based Systems
- Opportunities and Challenges Now Facing Us

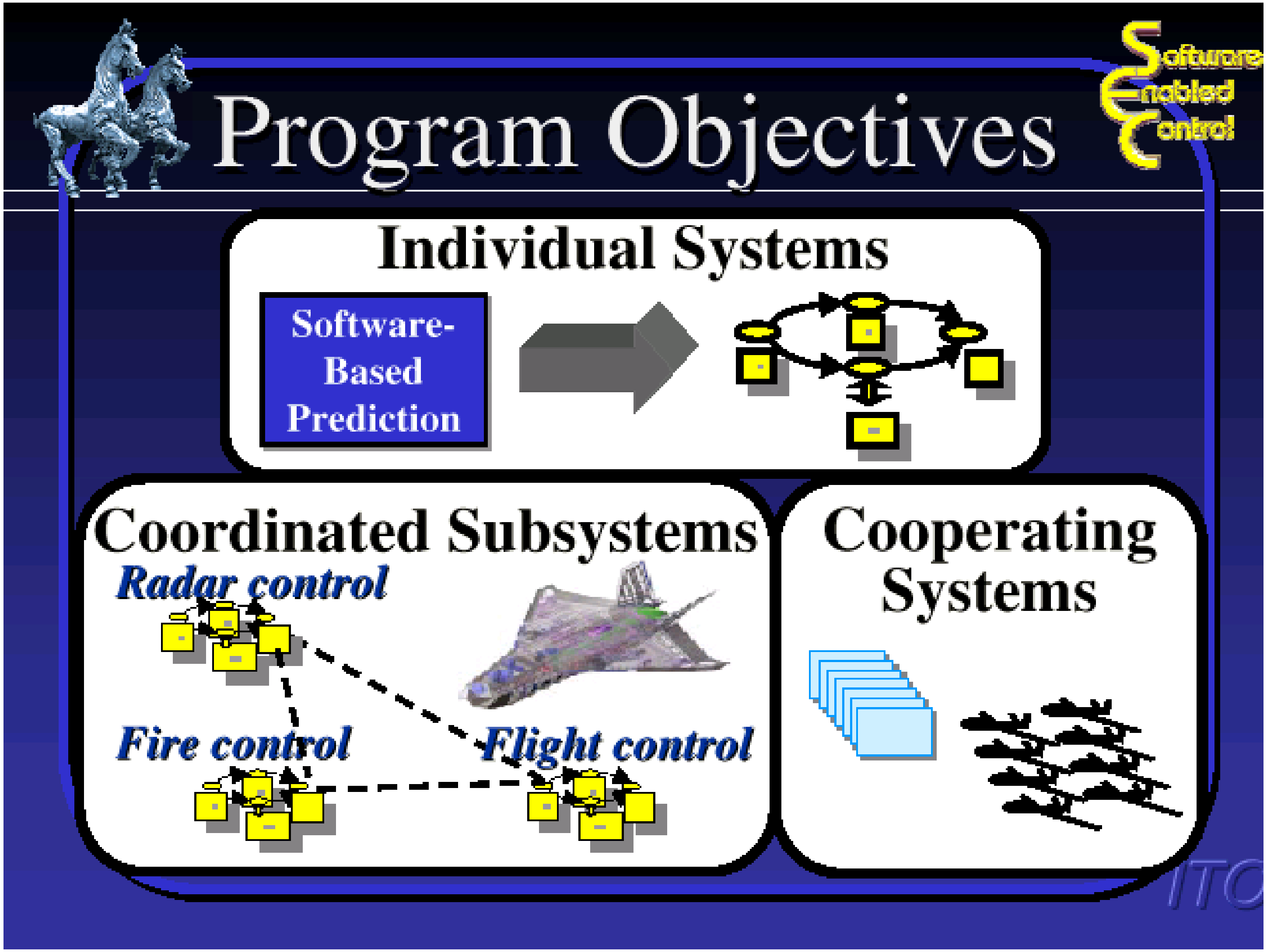
3. Applications, Opportunities and Challenges (30-40 pages)
- Aerospace and Transportation
- Information and Networks
- Robotics and Intelligent Machines
- Biology and Medicine*
- Materials and Processing*
- Other Applications
  - ▫ Environment*
  - ▫ Finance and Economics*

