NCS Lecture 14
Future Directions

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Caltech Control and Dynamical Systems
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Goals:

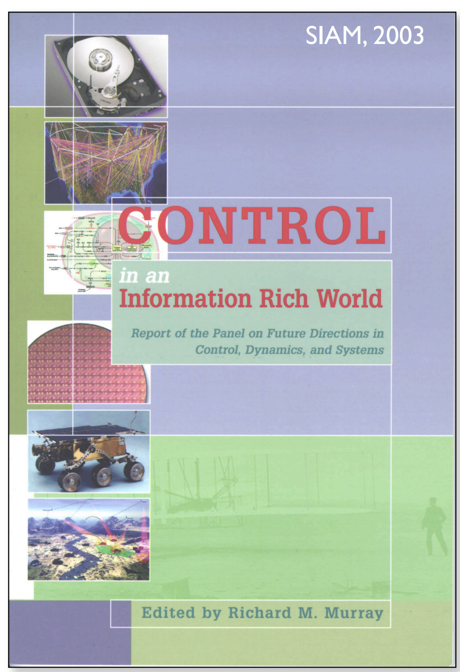
- Summary (semi-) recent reports of committes on future directions in control
- Discuss open areas of research in networked control systems

Reading:

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

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**



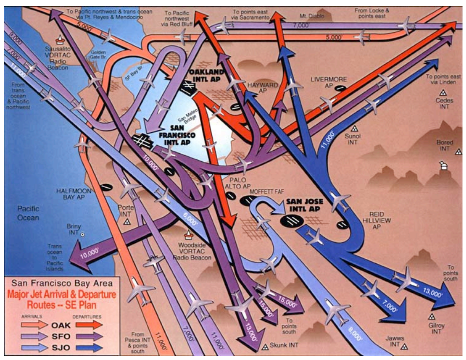
Transportation and Aerospace

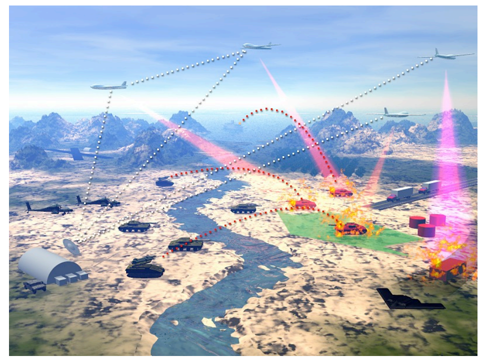
Themes

- 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

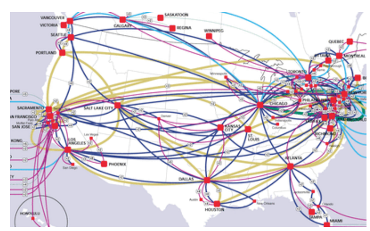
- Heterogeneous networks merging communica-tions, computing, transportation, finance, utili-ties, manufacturing, health, entertainment, ...
- Robustness/reliability are dominant challenges
- Need "unified field theory" of communications, computing, and control

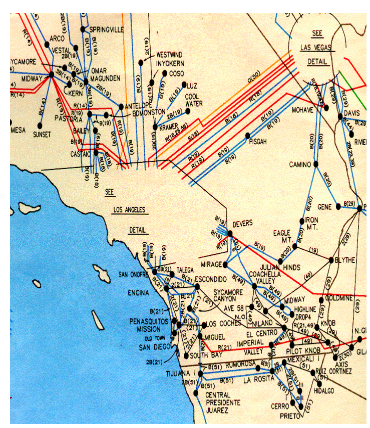
Many applications

- 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





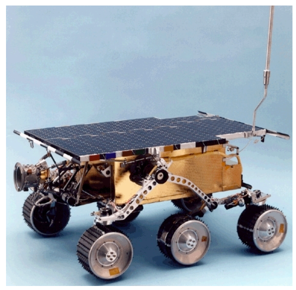
Robotics and Intelligent Machines

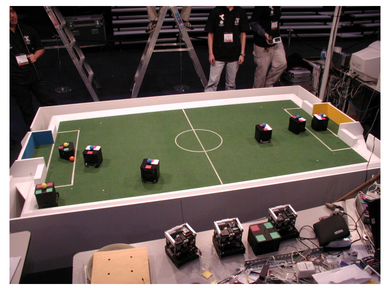
Wiener, 1948: Cybernetics

- 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"

