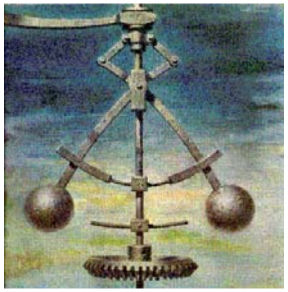
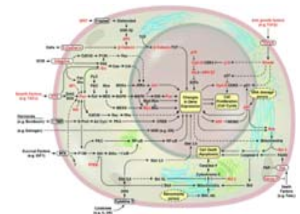


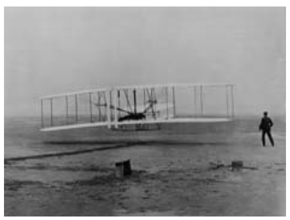
Future Directions in Control, Dynamics, & Systems



Richard M. Murray

Control and Dynamical Systems

California Institute of Technology



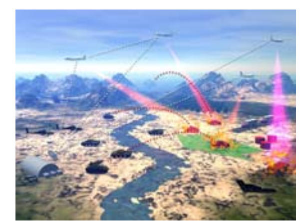
<u>Outline</u>

I. CDS Panel Overview

II. Findings and Recommendations

III. Some Grand Challenges

IV. Summary



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

Motivation for the Panel (Apr 00)

Articulate the challenges and opportunities for the field

- Present a vision 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

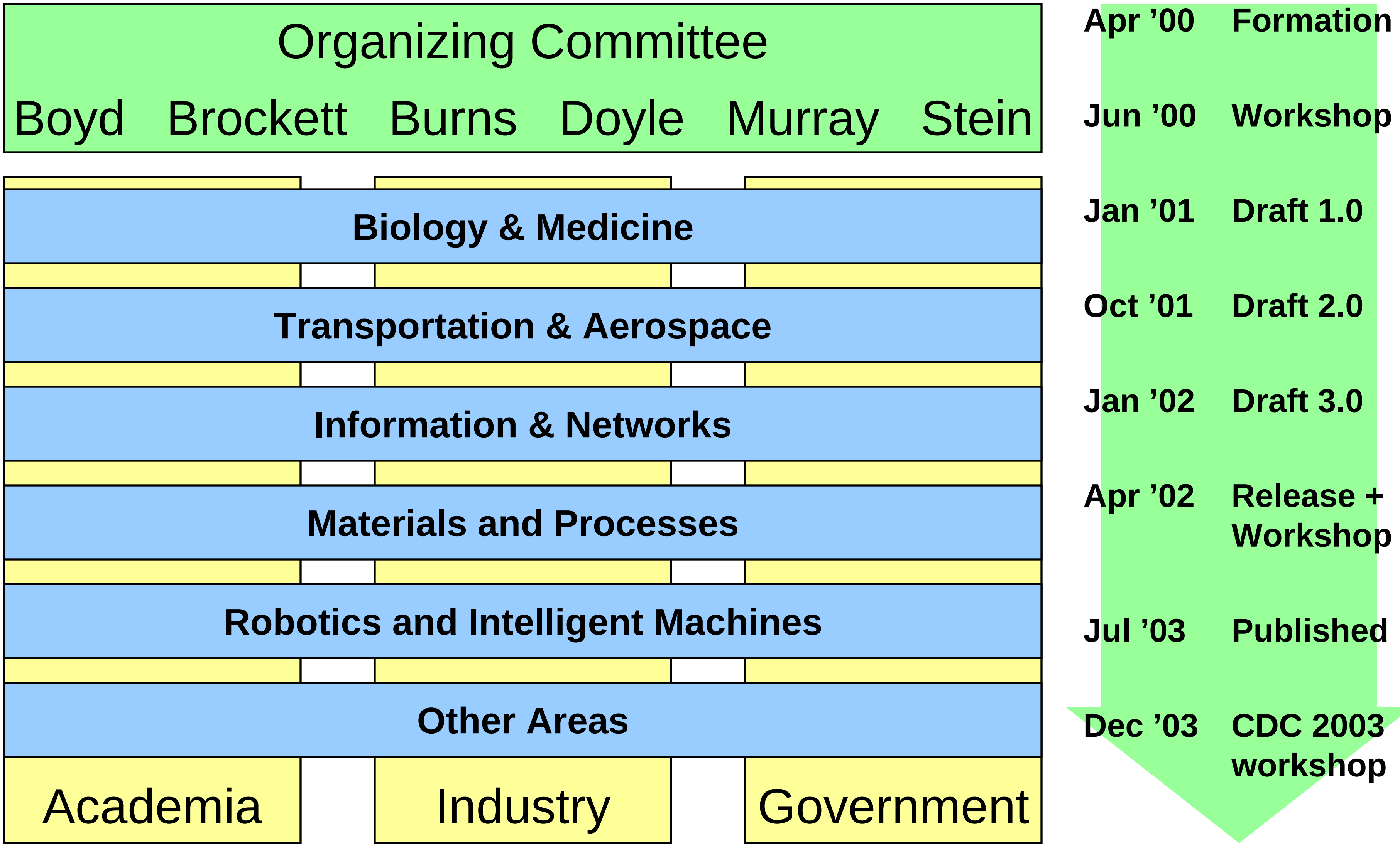
- Many new application areas where controls is playing a stronger role: biology, environment, materials, information, networks, …
- Controls engineers taking on a much broader, systems-oriented role, while maintaining a rigorous approach and practical toolset

