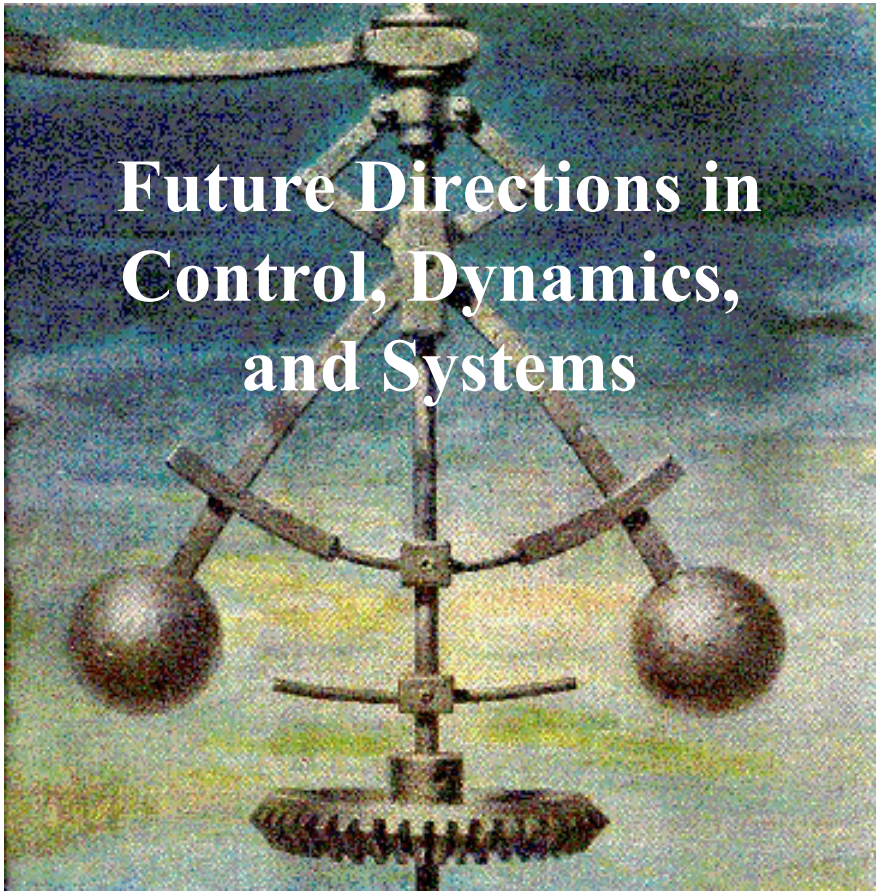


Panel on Future Directions in Control, Dynamics, and Systems

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

Motivation for the Panel

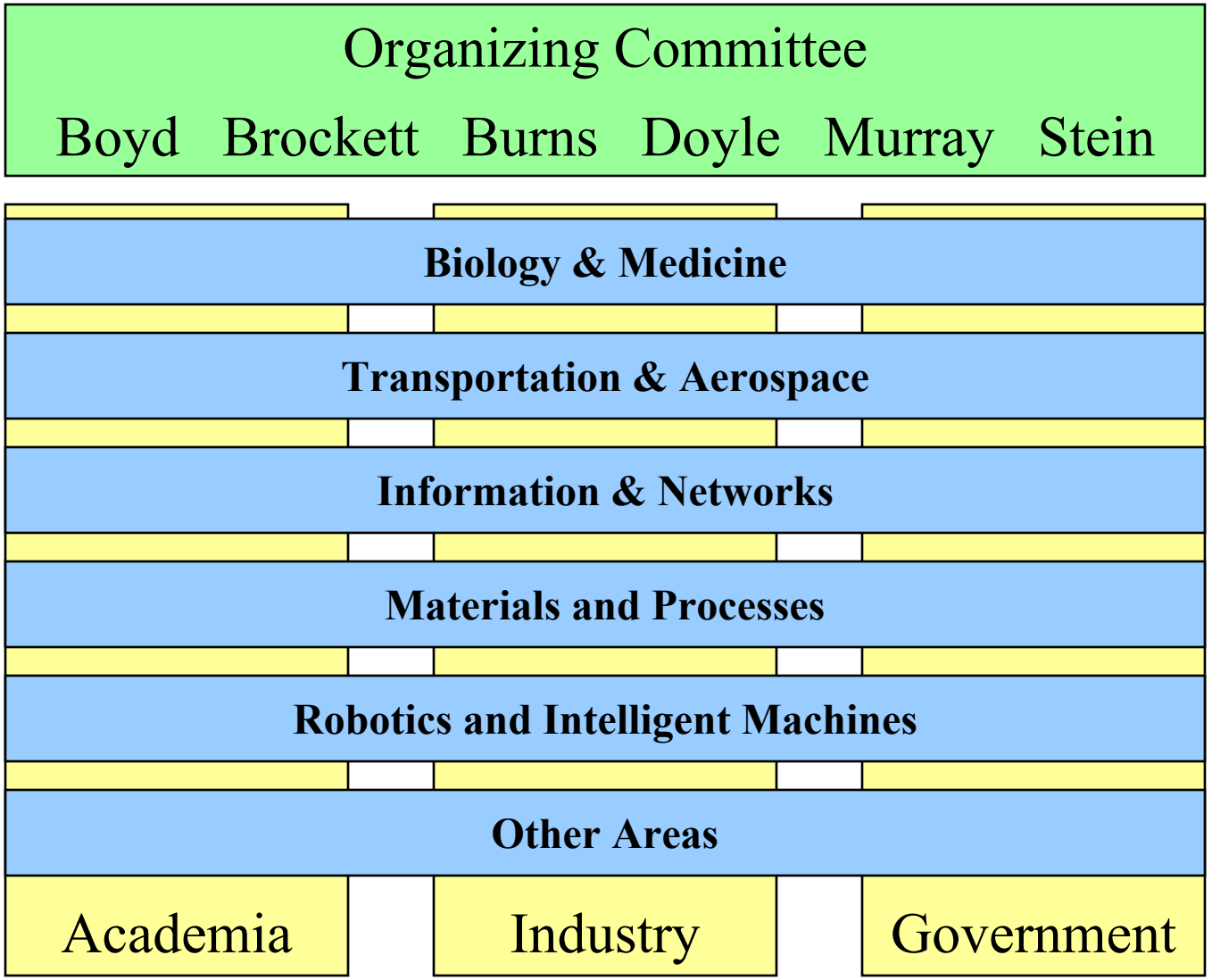
Articulate the challenges and opportunities for the field

- 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 Organization



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

Panel on Future Directions in Control and Dynamical Systems
16-17 June 2000

Meeting Summary

Adam Arkin Kishan Baheti Siva Banda John Baras Stephen Boyd
Richard Braatz Roger Brockett John Burns Jagdish Chandra
Munther Dahleh John Doyle Brian Farrell Eric Feron Charlie Holland
Jonathan How Dimitris Hristu Marc Jacobs Eric Justh Navin Khajeda
Pramod Khargonekar Dan Koditschek P.S. Krishnaprasad P.R. Kumar
Vijay Kumar Steven Low Greg McRae Steve Marcus Landis Markley
Jerry Marsden Kristi Morgansen George Meyer Igor Mezic
Richard Murray Andy Packard Tariq Samad Shankar Sastry Ben Shapiro
Eduardo Sontag Anna Stefanopoulou Gunter Stein Claire Tomlin
Allen Tannenbaum Pravin Varaiya Ram Venkataraman Kevin Wise

Overview of the Meeting

Friday

General Session – 8:30-11:00

- Overview of objectives, summary Fleming report
- Introductory talks by Doyle, Sastry, Brockett
- Discussion throughout talks focused on the role of control (who are we) and the necessary interaction with other groups

Breakout Groups – 11:00-4:30 pm

- Six groups with 4-8 people per group
- Desired output: 3 charts listing people, technologies areas, research issues, teaching and organizational needs

General Session – 4:30-5:30

- Presentation by each group of output
- Main themes: modeling, communications, computation, optimization, autonomy