4. Education and Outreach* (10 pages)

5. Recommendations (5 pages)

Aerospace and Transportation

(DARPA Software Enabled Control Program, H. Gill)



Program Objectives

Software Enabled Control

Individual Systems

Software-Based Prediction

Coordinated Subsystems

Radar control

Fire control

Flight control

Cooperating Systems

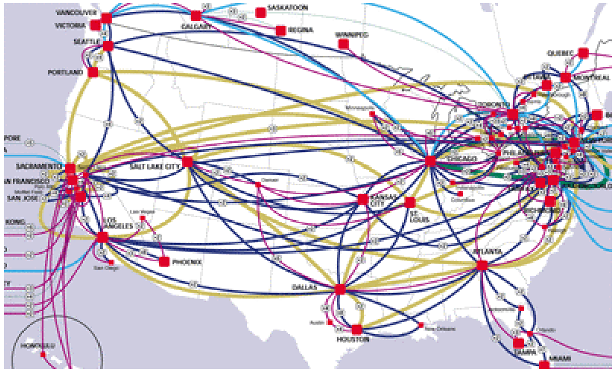
Information and Networks

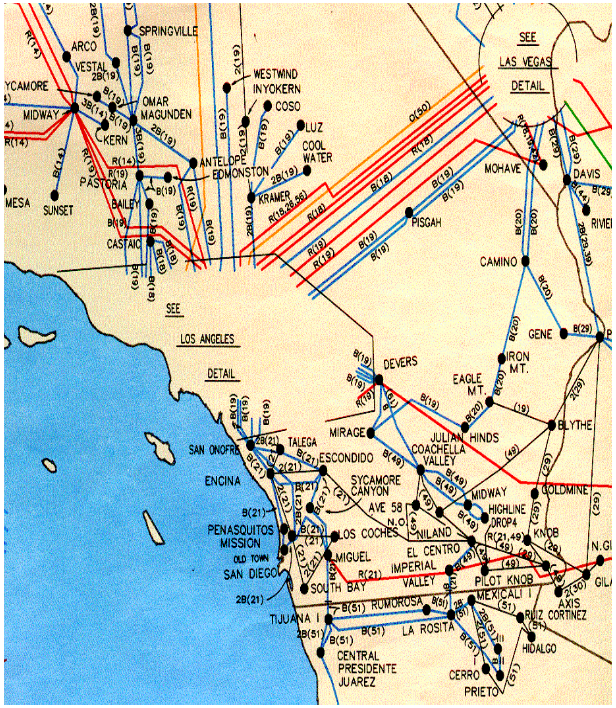
Pervasive, ubiquitous, convergent networking