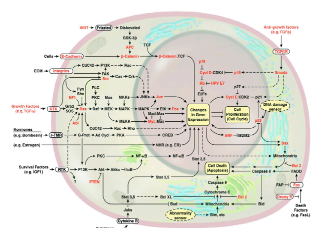
- Many molecular mechanisms for biological organisms are characterized
- Missing piece: understanding of how network interconnection creates robust behavior from uncertain components in an uncertain environment
- Transition from organisms as genes, to organisms as networks of integrated chemical, electrical,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

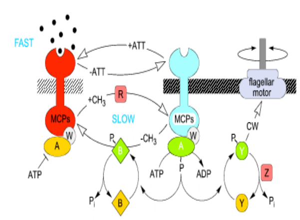
Key features of biological systems

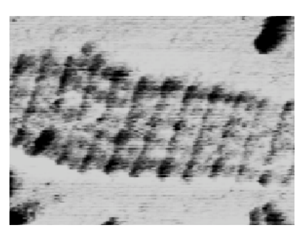
- Integrated control, communications, computing
- Reconfigurable, distributed control, at *molecular* level

Design and analysis of biological systems

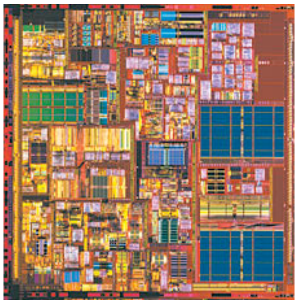
- Apply engineering principles to biological systems
- Systems level analysis is required
- Processing and flow of information is key







Materials and Processing

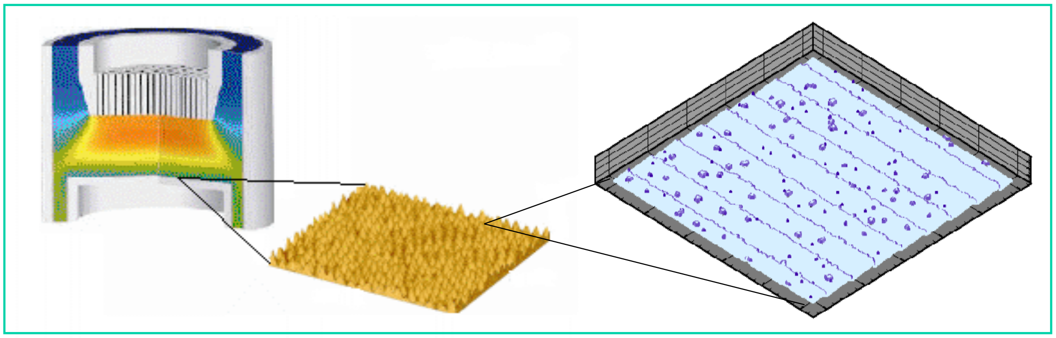


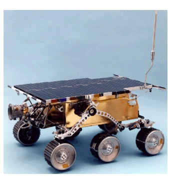
Multi-scale, multi-disciplinary modeling and simulation

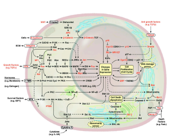
- Coupling between macro-scale actuation and micro-scale physics
- Models suitable for control analysis and design

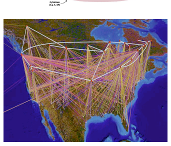
Increased use of in situ measurements

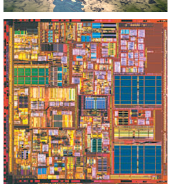
- Many new sensors available that generate real-time data about microstructural properties











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.**

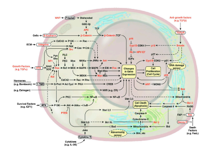
5. **Invest in new approaches to education and outreach for the dissemination of control concepts and tools to non-traditional audiences.**

Grand Challenges

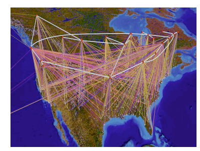
Mixed Initiative Control of Semi-Autonomous Teams (RoboFlag)
- Capture the flag with 10 robots, 2 people per team
- Limited sensing and communications; packet-based environment

