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 Stephen 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

The Panel on Future Directions in Control and Dynmical Systems held a meeting on 16-17 July 2000 at the University of Maryland, College Park. The meeting was attended by members of the panel and invited participants from the academia, industry, and government. A total of 47 people attended the meeting.

The purpose of the panel is to put forward a vision of future challenges and opportunities in the field of control and dynamical systems. The audience for the report includes decision makers in government and industry, program managers who are putting together new programs involving control and dynamical systems, and the research community itself. The report will be published by SIAM and be made available to the controls community as well as government agencies. The intent of the report is to raise the overall visibility of research in control and dynamical systems, highlight its importance in applications of national interest, and indicate some of the key trends which are important for continued vitality of the field.

The meeting was sponsored by the Air Force Office for Scientific Research and hosted by the Institute for Systems Research. Charmaine Boyd, from the Control and Dynamical Systems department at Caltech, and Pam White, from the Institute for Systems Research, provide administrative support for the meeting.

More information on the meeting as well as copies of the presentations and related reports is available via the CDS Panel Homepage:

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

Meeting Objectives

Obtain preliminary input from members of the control and dynamical systems community and the applications community that will be used as a basis for the panel's recommendations

- Identify future application areas of significant importance to the industrial and defense base that are enabled by control and dynamical systems theory and practice
- Identify a list of possible vignettes highlighting past successes and future opportunities
- Identify the possible organizational structures (universities, university-industry collaboration, funding agencies) that might be required to take move the field forward

Decide on next steps for producing the report

- Additional meetings, other mechanisms for collecting opinions and data
- Web page: copies of presentations + bulletin board discussion

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The objective of this first meeting of the panel was to collect some initial ideas about the possible scope and findings of the report, and to obtain input from the controls and applications community regarding the future of the field.

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

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The format of the meeting consisted of a half day of introductory talks, designed to seed the subsequent discussions, followed by breakout sessions in six applications areas:

- Biology and Medicine
- Information and Networks
- Transportation and Aerospace
- Materials and Processes
- Environmental Science
- Robotics and Intelligent Machines

Each area had 5-8 people who discussed some of the challenges and opportunities to that area. The initial outputs from these groups was discussed at the end of the first day, with the intent of informing everyone of some of the issues being discussed.

The second day opened with a general discussion of the previous days activities and the decision was made to combine the materials and enviroment groups and disperse the robotics and intelligent machines group (due to the small number of people remaining in that group). These new groups then met to articulate some of the overarching themes, some of the specific challenges and opportunities in each area, and candidate vignettes (along with names of people who could provide details).

The final session, on Saturday afternoon, consisted of a discussion by each group of their results and a general discussion of the overarching themes from the meeting.

Introductory Talks

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

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The first session consisted of introductory talks by Murray and Burns describing the purpose of the panel, the plan for the meeting, and a summary of the 1988 Fleming report. Burns described the process by which the Fleming report was written and disseminated, as well as giving an assessment of the strengths and weaknesses of the report.

A set of high-level, overview talks was given by Doyle, Sastry and Brockett. These talks focused on some of the emerging challenges for control, ranging from biology to information technology to quantum systems. The presentations and the discussions by the participants emphasized a number of issues that were repeated throughout the meeting:

- The need for the controls community to continue to move beyond the analysis and design of feedback controllers and to play a leading role in the design of large scale, complex, uncertain, dynamic systems across a variety of applications.
- The need to communicate and educate a broader group of researchers and practitioners about the tools and techniques that have been developed by the controls community.
- The need to maintain the rigor of the discipline, as well as our broad contact with mathematics as well as technology.

A clear message from the presentations was the broad range of problems that the controls community had not yet fully engaged. Doyle described some of the challenges for uncertainty management in systems and the need for a unified theory of computation, communications and control that accounted for interconnection, uncertainty and robustness. Sastry emphasized the role of embedded systems and the need to better take into account the underlying hardware and software architecture when building complex systems. Brockett discussed the strengths of the community, the need to better integrate with computer science, and the value of a rigorous, systems point of view toward problem solving.

