Annual Reviews in Control 49 (2020) 1–14

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Industry engagement with control research: Perspective and messages

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ARTICLE INFO

Article history:
Received 6 February 2020
Accepted 26 March 2020
Available online 23 May 2020

Keywords:
Advanced control
Industrial applications
Theory/practice gap
IFAC Industry Committee
Process control
Aerospace control
Automotive control
Biomedical control
Control education

ABSTRACT

Despite the enormous benefit that has accrued to society from control technology and the continued vitality of control science as a research field, there is broad consensus that the practitioners of control and the academic research community are insufficiently engaged with each other. We explore this concern with reference to the oft-cited theory/practice gap but also from an industry perspective. The core of this article is comprised of ten “messages,” intended primarily for researchers interested in the practical impact of their work, that we hope shed insight on the industry mindset. Results from surveys and other data are cited to underpin the points. Some educational synergies between industry and academia are also noted. To highlight the continuing relevance of control science to industry, several recent examples of successful, deployed advanced control solutions are presented. The authors of this article are members of the IFAC Industry Committee, formally established in 2017 with objectives that include (per the updated IFAC Constitution) “increasing industry participation in and impact from IFAC activities.”

1. Introduction

The field of systems and control has been remarkably successful, in both its research accomplishments and its practical impact. We have seen sustained growth in publications and conferences over the past several decades, and, today, it's hard to point to an engineered device or system in modern life that does not have a footprint of control—even if that footprint may be hidden from the casual observer. In both aspects, the future is bright too. Grand challenges and hot topics such as renewable energy, self-driving cars, clean air and water, personalized medicine, autonomous robots, large-scale satellite constellations, urban air mobility, and smart manufacturing will all require advanced control for their realization. On the theoretical front, new topics continue to keep the field vital; examples include cooperative and distributed control, distributed parameter systems, learning control, constrained and optimization-based control, human-in-the-loop systems, networked control systems, and game theory (Lamnabhi-Lagarrigue et al., 2017).

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https://doi.org/10.1016/j.arcontrol.2020.03.002

Table 1
Summary Data for the IFAC Industry Committee.

Membership (Oct. 2019)	95
Affiliation	Industry: 52; Academia: 37; Government: 4; Retired: 2
Geographic distribution	Europe: 45; N. America: 25; Asia-Pacific: 14; C./S. America: 6; Africa: 5
Countries with the highest representation	US: 23; Germany: 7; Australia and Netherlands: 5 each; China, Czech Republic, Spain, Japan, and South Africa: 4 each
Workstreams (5)	• Industry/Academia/Government Collaboration • Industry Engagement in IFAC TCs and Events • Gleaning the Voice of the Industry • Educating Control Engineers for Industry Roles • Industry Committee Communication

And yet, within the control community and especially its research constituency, a long-standing sense of a problem persists. Under labels of the theory-practice gap, transition to practice, and technology transfer, papers are being written, conference sessions organized, funding initiatives launched, and community souls searched. This concern has also led to stakeholder groups chartering task forces and committees to investigate the issues, to better understand and ultimately ameliorate them. Such objectives and charges are nebulous and complex; there are no silver bullets.

In 2017, the International Federation of Automatic Control (IFAC), established an Industry Committee. According to the constitutional change enacted for this purpose, the objectives of the Industry Committee “include increasing industry participation in and impact from IFAC activities.” The conjunction refers to a bidirectional influence: IFAC events, publications, and governance lack the voice of the industry, to the detriment of the organization’s achievements; and industry stands to benefit from what IFAC has to offer to a significantly greater extent than is being accomplished today. The establishment of a permanent Industry Committee that reports to the IFAC Council was presaged by a Task Force, chaired by Roger Goodall who was then on the IFAC Council, and a “pilot” phase of the committee that laid the groundwork for the eventual enshrinement of the new group within the institution.

The Industry Committee, chaired by the first author, has been constituted through a number of sources. IFAC National Member Organization (NMOs) and Technical Committees (TCs) were asked to nominate members and current Industry Committee members (from the original Task Force and the “pilot” phase) have also suggested additions. At the time of this writing, the membership includes 95 individuals. Some statistics are listed in Table 1. As can be seen, more than half the membership is currently affiliated with industry. The majority of the rest have had significant careers (decades-long in several cases) in industry. In terms of industry sector coverage, the process industries, aerospace, and automotive are the most prominent (in that order) and all have double-digit representation. Many members have also worked in other sectors—biomedical devices, mechatronic systems, finance, agriculture, buildings, marine, railways, power and energy, etc.

Five workstreams have been set up under the Industry Committee, each tasked with a specific aspect of industry engagement in IFAC and the research community. In addition to reports and presentations, the workstreams are also conducting surveys—and other surveys have been conducted by the Industry Committee itself. Results from some of these surveys are reported in this article.

In the rest of this article, we first briefly discuss the “theory/practice gap” in control, identifying a few reasons why the gap is more prominent in control than in most other disciplines. We then explore the state of control research, attempting to pin down the crux of the problem . The centerpiece of this article is a set of “messages,” primarily for control researchers and prepared with the intent of enhancing the awareness in the research community of several crucial issues related to control applications and deployments in industry. Next, we present a few capsule summaries of successful applications of advanced control technology. These are taken from diverse industry sectors and employ a variety of control technologies. Before concluding we note three “caveats”: that addressing industry needs is by no means all that control research is, or should be, about; that maintaining the standards of rigor and analytical thinking is a defining feature of our field and one we should not discard in the interests of following the latest fads; and that in focusing on research collaborations we should not overlook education. As may be apparent, our primary audience is the control research community. However, we hope that practitioners and educators will also benefit from what we have to say.

Before we delve into the theory-versus-practice discussion, a couple of additional remarks are in order. First, there is one additional, related lacuna that we also hope to bridge in this article. Successful applications require more than matching application needs with technology developments: A knowledge gap also exists between the research community and industry per se. Numerous considerations arise in corporate settings in the context of commercialization of applications: market size and growth, competition and market share, development and deployment processes, capital and operational expenditures, revenues and margins, supply chains and value chains, return on investment, intellectual property rights, distribution channels, customer segmentation, business strategy, and others. Such issues are part of the “industry perspective,” as distinct from an “application perspective,” and they must be considered for successful, sustainable, and at-scale products and services. Although we do not cover all these complexities here, this article attempts to introduce the research community to industry considerations that substantially influence technology transfer, productization, and commercialization decisions.

