Goals:
• Summary (semi-) recent reports of committees 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 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 of the network
Control over 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

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**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

Specification, 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

Synchronization of a repressilator, IAP ‘03

Elowitz and Lieber, 2000

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 customized 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
- Represillator (Elowitz, 2000)
- Biological "polaroid" (UCSF, UT Austin, 2005)

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

System Identification

Experimental Data → Conceptual Models → Mathematical Models with Uncertainty → Composable Models

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 do we make sure the design satisfies the specification

Alice example: safe vehicle operation in multithreaded environment
- Vehicle operation controlled by networked 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

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 systems

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, electromagnetics, biology, environmental science, etc

4. Maintain support for theory and interaction with mathematics

5. New approaches to education to disseminate control concepts and tools to non-traditional audiences