- 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

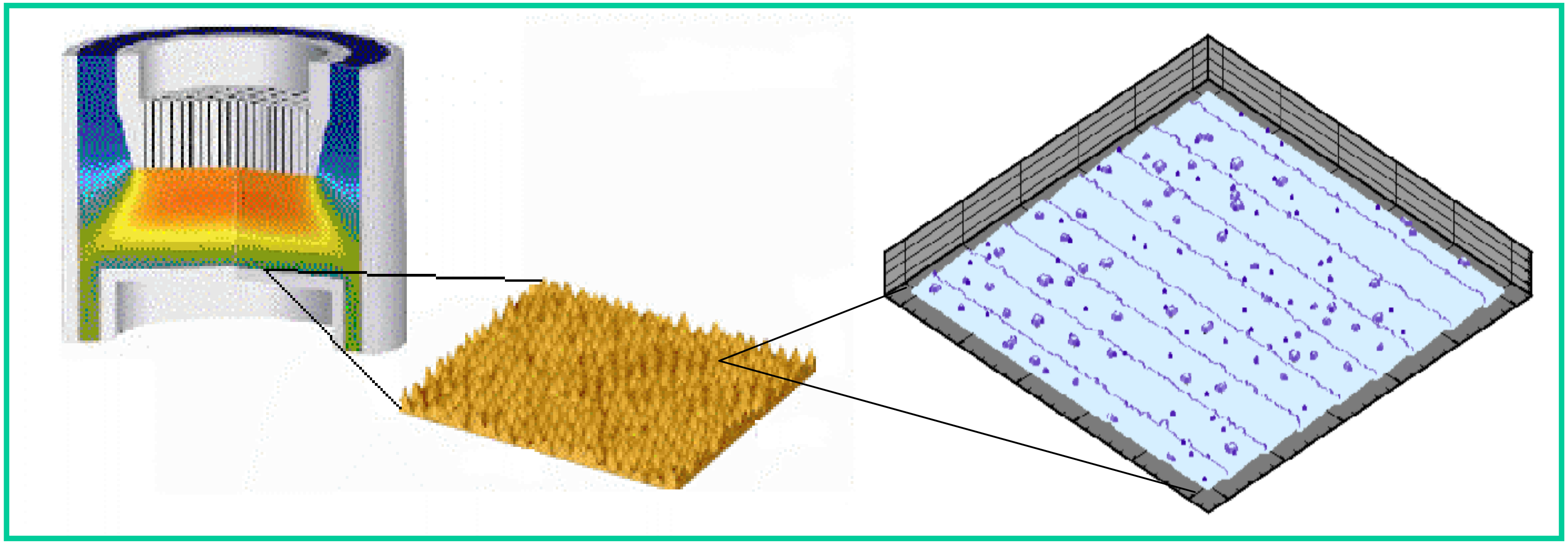
Many applications

- 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





Materials and Processing



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

Biology and Medicine

"Systems Biology"

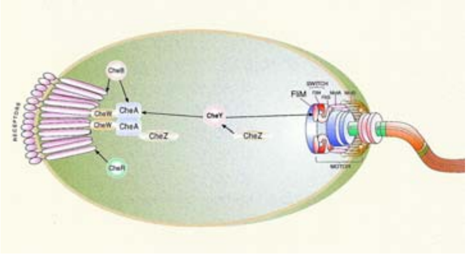
- Many molecular mechanisms for biological organisms are characterized
- Missing piece: understanding of how network interconnection creates robust behavior from uncertain components in an uncertain environment
- Transition from organisms as genes, to organisms as networks of integrated chemical, electrical,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

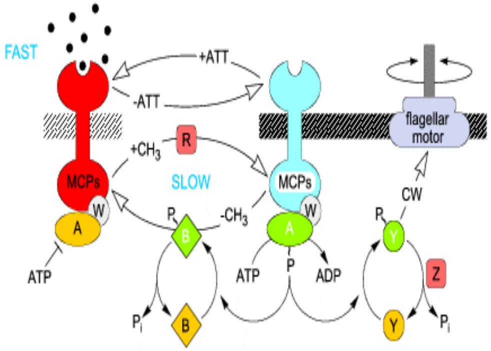
Key features of biological systems

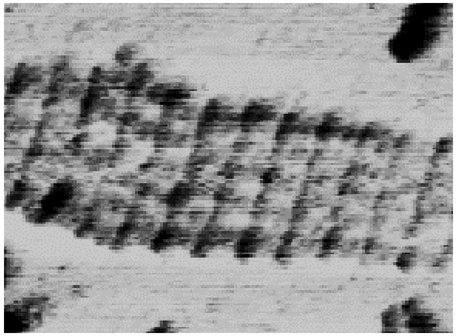
- Integrated control, communications, computing
- Reconfigurable, distributed control, built at molecular level

Design and analysis of biological systems

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







Software Control Theory
2001 ISAT Study on Vigilant High Confidence Systems

Goal: Info systems you can bet the country on

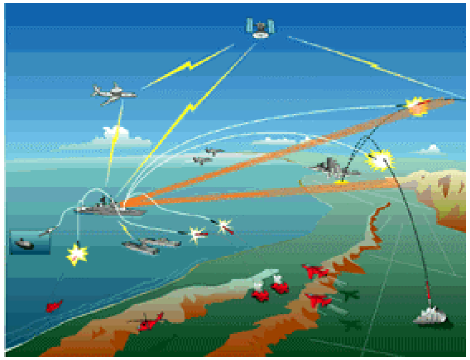
Approach: VIGILANCE via "software control theory"