Panel Composition

Karl Åström Lund Institute of Technology	**Siva Banda** Air Force Res. 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 (UIUC)	**Jerrold Marsden** Caltech	**Greg McRae** MIT	**George Meyer** NASA Ames

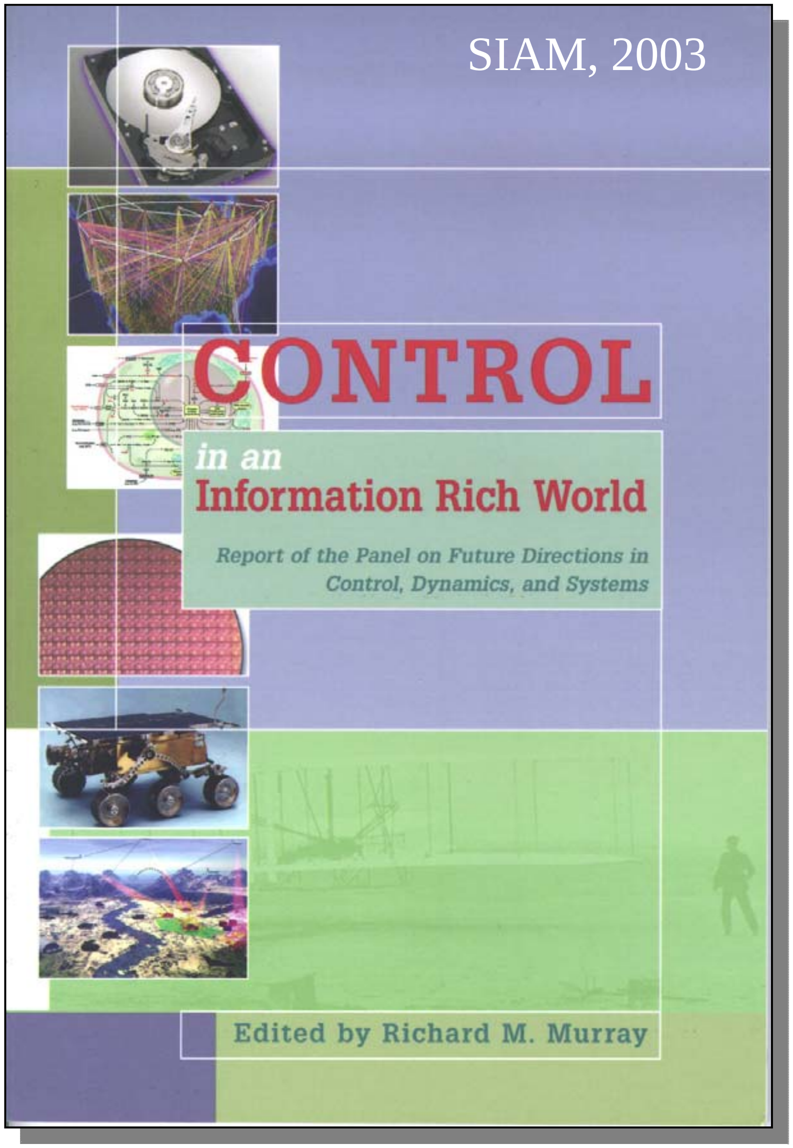
William Powers Ford	**Gunter Stein** Honeywell	**Pravin Varaiya** UC Berkeley

Panel Organization and Timeline



Control in an Information Rich World

1. **Executive Summary**
2. **Overview of the Field**
   - What is Control?
   - Control System Examples
   - Increasing Role of Information-Based Systems
   - Opportunities and Challenges
3. **Applications, Opportunities & 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**