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 instrumentaion for medicine and 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

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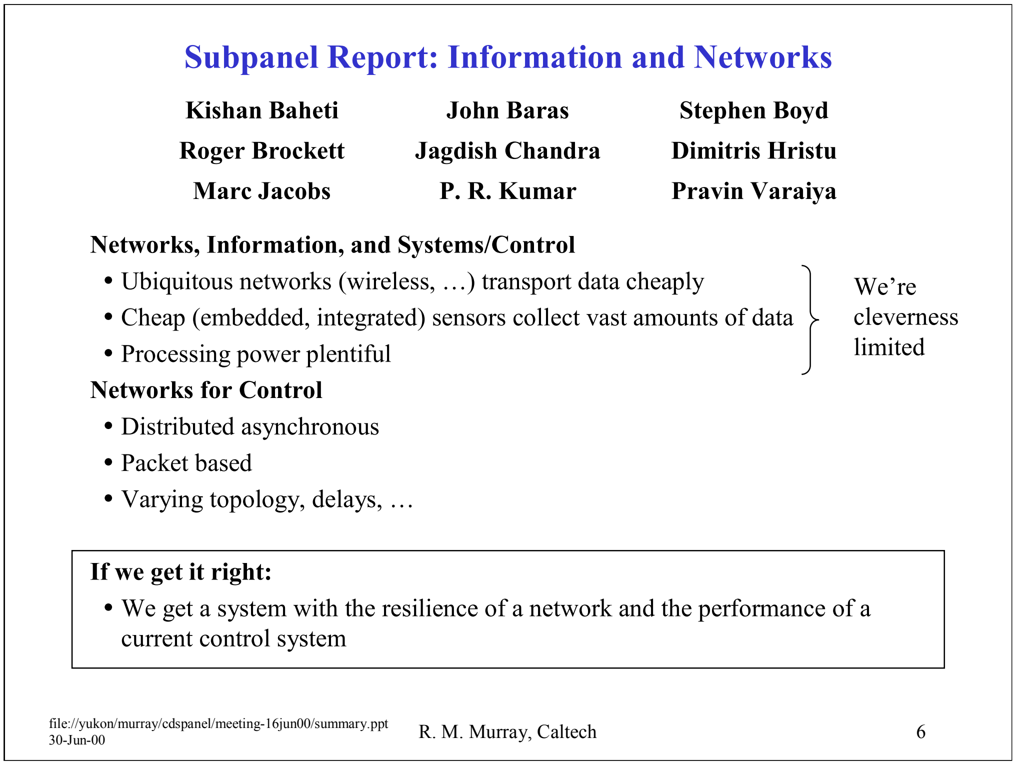
Overarching Themes: managing uncertainty and complexity

- Multi-resolution modeling for heterogeneous systems
- Integrated communications & computing for control of pervasive, embedded, …
- Data → info → knowledge → decision

Possible Vignettes



Overarching Themes

- Optimization, control and validation of networks
- Networks for control (coordinating embedded devices)
- Information extraction from dynamic data
- Distributed computation

Possible Vignettes

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

Overarching Themes

- Autonomy (levels of, local vs central)
- Interconnectivity (global, dynamic)
- Ultra-reliable control systems
- Multi-disciplineary teams (co-advisors, industry partnerships)
- Modeling for control

