Future Directions in Control

Surveys such as [1] provide an excellent resource for researchers looking to branch into new research fields and/or obtain insights on the key technology challenges in the areas in which they are already working. The report is the latest in a series of studies about the *future directions in control*, which includes an early analysis [2], the detailed reports stemming from a 2002–2003 panel discussion [3], [4], numerous technical articles [5]–[7], the in-depth analysis of the impact of control technology [9], and the 2016 Bode Lecture [10]. (Note that while I contributed to both [1] and [3], I am not considered an author of those reports.)

With 64 journal pages, [1] is an extensive report that identifies five societal challenges and seven crosscutting research and innovation challenges and provides numerous operational recommendations. The societal challenges are in the domains of transportation, energy, water, health care, and manufacturing, which is a similar list to [3] and [4]. However, there are several important distinctions.

In particular, water represents a very important addition to the list of societal challenges because population growth is leading to *water stress*. The result is that the "outlook for water sustainability is therefore grim" [1, p. 10]. Apart from generating more supply through better desalination, systems and control ideas can also help ease the stress through "measure—model—manage." This framework includes expanding and (possibly) reducing the cost of precision farming, improving the efficiency of irrigation techniques, improving water productivity by delivering water "on demand" according to crop needs, and using water-level measurements and models to enable markets of water reserves. Decentralized and distributed control strategies will likely be needed, given the large distances and scale of the systems. Cost will be a key factor in selecting the sensors and actuators, given the large number of devices that are necessary. Thus, the control design techniques must address the limitations in these devices and the communication networks used to support them.

The section on transportation broadens the previous discussions to include approaches that increase mobility for passengers and freight, while reducing the potential negative effects, such as congestion and environmental impacts. Of course, safety and automated/connected transportation systems play a prominent role in the conversation, with the associated need for improved verification tools and advances in cybersecurity. The discussion on energy highlights the control challenges associated with the *smart grid*, which has been a paradigm shift in how power is delivered to the end user. This includes dynamic market mechanisms integrated with real-time decision making and the creation of flexible demand-response capabilities. The modeling and control frameworks must be able to account for the uncertainties in the user demand and available supply (for example, from wind and solar farms). Reference [1] highlights that many current practices in electricity markets are suboptimal solutions to stochastic, multistage, dynamic programming problems, which suggests that there are opportunities to provide substantially improved solutions. However, a key challenge will be the adoption of these solutions to ensure sufficient performance gains and robustness of the approaches.

The health-care discussion in [1] has a different focus than [3] and [4], with less emphasis on biological networks (although Figure 19 in [1] appears in [3] as well). Instead, [1] concentrates more on disease research (modeling and analysis), which is described as "a new frontier" for systems and control science. Control of assistive devices is also discussed in detail, with the high degree of model uncertainty leading to many design challenges for these systems. The area of assistive devices is an exciting one because the societal impact of the work is clear, and there are numerous technical challenges to address. However, [1] cautions that "user acceptability" must be a

A subset of the *IEEE Control Systems Magazine* Editorial Board at the 2017 American Control Conference (from left): Behcet Acikmese, Yildiray Yildiz, Jonathan How, Francesco Borrelli, and Antonella Ferrara.

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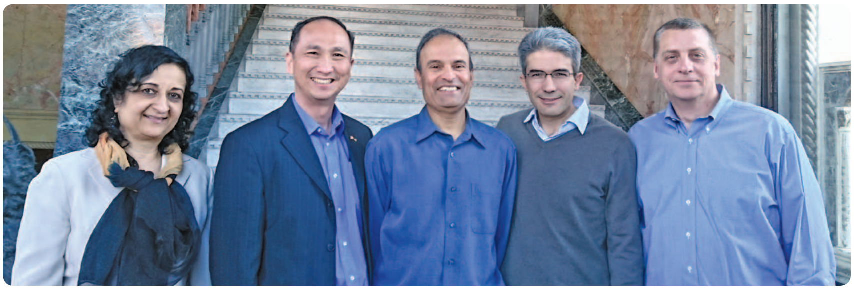
key part of the solution, and thus this research must "incorporate elements from the arts as well as the sciences" [1]. This sounds like very wise advice.

It is interesting to note that, while [4] discusses the future of control education at length and listed "invest in new approaches to education and outreach for the dissemination of control concepts and tools to non-traditional audiences" as one of its five major recommendations, [1] says very little on this topic. This is unfortunate because there are many issues to be addressed in determining how to effectively teach courses, such as control systems, that often have hands-on components in this new era of online classes and distance learning.

The seven technical challenges highlighted in [1] emphasize autonomy, complexity, cyberphysical systems (with and without humans in the loop), and data-driven systems. Like [3] and [4], there is a detailed discussion of the control of distributed network systems. However, it was interesting to see a discussion on improving the optimality of the networked performance through the *codesign* of both the control algorithms and networking protocols [1, p. 15]. This interest stems from my work with wireless mesh networking for multiagent systems that are attempting to coordinate plans and/or fuse their onboard measurements to develop a more coherent situational awareness. Hardware experiments on realistic communication hardware have shown that commonly used algorithms, such as consensus, place a significant burden on the communication network. Efforts to co-(re)design the algorithm and protocol could lead to much better overall performance as the bandwidth requirements of networked systems increase in the future.

As noted previously, the application domains are broad and the systems discussed are complex. For control research to have a large impact, that complexity will likely require less emphasis in the control community on mathematical theory applied to abstract models but, instead, more emphasis on dealing with the realities (nonlinearity, noise, modeling errors/uncertainty) of the systems under control. The system complexity could also require a larger focus on the design to meet performance goals, using tools such as online optimization, rather than just proving stability. As a famous researcher in the field recently said to me, "for many systems of interest, stability is overrated."



Members of the IEEE Control Systems Society Executive Committee relaxing after a hard day of meetings in Venice, Italy (from left): Anuradha Annaswamy, Edwin Chong, Venkataramanan Balakrishnan, Francesco Bullo, and Jonathan How. (Image courtesy of Li-Chen Fu.)

Progress in these complex problems will also typically require that control engineers form close collaborations with domain experts to "overcome the barriers between traditional disciplines" [1, p. 62]. That step requires learning how to be an effective teammate and interact with members of a new community to contribute in meaningful ways. I learned many of these lessons when I started to work with a large group of physicists on the isolation design for the LIGO project.

As a fresh graduate of MIT, I was full of what I thought were good ideas on multi-input, multi-output robust/optimal control solutions, but I quickly realized that the approach offered relatively small performance gains over a precision structural design coupled with nested single-input, single-output loops, while greatly increasing overall system complexity. I listened, adapted, and then identified ways to contribute. That took several years of working closely with the group of physicists who, it turns out, included some of the best control engineers I have ever met.

Addressing these interaction challenges will be crucial to ensure that the right technical challenges are being solved and that, when the solutions are created, they can be deployed and will be adopted. Identifying a new, important application area and spending the time to immerse yourself deeply enough in it that you can work fluidly with the domain experts represent the real future directions in the systems and control field.

As always, I look forward to your feedback on this topic.

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