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

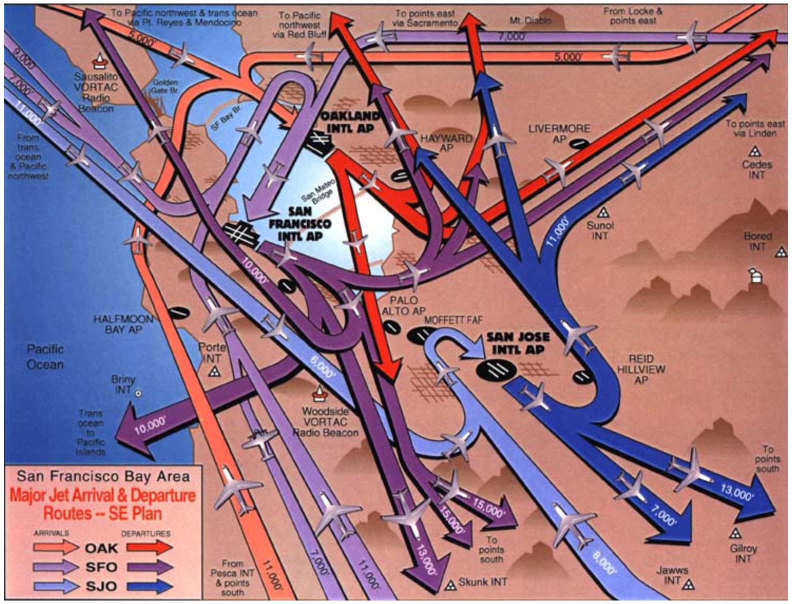
Transportation and Aerospace

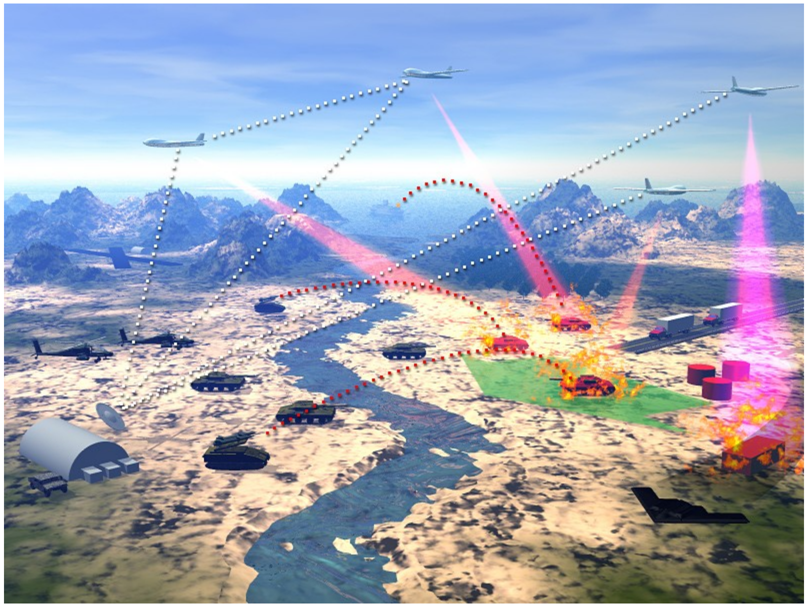
Themes

- Autonomy
- Real-time, global, dynamic networks
- Ultra-reliable embedded systems
- Multi-disciplinary teams
- Modeling for control
  - more than just $\dot{x} = f(x, u, p, w)$
  - analyzable accurate hybrid models

Technology Areas

- Air traffic control, vehicle management
- Mission/multi-vehicle management
- Command & control, human in the loop
- Ground traffic control (air & ground)
- Automotive vehicle & engine control
- Space vehicle clusters
- Autonomous control for deep space





Information and Networks

Pervasive, ubiquitous, convergent networking

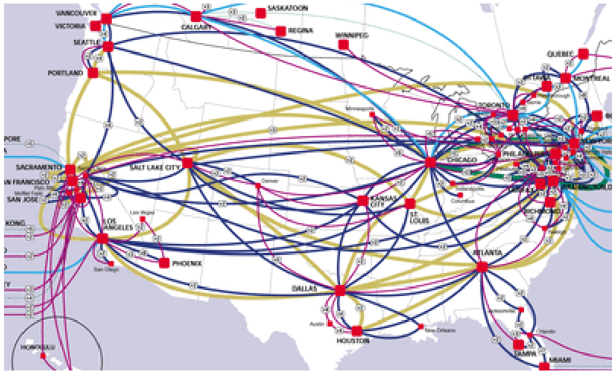
- Heterogeneous networks merging communications, computing, transportation, finance, utilities, manufacturing, health, entertainment, ...
- Robustness/reliability are dominant challenges
- Need "unified field theory" of communications, computing, and control