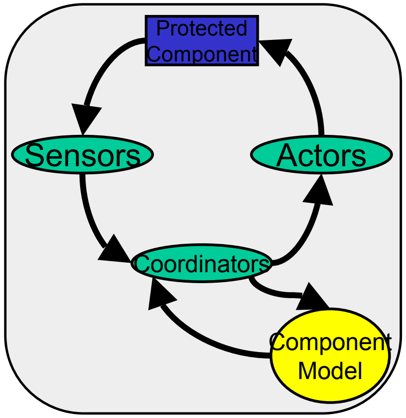
Why now?

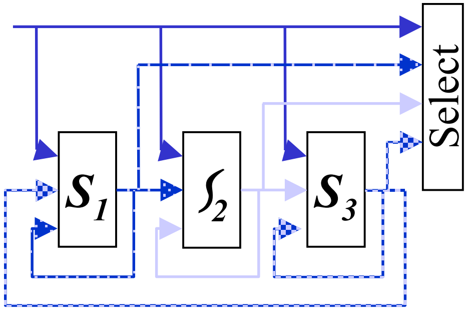
- Network-centric systems are enablers in military and commercial applications
- BUT, current approaches are inadequate
- Need new approach to robust info systems

Why will it work?

- Real-time monitoring, model checking now feasible
- New ideas in pervasive control, stream checking
- Preliminary investment: OASIS, DASADA, FTN, AT&T...



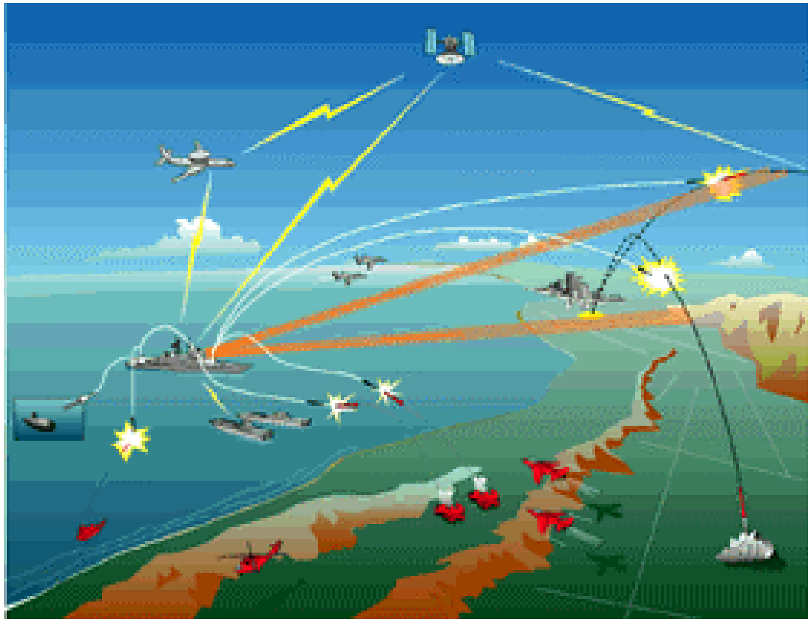




Example: Feedback Control for Distributed Sorting

Distributed sorting is a necessary operation in many missions

- Example: target prioritization across multiple platforms
- Current approaches: voting, consensus, deconfliction

