Chapter 4

Education and Outreach

Control education is an integral part of the community's activities and one of its most important mechanisms for transition and impact. In 1998, the National Science Foundation (NSF) and the IEEE Control Systems Society (CSS) jointly sponsored a workshop in control engineering education which made a number of recommendations for improving control education (see [1] and Appendix A). This section is based on the findings and recommendations of that report, and on discussions between Panel members and the control community. The Panel would particularly like to thank Jim Batterson for his contributions to this chapter.

4.1 The New Environment for Control Education

Control is traditionally taught within the various engineering disciplines that make use of its tools, allowing a tight coupling between the methods of control and their applications in a given domain. It is also taught almost exclusively within engineering departments, especially at the undergraduate level. Graduate courses are often shared between various departments and in some places are part of the curriculum in applied mathematics or operations research (particularly in regards to optimal control and stochastic systems). This approach has served the field well for many decades and has trained an exceptional community of control practitioners and researchers.

Increasingly, the modern control engineer is put in the role of being a systems engineer, responsible for linking together the many elements of a complex product or system. This requires not only a solid grounding in the framework and tools of control, but also the ability to understand the technical details of a wide variety of disciplines, including physics, chemistry, electronics, computer science, and operations research.

In addition, control is increasingly being applied outside of its traditional domains in aeronautics, chemical engineering, electrical engineering and mechanical engineering. Biologists are using ideas from control to model and analyze cells and animals; computer scientists are applying control to the design of routers and embedded software; physicists are using control to measure and modify the behavior of quantum systems; and economists are exploring the applications of feedback to markets and commerce.

This change in the use of control presents a challenge to the community. In the United States, discipline boundaries within educational institutions are very strong and it is difficult to maintain a strong linkage between control educators and researchers across these boundaries. While the control community is large and prosperous, control is typically a small part of any given discussion on curriculum since these occur within the departments. Hence it is difficult to get the resources needed to make major changes in the control curriculum. In addition, many of the new applications of control are outside of the traditional disciplines that teach control and it is hard to justify developing courses that would appeal to this broader community and integrate those new courses into the curricula of those other disciplines (e.g., biology, physics, or medicine).

In order for the opportunities described elsewhere in this report to be realized, control education must be restructured to operate in this new environment. Several universities have begun to make changes in the way that control is taught and organized and these efforts provide some insights into how this restructuring might be done successfully.

Often the first step is establishing a cross-disciplinary research center, where there is a larger critical mass of control researchers. Examples include the Coordinated Science Laboratory (CSL) at the University of Illinois, Urbana-Champaign, the Center for Control Engineering and Computation (CCEC) at the University of California, Santa Barbara, and the Institute of Systems Research (ISR) at the University of Maryland. These centers coordinate research activities, organize workshops and seminars, and provide mechanisms for continuing interactions between control students and faculty in different departments.

A second step is the establishment of shared courses between the disciplines, often at the graduate level. These shared courses encourage a broader view of control since the students come from varying backgrounds. They also provide an opportunity for the larger control community at the university to establish active dialogs and provide a mechanism for sharing students and building joint research activities. Many U.S. universities have adopted this model, especially for theory oriented courses.

Finally, some schools have established a separate M.S. or Ph.D. program in control. These are common in Europe, but have been much less prevalent in the United States, partly due to the traditional discipline structure around which most universities are organized. Examples in the U.S. include the Control and Dynamical Systems (CDS) program at Caltech and the Department of Systems Science and Mathematics (SSM) at Washington University. The advantage of a separate graduate program in control is that it gives the faculty better control over the curriculum and allows a less discipline-centric approach to control.

One other mechanism, popular in Europe but not yet established in the United States, is the creation of regional control alliances that build critical mass by linking together multiple universities in a geographic region. This mechanism is used very effectively, for example, in the Netherlands through the Dutch Institute of Systems and Control (DISC).[1] With the increased availability of real-time audio, video, and digital connectivity, it is even possible to create virtual alliances—with shared classes, reading groups, and seminars on specialized topics—linking sites that are not physically near each other.

4.2 Making Control More Accessible

Coupled with this new environment for control education is the clear need to make the basic principles of feedback and control known to a wider community. As the main recommendations of the Panel illustrate, many of the future opportunities for control are in new domains and the community must develop the educational programs required to train the next generation of researchers who will address these challenges.