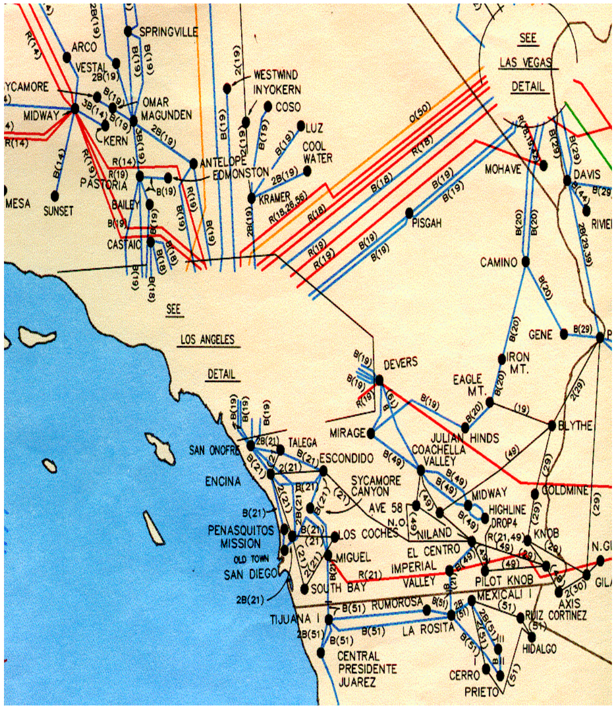
Many applications

- 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

Control <u>of</u> the network

Control <u>over</u> the network





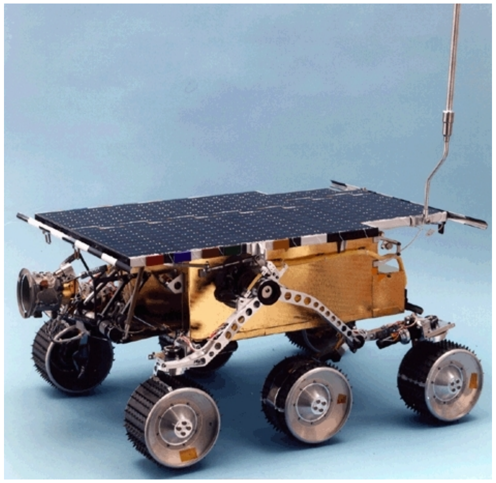
Robotics and Intelligent Machines

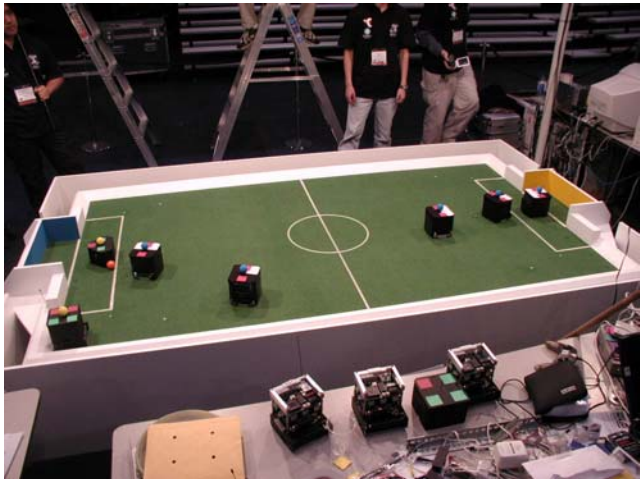
Wiener, 1948: Cybernetics

- Goal: implement systems capable of exhibiting highly flexible or ``intelligent'' responses to changing circumstances

DARPA, 2003: Grand Challenge

- LA to Las Vegas (400 km) in 10 hours or less
- Goal: implement systems capable of exhibiting highly flexible or ``intelligent'' responses to changing circumstances





Biology and Medicine

“Systems Biology”

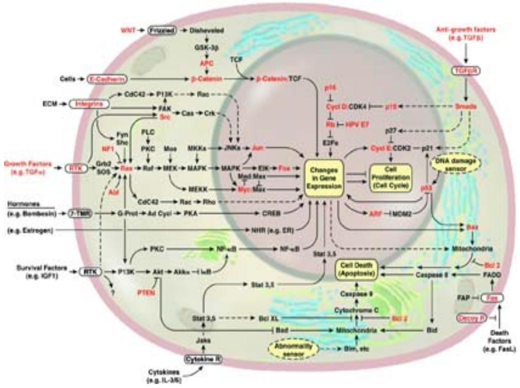
- Many molecular mechanisms for biological organisms are characterized
- Missing piece: understanding of how network interconnection creates robust behavior from uncertain components in an uncertain environment
- Transition from organisms as genes, to organisms as networks of integrated chemical, electrical,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

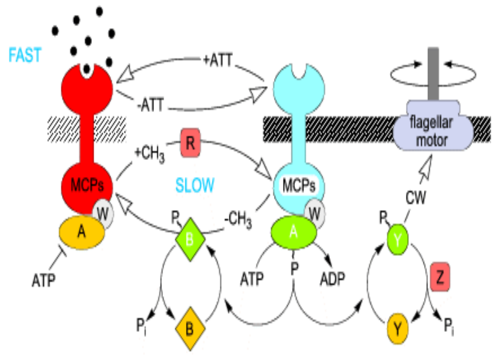
Key features of biological systems

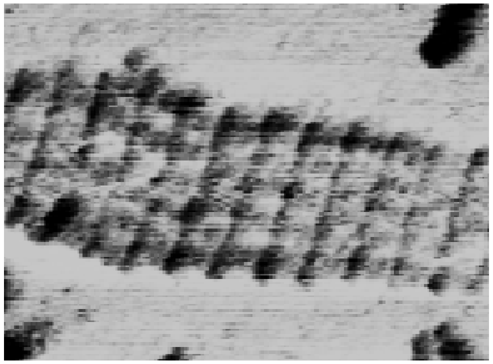
- Integrated control, communications, computing
- Reconfigurable, distributed control, at *molecular* level

Design and analysis of biological systems

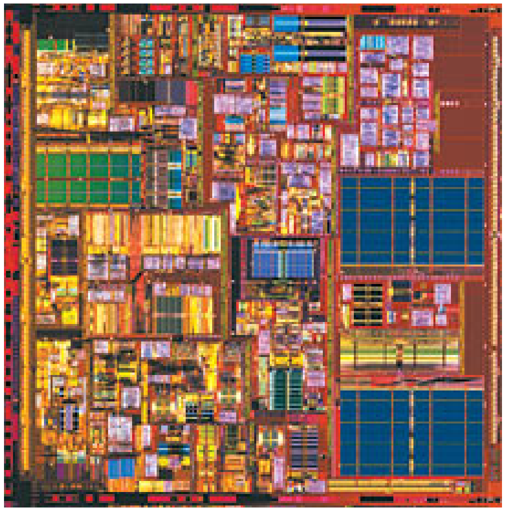
- Apply engineering principles to biological systems
- Systems level analysis is required
- Processing and flow of information is key







