Introduction and Summary

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The Impact of Control Technology

Control is everywhere. Aircraft and spacecraft, process plants and factories, homes and buildings, automobiles and trains, cellular telephones and networks . . . these and other complex systems are testament to the ubiquity of control technology. Some artifacts of modern times would simply not be possible without control. And for many others, substantial, even revolutionary, advances in their performance, safety, reliability, and affordability have been achieved as a result of the ingenuity and effort of control engineers and scientists.

The realized impact of control technology is matched—indeed, overmatched—by its anticipated future impact. Decades of successful applications have hardly exhausted the potential or vitality of the field. The number and size of control conferences and journals continue to grow, new societal imperatives highlight the importance of control, and investments in control technology and technologists are taking place in old and new industrial sectors. Control is not only considered instrumental for evolutionary improvements in today's products, solutions, and systems; it is also considered a fundamental enabling technology for realizing future visions and ambitions in emerging areas such as biomedicine, renewable energy, and critical infrastructures.

The increasing complexity of technological systems demands inter- and cross-disciplinary research and development. Collaborations between control and other fields have been consistently productive. In particular, in the course of these collaborations, a widening appreciation of the principles of control has been apparent. Wherever dynamics and feedback are involved—and they are increasingly recognized as pervasive properties of complex systems—control expertise is regarded as crucial. Control is also seen as the paragon of rigor and the systems perspective by experts in other disciplines, distinctions that are being exploited as larger-scale, safety-critical, and mission-critical systems are developed or envisioned.

But if control is everywhere in reality, it is also nowhere in perception. Despite its accomplishments and promise, control remains a "hidden technology" [1]. We can offer hypotheses for why this is the case—the value of control is in intangible algorithms, its rigor and formality are intimidating to the uninitiated, its applications and research are distributed across many scientific and engineering disciplines—but regardless, the fact remains that the breadth and scale of the impact of control are largely unknown and unheralded. Remarkably, this is true not only outside the controls community, but even within it!

Our motivation in preparing this report is to help rectify this lack of awareness by highlighting the to-date and to-come impact of control technology. To this end, we have included overviews of the applications of control systems to a number of domains, discussions of emerging research areas for the field, and summaries of specific control-related successes and challenges in industry and government. Each of these topics is covered in a separate part of the report.

Although the report includes sections on research directions for control theory, our principal focus is on the accomplishments and promise of control technology and not on laying out the theory road map for

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the field. In this sense, we consider this report as complementing, and not superseding, previous publications such as [2], which remains an excellent resource for the control research community.

Part 1: Application Domains for Control

The fundamentals of control science are universal, but the impact of control technology results from the combination of these fundamentals with application-specific considerations. The first part of the report consists of discussions of the role of control in both traditional and emerging application domains:

- Aerospace (C. Philippe et al.)
- Process industries (I. Craig et al.)
- Automotive (L. Glielmo et al.)
- Robotics (M. Spong and M. Fujita)
- Biological systems (F. Doyle et al.)
- Renewable energy and smart grids (E. Camacho et al.)

The material in these sections includes historical references, highlights from successful applications, economic and market information, and current and future challenges. Recommendations for research are also provided. We note that the above list of domains is hardly comprehensive; other important domains include buildings, railways, telecommunications, disk drives, and others.

Part 1 also includes two brief sections that offer integrative perspectives on control applications: K. Butts and A. Varga discuss control development processes and related tools and platforms, and G. Stewart and T. Samad discuss application-specific requirements and factors that are important for "real-world" control implementations.

Some general considerations stand out from the material in this part of the report:

- A few decades ago, discussion of the impact of control technology would have been limited to a few industries: aerospace systems, process plants, and homes and buildings. Today these traditional domains of control have been supplemented with a litany of others. The application domains represented here include ones where control has historically been prominent, ones that have embraced control technology relatively recently, and emerging domains that will, we expect, provide new opportunities for the field.

