Chapter 5

Recommendations

Control continues to be a field rich in opportunities. In order to realize these opportunities, it is important that the next generation of control researchers receive the support required to develop new tools and techniques, explore new application areas, and reach out to new audiences. Toward this end, the Panel developed five major recommendations for accelerating the impact of control.

5.1 Integrated Control, Computation, Communications

Inexpensive and ubiquitous sensing, communications, and computation will be a major enabler for new applications of control to large-scale, complex systems. Research in control over networks, control of networks, and design of safety critical, large-scale interconnected systems will generate many new research issues and theoretical challenges. A key feature of these systems is their robust yet fragile behavior, with cascade failures leading to large disruptions in performance.

A significant challenge will be to bring together the diverse research communities in control, computer science, and communications in order to build the unified theory required to make progress in this area. Joint research by these communities will be much more team-based and will likely involve groups of domain experts working on common problems, in addition to individual investigator-based projects.

To realize the opportunities in this area, the Panel recommends that government agencies and the control community

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

In the United States, the Department of Defense has already made substantial investment in this area through the Multidisciplinary University Research Initiative (MURI) program and this trend should be continued. It will be important to create larger, multidisciplinary centers that join control, computer science, and communications and to train engineers and researchers who are knowledgeable in these areas.

Industry involvement will be critical for the eventual success of this integrated effort and universities should begin to seek partnerships with relevant companies. Examples include manufacturers of air traffic control hardware and software, and manufacturers of networking equipment.

The benefits of increased research in integrated control, communications, and computing will be seen in our transportation systems (air, automotive, and rail), our communications networks (wired, wireless, and cellular), and enterprise-wide operations and supply networks (electrical power, manufacturing, service and repair).

5.2 Control of Complex Decision Systems

The role of logic and decision making in control systems is becoming an increasingly large portion of modern control systems. This decision making includes not only traditional logical branching based on system conditions, but higher levels of abstract reasoning using high level languages. These problems have traditionally been in the domain of the artificial intelligence (AI) community, but the increasing role of dynamics, robustness, and interconnection in many applications points to a clear need for participation by the control community as well.

A parallel trend is the use of control in very large scale systems, such as logistics and supply chains for entire enterprises. These systems involve decision making for very large, very heterogeneous systems where new protocols are required for determining resource allocations in the face of an uncertain future. Although models will be central to analyzing and designing such systems, these models (and the subsequent control mechanisms) must be scalable to *very* large systems, with millions of elements that are themselves as complicated as the systems we currently control on a routine basis.

To tackle these problems, the Panel recommends that government agencies and the control community

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

The extension of control beyond its traditional roots in differential equations is an area that the control community has been involved in for many years and it is clear that some new ideas are needed. Effective frameworks for analyzing and designing systems of this form have not yet been fully developed and the control community must get involved in this class of applications in order to understand how to formulate the problem.

A useful technique may be the development of experimental testbeds to explore new ideas. In the military arena, these testbeds could consist of collections of unmanned vehicles (air, land, sea and space), operating in conjunction with human partners and adversaries. In the commercial sector, service robots and personal assistants may be a fruitful area for exploration. And in a university setting, the emergence of robotic competitions is an interesting trend that control researchers should explore as a mechanism for developing new paradigms and tools. In all of these cases, stronger links with the AI community should be explored, since that community is currently at the forefront of many of these applications.

The benefits of research in this area include replacing *ad hoc* design methods by systematic techniques to develop much more reliable and maintainable decision systems. It will also lead to more efficient and autonomous enterprise-wide systems and, in the military domain, provide new alternatives for defense that minimize the risk of human life.

5.3 High-Risk, Long-Range Applications of Control

The potential application areas for control are increasing rapidly as advances in science and technology develop new understanding of the importance of feedback, and new sensors and actuators allow manipulation of heretofore unimagined detail. To discover and exploit opportunities in these new domains, experts in control must actively participate in new areas of research outside of their traditional roots. At the same time, mechanisms must be put in place to educate domain experts about control, to allow a fuller dialog, and to accelerate the uses of control across the enormous number of possible applications.

In addition, many applications will require new paradigms for thinking about control. For example, the traditional notions of signals that encode information through amplitude and phase relationships may need to be extended to allow the study of systems where pulse trains or biochemical "signals" are used to trace information.

One of the opportunities in many of these domains is to export (and expand) the framework for systems-oriented modeling that has been developed in control. The tools that have been developed for aggregation and hierarchical modeling can be important in many systems where complex phenomena must be understood. The tools in control are among the most sophisticated available, particularly with respect to uncertainty management.

To realize some of these opportunities, the Panel recommends that government agencies and the control community

> **Explore high-risk, long-range applications of control to new domains such as nanotechnology, quantum mechanics, electromagnetics, biology, and environmental science.**

A challenge in exploring new areas is that experts in two (or more) fields must come together, which is often difficult under mainly discipline-based funding constructs. There are a variety of mechanisms that might be used to do this, including dual investigator funding through control programs that pay for biologists, physicists, and others to work on problems side-by-side with control researchers. Similarly, funding agencies should broaden the funding of science and technology to include funding of the control community through domain-specific programs.

Another need is to establish "meeting places" where control researchers can join with new communities and each can develop an understanding of the principles and tools of the other. This could include focused workshops of a week or more to explore control applications in new domains or 4–6 week short courses on control that are tuned to a specific applications area, with tutorials in that application area as well.

At universities, new materials are needed to teach non-experts who want to learn about control. Universities should also consider dual appointments between science and engineering departments that recognize the broad nature of control and the need for control to not be confined to a single disciplinary area. Cross-disciplinary centers (such as the CCEC at UC Santa Barbara) and programs in control (such as the CDS program at Caltech) are natural locations for joint appointments and can act as a catalyst for getting into new areas of control by attracting funding and students outside of traditional disciplines.