Saturday

General Session – 8:15-10:00

- Who are we? Need to move beyond thinking just about the control law (usually very simple)
- What is our role? We are an essential element of a team needed to solve problems. We bring some unique tools
- How do we maintain our culture? Maintain rigor, don't abandon control

Breakout Groups – 10:15-noon

- Four groups with 6-10 people per group
- Desired output: 3 charts listing people, overarching themes, specific problems areas, research issues, vignettes

General Session – 1:00-4:00

- Presentation by each group of output
- Discussion of overarching themes, next steps

Introductory Session

Murray: Panel Meeting Overview

- Description of Panel
- Plan for the meeting

Burns: Fleming Report Overview

- How the report was produced and used
- Strengths and weakness of the report

Doyle: Complex Systems

- Dominant challenges:
  - Robustness of complex, interconnected dynamical systems and networks
  - "Unified theory" of control, communications, computing
- Role of control: robustness, interconnection, rigor, talent
- Applications: Turbulence, quantum systems, statistical physics, biological networks , engineering networks, volatility in financial markets, simulation-based design, ecosystems and global change, …

Sastry: Embedded Systems

- Need to make case for fundamental theory
- Need to address societal problems
- Embedded systems (software and physics) presents an opportunity for more controls involvement
  - Correct by construction
  - Autonomous systems
  - Mapping distributed control to hardware

Brockett: Systems and Control

- The value of the systems point of view
  - The rigorous training
  - The confidence it gives people
- The need for better integration with CS
- Applications
  - Communications
  - Molecular biology
  - Web related algorithms
  - Materials science

Subpanel Report: Biology and Medicine

Adam Arkin **Munzer Dahleh** **John Doyle**

Eduardo Sontag **Allen Tannenbaum** **Ram Venkataraman**

Science of reverse (and forward) engineering biological control networks

- gene regulation and signal transduction
- hormonal, immunology, cardiovascular
- neuroscience, neuroengineering
- muscular, locomotion, prosthesis
- active sensing, vision, proprioception
- attention and consciousness
- group dynamics, population, epidemics

Figuring out what and how it works, and what we can do to affect it.

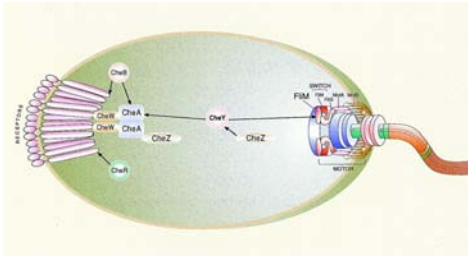
Systems technology and instrumentation for medicine/biomedical research

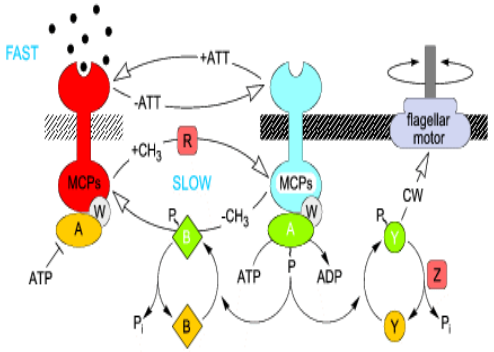
- Intelligent operation rooms and hospitals, from data to decision
- Systems-guided surgery and therapy
- Hardware and soft tissue integration
- Fluid flow control for medicine and biological assays
- Prosthesis

New Thrust: Biological Engineering

"Systems Biology"

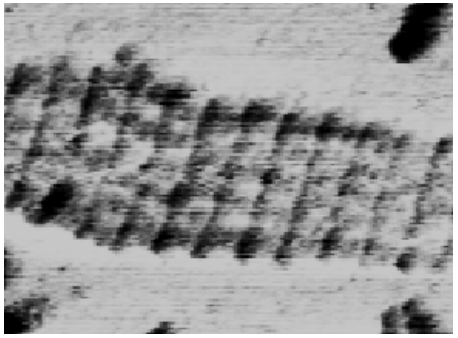
- Many molecular mechanisms for biological organisms are characterized
- Missing piece: understanding of how network interconnection creates robust behavior from uncertain components in an uncertain environment
- Transition from organisms as genes, to organisms as networks of integrated chemical, electrical,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