A key element is developing new books and courses that emphasize feedback concepts and the requisite mathematics, without requiring that students come from a traditional engineering background. As more students in biology, computer science, environmental science , physics, and other disciplines seek to learn and apply the methods of control, the control community must explore new ways of providing the background necessary to understand the basic concepts and apply some of the advanced tools that are available. Textbooks that are aimed at this more general audience could be developed and used in courses that target first year biology or computer science graduate students, who may have very little background in continuous mathematics beyond a sophomore course in scalar ordinary differential equations (ODEs) and linear algebra.

The following vignette describes one attempt to make control more accessible to a broader community of research scientists and engineers.

Vignette: CDS 110: Introduction to Control Concepts, Tools, and Theory (Kristi Morgansen and Richard Murray, Caltech)

The Control and Dynamical Systems Department at Caltech has recently undertaken a revision of its entry level graduate courses in control to make them accessible to students who do not have a traditional background in chemical, mechanical, or electrical engineering. The current course, CDS 110, is taken by senior undergraduates and first year graduate students from all areas of engineering, but has traditionally not been easily accessible to students in scientific disciplines, due to its heavy engineering slant. With the increased interest in control from these communities, it was decided to revise the course so that it could not only continue to serve its traditional role, but also provide an introduction to control concepts for first year graduate students in biology, computer science, environmental engineering, and physics.

The goal of the course is to provide an understanding of the principles of feedback and their use as a tool for altering the dynamics of systems and managing uncertainty. The main topics of the course are modeling, dynamics, interconnection, and robustness of feedback systems. On completion of the course, students are able to construct

[1] http://www.disc.tudelft.nl

control-oriented models for typical systems found in engineering and the sciences, specify and describe performance for feedback systems, and analyze open loop and feedback behavior of such systems. Central themes throughout the course include input/output response, modeling and model reduction, linear versus nonlinear models, and local versus global behavior.

The updated version of the course has two "tracks": a conceptual track and an analytical track. The conceptual track is geared toward students who want a basic understanding of feedback systems and the computational tools available for modeling, analyzing, and designing feedback systems. The analytical track is geared toward a more traditional engineering approach to the subject, including the use of tools from linear algebra, complex variables, and ordinary differential equations (ODEs). Both tracks share the same lectures, but the supplemental reading and homework sets differ.

In addition to the main lectures, optional lectures are given by faculty from other disciplines whose research interests include control. Hideo Mabuchi (Physics) and Michael Dickinson (Biology) are two such lecturers and they provide examples of some applications of feedback to a variety of scientific and engineering applications. These lectures are used to emphasize how the concepts and tools are applied to real examples, drawn from areas such as aerospace, robotics, communications, physics, biology, and computer science.

The first iteration of the course, taught in 2001–02, succeeded in developing a set of conceptual lectures (given as the first lecture in the week) that introduced the main ideas of control with minimal mathematical background. Based on these lectures, students are able to use the tools of control (e.g., MATLAB and SIMULINK) and understand the results. Two additional lecture hours per week are used to provide the more traditional mathematical underpinnings of the subject and to derive the various results that are presented in the conceptual lectures.

In the second iteration of the course, to be taught in 2002-03, we intend to refine the lectures and put more effort into dividing the class into sections based on research interests. Individual lectures in the sections will then be used to build the necessary background (for example, providing a refresher on linear algebra and ODEs for biologists and computer scientists) or to provide additional perspectives (for example, linking transfer functions to Laplace transforms in a more formal manner).

In addition to changes in specific courses on control, universities could also integrate modules on dynamics and control into their undergraduate mathematics and science curricula. Any linear algebra course could be strengthened by the addition of a short lesson on linear systems, eigenvalues, and their physical interpretation and manipulation through feedback. Freshman physics could be enriched by extending lessons on mechanical oscillators to the problem of balancing an inverted pendulum or the stability of person riding a bicycle.

