Teaching Feedback to Non-Traditional Audiences

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Goals
• Motivate the need to teach controls outside of the traditional disciplines
• Describe three experiences over the last decade and the results so far
• Open a discussion about possible next steps for educating scientists, engineers, and the public about feedback and control systems
April 2000: Panel on Future Directions in Control, Dynamics, Systems (US AFOSR)

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
Control in an Information Rich World (2001-03)

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

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

2. Substantially increase research in control at higher levels of decision making, moving toward enterprise level systems
   • Autonomy, formal methods, “big data”

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

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
Outline

1. CDS 101/110 - Analysis and Design of Feedback Systems
   • Joint work with Kristi Morgansen (U. Washington), Hideo Mabuchi (Stanford), Doug MacMartin (Caltech)

2. FBS - Feedback Systems: An Introduction for Scientists and Engineers
   • Joint work with Karl Åström (Lund University)

3. CDS 273 - Frontiers in Control and Dynamical Systems
   • Joint work with Hideo Mabuchi (Stanford) and dozens of Caltech faculty...
CDS 101/110a: Introduction to Feedback and Control

CDS 101 course for non-majors on “Feedback Systems”
- Aimed at a broad audience of scientists and engineers
- Focused on teaching principles and computer tools (MATLAB based)
- Format:
  - Monday: powerpoint lecture on concepts, with examples and experiments
  - Friday: recitation or “seminar” lectures by Caltech faculty on current applications

Co-taught with CDS 110, a traditional engineering course on control
- Monday lectures shared with CDS 110; Friday recitations (broken out by discipline)
- Wednesday: engineering details and derivations (usually a blackboard lecture)
## Overview of the Course

<table>
<thead>
<tr>
<th>Wk</th>
<th>Mon/Wed</th>
<th>Fri</th>
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<tbody>
<tr>
<td>1</td>
<td>Introduction to Feedback and Control</td>
<td>MATLAB tutorial (Luis)</td>
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<td>2</td>
<td>System Modeling (ODEs)</td>
<td>SIMULINK tutorial (George)</td>
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<td>3</td>
<td>Stability and Performance</td>
<td>Recitation sections</td>
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<td></td>
<td>• Nonlinear systems, Lyapunov stability</td>
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<td>4</td>
<td>Linear Systems</td>
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<td>5</td>
<td>State space feedback</td>
<td>Review for midterm (Sawyer)</td>
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<td></td>
<td>• Reachability, eigenvalue placement</td>
<td></td>
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<td>6</td>
<td>Transfer Functions</td>
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<td>7</td>
<td>Loop Analysis of Feedback Systems</td>
<td>Application lectures (outside speaker)</td>
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<td></td>
<td>• Nyquist criterion</td>
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<tr>
<td>8</td>
<td>PID Control</td>
<td>Thanksgiving holiday</td>
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<tr>
<td>9</td>
<td>Loop Shaping</td>
<td>Application lecture (outside speaker)</td>
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<tr>
<td>10</td>
<td>Limits of Performance</td>
<td>Review for final (Julia)</td>
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<td></td>
<td>• Bode's integral formula</td>
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<td>• Effects of RHP poles, zeros</td>
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CDS 101/110 Feedback Mechanisms

Mud cards
- 3 x 5 cards passed out at beginning of each lecture
- Describe “muddiest” part of the lecture (or other questions)
- Turn in cards at end of class
- Responses posted on FAQ list by 8 pm on the day of the lecture
- (Replaced with Piazza in 2010)

Homework hours
- How much time did you spend on the homework set (including reading)?
- Write on back of first page of HW set
- Use to modify questions for next year

Midterm and final surveys
- Midterm: what’s working? Adjust activities in the second half of the course
- Final: what worked (use for following year)

What does closed loop mean?

Richard Murray, 29 Sep 02
"Closed loop" refers to the feedback interconnection between two or more systems, such that the information flows in a cycle. Often, this interconnection is implemented by having the action of a system dependent on the deviation between the measured and desired performance. This is in contrast to "open loop", in which this cycle of information is interrupted and there is no corrective action based on the measurement.
Lessons Learned: CDS 101/110

Teaching to students with a broad background requires non-standard approaches
- Find TAs coming from same background as students; tune material in recitations
- Required few tutorial sessions in the first weeks of class: MATLAB, linear algebra, ...