Subpanel Report: Information and Networks

Kishan Baheti **John Baras** **Stephen Boyd**
Roger Brockett **Jagdish Chandra** **Dimitris Hristu** **Marc Jacobs**
P. R. Kumar **Steven Low** **Pravin Varaiya**

Networks, Information, and Systems/Control

- Ubiquitous networks (wireless, …) transport data cheaply
- Cheap (embedded, integrated) sensors collect vast amounts of data
- Processing power plentiful

} We're cleverness limited

Networks for Control

- Distributed asynchronous
- Packet based
- Varying topology, delays, …

If we get it right:

- We get a system with the resilience of a network and the performance of a current control system

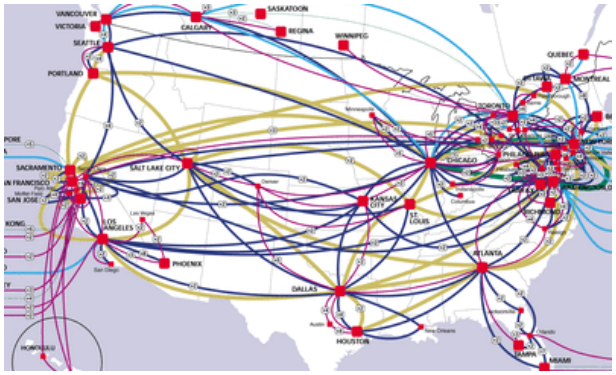
Complex, Multi-Scale Networks and Systems

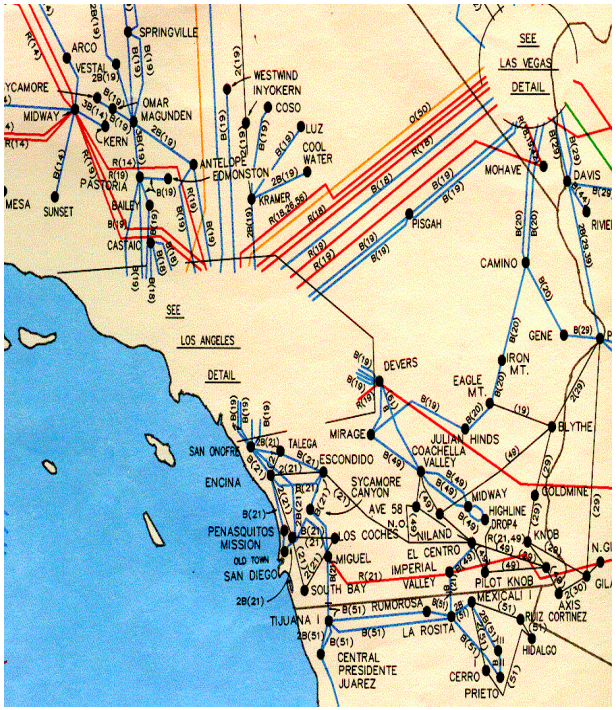
Pervasive, ubiquitous, convergent networking

- 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





Subpanel Report: Transportation and Aerospace

Siva Banda **Jonathan How** **Eric Justh** **Landis Markley**
George Meyer **Kristi Morgansen** **Andy Packard** **Anna Stefanopoulou**
Gunter Stein **Claire Tomlin** **Kevin Wise**