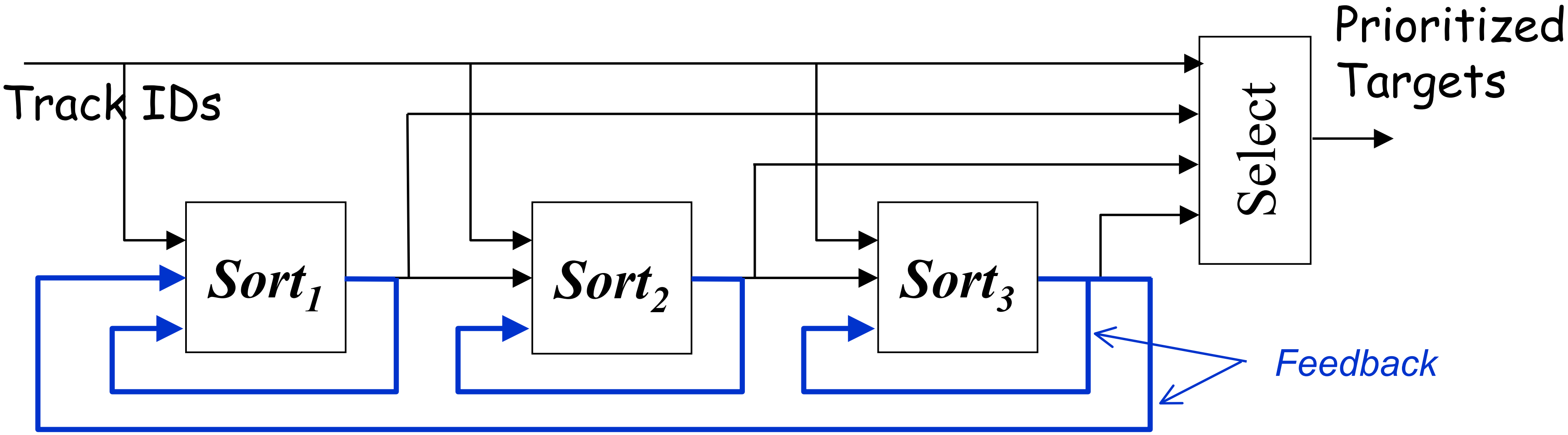


Question: can we use *vigilance* to provide *robust* operation?

Feedback Algorithm for Target Prioritization

Approach: Interconnect individual modules to get fast, robust, distributed sorting

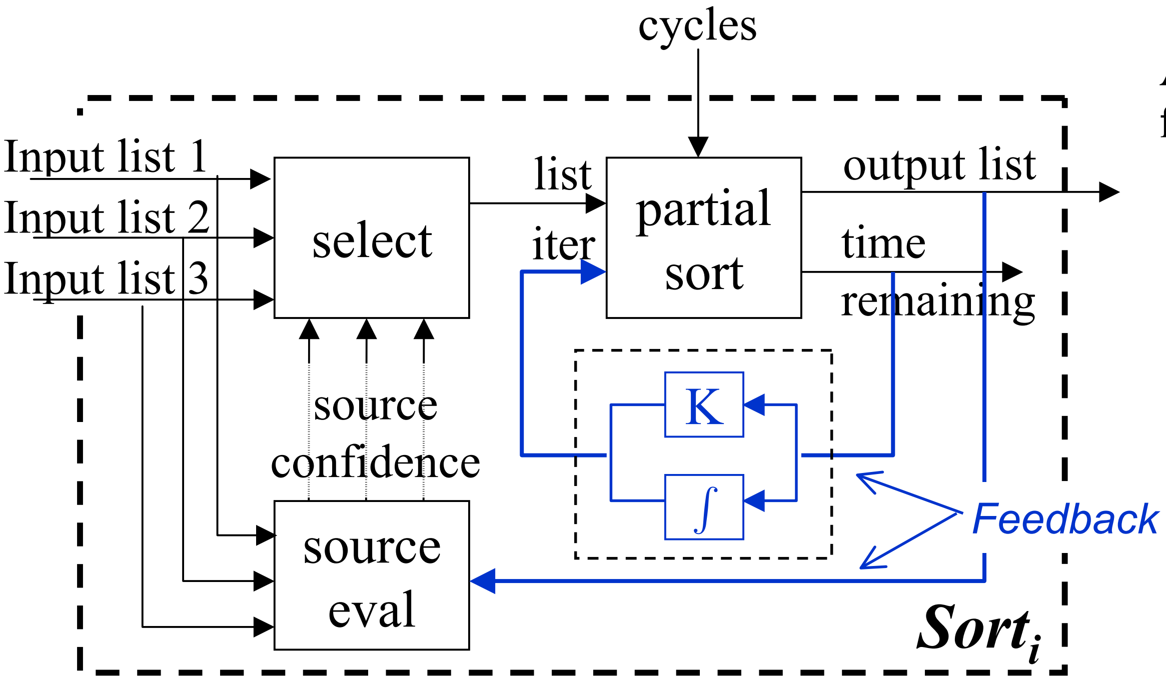
- **Stability**: bounded computational time in each node + finite time convergence
- **Robustness**: algorithm converges, even if processor fails or node is hacked
- **Performance**: sort time is optimal with respect to stationary cycle time distribution
- **Robust performance**: algorithm converges quickly even in worst case (eg, hacked node exploiting feedback structure)