Materials and Processing

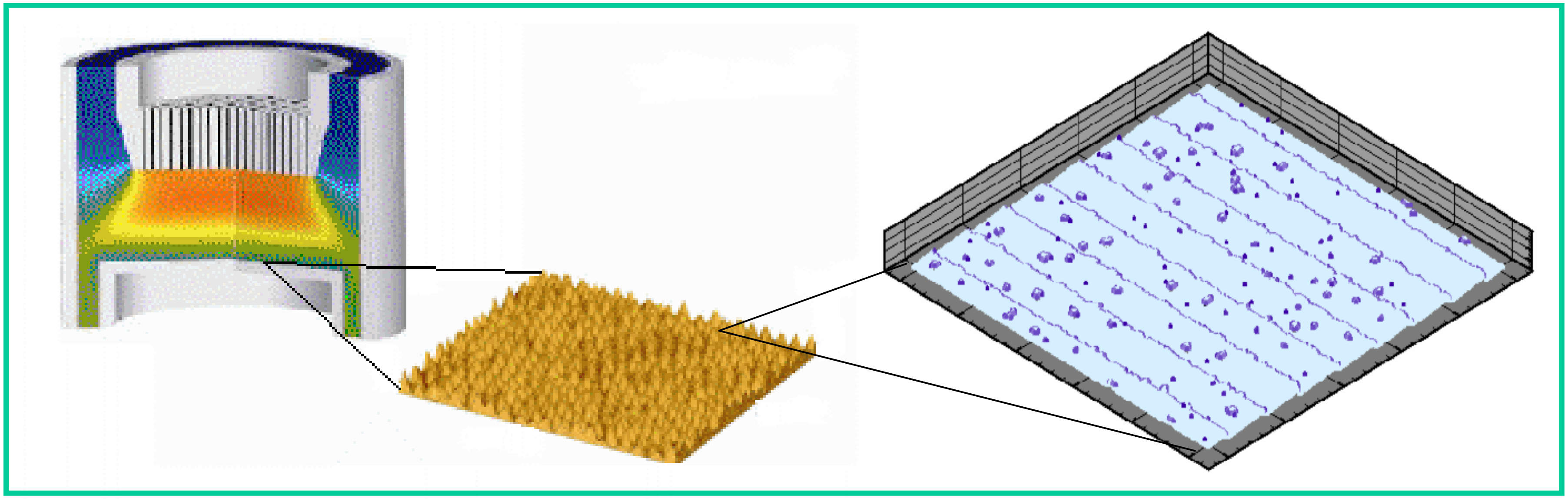


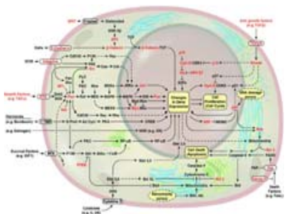
Multi-scale, multi-disciplinary modeling and simulation

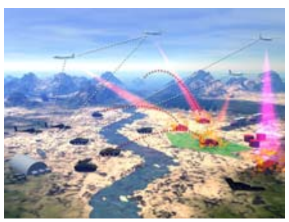
- Coupling between macro-scale actuation and micro-scale physics
- Models suitable for control analysis and design

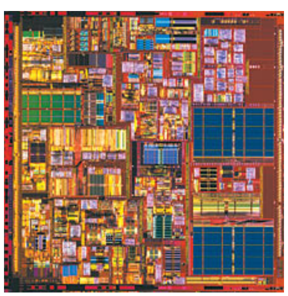
Increased use of in situ measurements

- Many new sensors available that generate real-time data about microstructural properties









CDS Panel Recommendations

1. Substantially increase research aimed at the integration of control, computer science, communications, and networking.

2. Substantially increase research in control at higher levels of decision making, moving toward enterprise level systems.

3. Explore high-risk, long-range applications of control to areas such as nanotechnology, quantum mechanics, electromagnetics, biology, and environmental science.

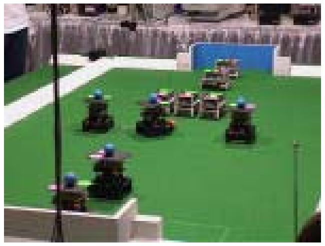
4. Maintain support for theory and interaction with mathematics, broadly interpreted.

5. Invest in new approaches to education and outreach for the dissemination of control concepts and tools to non-traditional audiences.

Some Grand Challenges (RMM, Dec 02)

World Cup Robotic Soccer Team

- Good enough to compete against humans in World Cup and win!
- Other apps: search & rescue, security forces, cooperative robotics



InternetRT

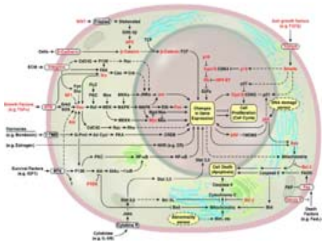
- Provide real-time connections between sensors, actuators, & computation
- Allow control laws to reside anywhere on network (anywhere in the world)

Dynamically Reconfigurable Air Traffic Control

- 99% on time arrivals; planes that are 90+% full; no delays due to weather
- Other applications: supply chains and the power grid

Redesign the Feedback Control System of a Bacteria

- Redesign “circuitry” to change behavior in response to external stimuli
- Applications: new medical treatments, *in vivo* sensing systems