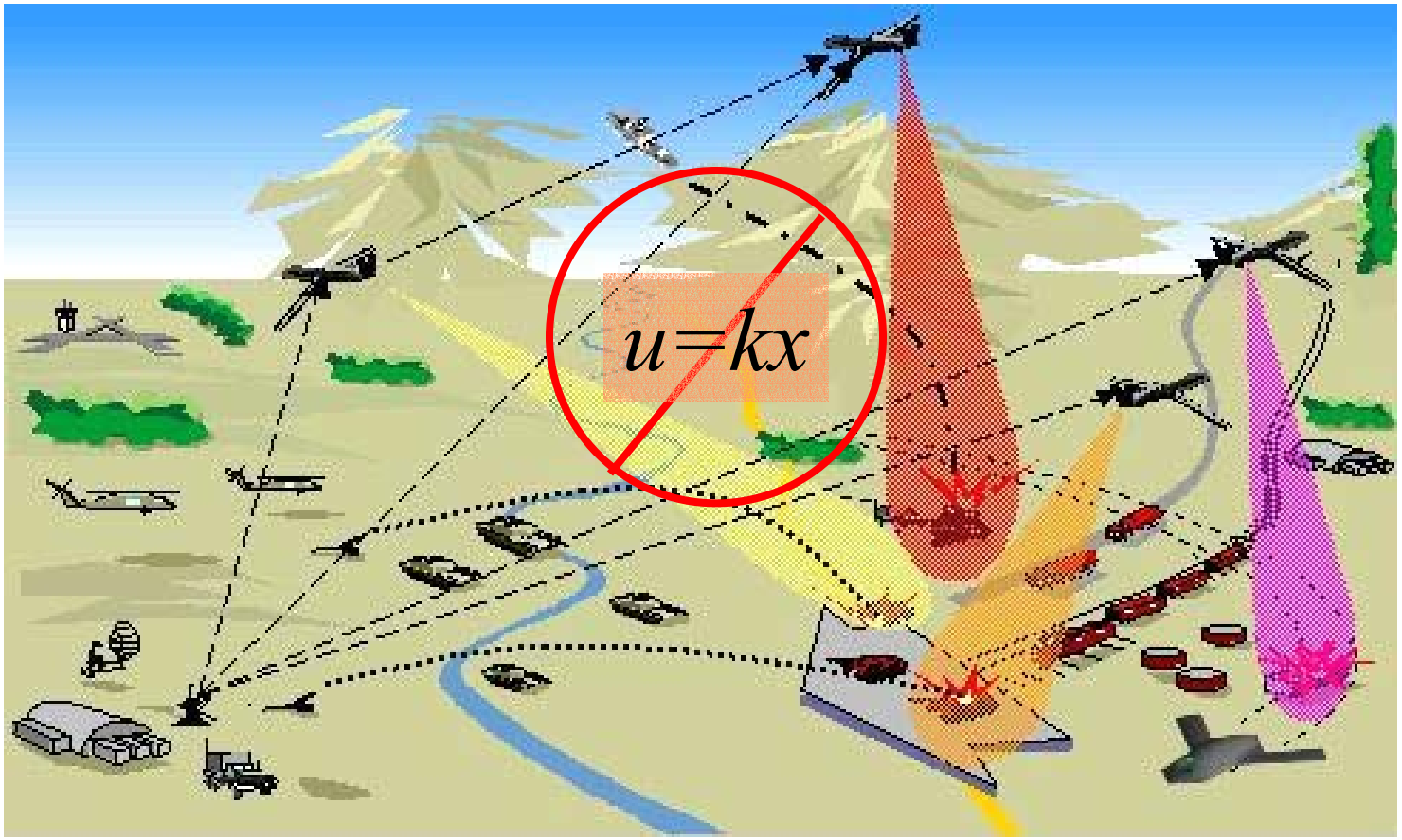
Themes

- Autonomy
- Global dynamic interconnectivity
  - real-time
- Ultra-reliable control systems
  - embedded software
- 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 and control of battlefield
  – people in the loop
- Ground traffic control (air & ground)
- Automotive vehicle & engine control
- Topology/architecture (dynamic)
- Space vehicle clusters
- Autonomous control for deep space travel

Future Battlespace Systems



Subpanel Report: Materials, Processes, Environment

Richard Braatz **John Burns** **Brian Farrell** **Navin Khaneja**
Pramod Khargonekar **P. S. Krishnaprasad** **Greg McRae** **Jerry Marsden**
Igor Mezic **Tariq Samad** **Ben Shapiro**

Modeling

- multi-scale, time and space
- model reduction
- model identification
- heterogeneous model integration
- hierarchical
- uncertainty
- role of data/statistics/noise
- complex systems
- exploiting problem structure

Paradigm Shifts

- data centric
- coordinated control
- complex systems
- spatially multidisciplinary teaming
- control configured design