Second, a cautionary note: Drawing categorical distinctions such as researchers/engineers, industrialists/academics, and theory/practice can result in exaggerating differences among communities that share many of the same objectives and perspectives. Indeed, many faculty members in universities have contributed to commercial success stories, through consulting and other industry collaborations and entrepreneurial ventures. Similarly, we know of many industry practitioners who follow research developments—and even contribute to them by collaborating on models, facilitating demonstrations and pilots, and providing data from production systems. And although “pure” research has its exponents too—we do not gainsay research for the sake of expanding knowledge, as also noted later—most controls researchers are interested in ultimately transitioning their work to the practical realm. Even as we discuss differences and disconnects, the reader should keep in mind that control is a broad engineering science. Its holistic breadth, scientific rigor, pervasive applications, and fundamental insights that connect theory and practice distinguish it from many other disciplines. We seek improvements to the community that will benefit all its stakeholders and build crossroads for, not walls within, its constituents.

2. The theory/practice gap in control science and engineering

The gap between research and practitioner communities has been a topic of much debate, especially by the former side of the divide. In control systems, the discussion can be traced to at least (Foss, 1973), who, writing in the context of process control, stated that, “Indeed, the theory of chemical process control has some rugged terrain to traverse before it meets the needs of those who would apply it.” Several papers and articles have subsequently been written as well, including in a special section of the *IEEE Control Systems Magazine* issue of December, 1999 devoted to the theory-practice gap (Bernstein, 1999; Joshi, 1999; Ridgely & McFarland, 1999; Ting, 1999) and elsewhere (Astrom & Kumar, 2014; Bay, 2003; Blondel et al., 1995; Samad, 1997; Samad & Stewart, 2013; Sánchez-Peña, Quevedo Casín, & Puig Cayuela, 2007). A summary of a forum on the topic at the 2004 American Control Conference appears in (Gao & Rhinehart, 2004).

Although by no means limited to control, the issue may be especially prominent in our field. A few reasons come to mind for why this could be the case. First, expertise in control requires the understanding of a deep and extensive base of abstract theory. Even though control is mostly taught in engineering departments, research in the area is often as much research in applied mathematics as engineering. (For example, the list of Activity Groups in the Society for Industrial and Applied Mathematics [SIAM] includes “Systems and Control Theory” along with numerous topics more specifically related to mathematics.)

A related point is that control is relevant across a breadth of application domains and industry sectors that is truly remarkable. This otherwise commendable fact has a corollary that expertise and education in control theory tends to be divorced from detailed exposure to specific applications or even classes of applications, at least in terms of real-world technology. Inverted pendula and stirred tank reactors are the simulation and laboratory test beds of choice, but a control course that is intended for students across all engineering disciplines cannot afford the time to investigate details of control implementations in chemical plants and automobiles. A combination of deep domain expertise in the application at hand with control expertise is required in order to achieve truly innovative and leading solutions. (This often means that control solutions are derived through teamwork, which is perhaps the most natural bridge to cross the gap between theory and practice.)

In the words of Karl Åström, control is a “hidden technology” (Åström, 1999). Control expertise is manifested in engineered artifacts at all scales, from microelectromechanical devices to power grids and the global internet, but it is not apparent to the observers of the systems. Even in cases where control actions are visible, such as a robot manipulator, it is easy to overlook the fact that the precise mechanical movements are enabled by the dynamic manipulation of information, and that without this algorithmic element the sensors and actuators and materials of the machine would be useless. We may also note that the control algorithm itself is a substantial intellectual challenge that isn’t readily appreciated by the general public, whose understanding of feedback has little if anything in common with the feedback control of complex dynamical engineered systems.

Finally, a broader interpretation of the theory/practice-gap bromide is warranted, particularly for industry/academia collaboration. A disconnect exists not just in research but also in education. Both stakeholder groups have a role to play in addressing this divide too. Industry’s participation in research projects with academia can convey the former party’s priorities for education in that process, and academia, for its part, needs to keep its educational mission in mind in its research with industry partners. We will continue to focus on research interactions in the rest of this article, with educational implications briefly noted as well.

3. The state of control research and innovation—is there a problem?

The above remarks may suggest a discipline that is struggling for recognition and viability outside of ivy-covered walls, or that the state of industry applications is stagnant, but such impressions would be mistaken. Major conferences in control research are thriving, with consistent increases in papers published (see Fig. 1, other major control conferences have also seen similar growth); the number of journals in control is steadily increasing; and research funding has apparently been available to fuel these indicators of progress. By these measures, the field is healthy—although it should be noted that conference participation has been growing globally in most research communities (Van Dooren, 2014).

For investigating whether industry is investing in control system innovation, it is important to find diverse metrics. Involvement with the scientific community and the publishing of technical papers alone may not provide a comprehensive picture because neither of those activities usually provides a direct return to the companies. An alternative, quantifiable, and industry-focused way to track company investments in control system innovations are patent portfolios.

Patents are filed to protect innovations for the company’s new technologies and products as well as for other reasons. Searching in a patent database for published patents containing the words “control system” in titles, abstracts, or claims, over the period from January 1, 1998 to December 31, 2017, across the world patent offices, provides the results shown in Fig. 2. As can be seen, over the years the number of control-related patents has grown significantly, with an initial-to-final ratio of 7.60. During the same period, the total number of patents grew by a factor of 3.17, which means that the control-related patents grew more than 2x faster than the total. There are indeed differences around the world. Control-related patents filed in the US grew by 4.9x, which is in line with the total growth of patents, while in China the control-related patents grew by 130x with respect to a total patent growth of 38x, and hence control-related patents grew 3x faster than the total.

Based on patent analysis, one could argue that industry investment in control system innovation is robust, matching and sometimes outpacing the average, thus indicating that industry sees importance in innovation of control technology, whose results are worth protecting by means of patents.

What, then, is the problem? Why the castigation and concern that has led to the chartering of committees and task forces (such as the IFAC Industry Committee)?

In contrast to the positive statistics above, examining the participation of industry in the research community paints a negative picture. One metric is the involvement of industry-affiliated volunteers in research-oriented control organizations. Fig. 3 graphs the percentage and absolute numbers of the leadership of IEEE Control Systems Society (IEEE-CSS) whose affiliation was with industry. The data is taken from http://ieeecss.org/pages/leadership-over-years (accessed 23 Sept. 2019, data for 1963 is missing) and covers the history of IEEE-CSS except for the initial years of 1957-60. Leadership was defined to include all roles listed except for those associated with a specific publication (editors-in-chief, editors, and associate editors).