The control community also must continue to implement its tools in software, so that they are accessible to users of control technology. While this has already occurred in some areas of control (such as classical and modern linear control theory), there are very few general purpose software packages available for analysis and design of nonlinear, adaptive, and hybrid systems—and many of these are not available on general purpose platforms (such as MATLAB). These tools can be used to allow non-experts to apply the most advanced techniques in the field without requiring that they first obtain a Ph.D. in control. Coupled with modeling and simulation tools, such as SIMULINK and Modelica, these packages will be particularly useful in teaching the principles of feedback by allowing exploration of relevant concepts in a variety of domains.

4.3 Broadening Control Education

In addition to changes in the curriculum designed to broaden the accessibility of control, it is important that control students also have a broader grasp of engineering, science, and mathematics. Modern control involves the development and implementation of a wide variety of very complex engineering systems and the control community has been a major source of training for people who embrace a systems perspective. The curriculum in control needs to reflect this role and provide students with the opportunity to develop the skills necessary for modern engineering and research activities.

At the same time, the volume of work in control is enormous and so effort must be placed on unifying the existing knowledge base into a more compact form. There is a need for new books that systematically introduce a wide range of control techniques in an effective manner. This will be a major undertaking, but is required if future students of control are to receive a concise but thorough grounding in the fundamental principles underlying control, so that they can continue to extend the research frontier beyond its current boundary.

Increasingly, control engineers are playing the role of "systems integrator" in large engineering projects. This occurs in part because they bring systems insight that is required for successful operation of a complex engineering product, but also because control is often the glue that ties together the components of the system (often in the form of embedded control software). Unfortunately, most control curricula do not emphasize the types of leadership and communications skills that are critical for success in these environments.

A related aspect of this is strengthening the skills required for working in teams. All modern systems design is done in interdisciplinary teams and it requires certain skills to understand how to effectively interact with domain experts from a wide variety of disciplines. Project courses are an effective mechanism for developing this type of insight and these should be more aggressively incorporated into control curricula at both undergraduate and graduate levels. Another effective mechanism is participation in national competitions where control tools are required, such as RoboCup[2] and FIRST[3].

It is also important that control students be provided with a balance between theory, applications, and computation. In particularly, it is essential that control students build a deep domain knowledge in one or more disciplines, so that they un-

[2] http://www.robocup.org
[3] http://www.usfirst.org

derstand how this knowledge interacts with the control methodology. Independent of the specific domain chosen, this approach provides a context for understanding other engineering domains and developing control practices and tools that bridge application areas.

Experiments continue to form an important part of a control education and projects should form an integral part of the curriculum for both undergraduate and graduate students. Shared laboratories within individual colleges or universities as well as laboratories shared among different universities could be used to implement this (with additional benefits in building cross-disciplinary and cross-university interactions). New experiments should be developed that explore the future frontiers of control, including increased use of computing, communications and networking, as well as exploration of control in novel application domains.

4.4 The Opportunities in K-12 Math and Science Education

Much as computer literacy has become commonplace in our K-12 curriculum, an understanding of the requirements, limits, and capabilities of control should become part of every scientifically literate citizen's knowledge. Whether it is understanding why you should not pump antilock brakes or why you need to complete a regimen of antibiotics through the final pills even after symptoms disappear, an understanding of dynamics and control is essential. The development of inexpensive microprocessors, high-level computer languages, and graphical user interaces (GUIs) has made the development of test apparatus and small laboratories for rudimentary control experiments and demonstrations available within the budgets of all school districts. The U.S. National Science Foundation recognizes the importance of its funded programs impacting the general public through its "Criterion 2" (Broader Impacts) in the evaluation of all submitted proposals. Because of the broad applications of control to the public good and standards of living, it is important to develop a curriculum for inclusion in pre-college (K-12) education.

Currently, mathematics, science, and computer technology are taught in separate departments in the vast majority of K-12 curricula. Even sciences are compartmentalized at many schools. As at universities, the multidisciplinary nature of control is very much antithetical to that traditional thinking and structure in K-12 education. However, there is some evidence of advances toward application and integration of mathematics with science. The Consortium for Mathematics and Its Applications (COMAP)[4], which develops curriculum materials and teacher development programs in mathematics, is one example. Indeed, the leveraging of efforts with COMAP could prove fruitful and the control community could work with COMAP to enhance the current textbooks and curricula that have been developed by that consortium over the past two decades. Another resource is the Eisenhower National Clearinghouse,[5] which maintains a database of teaching modules and resources for K-12 math and science education.