Monday lectures provide a good overview, with diverse examples
- Forced to use examples that could be understood across disciplines => typically things that people had a good sense of from everyday experiences
  - Mechanical: cruise control, “balance systems” (Segway)
  - Scientific: predatory-prey, insect flight control
  - Computing: queueing theory, congestion control

Good homework sets were critical elements (and required time to create)
- Can’t always assume familiarity with a given topic area => problems tended to require a description of the underlying physics/chemistry/biology (not always good)
- Shot for a mixture of theory, practice, MATLAB; separate sets for CDS 101/110

The use of feedback was seen by the students as very useful
- Mud cards and Piazza provide very fast response time
- Surveys allowed tuning of approaches in second half of course (not always stable!)
- Homework times allowed adjustment of course structure from year to year
FBS: Feedback Systems (textbook)

Motivation: serve as a textbook for CDS 101/110
- Existing textbooks (at the time) were too focused on ChE, EE, ME audiences
- Wanted a newer set of examples that build on Monday (and Friday) lectures

Features that we wanted to incorporate based on needs and goals
- Cover state space first: biologists, economists and computer scientists don’t have intuition for frequency response
- Make sure examples don’t favor just one discipline
- Don’t require the use of Laplace transforms
  - Derive transfer functions using the notion of “exponential response” (in second half of book)
- Drop topics that are not frequently used
  - Routh-Hurwitz appears in exercises (3rd order)
  - Root locus only appears as a parametric plot
- Use online materials to supplement print
  - Book serves as “tip of the iceberg”
- Put everything online and freely available
  - PDF file of final text (+ iPad version)
  - MATLAB files for all examples
Book Outline and Features

Part I: State space analysis and design
- Ch 1 - Introduction
- Ch 2 - System Modeling
- Ch 3 - Examples
- Ch 4 - Dynamic Behavior
- Ch 5 - Linear Systems
- Ch 6 - State Feedback
- Ch 7 - Output Feedback

- History and examples
- Modeling principles; ODEs + discrete time
- Sample applications/running examples
- Nonlinear ODEs, Lyapunov stability (lite)
- LTI systems, matrix exp, convolution equation
- Reachability, eigenvalue placement, (LQR)
- Observability, estimators, 2 DOF design, (KF)

Part II: Frequency domain analysis and design
- Ch 8 - Transfer Functions
- Ch 9 - Frequency Domain Analysis
- Ch 10 - PID Control
- Ch 11 - Frequency Domain Design
- Ch 12 - Robust Performance

- Exponential response, Bode plots
- Nyquist criterion, stability margins
- Design for performance, Ziegler-Nichols
- Loop shaping, Bode integral formula
- Uncertainty modeling, RHP poles/zeros

Running examples (throughout the text)
- Balance systems
- Predator prey
- Cruise control
- Bicycle dynamics
- Congestion control
- Drug administration
- Op amps
- AFM
Lessons Learned: Feedback Systems

Different audiences want to teach the material in different order
- Many courses need to teach frequency domain first, followed by state space
- Courses with integrated labs need some notion of feedback early in the course
- Many instructors feel it is important to include root locus, Routh-Hurwitz, ...

Hard to get the right mathematical level for the book
- Idea: require only sophomore level linear algebra and ODEs
- Many students still find the level of mathematics to be confusing

Reviews (from courses) have been mixed
- Instructors like the broad variety of examples (less clear for students)
- Students complaints range from too shallow to too mathematical
- First review on amazon.com: “Useless for learning” (got better after that)

Second edition is in progress
- Moved Ch 3 (examples) to appendices; inserted chapter on “Feedback Principles”
  - Most instructors skipped Ch 3 and assigned sections based on homework
  - Allows more rapid demonstration of simple controllers that can be used in labs
- Improvements throughout the book based on feedback from instructors, students
- Preprint to be posted to web site in early 2014; send e-mail if you want early copy
CDS 273: Frontiers in Control and Dynamical Systems