In the first full decade, there were only three leadership positions every year and the majority were held by volunteers from industry. The number of positions has grown since. As the graphs show, not only has the proportion of industry-affiliated leaders

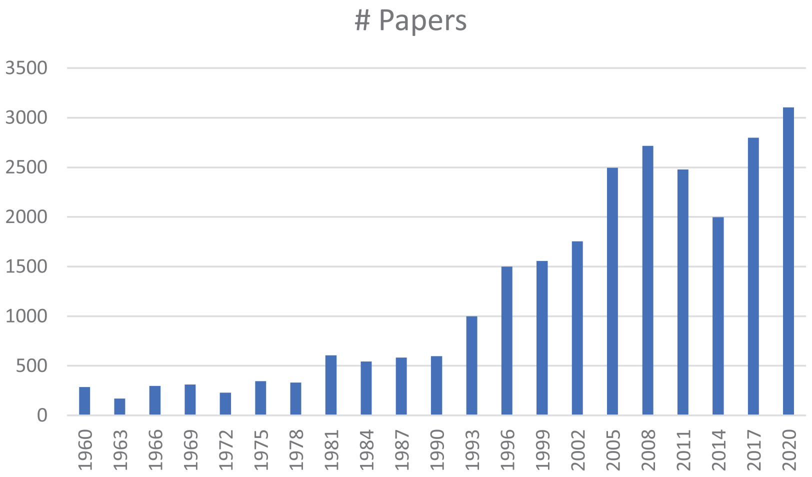

Fig. 1. Number of papers accepted for IFAC World Congresses, 1960–2020 (data from Congress reports, the IFAC Secretariat, and the 2020 World Congress).

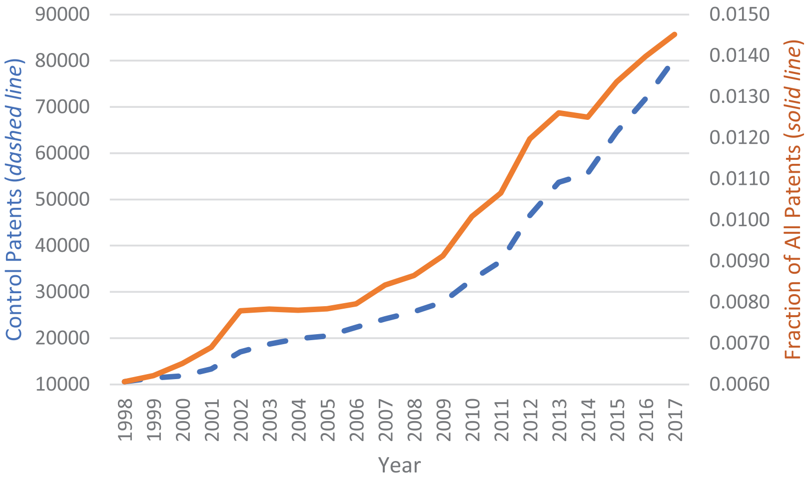

Fig. 2. The number and fraction of all patents awarded globally that included "control systems" in the title, abstract, or claims (data compiled from lens.org, accessed Dec. 12, 2019).

shrunk steadily, but absolute numbers have also declined. The downturn over the decades has reached the nadir: there has been zero industry involvement in the society's leadership since 2011.

Industry attendance at IFAC events also appears to be on a downturn. Based on data provided by the IFAC Secretariat, an analysis of industry attendance at IFAC conferences, workshops, and symposia shows a reduction between the 2000–2002 and 2012–2014 triennia from 19% to 14%. A consensus within the Industry Committee has also emerged that whereas control researchers working in industry are aware of IFAC, at leadership levels there is little or no knowledge or appreciation of the organization.

One conclusion that could be drawn from the data and analysis above is that the problem is not about the vitality of the field, but specifically about the lack of industry involvement in the control research enterprise. Two reasons for this have emerged from discussions. First, industry may see little benefit in supporting professional societies, in part because returns within time horizons of interest to it appear unlikely, and, second, industry perceives a lack of interest in its participation and of recognition of its contributions.

Whatever the reasons, an opportunity cost is being accrued. If different constituencies within the controls community are not engaged with each other as well as they could be—engagements that organizations such as IFAC, IEEE-CSS, and the American Automatic Control Council (AACC) seek specifically to mediate—then the transition from research to practice, or indeed from practice to research, is not being well-facilitated. Complex control applications may not be operating as efficiently and effectively as they could be if they were to take advantage of research results and future applications will be similarly disadvantaged. Similarly, novel and effective control methods may never see impact in the real world, ultimately being prematurely dismissed as impractical. Control is a successful discipline and advances in the field are being put to good use for the benefit of society and industry, but there remains no shortage of societal problems that can only be successfully addressed if the full capabilities of the control systems community, both the theoretical and the practical, can be brought to bear.

Arguably, organizations like IFAC have more at stake here than, for instance, a university research group or a corporation (which can seek to resolve their concerns to their benefit through their networks and relationships), so it behooves IFAC to take a leading role—as it has done by constituting the Industry Committee.

4. Messages for the research community

Based on Industry Committee discussions, surveys, and research, several "messages" for the research community (and in one case educators) have been formulated. We present these below.

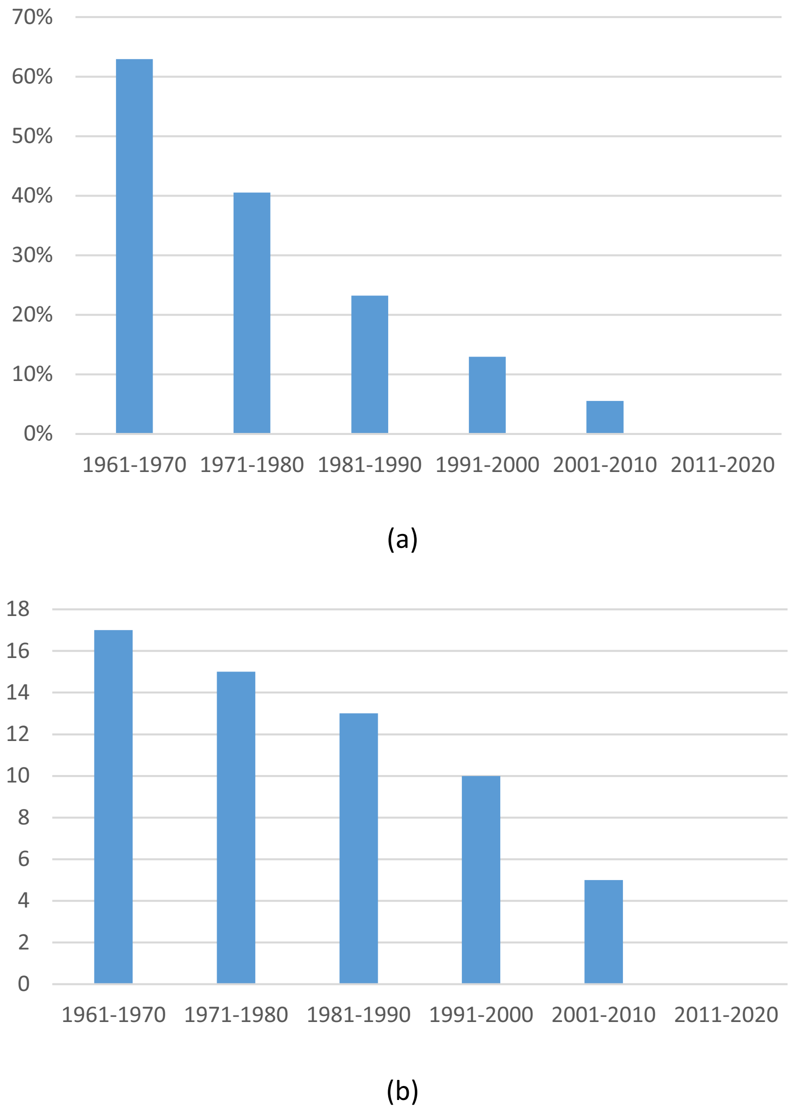

Fig. 3. Leaders of the IEEE Control Systems Society whose affiliation is with industry: (a) percentage by decade, (b) absolute numbers by decade. See text for explanation.