- In addition to the broadening of industry scope, control has also developed into a highly scalable technology. In multiple application areas, we have seen control principles initially being applied to individual sensors and actuators, then on multivariable systems, and even at plantwide scales. Ambitions now reach enterprise and "system of systems" levels.

- Successful applications of control are not the result of control expertise alone. In-depth domain knowledge has always been necessary. As the applications of control have broadened, the connections with traditional and new domains have been established and strengthened.

- Furthermore, technological prerequisites must be satisfied before control, especially advanced control, can be applied. Several new application areas have become viable for control as a result of developments in novel sensors and actuators, for example.

- Quantifying the impact of control technology is difficult. A control algorithm doesn't solve any problem in and of itself; the control innovation is linked with ancillary developments. In cases where economic or other societal benefits have been estimated, the results point to tremendous scale of impact [3].

Part 2: Success Stories in Control

After the broad application-oriented discussions in Part 1, the next part of the report highlights significant specific accomplishments of the field in a form intended for communication both within the controls community and with its stakeholders. The two-page flyers on "success stories" featured here were solicited from the controls community worldwide. The flyers include some technical details, but we have attempted, as far as possible without risking superficiality of treatment, to keep them accessible to a non-controls audience. Some documentation of societal/industrial benefit is included in all cases.

Examples from the content of Part 2 are:

- Mobile telephones rely on control—to the tune of billions of feedback loops across the globe.
- With antilock brakes and stability and traction control, automotive safety has been revolutionized by control technology.
- A mechanical control invention for automotive suspensions resulted in a win on its first use in Formula One.
- Advanced control is now widely implemented in devices like printers and copiers.
- Collision avoidance systems are well established in air traffic management and rely on estimation and control algorithms.
- Optimization and control technology implemented in railroads is reducing fuel consumption by tens of thousands of gallons per year, per locomotive.
- Paper machines manufacture paper whose thickness is controlled to within microns—over reels of paper that are often 40 km in length.
- Hundreds of ethylene processes are dynamically optimized with model predictive control techniques, resulting in over $1 million of increased production annually per plant.
- Warehouse operations are autonomously controlled by hundreds of mobile robots.
- Improved audio reproduction technology derived from control theory enhances perceptual quality by over 30% and is implemented in over 15 million integrated circuits.

These and the other success stories included are a small fraction of what has been achieved with control. Nevertheless, the significance and variety of these contributions is an indication of how extensive the true footprint of control is!

Part 3: Cross-Cutting Research Directions

We next move to the forward-looking content of the report. Part 3 consists of discussions of four topics of current research that are gaining increasing interest, both in the research community and for government investment. The topics covered are:

- Networked decision systems (M. Dahleh and M. Rinehart)
- Cyberphysical systems (R. Baheti and H. Gill)
- Cognitive control (M. Buss, S. Hirche, and T. Samad)
- Systems of systems (T. Samad and T. Parisini)

A few points of commonality among these topics are worth noting:

- The research required is interdisciplinary and multidisciplinary, an observation that emphasizes the critical need for the controls community to collaborate with other fields. Connections with computer science, other algorithmic fields such as information theory, and relatively new sources of inspiration such as cognitive science have been and are being established and need to be further promoted.

- Networks are pervasive. The term may only appear in one of the section titles, but it is implicit in the others. Centralized approaches are seen as being untenable for several reasons. Solution methods and architectures are increasingly distributed, decentralized, coordinated, and collaborative.

- In many situations, subsystems have high degrees of autonomy and heterogeneity. A continuing research imperative is to figure out how we can realize system-level goals for performance, predictability, stability, and other properties through appropriate system designs and subsystem interactions.

- These research directions are cross-cutting in the sense that each is relevant for a variety of challenges that are engaging industry, society, and government. Examples include smart grids, intelligent transportation systems, complex infrastructures, and emergency response teams. These and other examples are mentioned in multiple sections. Some overlap of concerns is unavoidable, but these themes highlight different facets of these complex needs.