Idea: bring together students from CDS and “application” areas (science/engin)

- Instructors seek out other faculty to provide a project idea plus 2 students for course
- Student teams: 2 controls (graduate) students + 2 students from application area
- Output: conference paper and/or first draft research proposal

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<tr>
<th>Project</th>
<th>Faculty sponsor</th>
<th>Team</th>
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<tbody>
<tr>
<td>Robust Inverse Design with Photonic Bandgap Structures</td>
<td>Hideo Mabuchi and Oskar Painter</td>
<td>Kartik Srinivasan, Demetri Spanos, Kevin McHale, Mike Armen, John Au</td>
</tr>
<tr>
<td>Synthetic Biology: Genetically-Encoded Finite State Machines</td>
<td>Richard Murray, Michael Elowitz, Christina Smolke</td>
<td>Domitilla Del Vecchio, Mary Dunlop, Jeff Endelman, Jimmy Fung, Shaunak Sen, Wanwan Yang</td>
</tr>
<tr>
<td>Real-Time Information Theory</td>
<td>Leonard Schulman</td>
<td>Dennice Gayme, Zhipu Jin, Ling Shi, Kevin Tang, Steve Waydo</td>
</tr>
<tr>
<td>Autonomous Desert Racing</td>
<td>Richard Murray, Joel Burdick, Pietro Perona</td>
<td>Lars Cremean, Sean Humbert, Dmitriy Kogan</td>
</tr>
<tr>
<td>Planetary Entry, Descent and Landing (EDL)</td>
<td>JPL (John Carson)</td>
<td>John Carson, Michael Epstein, Doug MacMartin</td>
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</table>

- Week 1: organization - overview of projects, hand out signup form
- Week 2: announce assignments, first meeting of groups
- Week 5: midterm presentation to instructors (to keep the course moving)
- Final report: 10-20 pages summarizing results (findings, examples, open questions)
Sample Project: Jellyfish Locomotion (2006)

Sponsor: John Dabiri
- Aeronautics/Bioengineering
- Biological propulsion systems

Students
- CDS: David Pekarek (Marsden), Elisa Franco (Murray)
- Aero: Kakani Young, Hisashi Date, Stephanie Chan
- BE: Jifeng Peng

Results
- Application of finite-time Lyapunov exponents (FTLE) to determine coherent structures
- Submitted results to *J. Fluid Mechanics* with Franco as lead author; published in 2007
- Dabiri added a CDS student to group the following (2013 PhD)

Non-invasive studies of animal propulsion and sensing

Project Goals
- How to identify flow geometry?

Lagrangian solution:
Finite-time Lyapunov exponent field (FTLE)

Geometry of unsteady fluid transport during fluid–structure interactions

Elisa Franco¹, David N. Pekarek², Jifeng Peng³ and John O. Dabiri¹,⁴

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Lessons Learned: CDS 273

Extremely useful course for both controls majors and non-majors
• Allowed non-majors to understand some of the tools and approaches from controls
• Gave CDS students broader perspective on potential applications of tools and theory
• Served as a source of PhD projects for a number of CDS majors (eg, Del Vecchio)

Provided many collaborative projects and proposal opportunities for years after
• Many projects resulted in joint activities in subsequent years (via CDS 273 students)
• Provided means for faculty in CDS & other areas to learn about each other’s work

Requires relatively little effort, but broad set of connections + good collaborators
• Need to identify colleagues who are working on areas where CDS tools can help
• Colleagues need to be willing to contribute ideas + students + some of their time
Summary and Future Directions Discussions

Creating courses for students outside of the traditional engineering disciplines

- Computing systems: feedback, dynamics, uncertainty, robustness
- Economics/finance: feedback, dynamics, uncertainty, robustness
- Systems biology: feedback, dynamics, uncertainty, robustness

Creating educational materials that are easily accessible to broad set of audiences

- Books for the public
- MOOCs?
- “Five minute” lectures

What control courses should students in these majors take?
References and Further Information


