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Control for Societal-Scale Challenges

ROAD MAP 2030

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The world faces some of the greatest challenges of modern times. How we address them will have a dramatic impact on society at large for generations to come. The field of control systems pertains to specific methods and principles to control dynamic systems and produce desired outcomes despite uncertainties in the system and in the environment. The development of these principles and methods has been both broad and deep, from aerospace systems and wireless networks to bioengineering and traffic control. These methods are deeply embedded in many sectors, including energy, transportation, health care, manufacturing, and robotics. With their advanced toolbox for understanding and designing feedback, robustness, dynamics, and decision making in complex systems, control systems have an opportunity to play a central role in the development of technologies and solutions for many of the key challenges that society faces.

The scope of applications of control systems has continuously increased over the past few decades. It has moved from feedback control of a single device or system to optimizing and making decisions in large-scale systems, systems of systems, and infrastructure systems. This impressive growth of scope and scale is supported and

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accompanied by large paradigm shifts in enabling technologies. Digital transformation has been all-pervasive, both enabling significant advances in mature engineering systems and introducing new concepts and computational constructs in nonengineering systems. This increased cyber footprint and related exponential advances in computational, communication, and actuation technologies have introduced the concept of automation into new domains and, in many cases, accelerated its implementation. Applications such as self-driving vehicles and automatic control of aerial robots have entered the social lexicon and captured the imagination of the general population. Automation not only underpins these applications but is also being introduced into a host of other domains. All of these advances and transformations have set the stage for the creation of the document "Control for Societal-Scale Challenges: Road Map 2030" [1].

The initiative to develop this road map on control for societal-scale challenges was taken by us more than two years ago. In 2019, discussions began in the IEEE Control Systems Society (CSS) Executive Committee about the need for a document delivering a broad picture of how control systems can effectively address societal challenges. The three of us joined forces and together organized two workshops, one held virtually in June 2021 and another in Stockholm in June 2022, both of which focused on the topic of *Control for Societal-Scale Challenges*. On both days, the first half of the day was an open session attended by about 300 people worldwide. The second half of each day was dedicated to creating the road map. The open sessions consisted of six panels organized around a range of topics, including safety-critical autonomous systems, resilient infrastructure systems with artificial intelligence (AI) and the Internet of Things, decision making with real-time and distributed data, control with human-in-the-loop, control for climate change mitigation and adaptation, and education and training. About six panelists participated in each panel, with presentations focused on the topic at hand, the role of control, the underlying challenges, barriers to entry, and the potential societal challenges that this topic will impact. The topics were expanded on and organized around suitable headings, setting the stage for the writing of the road map. Gaps and overlaps were identified over subsequent months, and steps were taken to allow better exposition and more comprehensive coverage of the major topics.

Over the following 12 months, regular conversations were organized to brainstorm the overall structure of the road map. This brainstorming included an appropriate classification of topics to suitably capture the major societal challenges to be presented in the road map. An overall structure emerged, with about six to seven chapters, spanning societal drivers, technological trends, key methodologies, technology transition, and education and training. The road map shows how main control methodologies can be brought to bear on the societal drivers of global challenges and the emerging technologies that can help address and potentially mitigate these challenges.

In addition to discussing drivers, challenges, and methodologies, the road map also addresses the transition from control research to products and solutions in various application domains. Considerations and pathways for technology transfer, understanding barriers and roadblocks in various application domains, and the cost-benefit of automation and other control solutions are articulated.

Readers will note that the title of this document specifies the year 2030. As this target is only eight years away from the time of writing, the time horizon for the methods outlined in this chapter is not that far away. We have chosen 2030 to emphasize that many of the glide paths that we need to embark on to meet the global challenges should be created to meet this time frame. An additional point to note is that in many of these cases, whether they concern realizing a high penetration of renewables, the aggressive reduction of greenhouse gas emissions, or phasing out internal-combustion engine-based automobiles, the year 2030 figures prominently as the milestone for achieving the desired targets. We have therefore chosen this year as the focus for advancing and transitioning the requisite control systems technologies.