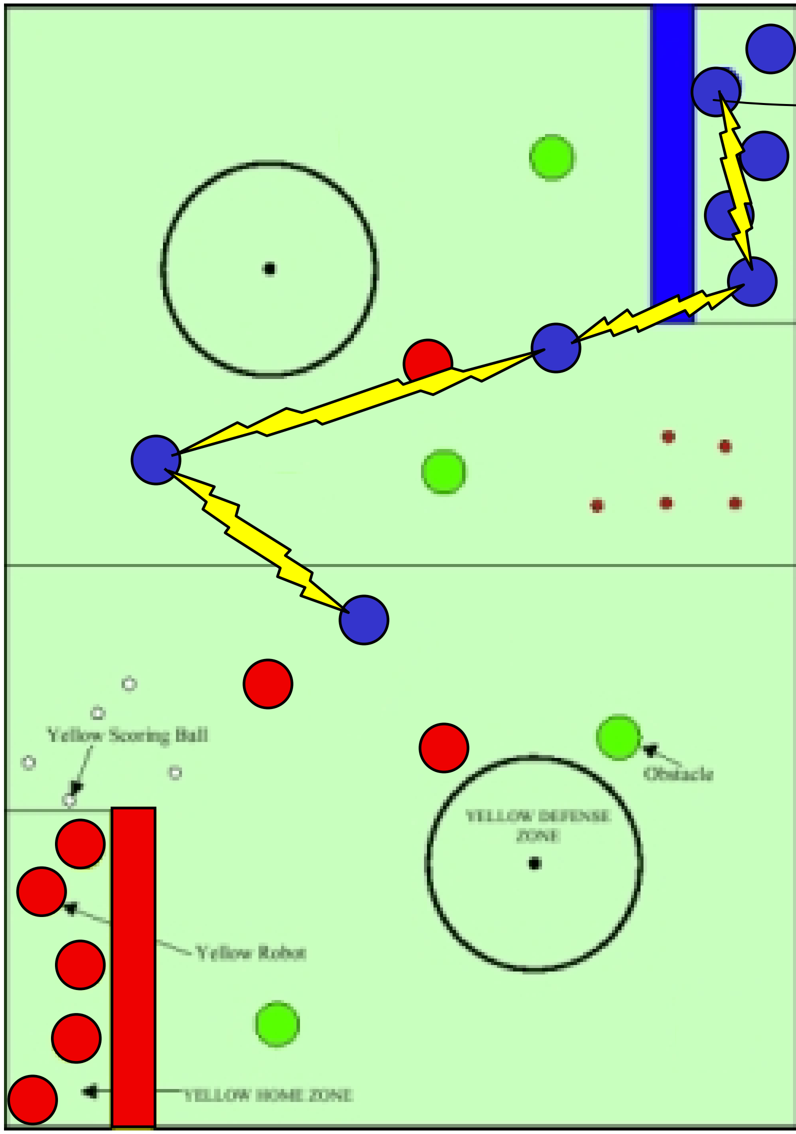


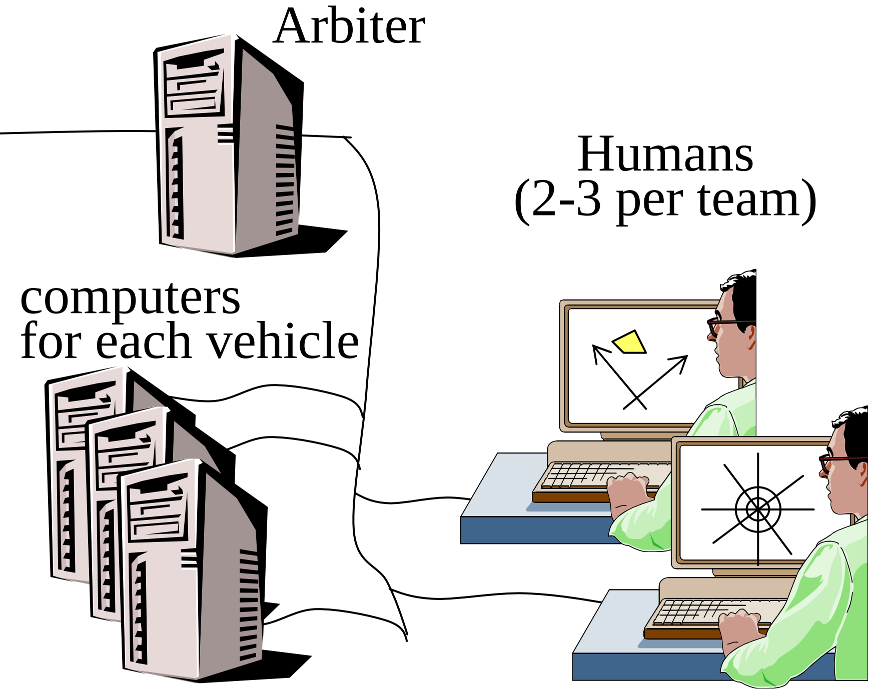
Packet-Based Control Theory

- Control theory basic input/output singles are data packets
- May arrive at variable times, not necessarily in order, sometimes not at all

D'Andrea & M
ACC 2003

Example: RoboFlag (D'Andrea, Cornell)