[4] http://www.comap.com
[5] http://www.enc.org

In the control arena, simple experiments involving governors, thermostats, and "see-saws" can be performed as early as elementary school to illustrate the basic concepts of control. As mathematical sophistication increases through middle school and high school, quantitative analysis can be added and experimentally verified. Some schools are beginning to teach calculus in the junior year and so a post-calculus course in applied mathematics of differential equations and dynamical systems could be created bridging chemistry, physics, biology, and mathematics.

Complementary to the development of educational materials and experiments, it is also important to provide K-12 teachers with the opportunities to learn more about control. As an example of how this could be done, NASA Langley Research Center sponsored a program for teachers under the auspices of the HPCCP (High Performance Computing and Communications Program) several years ago. In this program teachers from six school districts spent 8 weeks learning the state of the art in computer hardware and software for engineering and science. Most days were spent with new material delivered in a lecture or laboratory environment in the morning with a "homework" laboratory in the afternoons. Teachers were paid a fellowship that approximated the per diem rate of entry-level teachers. This type of residential environment allowed for a total immersion in the material. In addition to becoming familiar with research-grade hardware and software and the Internet, the participants formed partnerships with each other that promoted continued collaboration throughout the coming academic years.

There are numerous curriculum development and general education meetings and conferences throughout the country each year. In particular, most states have an active association of school boards and there is a National School Boards Association. A presentation at these meetings would communicate directly with the policy and decision makers. Such a presentation would have to be tailored for the lay person but might produce a pull to match a push from one of the ideas above.

4.5 Other Opportunities and Trends

In addition to the specific opportunities for education and outreach described above, there are many other possible mechanisms to help expand the understanding and use of control tools.

Popular Books and Articles

In September 1952, *Scientific American* published an entire issue dedicated to Automatic Control [39]. The issue highlighted the role that control was playing in the new advancements of the time, particularly in manufacturing. The introduction of cruise control (originally called Autopilot) a few years later provided direct experience with the main principles of feedback.

Since that time, control has become less and less visible to the general public , perhaps in part because of its success. Individuals interact with control systems and feedback many times every day, from the electronic amplifiers, tuners, and filters in television and radio, to congestion control algorithms that enable smooth Internet communications, to flight control systems for commercial aircraft. Yet most people are unaware of control as a discipline. Other fields, such as artificial intelligence, robotics, and computer science have often been given credit for ideas whose origins lie within the control community.

There is a great need to better educate the public on the successes and opportunities for control. This public awareness is increasingly important in the face of decisions that will need to be made by government funding agencies about support for specific areas of research.

The use of any number of popular outlets for communication can reach this group. Many local newspapers now have a science page or section on a weekly basis. The development of a popular level series of articles on dynamics and control could be prepared for these pages. The New York Times publishes a science section every Tuesday; a series of articles could be developed for this section spanning several weeks. A number of science museums have been developed across the nation in recent years and many of these museums are allied through professional associations. The development of interactive dynamics and control displays for these museums would be beneficial to the museum by giving them a new exhibit and the displays reach the entire age range of the public from children through adults.

Books written for non-specialized audiences and chapters in high school textbooks are another mechanism for increasing the understanding of control principles in the general population. The dynamical systems community has been very successful in this regard, with many books available on chaos, complexity theory, and related concepts. Currently available books on control include books on the history of control [8, 9, 27] and a book entitled "Out of Control" [22] that discusses many control concepts.

Multimedia Tools

There is an increasing need for educational materials that can be used in a variety of contexts for communicating the basic ideas behind control. One possible mechanism is to develop a multimedia CDROM that would include materials on the history and concepts of control, as well as tutorial material on specific topics and public domain software tools for control analysis and design.

The fluid mechanics community has recently developed such a multimedia CDROM that can be used as a supplement to traditional courses in fluid mechanics [18]. It contains historical accounts of fluid mechanics, videos and animations of important concepts in fluids, and detailed descriptions of fundamental phenomena. It can be purchased through university bookstores or online from Amazon.com.