Possible Vignettes

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

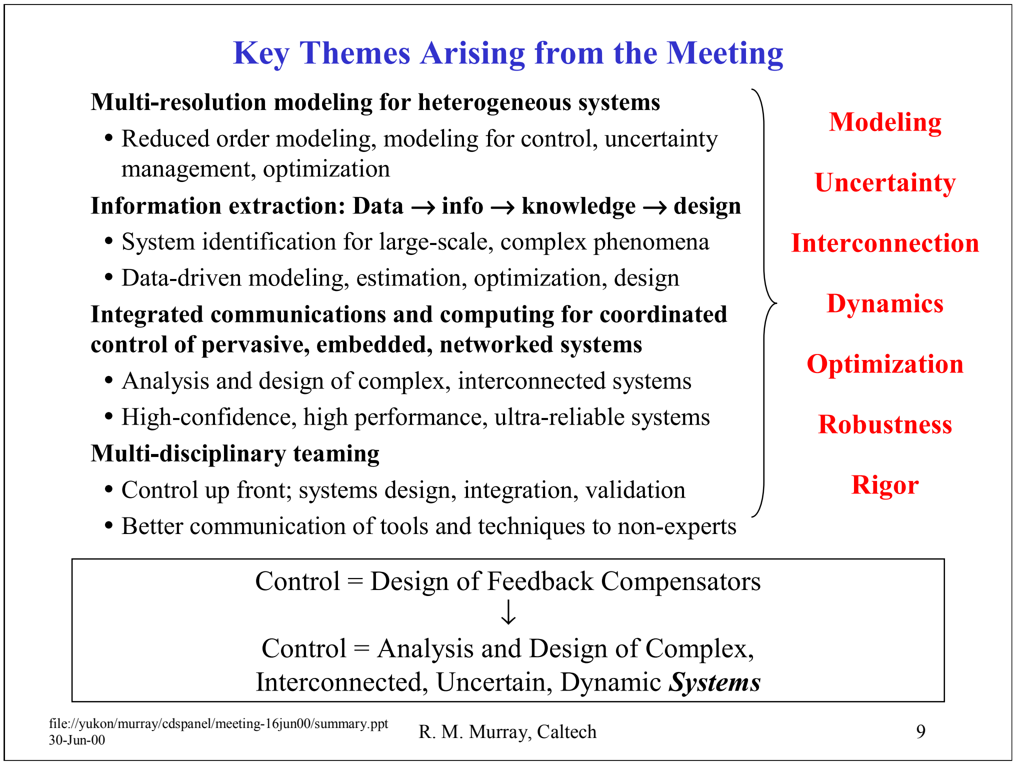
Computation
- algorithmic and software interfacing
- structured algorithms
- distributed computing
- dynamic resource allocation
- algorithmic development
  ADIFOR, optimization, sensitivity
- hierarchical/multiscale
- uncertainty/verification

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

Overarching Themes: Control = Everything

- Modeling
- Computation
- Paradigm Shifts
- Experiments/verification (practice on real problems/implement)

Possible Vignettes



A number of key themes arose during the meeting, both through subpanel discussion as well as discussions among the entire group. An overriding message was that the controls community needed to continue and accelerate the trend towards expanding the scope of the field to include issues in modeling, uncertainty, interconnection, dynamics, optimization, and robustness. These are much more broadly applicable concepts than feedback analysis and synthesis and there are many applications and disciplines which are interested in learning and using our tools.

A missing element of the current activity in controls appears to be the communication of our ideas and techniques to other communities, both practitioners within controls as well as members of other technical communities. Many of our textbooks are impenetrable to outsiders and scientists, engineers and mathematicians from other disciplines remain unaware of many of the tools we have developed. Controls as a discipline requires interaction with other disciplines to have an impact and, as such, multi-disciplinary teaming is essential. The use of controls in the design phase of new products as well as the application of controls tools for modeling and analysis require our increased interaction with discipline experts from other domains and the development of educational programs the enable such multi-disciplinary teaming.

Although much of the theory is driven by applications, the health and strength of the field clearly relies on maintaining our broad contact with mathematics, in addition to our contact with technology. The rigor which has defined the controls community must be maintained if we are to solve the problems associated with analysis and design of complex, interconnected, uncertain, dynamic systems.

Issues to be Addressed by the Report

Who are we?

- Control (laws) versus systems; control inside, control up front, systems outside
- Analysis versus synthesis; modeling with uncertainty
- Role of dynamics; real-time issues ("design of dynamics", "dynamics *matter*")
- Many multi-disciplinary interactions, with core ideas that are widely applicable
- How do we maintain community while exploring diverse set of applications?