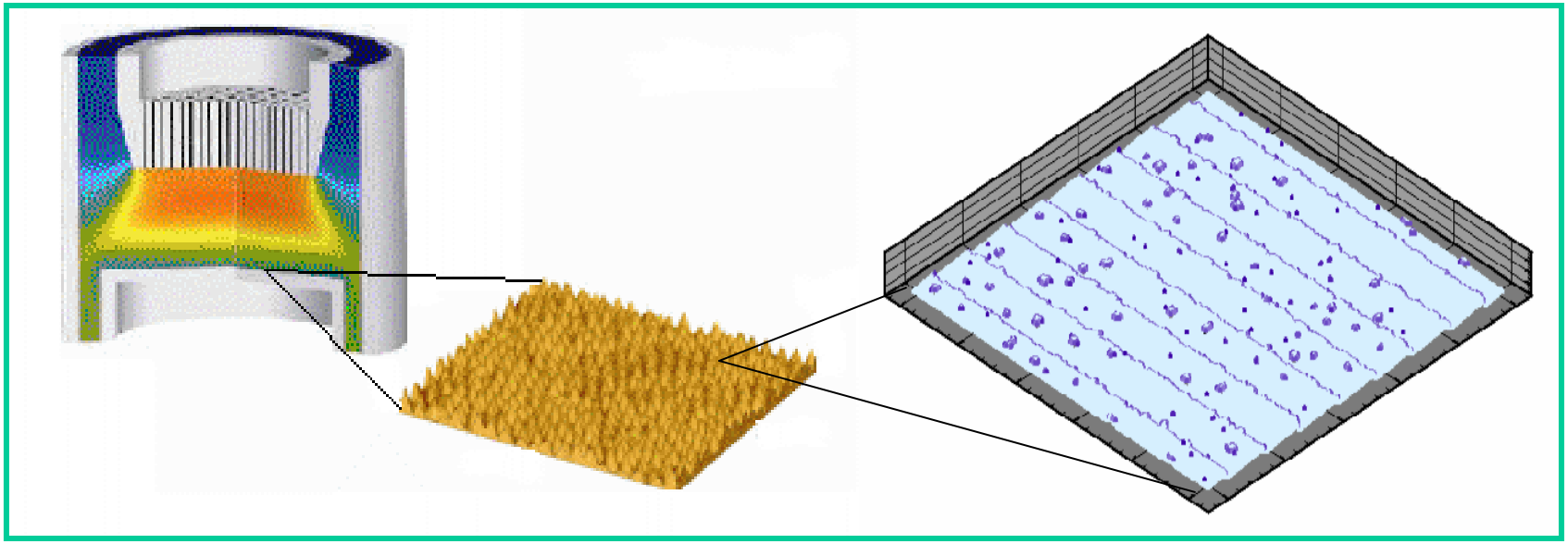
Computation

- algorithmic and software interfacing
- structured algorithms
- distributed computing
- dynamic resource allocation
- algorithmic development
  - ADIFOR, optimization, sensitivity
- hierarchical/multiscale
- uncertainty/verification

Experiment/Validation

- physical
- computational
- interface (with modeling, computation)
- new technology (sensor, etc)
- distributed (control, sensors…)

Challenge: Control of Surface Morphology



Question: can control be used to modify surface morphology?

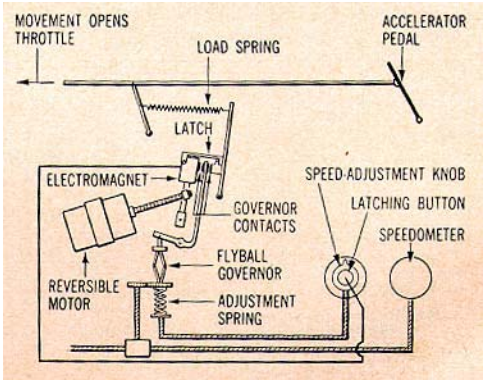
- Use unsteady processing conditions and *in situ* diagnostics to alter growth
- Provide more structured approach than existing techniques
- Can also be used to understand actuation of domain walls