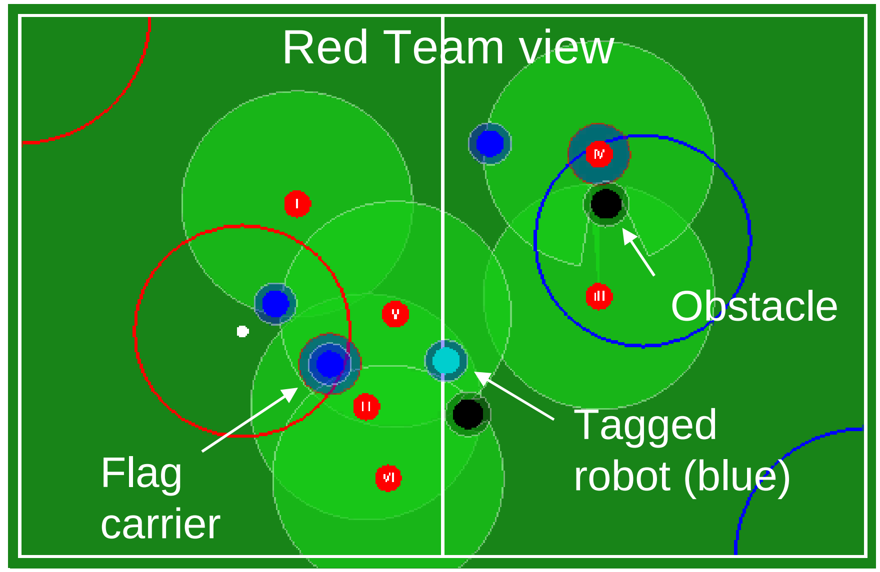


Robot version of "Capture the Flag"

- Teams try to capture flag of opposing team without getting tagged
- Mixed initiative system: two humans controlling up to 6-10 robots
- Limited BW comms + limited sensing

RoboFlag Demonstration

Hayes et al
ACC 2003



Caltech Summer Undergraduate Research Fellowship (SURF) Program

- Team Ithaca vs Team Caltech: mixture of undergraduates and grad students
- 10 robots + 2 people per team; only *local* sensing information is available
- Full simulation used to develop “strategic program environment”
- Last year’s competition (22 Aug 02): 2 people + 6 robots
  - Ithaca: AI-based approach. High level plays, dynamic robot allocation
  - Pasadena: HCI-based approach. Manually command robot(s) to perform actions. Visualization of sensor environment (shown on right screen).

RoboFlag Research Challenges

Integration of computer science, communications, and control

- Time scales don't allow standard abstractions that isolate these disciplines
- Example: how do we maintain a consistent, shared view of the field, even when obstacles are coming in and out of view?

Higher levels of decision making and mixed initiative systems

- Where do we put the humans in the loop? what do we present to them?
- Example: provide an abstract description of a "play" and alert the human when the strategic intent no longer seems appropriate
- Example: predict "plays" by the other team, predict next step, and react

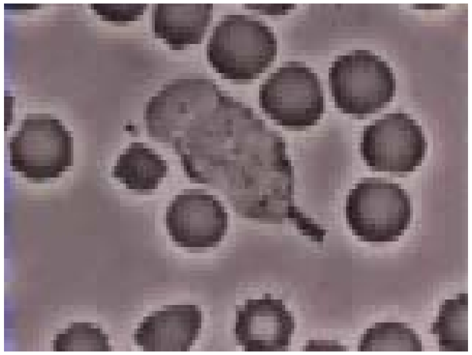
Mathematical framework

- How do we frame the questions in a precise manner?
- Current hybrid systems' techniques don't seem well suited

Interaction between research communities

- Progress requires combination of CS, AI, EE, networking, control, biologists, social scientists (?), etc. How do we get these very large (and sometimes separated) communities talk to each other?