4.1. Advanced control technologies vary significantly in their impact and perceptions thereof

Table 2 shows the results of a survey conducted by the Industry Committee in March, 2018. The results of an earlier, similar survey, with similar results, are reported in (Samad, 2017). Respondents—members of the Industry Committee—were asked whether each technology in the list had demonstrated "high impact in multiple sectors," "high impact in a single sector," "medium impact," "low impact," or "no impact." Assessments of both "the present level of impact" and "the potential for future impact … over the next 10 years" were prompted for. Of the 77 members of the committee then, 66 responded.

The intent of the survey was to determine Industry Committee members' opinions regarding the real-world impact of advanced control technologies, such as model predictive control (MPC), robust control, adaptive control, etc. The survey also included cross-cutting ancillary topics such as system identification, data analytics, and estimation. PID control was also included—not as an advanced control technology but for calibration purposes. The survey as distributed included a glossary for the terms used (for example, the glossary noted that nonlinear control included feedback linearization, dynamic inversion, sliding-mode control, etc.).

Table 2
The percentage of survey respondents indicating whether a control technology had demonstrated ("Current Impact") or was likely to demonstrate over the next five years ("Future Impact") high impact in practice.

	Current Impact	Future Impact
Control Technology	%High	%High
PID control	91%	78%
System Identification	65%	72%
Estimation and filtering	64%	63%
Model-predictive control	62%	85%
Process data analytics	51%	70%
Fault detection and identification	48%	78%
Decentralized and/or coordinated control	29%	54%
Robust control	26%	42%
Intelligent control	24%	59%
Discrete-event systems	24%	39%
Nonlinear control	21%	42%
Adaptive control	18%	44%
Repetitive control	12%	17%
Hybrid dynamical systems	11%	33%
Other advanced control technology	11%	25%
Game theory	5%	17%

As can be observed, MPC is clearly considered more impactful, and likely to be more impactful, vis-à-vis other control technologies, especially those that can be considered the "crown jewels" of

Table 3
Assessments of the current impact of four advanced control technologies by respondents with different industry backgrounds.

	MPC		Robust Control		Adaptive Control		Nonlinear Control	
	%High	%Low/None	%High	%Low/None	%High	%Low/None	%High	%Low/None
Process Industry	59	9	9	44	9	50	9	56
Aerospace	64	14	36	14	29	36	36	21
Automotive	60	10	10	30	30	50	20	30

control theory—robust control, adaptive control, and nonlinear control. It is notable that MPC itself is not one of these developments that arose out of theoretical work; its provenance is not academic research but industry implementation (Qin & Badgwell, 2003). System identification and estimation also assess highly, and MPC implementations—as well as implementations of other feedback control techniques—often rely on these important ancillary technologies. The survey data reinforces a perception in the research community. For example, as noted in (Blondel et al., 1995) and attributed to M. Fliess, “Some of the existing theories do not seem to be really helpful in practical applications. A major challenge is to understand why and to propose remedies.”

4.2. The control research community is broadly unaware of the impact of advanced control

The 2018 survey also asked respondents about their industry sector backgrounds. Three sectors had double-digit representation: process control (34 respondents), aerospace (14), and automotive (10). Table 3 shows how responses differed based on backgrounds. (Several respondents indicated experience with multiple industry sectors.)

A few notable conclusions from the table are as follows:

- Although assessments of MPC impact are, by and large, consistent across respondents, assessments of robust, adaptive, and nonlinear control differ significantly. For the latter technologies, no sector category is overall sanguine about their impact, but the process-industry-background respondents are the most skeptical.
- Robust, adaptive, and nonlinear control are often associated with aerospace, and as a whole this sector has the most favorable opinion about these technologies, but yet only a third or so of those with aerospace backgrounds offer high-impact assessments.
- The data suggests a lack of awareness among the respondents—and, by extension, among the control community—of the applications of advanced control. Several Industry Committee members are personally aware of substantial impact with various technologies (including MPC and robust/adaptive/nonlinear control). In the case of MPC, several thousand applications based on five products are noted in (Qin & Badgwell, 2003) as of 2003—the majority in refining, petrochemicals, and chemicals, but also including non-process-industry sectors such as aerospace, defense, and automotive. Numerous examples of practical applications with other technologies are listed in (T. Samad & Annaswamy, 2014). Yet, apparently, the word is not out, suggesting an area of emphasis for the Industry Committee.

Several members of the IFAC Industry Committee who work in academia or in corporate R&D groups are also aware of unpublicized insertions of control-technology in successful products. Companies may not publish such information because of confidentiality needs, the lack of incentives for dissemination, and other reasons.

Successful industry applications are, nonetheless, challenging, for reasons elaborated below.

4.3. Real-world success requires domain understanding

It seems paradoxical at first thought: Control research has relevance across a large number of industry sectors, yet applying it successfully and at broad scale to even one is challenging. However, impact from control requires not only expertise in control but also a deep familiarity with the domain of application and the industry. Specific issues include the following:

- Some aspects of the domain understanding required are technical in nature. Knowledge of the physical/chemical/biological phenomena involved is required to specialize a theoretical framework for an application, and the specialization required can vary dramatically among sectors such as aerospace, oil and gas, automotive, biomedical, disk drives, and others. Just the time scales involved can differ by orders of magnitude—from milliseconds to minutes and longer. As one example of a “detail” that can substantially influence the choice of control methodology, linearity of processes is generally and successfully assumed in most applications in the refining sector, whereas in flight control nonlinearities must be explicitly dealt with. Another example is the ability to develop first-principle models that can be used for control purposes—in flight control researchers and developers can start with equations of motion whereas in most process industry applications model development is based on empirical data and system identification.
- Success in innovation also requires knowledge of other aspects of industries and industry sectors, for example as related to regulations and standards. In some industries, regulatory laws need to be complied with and elaborate certification processes may need to be followed (e.g., commercial aerospace, biomedical, automotive, food and beverage, pharmaceuticals). Such issues are hurdles to the rapid (or too-rapid) development and deployment of novel control technology. Indeed, to at least some extent because of certification requirements and the associated time-consuming verification and validation, today’s commercial aircraft still fly with gain-scheduled PID loops for their flight control systems (but advanced control technologies are extensively used in control design and verification), whereas MPC controllers are running online in refineries, petrochemical plants, and paper machines.
- The value chains in the design and development process in an industry determine responsibilities for requirements specification, control design, control software development, controller implementation, and verification, and it is rarely the case that the same company conducts all of these steps. In the automotive sector, companies such as Bosch and Delphi may provide the hardware systems for control (and themselves rely on others to provide components such as microcontrollers), others such as AVL and Ricardo may provide simulation and testing services, and original equipment manufacturers (OEMs) such as Audi or Ford may ultimately launch the car into production. In the pulp and paper industry, third-party consulting companies may be involved in developing new control solutions that will then be implemented in the control system, provided by

an ABB or a Honeywell, and the paper mill may then operate the new system under the oversight of its operational staff.