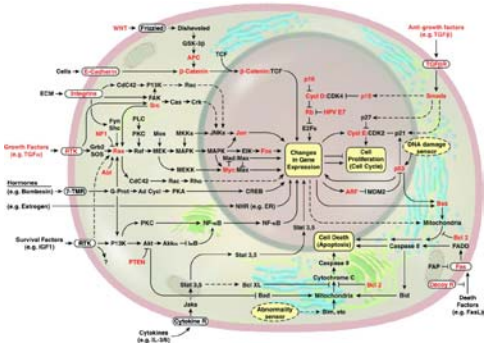
Challenges

- 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

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**





Panel Recommendations

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

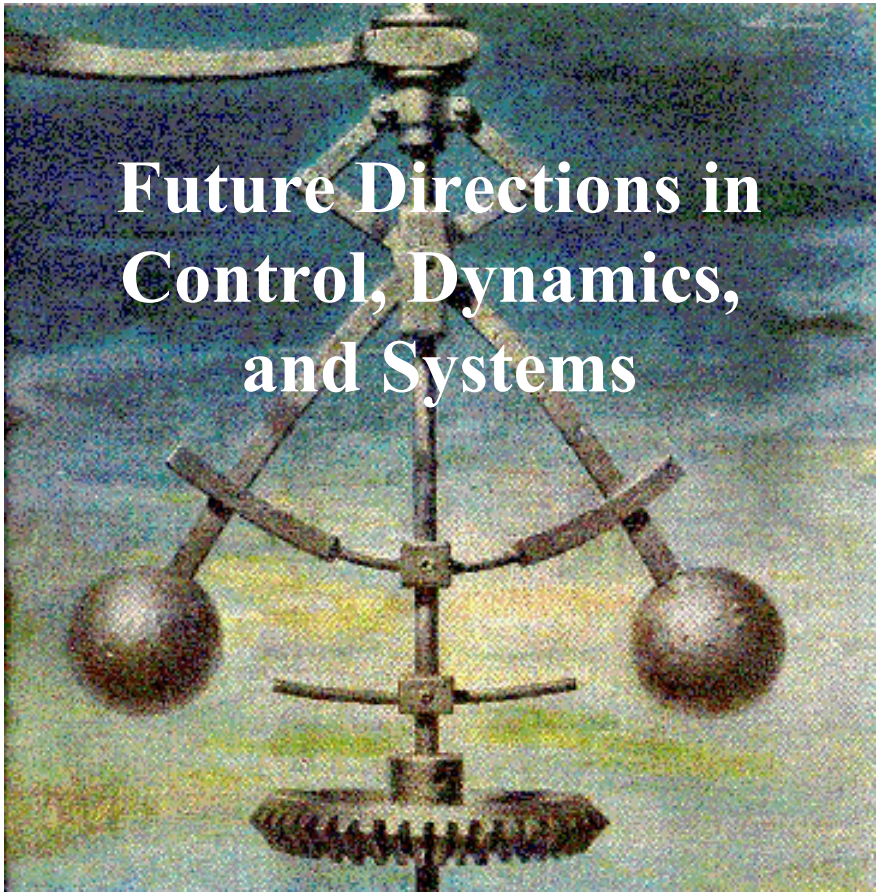
2. **Substantially increase research in control at higher levels of decision making, moving toward enterprise level systems.**

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.**

Next Steps



26 Apr 01: Report Released (!)

SIAM book available 10/02

- Will include high resolution images plus complete index
- Will be sent to congressional offices, S&T leaders, program managers
- Need ideas for a cover (send to murray@cds.caltech.edu)

Web version of report available

- Working on searchable HTML

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

Acknowledgement and Thanks

CDS Panel Writing Committee

Karl Astrom, Stephen Boyd, Roger Brockett,
John Burns, John Doyle, Gunter Stein

Everyone who attend the meetings, sent in comments, publicized the activity

- 50+ participants in the June 2000 panel meeting
- 200+ subscribers to the cdspanel mailing list
- 500+ e-mails with support, criticism, and comments over the last two years

Special thanks to Marc Jacobs for his support of Dynamics and Control Research and encouraging the formation of the Panel.