Autonomous Driving in Urban Environments
- 60 miles of driving in regular traffic, completely autonomously
- DGC07 demonstrated feasibility, but many open research problems remain

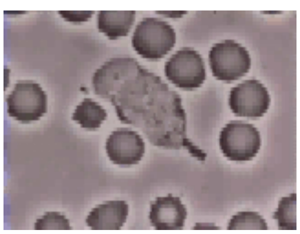
Synthetic Biology: Redesign the Feedback Control System of a Bacteria
- Redesign “circuitry” to change behavior in response to external stimuli
- Applications: new medical treatments, *in vivo* sensing systems



Specificication, Design and Verification of Distributed Embedded Systems
- How do we specify complex behaviors for (hybrid/networked) systems
- What design tools are required to satisfy performance specifications?
- What analysis tools are required to verify safety specifications?



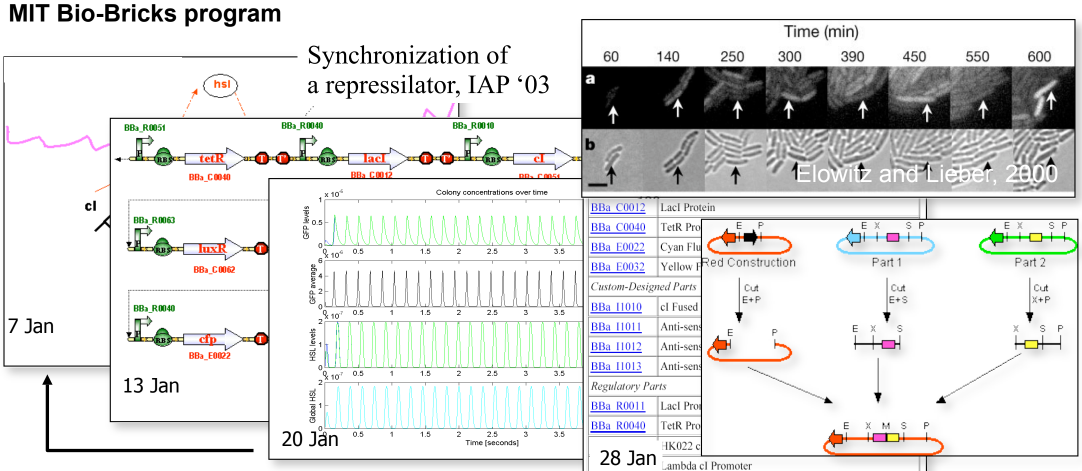
Biological Systems



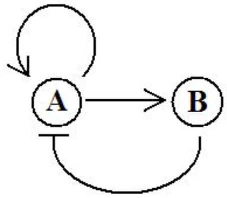
Crawling Neutrophil “Chasing” a Bacterium
- Human polymorphonuclear leukocyte (neutrophil) on blood film
- Red blood cells are dark in color, principally spherical shape.
- Neutrophil is "chasing" Staphylococcus aureus micro-organisms, added to film.

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

MIT Bio-Bricks program

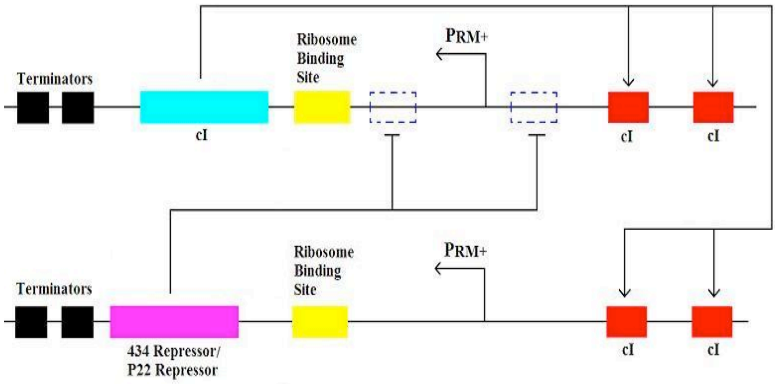


Example: Synthetic Biology Competition 2004



Boston U, Caltech, MIT, Princeton, U Texas

- Caltech: 7 undergrads + 3 grad students + 3 faculty
- Project #1: alternative oscillator designs
- Project #2: serial “adder” (finite state machine)
- Caltech faculty: Elowitz (Bi/APh), Smolke (ChE), M