There are many areas ripe for the application of control and increased activity in new domains will accelerate the use of control and enable new advances and insights. In many of these new application areas, the systems approach championed by the control community has yet to be applied, but it will be required for eventual engineering applications. Perhaps more important, control has the opportunity to revolutionize other fields, especially those where the systems are complicated and difficult to understand. Of course, these problems are extremely hard and many previous attempts have not always been successful, but the opportunities are great and we must continue to strive to move forward.

5.4 Support for Theory and Interaction with Mathematics

A core strength of control has been its respect for and effective use of theory, as well as contributions to mathematics driven by control problems. Rigor is a trademark of the community and one that has been key to many of its successes. Continued interaction with mathematics and support for theory is even more important as the applications for control become more complex and more diverse.

An ongoing need is making the existing knowledge base more compact so that the field can continue to grow. Integrating previous results and providing a more unified structure for understanding and applying those results is necessary in any field and has happened many times in the history of control. This process must be continuously pursued and requires steady support for theoreticians working on solidifying the foundations of control. Control experts also need to expand the applications base by having the appropriate level of abstraction to identify new applications of existing theory.

To ensure the continued health of the field, the Panel recommends that the community and funding agencies

> **Maintain support for theory and interaction with mathematics, broadly interpreted.**

Some possible areas of interaction include dynamical systems, graph theory, combinatorics, complexity theory, queuing theory, statistics, etc. Additional perspectives on the interaction of control and mathematics can be found in a recent survey article by Brockett [11].

A key need is to identify and provide funding mechanisms for people to work on core theory. The proliferation of multi-disciplinary, multi-university programs have supported many worthwhile projects, but they potentially threaten the base of individual investigators who are working on the theory that is required for future success. It is important to leave room for theorists on these applications-oriented projects and to better articulate the successes of the past so that support for the theory is appreciated. Program managers should support a balanced portfolio of applications, computation, and theory, with clear articulation of the importance of long term, theoretical results.

The linkage of control with mathematics should also be increased, perhaps through new centers and programs. Funding agencies should consider funding national institutes for control science that would engage the mathematics community, and existing institutes in mathematics should be encouraged to sponsor year-long programs on control, dynamics, and systems.

The benefits of this investment in theory will be a systematic design methodology for building complex systems and rigorous training for the next generation of researchers and engineers.

5.5 New Approaches to Education and Outreach

As many of the recommendations above indicate, applications of control are expanding and this is placing new demands on education. The community must continue to unify and compact the knowledge base by integrating materials and frameworks from the past 40 years. As important, material must be made more accessible to a broad range of potential users, well beyond the traditional base of engineering science students and practitioners. This includes new uses of control by computer scientists, biologists, physicists, and medical researchers. The technical background of these constituencies is often very different than traditional engineering disciplines and will require new approaches to education.

The Panel believes that control principles are now a required part of any educated scientist's or engineer's background and we recommend that the community and funding agencies

> **Invest in new approaches to education and outreach for the dissemination of control concepts and tools to non-traditional audiences.**

As a first step toward implementing this recommendation, new courses and textbooks should be developed for both experts and non-experts. Control should also be made a *required* part of engineering and science curricula at major universities, including not only mechanical, electrical, chemical, and aerospace engineering, but also computer science, applied physics, and bioengineering. It is also important that these courses emphasize the *principles* of control rather than simply providing tools that can be used in a given domain.

An important element of education and outreach is the continued use of experiments and the development of new laboratories and software tools. These are much easier to do than ever before and also more important. Laboratories and software tools should be integrated into the curriculum, including moving beyond their current use in introductory control courses to increased use in advanced (graduate) course work. The importance of software cannot be overemphasized, both in terms of design tools (e. g., MATLAB toolboxes) and implementation (real-time algorithms).

Increased interaction with industry in education is another important step. 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 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.

Additional steps to be taken include the development of new teaching materials that can be used to broadly educate the public about control. This might include chapters on control in high school textbooks in biology, mathematics, and physics or a multimedia CDROM that describes the history, principles, successes, and tools for control. Popular books that explain the principles of feedback, or perhaps a "cartoon book" on control should be considered. The upcoming IFAC Professional Briefs for use in industry are also an important avenue for education.

The benefits of reaching out to broader communities will be an increased awareness of the usefulness of control, and acceleration of the benefits of control through broader use of its principles and tools. The use of rigorous design principles will result in safer systems, shorter development times, and more transparent understanding of key systems issues.

5.6 Concluding Remarks

The field of control has a rich history and a strong record of success and impact in commercial, military, and scientific applications. The tradition of rigorous use of mathematics combined with strong interaction with applications has produced a set of tools that are used in a wide variety of technologies. The opportunities for future impact are even richer than those of the past, and the field is well positioned to expand its tools to apply to new areas and applications.

The pervasiveness of communications, computing and sensing will enable many new applications of control but will also require a substantial expansion of the current theory and tools. The control community must embrace new, information rich applications and generalize existing concepts to apply to systems at higher levels of decisions making. Combined with new, long-range areas that are opening up to control techniques, the next decade promises to be a fruitful one for the field.

The payoffs for investment in control research are substantial. They include the successful development of systems that operate reliably, efficiently, and robustly; new materials and devices that are made possible through advanced control of manufacturing processes; and increased understanding of physical and biological systems through the use of control principles. Perhaps most important is the continued development of individuals who embrace a systems perspective and provide technical leadership in modeling, analysis, design and testing of complex engineering systems.