Integrating Feedback into Algorithms

Question: how do we compute in face of uncertainty?

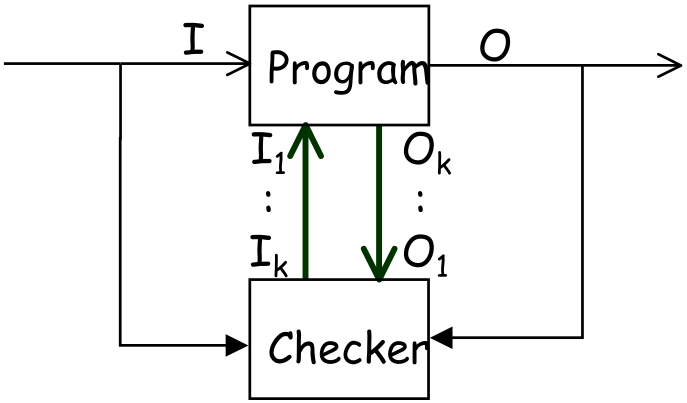
- Distributed algorithm with component failure, data corruption possible
- Variable CPU time available on each processor, due to other tasks
- One or more processors might be taken over by adversary
- Require high performance (fast, accurate, dynamically balanced)

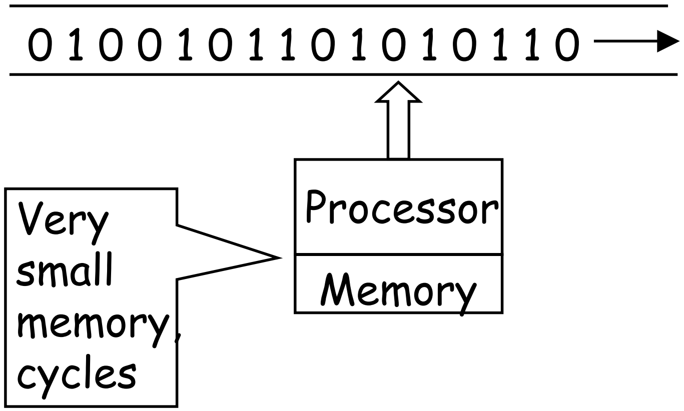


Answer: robustness through feedback

- Dynamic load balancing by modulating iterations in partial sort
- Robustness to software failures and data corruption by source selection and feedback
- Requires accurate sensors

Fast Select:
New Tools in Program and Stream Checking





Program checking by comparing input/output streams gives confidence levels

- New results give O(log(n)) check of approximate correctness (1-ε sorting)
- Ideas fit well with control approach: provide "sort" metric