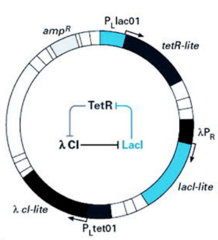
Status:

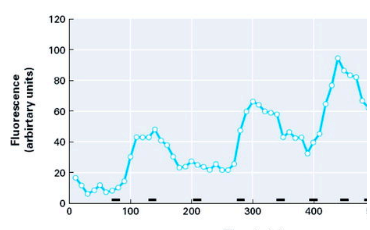
- Two gene regulator circuits customed design, relying on simulations
- Two test parts sent out for fabrication; currently being tested
- BBa_I12019 – 3352 base pairs
- BBa_I12020 – 5171 base pairs

State of the Art: Synthetic Biology

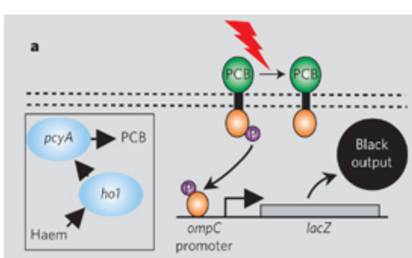
Applications

- Repressillator (Elowitz, 2000)





- Biological “polaroid” (UCSF, UT Austin, 2005)



Theory

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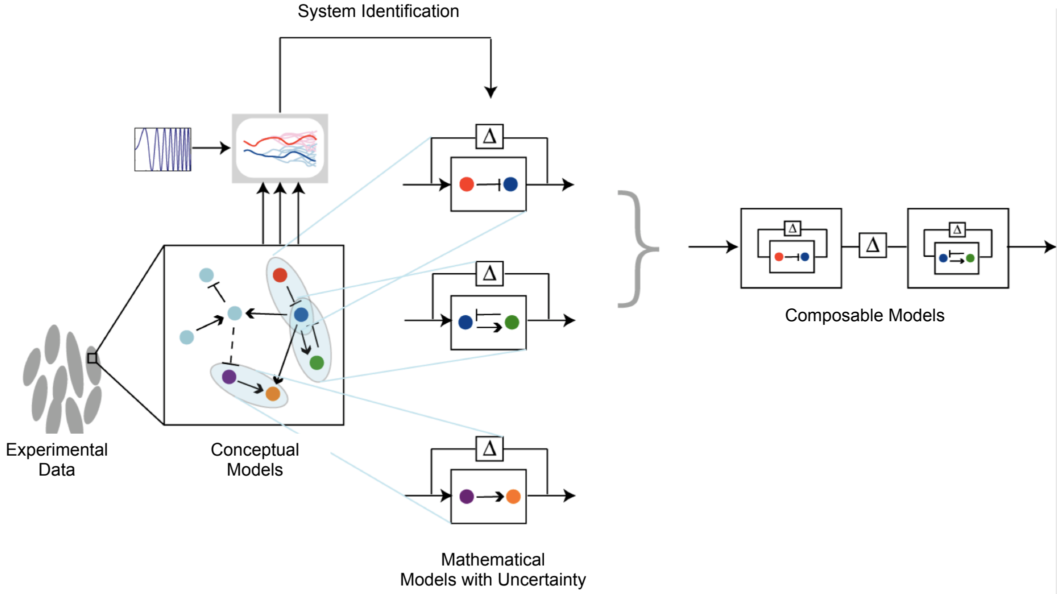
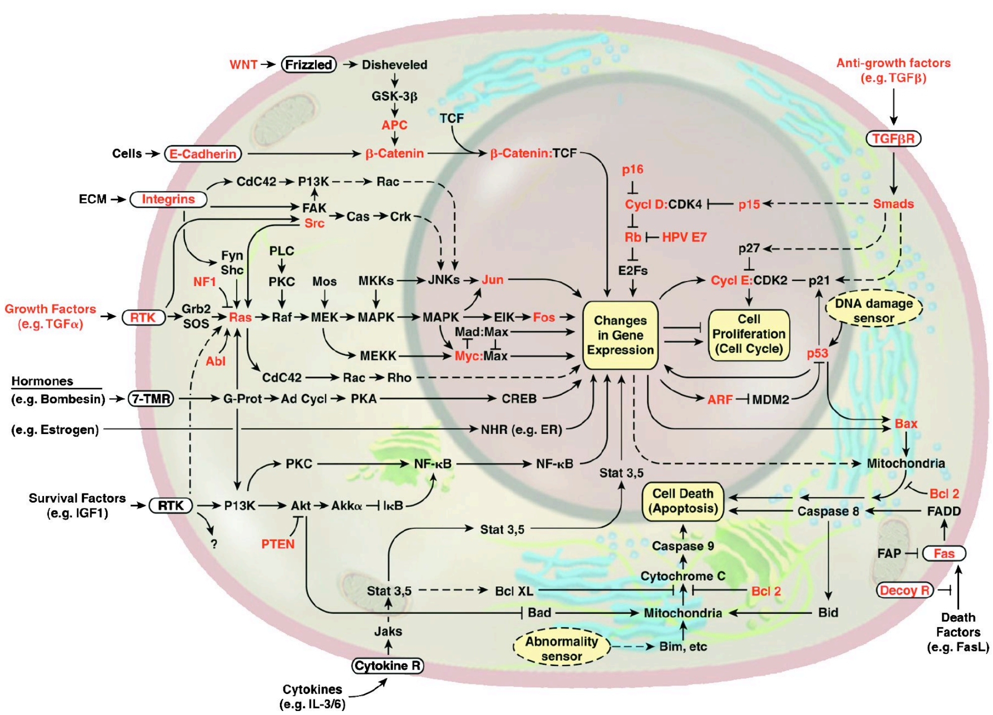
- Some modeling, but mainly after the fact
- Only simple circuits are possible
- More progress on modeling existing systems (in nature)