- In some industries—examples include the process industry sector and commercial buildings—each instance of a control system is custom-designed-and-implemented. A controller for a chemical reactor is tailored for that specific reactor. Once implemented, it can then be modified as necessary. This level of supervision is justified by the economics involved—the reactor's production may be worth tens of millions of dollars annually—and in the scheme of things having a control engineer onsite to ensure that the controller continues to operate well is a small cost to pay. For an implanted biomedical device or a car, however, there may be tens or hundreds of thousands of identical copies all over the world and each has to have the same control algorithm embedded in it. A change to the controller, once launched, will require a recall which, among other problems, is a highly expensive proposition for the manufacturer. This consideration puts a higher premium on controller validation prior to its operational use than in the process industries, where onsite and site-specific tuning is typically involved and changes to the control system, while not desirable, are feasible to undertake.

It should be noted here that no one person—researcher or practitioner—can be expected to be cognizant of these sundry complexities of taking a technology development to market. It is important for application-focused researchers to develop an appreciation of such considerations. The work itself will require appropriate sharing of information and cross-functional collaboration.

4.4. Control technology implementation infrastructures and architectures are industry-specific

The product of control research that may be considered for practical application is, typically, an algorithm. Before this algorithm can be operationalized a number of steps must be taken—software implementation, connectivity to sensors and actuators, integration with the automation and control system, and others. The procedures and processes involved are not uniform across different industries, and researchers hoping for the practical application of their algorithms need to have some understanding of these technology infrastructure aspects in the industry they are targeting.

Aspects of Implementation Infrastructures. We itemize the primary aspects below:

- Processing power on computational platforms that are used to run control algorithms is a significant determinant of the complexity of the algorithms that can be employed. Embedded processors are often several generations behind desktop processors, because of intrinsic limitations imposed by real-time processing, the need to operate in harsh environments, and long certification processes for safety-critical applications (for a comparison of processors for desktop, automotive, and spacecraft applications see (Di Cairano & Kolmanovsky, 2018)). Economic factors also come into play: As of 2012 several digital thermostat manufacturers were still using 8-bit microprocessors for some of their products (personal communication to the first author from Honeywell engineers).
- Sensors can be expensive to install—often for the labor involved in the installation more than the equipment cost. Their maintenance adds expense too, and where the sensor installation is in a corrosive or otherwise harsh environment (e.g., a chemical reaction or under the hood of a car or truck), ensuring correct operation may be more trouble and impose more cost than can be borne for the value the sensor is providing. Installations are done where there is business justification. Similar concerns apply to actuators as well. (With appropriate advanced control and estimation algorithms the numbers of sensors and actuators can often be reduced.)
- Communication protocols are standardized through standard-setting organizations in all major industries that rely on automation. Although general standards exist and are used in industry for communication—e.g., Ethernet—the distinctive characteristics of an industry sector typically result in tailored protocols and networks. These characteristics include temporal determinism, latency, reliability, cost, and scalability. Sometimes an industry standard is derived from an established general one—e.g., Fault-Tolerant Ethernet in the process industries—and in other cases developed *ab initio*—e.g., SAFEBUS for commercial aviation or CAN for automotive.
- A communication technology that has rapidly become popular in industry is wireless. Wireless transmitters are readily available for process industry plants, and in systems such as aircraft engines wireless data transmission is being used for monitoring and condition-based maintenance. It is important to keep in mind that the wires that are being cut can be either or both of two types: power and signal. For safety-critical systems especially, assurance is required on both parameters. In many cases, wireless devices are still line-powered—even if a battery were to last a few years, with possibly over ten thousand sensors in an industrial plant several full-time workers could be required solely for battery replacements.
- User interfaces and user stations are required for many control systems and differ substantially across industry sectors . The sophistication and cost of cockpit displays and other equipment in airplanes is of a completely different nature than the interface provided by a thermostat to a homeowner. For power generation, the process industries, large buildings, and space missions, "control rooms" are set up with multiple user stations. With mobility technologies, tablets and smartphones are being used as user interfaces as well: roving operators and technicians can remotely access schematics and other information on their devices.
- Finally, cloud infrastructures are being adopted in virtually all industries. Their use ranges from data archiving to analytics to large-scale optimization. In some cases loops can be closed as well—for example, geofencing for home automation and other mobility support. Control suppliers and their (business-to-business) customers are setting up private cloud resources. Issues of data privacy, confidentiality, and security are crucial to address. For control researchers, the availability of data and processing power in the cloud can provide the wherewithal to enable the deployment of more, bigger, and better algorithms, but the details vary by industry and they make all the difference.

The Overarching Importance of Architecture. A cross-cutting term that is relevant here is "architecture." In manifestations such as system architecture, software architecture, service architecture, and platform architecture, the term connotes the overall organization and structure of the elements and component technologies of solutions, products, and systems. It is the architecture that is the key to a holistic understanding, from a technological viewpoint, of a product family or even an industry. Control principles are relevant to architecture and it behooves control engineers to gain an architectural understanding of the domain in which their innovations will be applied—focusing solely on algorithms, or other "component" technologies, will be a hindrance to the ultimate success of their efforts.

Legacy Systems. Clean-sheet-of-paper designs and implementation are a rarity in industry. Systems must be designed to work with equipment and infrastructure already in place. Legacy considerations are pervasive; they encompass hardware, software, sensors, actuators, networks, user interfaces, and much else (including architecture). It is not just the production or customer installation that has to be considered; a company updating a design or introducing a new product or solution will need to leverage existing components and technology. The issue is exacerbated in many control-intensive industries where product life-cycles are prolonged; for example, aircraft, process plants, and power generation equipment can operate for (many) decades after release or commissioning.

4.5. Advanced control is more than feedback control … it's a systems-oriented, rigorous mindset

In equating advanced control with techniques such as MPC, robust control, adaptive control, and the like, we are in danger of making a categorical error that does not serve our field well. Experts in control—e.g., M.S. and Ph.D. graduates who have specialized in control—also have expertise in topics like estimation, system identification, simulation, and analytics. The skills of control engineers are relevant well beyond control design, and indeed many control engineers in industry are working on projects that are not about developing new feedback control but about algorithms and methodologies for diagnostics, prognostics, monitoring, modeling, and verification and validation.