A few details regarding the structure of this road map follow. In Chapter 2, we examine a few major societal challenges that face the world in the 21st century. The first of those challenges is climate change, a problem of increasing urgency that we are continuously exposed to. Health-care issues that affect the quality of life are next addressed. Infrastructure systems that provide fundamental services such as energy, water, and transportation are discussed, especially the impact of digitalization and empowered consumers. As we proceed deeper into the 21st century and resources become scarce, new concepts of resource sharing (including the sharing economy) are shaping society, and these are also discussed. Finally, concerns about global security and risks that affect the socioeconomic landscape are delineated.

In Chapter 3, we outline emerging technological trends that support a large fraction of the efforts of the scientific community at large. These include biological engineering, robotics in the real world, large-scale electrification, and

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the roles of AI and big data. Each one of these trends presents a range of opportunities for the control systems community to play a role in addressing and mitigating the societal challenges presented in Chapter 2.

Meeting the challenges and opportunities presented in Chapters 2 and 3 requires new methodologies in control systems, some of which are outlined in Chapter 4. These include learning- and data-driven approaches, methods for safety-critical systems, methods for resilience, the analysis and synthesis of cyberphysical-human systems, and novel control architectures. In each case, the near-term and far-term challenges associated with each of these methods are outlined.

Chapter 5 articulates the need for a validation infrastructure to illustrate the performance of new control methods and demonstrate their impact. This chapter also points out the importance of engaging industry and the public sector in the overall conversation of advanced control technologies and their tangible benefits in various applications. The important problem of bridging the gap between industrial needs and economic and financial expectations on the one hand and relevant and significant research advances on the other is addressed.

Recognizing that education is the cornerstone for the growth and prosperity of the field of control systems, Chapter 6 discusses university curriculum changes. It provides specific suggestions on what concepts and methodologies should be emphasized and how to adapt to a new generation of students. Finally, in Chapter 7, we emphasize that the control systems community has an important role to play in future technology designs that respect human rights and human values, ensure ethics and fairness, and meet regulatory guidelines while safeguarding our environment and our natural resources.

Also included as appendices are details associated with some of the societal drivers. Visuals are provided throughout the document to highlight key ideas and underlying concepts. References are listed at the end of each chapter for further reading.

While we believe the road map will be of strong and broad interest to many individuals and organizations, we have prepared it with two principal audiences in mind.

1) The first principal audience is young researchers who are in a nascent stage in their careers. We want to draw their attention to open and important problems that can lead to significant breakthroughs.
2) The second principal audience consists of funding agencies. We want to underscore the need for support to develop methodologies that can lead to groundbreaking results and can be transitioned to societal-scale systems.

We have made every effort to include all major imperatives that will shape the research directions that the control systems community engages in. An effort is also made to outline a few other directions that our community ought to engage in, such as ethics, fairness, socially responsible automation, and intersections with regulatory agencies and policymakers.

Finally, we would like to express our deepest appreciation for the commitment and dedication of all our colleagues who contributed to the road map and the activities that led up to it and who reviewed various versions of it. We are grateful to the leadership of the CSS for launching this initiative and supporting it from the beginning. Without the significant financial funding from the CSS, IFAC, U.S. National Science Foundation, and Digital Futures, this project simply would not have been possible to execute. Most importantly, we are indebted to Amritam Das and Angela Fontan, who tirelessly, unfailingly, and cheerfully carried out innumerable editorial and organizational tasks. Our sincere thanks go to all of these individuals and organizations.

We would like to emphasize that this entire road map exercise has been a community effort, with significant and focused contributions from various leaders in the community as well as inputs from the community at large. This information was gathered through open invitations to articulate grand visions and broad roles in which the control systems community could participate. We hope that this road map is one of many such community-driven strategic plans that may follow. Our ultimate goal is that this road map will provide guidelines for participation in the overall scientific endeavor to develop methods for the betterment of humanity.

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REFERENCE

[1] A. M. Annaswamy, K. H. Johansson, and G. J. Pappas, Eds., "Control for societal-scale challenges: Road map 2030," *IEEE Control Syst. Soc.*, 2023. [Online]. Available: http://ieeecss.org/post/control-societal-scale-challenges-roadmap-2030

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