Example: Biological Systems

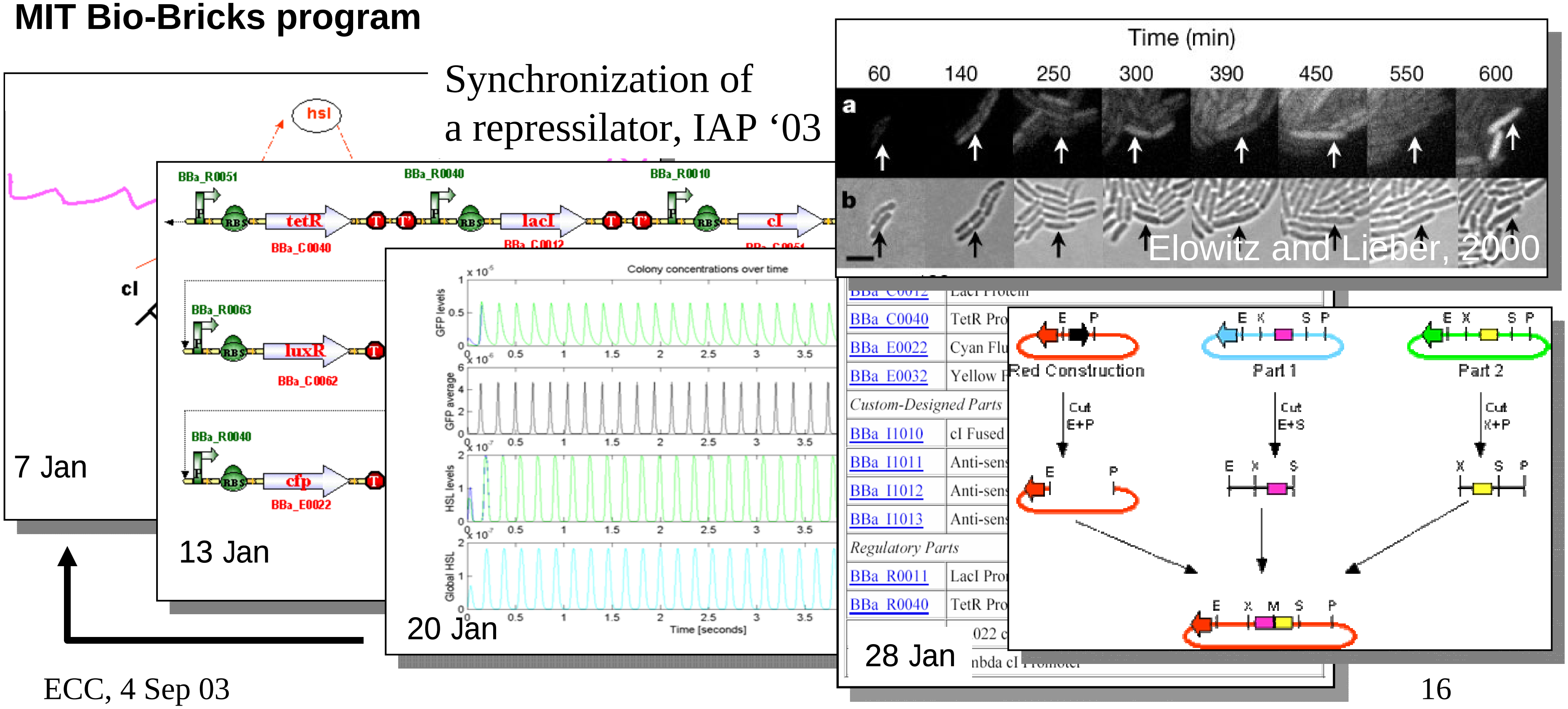


Crawling Neutrophil “Chasing” a Bacterium

- Human polymorphonuclear leukocyte (neutrophil) on blood film
- Red blood cells are dark in color, principally spherical shape.
- Neutrophil is "chasing" Staphylococcus aureus micro-organisms, added to film.

Tom Stossel, June 22, 1999
http://expmed.bwh.harvard.edu/projects/motility/neutrophil.html

MIT Bio-Bricks program



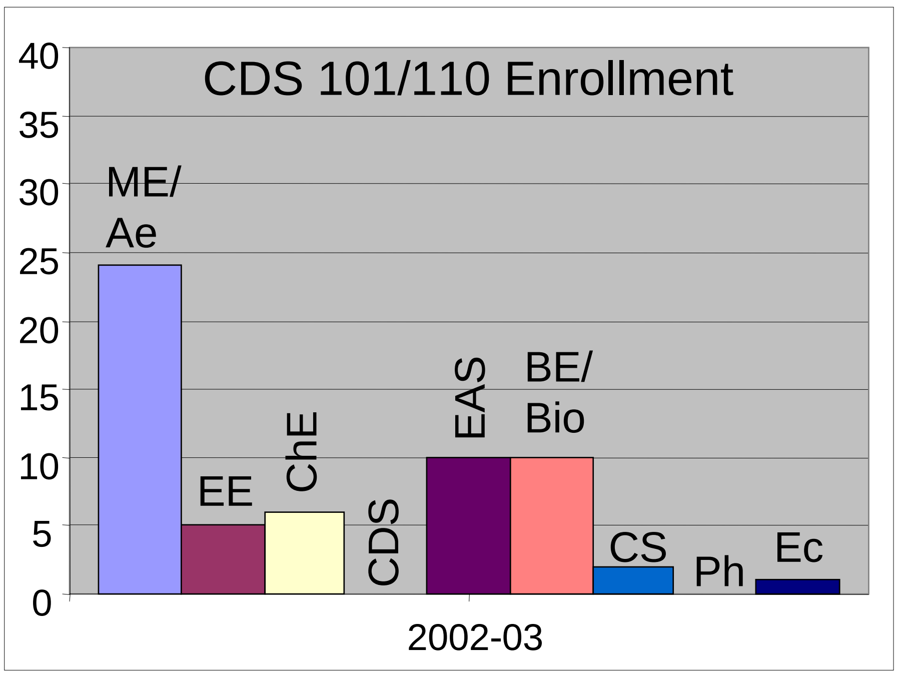
Challenge #6: Teaching Control to Non-Engineers

Traditional courses in control assume strong background in engineering

- Not a good match for computer scientists, biologists, economists

Caltech CDS 101: new course on "Principles of Feedback and Control"

- Aimed at a broad audience of scientists and engineers (CS, Bio, Ec, Ph)
- Focused on teaching principles and computer tools (MATLAB based)



Course Features

- No Laplace transforms, although extensive use of transfer functions
- Stronger emphasis on state space, nonlinear, Lyapunov stability
- Early treatment of controllability, observability
- Elimination of Routh Hurwitz, root locus
- Co-taught w/ traditional CDS course

Summary: Future Directions in Control

Control remains an exciting area, with *many* new applications

- Community needs to get involved in new applications (already happening!)
- Need to maintain support for control research by government, industry

Panel Recommendations

1. Increase research aimed at the integration of control, computer science, & communications
2. Increase research in control at higher levels of decision making, moving toward enterprise level systems
3. Explore high-risk, long-range applications of control in nanotechnology, quantum mechanics, electro-magnetics, biology, environmental science, etc
4. Maintain support for theory and interaction with mathematics
5. New approaches to education to disseminate con-trol concepts and tools to non-traditional audiences