The importance of verification and validation (V&V) in some industries has been alluded to above and is worth highlighting. In commercial aviation, for safety and certification reasons, elaborate and extended processes are documented and followed. Indeed, the V&V process can often take longer than the control design process. The "systems engineering" label under which V&V is conducted is well-suited for control experts, with their broad and rigorous understanding of complex dynamical systems. In the academic world, however, verification and validation are more likely to be researched and taught within computer science departments than in control engineering.

Furthermore, expertise in control goes beyond competency in theories, algorithms, and specific subjects in curricula. Particularly at the graduate levels, the value of the "control mindset" cannot be overemphasized. This mindset is developed through the exercise of rigorously formalizing and analyzing problems; labeling systems, subsystems, inputs, states, disturbances, etc.; representing complex physical phenomena by descriptive yet simplified mathematical models; using mathematical tools for design and analysis; and yet appreciating that models and simulations will diverge from reality. The mindset is also related to interdisciplinary fields such as systems thinking (Meadows, 2008) and system dynamics (Sterman, 2000); in fact it has enabled their development. As a result, experts in control, in partnership with domain experts, are able to contribute to applications and technologies outside of their immediate experience (as also noted next).

4.6. Control science has broad-based relevance for new and emerging technologies

The annual "Hype Cycle for Emerging Technologies" report, published by Gartner, is a widely followed resource for monitoring which nascent technologies are attracting investment and interest and how far they are from commercialization. In the 2019 edition, the following technologies are among the 29 being tracked (Panetta, 2019): Nanoscale 3D printing, augmented intelligence, flying autonomous vehicles, light cargo delivery drones, edge AI, low-earth-orbit satellite systems, autonomous driving (levels 4 and 5), edge analytics, biochips, 5G, graph analytics, and 3D sensing cameras. "Control" doesn't appear by name, but in all of these cases, dynamical systems must be modeled, designed, regulated, and optimized.

Students in control are being recruited to work in these areas—in companies large and small, established and starting up—but the institutions of the field (such as IFAC) are slow to respond. Journals, conferences, and technical committees, at least in control organizations, are not agile entities. As a result, even though many control engineers are working in autonomous driving, robotics, video and image processing, unmanned aircraft, advanced telecom, etc., the papers they publish, the conferences they attend, and the associations they participate in are more likely to be in other technological fields.

Not on the 2019 Gartner list—but it appeared at the peak of the hype cycle in 2018 (Panetta, 2018)—is "digital twin," another hot topic that is close to the heart of control analysis and simulation. Such labels come and go, and often they are repackagings of other topics (real-time simulation?) for marketing reasons. Regardless, once they gain mindshare in industry, resources and attention are directed accordingly.

4.7. Corporate R&D can (aometimes) aerve as a bridge for technology transfer of academic research

Control (and control-enabled) industries include many large corporations with significant R&D organizations—the work in which can cover the gamut from basic research to productization and product support. In many cases, these organizations also fund academic research and they partner with academia for government-funded projects.

Corporate R&D centers are by no means an infallible solution to bridging the theory/practice gap. Their effectiveness depends, *inter alia*, on how well-connected they are with product divisions of the corporation (being under the same corporate banner does not automatically make researchers a credible resource for practitioners). But, when successful, corporate R&D can help translate product and customer needs to research goals, evaluate the relevance of research for the business, and be a productive intermediary between external researchers and business units.

In our experience, a particularly effective function that corporate research can perform in this context is serving as a conduit for people. Transfer of academic research results is often best accomplished by attracting those involved in the research to the corporation. Graduate students, post-docs, and even faculty are more likely to be attracted to research groups in corporations than to product divisions, and once they are within the corporation it is easier for their expertise to be recognized and used beyond the research group. Many examples of the transfer of advanced control methods to industrial products and services have been possible because of the transfer of people with relevant expertise from academia to industry, and specifically to R&D groups in the latter.

4.8. Cost reduction is a high-priority for industrial innovation in control

In research developments in the field, "performance" attributes are almost always the metrics of interest. Parameters such as speed of response, robustness to process/model mismatch, and disturbance rejection are evaluated and used to claim improvements over the state of the art. (Robustness and performance are usually considered as diametrically opposed parameters, although both relate to how well the system under control "performs.")

In order to assess the industry viewpoint on what is needed for new products and services, two of the workstreams of the Industry Committee, led by Silvia Mastellone and Alex van Delft, conducted a survey of industry respondents (both members of the committee and others). Survey respondents were asked to rank twelve "key drivers for further improvements for the future for the next generation of product/processes and services." "Performance" was one

Table 4
Top three responses to the question, “What are key drivers for further improvements for the future for the next generation of product/processes and services?” by industry sector. Numbers in parentheses indicate the number of respondents from each sector. Data courtesy of Silvia Mastellone and Alex van Delft.

Aerospace (5)	1. Cost reduction 2. Availability and reliability 3. Performance
Automotive & Transportation (13)	1. Energy efficiency 2. Performance 3. Cost reduction
Energy, Oil, & Gas (13)	1. Cost reduction 2. Availability and reliability 3. Performance / Productivity (tie)
IT HW & SW (7)	1. Time to market 2. Cost reduction 4. Energy efficiency
Manufacturing Industry (5)	1. Time to market 2. Cost reduction 3. Energy efficiency
Medical Technology (3)	1. Performance (tie) 2. Quality (tie) 3. Time to market
Process Industry (31)	1. Cost reduction 2. Quality 3. Availability and reliability
Robotics (2)	1. Productivity 2. Cost reduction 3. Performance / Quality (tie)

of the factors, as were “cost reduction,” “availability and reliability,” "productivity,” “time to market,” “and energy efficiency.” The results, by industry sector, are shown in Table 4.

Cost reduction is prominent overall—it appears in seven of the eight sectors and is the highest-ranked “key driver” for aerospace, energy and oil & gas, and the process industry. (The prominence is not universal, though; cost was not indicated as a major factor in medical technology developments.)

Yet cost reduction is rarely discussed as an objective in control research. The table also provides a corollary to our earlier message on the importance of domain understanding. Significant differences are apparent here.

4.9. Economic expectations influence industry investment in research

The section above discusses drivers for control research, but there are bigger questions that corporations have to address first: How much should they invest in research and what technology areas should their research investments focus on. Two economic factors that influence these decisions are outlined here.

The expected industry growth. Industry sectors that are rapidly growing will, other things being equal, invest more in technology research. In an expanding market, competition-beating technology enhancements will lead to substantially higher revenues, and probably higher profits. In comparison, in sluggish industries companies tend to seek to cut costs to raise profit margins. Research budgets are among the top targets for cost-cutting (although research can also help in reducing capital and operational costs of systems—see above).