One initial activity in developing such tools for control has been made by Wilson J. Rugh at Johns Hopkins University, who has created a series of interactive demonstrations of basic concepts of control that can be executed over the web.[6] Modules include Fourier analysis, convolution, the sampling theorem, and elementary control systems. One of the most sophisticated tools demonstrates robust stabilization, including the ability to specify an uncertainty weight by moving poles and zeros of the weighting transfer function with the mouse. A controller can

[6] `http://www.jhu.edu/~signals`

then be designed by dragging the compensator poles and zeros to achieve robust, closed loop stability.

Software

One of the success stories of control is the wide availability of commercial software for modeling, analyzing, designing, and implementing control systems. The Controls Toolbox in MATLAB provides the basic tools of classical and modern control and many other toolboxes are available for more implementing more specialized theory. These toolboxes are used throughout academia, government, and industry and give students, researchers, and practitioners access to powerful tools that have been carefully designed and tested.

Despite the impressive current state of the art, much of this software is restricted to a very small class of the systems typically encountered in control and there are many gaps that will need to be filled to enable the types of applications described in the previous chapter. One area where substantial progress has been made recently is in modeling tools, where there are several software packages available for modeling, simulation, and analysis of large-scale, complex systems. One such is example is *Modelica,*[7] which provides an object oriented language for describing complex physical systems. Modelica is particularly noteworthy because it was designed to model systems with algebraic constraints, allowing a much richer class of systems to be represented.

Additional tools are needed for control-oriented modeling, analysis, and synthesis of nonlinear and hybrid systems, particularly those that have a strong interaction with information rich systems, where good scaling properties are required. As yet, there is not a standard representational framework for such systems (beyond symbolic representations) and hence software tools for nonlinear or hybrid analysis are much less used than those for linear systems. One of the main issues here is to capture the relevant dynamics in a framework that is amenable to computation. Analysis and synthesis must be able to handle systems containing table lookups, logical elements, time delays, and models for computation and communication elements.

The payoff for investing in the development of such tools is clear: it brings the advanced theoretical techniques that are developed within the community to the people who can most use those results.

Interaction with Industry and Government

Interaction with industry is an important component of any engineering research or educational activity. The control community has a strong history of impact on many important problems and industry involvement will be critical for the eventual success of the future directions described in this report. This could occur through cooperative Ph.D. programs where industrial researchers are supported half by companies and half by universities to pursue Ph.D.'s (full-time), with the

[7] `http://www.modelica.org`

benefits of bringing more understanding of real-world problems to the university and transferring the latest developments back to industry. In addition, industry leaders and executives from the control community should continue to interact with the community and help communicate the needs of their constituencies.

The NSF/CSS workshop also recognized the important role that industry plays and recommended that educators and funding organizations

> encourage the development of WWW-based initiatives for technical information dissemination to industrial users of control systems and encourage the transfer of practical industrial experience to the classroom [1].

The further recommended that cooperative efforts between academia and industry, especially in terms of educational matters, be significantly expanded.

The International Federation of Automatic Control (IFAC) is creating a collection of IFAC Professional Briefs. These Professional Briefs are aimed at a readership of general professional control engineers (industrial and academic), rather than specialist researchers. The briefs provide an introduction and overview of a "hot topic," illustrative results, and a sketch of the underlying theory, with special attention given to providing information sources such as useful Internet sites, books, papers, etc. Eight titles have been selected to launch the Professional Briefs series:

Computer Controlled Systems
PID Auto-Tuning
Control of Biotechnological Processes
Control Busses and Standards
Physical-Based Modeling of Mechatronic Systems
Genetic Algorithms in Control Systems Engineering
Low Cost Automation in Manufacturing
Engineering Dependable Industrial Real-Time Software.

Another avenue for interaction with industry is through the national laboratories. In the United States, many government laboratories have summer faculty programs and student internships. Extended visits serve not only to transfer ideas and technology from research to application, but also provide a mechanism for understanding problem areas of importance to the government and the military. The U. S. Air Force Research Laboratory has been particularly active in bringing in visitors from universities and provides an example of successful interchange of this kind

Finally, there are many opportunities for control researchers to participate in government service. This can range from serving on review committees and advisory boards to serving as a program manager at a funding agency. Active participation by the control community is essential for building understanding and support of the role of control.