Composition of Biological Circuits



Networked Control System



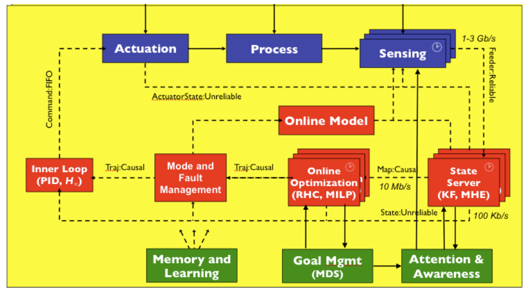
Open Challenge: Verification of NCS Designs

Missing: V&V based design environment

- Specification: how do we describe what the (sub) systems must do?
- Design: how do we design protocols, interfaces, modules, controllers?
- Verification: how to do we make sure the design satisfies the specification

Alice example: safe vehicle operation in multithreaded environment

- Vehicle operation controlled by net-worked interface; responsible for fail safe operation
- Requires careful reasoning about message passing, external events, internal failures
- Asynchronous operations (message passing, failures, environment) complicate verification
- Experience shows this is where we are weakest



Approach: temporal logic + SOS

- Formulate control goal using temporal logic specs w/ continuous+ discrete vars
- Use Lyapunov functions to reason about dynamics and protocols

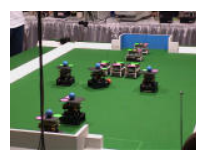
Results to date

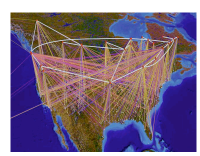
- Specification using linear temporal logic
- Initial verification using LTC software
- Working on incorporating dynamics via SOS certificates to bound possible motion

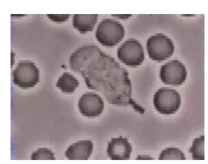
Some Future Directions in ~~Control Theory~~ Network Science

NRC, 2005

1. **Dynamics, spatial location and information propagation in networks**
   - Integrated communications, computation and control
   - Distributed representations and coordinated operations
2. **Verification and validation of large feedback systems**
   - Proof certificates for complex embedded SW sysems
3. **Design and synthesis of networks and protocols**
   - What should the network topology look like (and why)
   - When do I use TCP vs UDP vs broadcast
4. **Increased rigor and mathematical structure**
   1. How do we model & analyze Alice? MS Word? E. coli?
5. **Abstracting common concepts across fields**
   - Bio, Ec, CS …
6. **Robustness and security of networked control systems**







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