Stream checking for rapid assessment and selection of output

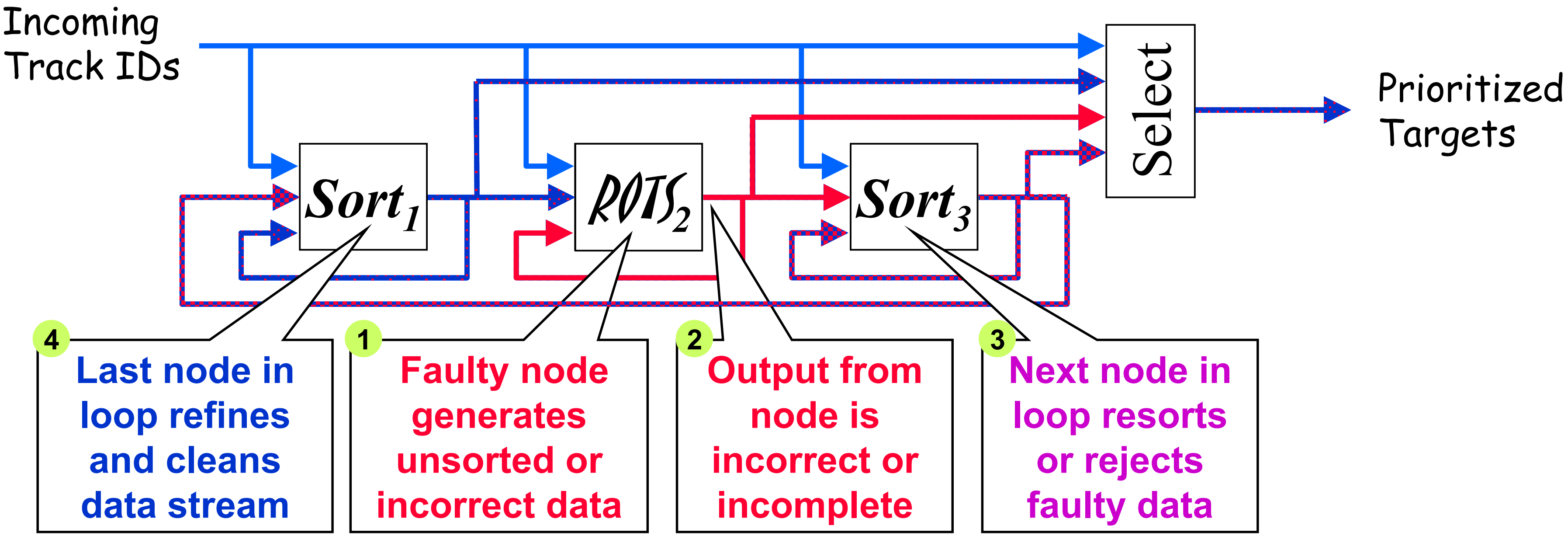
- Use to quickly determine closeness of streams
- Provides fast computation of L_1 distance with O(log(n)) memory usage

New results provide ideas for fast and accurate sensors that can be used for feedback

Upgrade and Repair in Sort Example

Question: what happens if we insert faulty code into sort loop?

- Feedback mechanisms correct (resort or reject) data



4 Last node in loop refines and cleans data stream

1 Faulty node generates unsorted or incorrect data

2 Output from node is incorrect or incomplete

3 Next node in loop resorts or rejects faulty data

- Analysis capability: use norms to bound error
  - Can characterize allowable deviation of algorithm and verify stability

CDS Panel Recommendations

1. **Substantially increase research aimed at the integration of control, computer science, communications, and networking.**
   - Principles, methods and tools for control of high level, networked, distributed systems
   - Rigorous techniques for reliable, embedded, real-time software.

2. **Substantially increase research in Control at higher levels of abstraction, moving toward enterprise level systems.**
   - Dynamic resource allocation in the presence of uncertainty
   - Learning, adaptation, and artificial intelligence for dynamic systems.