- Although control systems have never been isolated components, the interconnections between control and other areas have not been fully explored in the past. This limitation is now being overcome. Interconnections and integration with real-time platforms, with humans as users and in other roles, and with other systems are points of focus.

Complexity is an overarching feature in this part of the report, but the themes provide color and specificity to this buzzword. The networked aspect is central, but it is a substrate and a metaphor. The complexity of control research is manifested in the integration and synthesis among controllers and optimizers, hardware and software components, humans and engineered intelligent agents, in more or less cooperative environments, with hierarchical and heterarchical structures, across physical domains that span most fields of engineering, representing spatial and temporal time scales ranging from the nano and micro to the mega and macro. The articles in Part 3 reflect these trends in control research.

Part 4: Grand Challenges for Control

Whereas Part 3 focuses on cross-application research themes, Part 4 outlines a set of exciting research opportunities in control that target domain-related challenges.

Analogous to Part 2, this part of the report also consists of two-page illustrated briefs. The focus here, however, is not on past accomplishments but on future opportunities. The close to 20 featured here demonstrate the expanding scope and scale of control. Examples of the featured challenges, for all of which control technology is a critical need, are:

- An artificial pancreas for treatment of diabetes is under development—control scientists are leading the effort.
- Control-enabled high-altitude wind energy devices have been demonstrated and promise efficiencies that are substantially higher than for today's turbines.
- Feedback and dynamics are essential for the development of smart grids—the smart grid can be considered an end-to-end optimization and control problem.
- Active control of unstable combustion phenomena will be essential for realizing higher efficiency and reliability and lower emissions in turbine engines.
- Next-generation air traffic control approaches are being developed with the objective of substantially reducing the energy use associated with air transportation.
- With successes in applying control to process units and even plantwide, industries are seeking to close the loop around entire supply chains.
- In automotive systems, vehicle-to-vehicle and vehicle-to-infrastructure coordination is projected to improve the efficiency and safety of road transportation.
- Advanced control is increasingly recognized as critical for achieving dramatic reductions in energy consumption in buildings.
- The ability of atomic force microscopes to image and manipulate matter at the nanometer scale is entirely dependent on the use of feedback loops.

Appendices

This report also includes two appendices: a brief account of the Berchtesgaden workshop and affiliations and e-mail addresses for the principal authors of the sections and flyers in this report.

Concluding Remarks

There's more to control technology than is typically appreciated—whether by its exponents, its beneficiaries, or others directly or indirectly associated with the field. Control has played an instrumental, if often behind the scenes, role in the development of engineering solutions to outstanding problems, resulting in substantial societal and industry impact. The report discusses the role of control in a number of prominent application domains and illustrates successes achieved in these domains and in others.

The report also highlights the fact that there is no dearth of opportunity for research in control. Control is flourishing as a research field unto itself and even more so as a keystone discipline for addressing multidisciplinary challenges. Evolving from and strengthened by a mature core focused on single systems, the new network-centric centers of gravity of control research, through productive interactions with other scientific disciplines and with an increasing number of application domains as targets, are demonstrating the power and advantage of the systems and control approach in new arenas.

We hope this report will help lift the veil on the "hidden technology" that control often seems to be. But this is not to say that we have exposed the impact of control in its entirety. Any artifact such as this report—a snapshot of success and opportunity in a dynamic and vibrant field—is inevitably incomplete. We suggest that as a Web-based resource, this report itself can be dynamic. . . . Additional success stories and grand challenges can conveniently be integrated, and new sections discussing application domains and research directions can be incorporated as well. We invite volunteers from the controls community to contribute to, and help lead, this effort.

References

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[3] J. Pereira (ed.). Monitoring and Control: Today's Market and Its Evolution till 2020. Luxembourg: Office for Official Publications of the European Communities, 2009.