What can we do?

- What are the current tools/approaches that will be important for the future?
- What are the new tools/approaches that will be needed to invent the future?
- How do we avoid the fate of "general systems theory"?

Why us?

- What is unique about this community that warrants our continued interaction as a discernable group?
- Should we define ourselves precisely through the common features across a wide spectrum of applications (vehicles, biology, information, materials, environment)? [ala mathematics, early dynamical systems community, etc]

What is missing? What should we be doing different?

- How do we increase visibility of control/systems to the general public, decision makers?
- How do we make results in control more accessible to people who could use them?
- Do we need to change the way we educate our students to reflect systems emphasis?

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The are many questions that should be addressed by the panel report, including describing who we are, what we can do, and why we are the right community to do it. To insure the continued vitality of the field, this must be done in a way that increases the visibility of systems and control to the decision makers in government, as well as to other disciplines.

There was considerable discussion of education and teaching, and possible recommendations for educational reform in the systems and control area should be addressed by the panel. Currently, controls is often fragmented across departments, with different courses for mechanical, electrical, and chemical engineers as well as applied mathematicians. Research institutes (eg, ISR at Maryland, CSL at Illinois, LIDS at MIT) have attempted to bridge this gap, but they often do not address teaching and other educational issues. Broader communication of systems and control skills through new courses and new educational structures are a pre-requisite for long term growth of the field.

Another issue that arose in the discussion was the role of dynamical systems, which was not strongly emphasized in the meeting. This should either be addressed explicitly by the report or dropped from the title of the panel. More generally, the panel should decide if Control and Dynamical Systems is the right title for this community. Perhaps "Systems and Control" is a better definition for the range of applications, techniques, and theory that are embraced by the community.

Finally, the panel should consider the use of success stories to communicate some of the accomplishments of the controls community and the value of the systems approach that it brings. These must be done carefully so as to give proper credit to other communities that were essential partners in the multi-disciplinary activities that we participate in.

Next Steps

Continue to solicit input from the controls community

- Organize meetings and special sessions at upcoming events to discuss findings to date and collection additional input
  - AFOSR Contractor's Meeting: 21-23 Aug 00
  - DARPA SEC PI Meeting: Oct 00
  - NSF, ARO, ONR mini-workshops?
- Encourage the use of the web page for posting ideas, thoughts, criticisms

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

Organize a writing committee to produce a draft of the report

- 8-10 volunteers (not necessarily panelists) who will draft sections and focus the message on a few key items
- Writing committee should maintain a broad view: don't let the report become a collection of everyone's favorite topics
- Keep draft versions public; encourage input and eliminate surprises

The panel meeting largely achieved the objectives that were set. The subpanels put together ideas for application areas of significant importance to the industrial and defense base, identified some possible vignettes highlighting past successes and future opportunities. Organizational structures and obstacles to continued growth were discussed at length, although no concrete recommendations have yet emerged. Overall, there was a shared sense that the future of the field is bright, if we accelerate our interaction with other disciplines while maintaining the mathematical rigor that has been the hallmark of our community.

The immediate next steps for the panel include continued gathering of input from the controls community, as well as promoting discussion in other forums about future directions in the field. A few of these opportunities are listed agove. The bulletin board on the web is a mechanism to solicit broad input and it is hoped that these notes will help increase the visibility of the panels efforts and solicit additional inputs.

In order to produce the report, a writing committee of 8-10 will be formed to attempt to summarize findings of the panel and produce a draft set of recommendations. This will be accomplished through a meeting of the writing committee in mid to late summer, in which the first draft will be generated. This will then be distributed to the panel for comment and posted on the web site for general dissemination. The final draft of the report will be written in the fall, with the goal of delivering it to the printers by the end of the year. This will allow publication of the report by February or March 2001, before the congressional budget cycle.

Richard Murray

30 June 2000