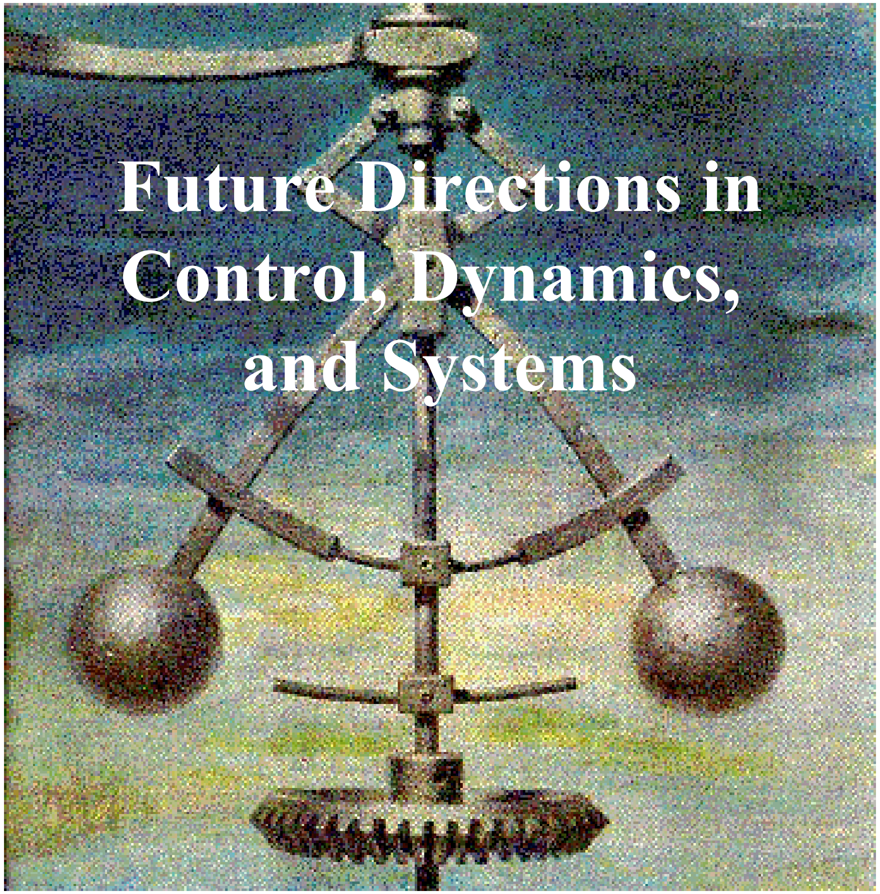
3. **Explore high-risk, long-range applications of Control**
   - Nanotechnology, quantum mechanics, biology, and environmental science.
   - Dual investigator funding might be particularly useful mechanism in this context.

Preliminary Recommendations, con’t (from draft report)

4. **Maintain support for theory and interaction with mathematics, broadly interpreted**
   - Dynamical systems, graph theory, combinatorics, complexity theory, queuing theory, etc
   - Strength of field relies on its close contact with rigorous mathematics; increasingly important in the future.

5. **Invest in new approaches to education and outreach for the dissemination of basic ideas to nontraditional audiences.**
   - For Control to realize its potential, we must do a better job of educating those outside Control on the principles of feedback and its use as a tool for altering the dynamics of systems and managing uncertainty.

Panel Timeline



Next steps

- Jul ’01: updated draft available
  - Post to web, distribute to m-list
- Aug ’01: finish missing sections, collect feedback
  - Biology and medicine
  - Materials and processing
  - Environment, finance, etc
  - Education
- Sep ’01: issue final draft
- Oct ’01: release report, send to SIAM
- Nov ’01: distribute report to Congress, funding agencies, program managers

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

Lecture #1
Overview of Feedback Control

Goals

- Provide engineering context for “active control technology”, through examples
- Survey some of the standard approaches and tools for feedback control
- Describe some of the future directions for the field

Lecture Outline

1. What is Control?
2. Basic Concepts in Feedback Control
3. Application Examples
    - Automotive Control
    - Flight Control
4. Future Directions

Reference: Report of the Panel
On Future Directions in Control,
Dynamics and Systems, 2001

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

Controls Primer
Fall 2001

Objectives

- Provide familiarity of the basic concepts in feedback control
- Survey tools in Lyapunov and optimization-based control

Proposed Schedule

4 Sep	Overview of feedback control	Richard	Tue 10 am PDT
11 Sep	Introduction to state space control and feedback	Raff	
18 Sep	Lyapunov stability and control	Lars	
25 Sep	Lyapunov, continued	Lars	
2 Oct	Optimal control theory	Reza	TBD
9 Oct	Optimal, continued	Reza	
16 Oct	Model predictive control	Bill	
12 Oct	MPC, continued	Bill	

http://www.cds.caltech.edu/~murray/courses/primer-fa01