Business leaders are acutely attuned to the economic dynamics of their industries. Forecasts for growth are closely monitored and investment decisions made accordingly. The traditional application domains for control are large—annual revenues are measured in the tens of billions of dollars or more—but growth prospects are modest (see Table 5). For some of the traditional application domains for control—industrial control, automotive control, and flight control—growth rates are in the mid-single-digits. In contrast, industrial robotics and home automation, for which control is one of several important enabling technologies, boast double-digit growth-rate expectations. Seen in this light, it is no surprise that companies in industrial robotics and smart homes have higher investments in R&D, in terms of proportion of sales.

The perceived relevance of research fields for delivering business growth. Decision makers in corporations are faced with a constellation of research areas that they can invest in, with limited R&D funding available. Choices of which research topics to focus on are based on projections and expectations of business return.

Three technology areas of cross-industry importance today are cybersecurity, digital transformation, and the internet of things (IoT). These are “buzzwords” in industry and discussions in executive leadership circles on trends, opportunities, and challenges are likely to feature these much more so than control. Table 5 also shows market sizes and trends for these. As is apparent, growth in these technologies far outpaces that of the control industry sectors.

Generally, industry seeks the “financial optimum” for its research investments. This criterion applies for control research too. A potential advanced control development needs to compete with a traditional solution, which has typically been fine-tuned and optimized over many years, and will be pursued only if it is considered financially advantageous.

4.10. The industry-academy disconnect extends to education

The “Educating Control Engineers for Industry Roles” workstream of the Industry Committee, together with the IFAC Technical Committee on Education (TC 9.4), is conducting surveys of both professors and industry staff working in control systems to prioritize various topics that could be included in a “first and only” control course. This focus is motivated by the realization that most engineering students are not specializing in controls and may only take one course in controls. In a piloting phase, the survey was distributed to a limited group of forty-three individuals, thirty-one from academia and twelve from industry. Opinions were sought both on the topics to be included in the first control course, and on the design and administration of the survey itself. The results from the pilot survey are presented in (Rossiter, Zakova, Huba, Serbezov, & Visioli, 2019). Industry and academia were aligned on core

Table 5
Sales volumes and compound annual growth rates (CAGR) for selected control-related industry sectors and cross-industry technologies. Sources listed are market reports and press releases thereof and were accessed Dec. 27, 2019.

Control industry sectors	**Sales volume (year) in $B**	**Growth (CAGR)**	**Period for CAGR**	**Source**
Industrial Control	117 (2017)	5.3%	2018-2025	https://tinyurl.com/yxd2gya7
Automotive Control	63.6 (2017)	4.4%	2019-2025	https://tinyurl.com/uy78wfp
Aircraft Flight Control	11.1 (2017)	3.52%	2018-2023	https://tinyurl.com/ydf7uqo8
Industrial Robotics	16.5 (2017)	12.0%	2020-2022	https://tinyurl.com/wkd3d23
Smart Home Automation	75 (2018)	11.8%	2019-2025	https://tinyurl.com/vz2ozk5
Cross-Industry Technology Areas				
Cybersecurity	119 (2018)	14.5%	2019-2024	https://tinyurl.com/ve82q32
Digital Transformation	262 (2018)	18.2%	2019-2026	https://tinyurl.com/yynu6plb
Internet of Things	190 (2018)	24.7%	2019-2026	https://tinyurl.com/y2czseqh

Fig. 4. Examples of the impact of advanced control, left to right, top to bottom: an ethylene plant, the original Kiva robots, the ESA ATV-3, a water irrigation channel, Airbus A350, a mobile phone, the Medtronic MiniMed 670G, a Seagate hard disk drive (Airbus photograph by P. Masclet / master films; © Airbus 2018).

concepts, such as first principles modeling, stability, transfer functions, and PID control. The early responses, however, also point to divergence in the prioritizations. For example, the top priority for academic respondents was software laboratories whereas this was ranked quite low by the industry participants. Frequency response and Bode diagrams also showed a similar difference of valuation. On the other hand, topics considered important by industry but less so by academia included optimal control and modeling from real data.

Taking advantage of some lessons learnt with the pilot delivery, a large-scale survey was released to the global control community in June 2019. The survey was promoted at several conferences and professional society meetings. The IFAC Industrial Committee put significant effort to reach out to the industrial control base. The survey results are expected to be available before the 2020 IFAC World Congress in Berlin and will be presented in a panel session that is being organized for this purpose.

This survey addresses but one aspect of the industry impact of control educators. There are numerous others. At the other end of the experience curve, control scientists have also been addressing the need to enhance the skills of working engineers in industry (Abramovitch, 2019).

5. Successes of advanced control in industry

This section consists of a sampler of “success story” vignettes in control. In each case the applications noted have had significant impact in industry and society. The diversity of the control technologies involved (Fig. 4) as well as the industry sectors that have benefited from the technology developments are worth noting. For additional success stories across numerous application areas see (Åström & Kumar, 2014; T. Samad & Annaswamy, 2014). (Åström & Kumar, 2014) also includes a broad-ranging historical perspective on control applications and on the impact of control theory on them.

5.1. Cellular telephony

What product category has the highest number of control loops implemented worldwide? To the best of our knowledge, the answer is surprising—at least inasmuch as the product category in question is often overlooked in discussions of control applications. There are about 13 billion mobile telephones worldwide and over 4.5 billion mobile phone users (Statista, 2018; The Radicati Group, 2019). Each phone has a half-dozen or more function-critical control loops (Bernhardsson, 2014). For the access control function itself, these loops include automatic gain control, automatic frequency control, transmission power control, timing control, and feedback control of coding and modulation. Control loops are also widespread in the circuit level and for application management (e.g., controlling computational resources and temperature).

To elaborate on one feature, transmission power must be coordinated between the base station and the mobiles in a radio cell. In the 3G WCDMA FDD standard, all mobile phones in a cell transmit simultaneously at the same frequency, and failed power control in one phone can destroy the operation of the cell. A “soft handover” mechanism, in which multiple base stations attempt to simultaneously control one phone’s output power, is also addressed by a control algorithm.

5.2. Mobile robots in smart warehouses

In 2012, Amazon acquired the robotics company Kiva Systems that was founded by Raffaello D’Andrea, a control professor at Cornell University (now at ETH Zurich), and two colleagues, for $775 million. Kiva Systems, which now operates as Amazon Robotics, designs autonomous robots that are used to move inventory in warehouses to operators (D’Andrea, 2014). Sensors and advanced control algorithms allow safe navigation. With hundreds of robots simultaneously operating in a warehouse, coordinated control among them is also essential; a hierarchical structure similar to that used in air traffic management is used. Robots also share information; adaptation and learning result in improved performance over time.

Kiva robots are now dedicated to Amazon, but they were previously deployed in numerous retail companies including Crate and Barrel, Dillard's, Gap, Office Depot, Staples, and Walgreens. A 2016 report estimates that the robots have cut operating expenses by about 20% at the Amazon fulfilment centers where they have been deployed, totaling about $22 million in cost savings at each center (Kim, 2016). These benefits accrue from a cycle-time reduction from 60-75 minutes to about 15 minutes and an increase in inventory space by 50%. With Kiva and recent updated designs, Amazon has 20,000 robots working at distribution facilities worldwide (Holley, 2019).

5.3. Ethylene plantwide control and optimization

Ethylene is the largest-volume industrial bulk commodity in the world, and the source material for plastics ranging from food wrap to impact-absorbing car dashboards. The plantwide control and optimization solution developed at Honeywell (Lu & Nath, 2014) integrates a global optimizer and 15–30 multivariable model predictive controllers; the latter operate every 30 to 60 seconds with the global optimizer providing higher-level targets every minute. Multiple linear dynamic models are used for the MPC controllers. Steady-state nonlinear models are also used for calculating critical parameters (e.g., furnace yield gains).

A project to implement plantwide optimization and control typically takes 9 to 12 months. Little maintenance is subsequently required and plants either dedicate a half-time control engineer for monitoring and minor service or depend on quarterly visits by Honeywell staff. Operational objectives for an ethylene plant include yield improvement, production maximization, and energy efficiency. The plantwide optimization and control solution typically results in $1.5–$3 million in production increases annually. Energy savings are an additional and significant benefit.

5.4. Closed-loop artificial pancreas for diabetes treatment

The first commercially available closed-loop system that integrates control algorithms, subcutaneous sensing, and automated insulin delivery—thus acting as an artificial pancreas—was launched by Medtronic after FDA approval in September 2016. It was originally available for people 14 and older, with further FDA approval for children aged 7-14 obtained in June 2018. The heart of the system is a hybrid controller that incorporates adaptive control, model-based insulin feedback, and a feedforward signal with a PID algorithm (Grosman et al., 2016).

The Medtronic MiniMed 670G controls patients' insulin demands automatically. Patients need to provide their carbohydrate intake estimate before each meal; this estimate is used as a feedforward signal to the control algorithm. Adaptation is used to tailor closed-loop operation for each patient—controller gains, constraints on insulin delivery, and internal mathematical models used for estimating glucose and insulin in plasma are updated every minute. The MiniMed 670G is an economic success for Medtronic with revenues in the billions of dollars. More importantly, it is a societal success story: it has reduced hospitalization rates caused by diabetes complications and it enables people with diabetes to live a close-to-normal life. The system is implanted in over 200,000 patients.

In December 2019, the FDA granted approval for two newly available products that also integrate advanced control technologies: Control-IQ from Tandem Diabetes Care (FDA, 2019) and iLet from Beta Bionics (JDRF, 2019). Further advancements are actively being explored as well (Sánchez-Peña & Chernavvsky, 2019).

5.5. Online Fault Detection for the Airbus A350

A control-theoretic approach for early fault detection is now deployed across the Airbus 350 fleet. The innovation story started earlier, with the superjumbo A380. Because of the use of new-generation actuators and more stringent load requirements, A380s could not be equipped with legacy fault detection strategies, which mainly relied on basic signal processing techniques. A model-based fault detection and isolation (FDI) approach was developed to cover fault detection on all control surfaces (Goupil, 2010). The approach included a nonlinear hydraulic actuator model for estimating the position of hydraulic actuators, with some model parameters (hydraulic pressure, actuator damping coefficient, etc.) fixed to their most probable values.

The new development, the result of collaboration between Airbus and the University of Bordeaux, France, incorporates online physical parameter estimation of the actuator model, which de facto improves the model accuracy. The estimation process is based on a nonlinear local filtering algorithm that relies on robust control theory. Smaller fault amplitudes can be detected earlier than with conventional systems (Zolghadri, Henry, Cieslak, Efimov, & Goupil, 2014). The benefits include weight saving because of structural design optimization (structural reinforcements would have been needed without the new solution), which in turn reduces the aircraft's environmental footprint (e.g., reduced fuel consumption).

This new FDI algorithm went through extensive verification & validation before certification and entering commercial service. The inaugural commercial flight of an A350 aircraft took place on January 15, 2015, between Doha and Frankfurt.

5.6. Robust control for hard disk drives

Over the years the amount of information stored has grown from megabytes to zettabytes, reinforcing the need to successfully store, access, and manage unprecedented amounts of data. A Seagate-commissioned study by the International Data Corporation (IDC) forecasts that the global datasphere will grow from 41 zettabytes in 2019 to 175 zettabytes by 2025 (Reinsel, Gantz, & Rydning, 2018). A significant amount of this data is expected to end up in hard disk drives (HDDs) at data centers. As demand for data storage and management technology grows, the need for greater efficiency and more advanced HDD capabilities continues to evolve.

HDDs are, foremost, mechanical devices with components that require advanced control algorithms to get the most out of them. One of the key hard drive features is suspensions. These are built to enable the high track and areal densities required for higher capacities. Since 2007, Seagate has shipped billions of suspensions with mu-synthesis methods from the robust control literature as the primary feedback control mechanism for ensuring optimal performance and robust stability. In collaboration with university-sponsored researchers, Seagate developed controller analysis and synthesis tools that are at the forefront of applying robust controls to industrial applications (Young, Morris, & Ho, 2003).

5.7. Networked control for autonomous irrigation systems

Since the onset of urbanization, large-scale networks of open water channels have been used to improve food production by reducing the effect of the vagaries of rainfall on agricultural crops. Presently, 50% of all water extraction in the world is used for food production in gravity-based irrigation systems, with an average conveyance efficiency of around 50% (in some cases as low as 30%). Control researchers and practitioners at the University of Melbourne and Rubicon Water Pty Ltd. have collaborated to develop a suite of modern sensors and actuators interconnected with a wireless communication network. Such an irrigation network becomes a networked internet of things that can be managed in autonomous fashion using modern network control theory (Cantoni et al., 2007).

Based on this work, Rubicon Water Pty (https://www.rubiconwater.com/) has commercialized a decentralized, distributed control system, Total Channel Control®. With this product, farmland can be irrigated with precision, improving land utilization; water runoff and seepage can be reduced, improving the ecological footprint of cropping and reducing fertilizer needs; and the timing of water delivery can be responsive to the physiological needs of the crop, improving crop productivity. Quantified benefits include improved water conveyance efficiency to near 90% for heavy clay soil channels or lined channels. In addition, farmers report significant crop productivity gains and cost reductions through reduced fertilizer and labor cost.

The system has been deployed in Australia (where some of the largest irrigation districts are now nearly all fully automated), New Zealand, the U.S., China and India.

5.8. Robust control for spacecraft

The spacecraft and satellite sector is traditionally conservative, particularly for human spaceflight and telecommunication applications. This is in the process of changing and has been facilitated by R&D with joint development projects from academia, industry, and space agencies.

The Rosetta comet lander mission from the European Space Agency (ESA) was the first to use robust H-infinity control in space (Falcoz et al., 2015). Robust control was not the first choice, but it ultimately provided pointing and slewing performance even with the large, flexible solar panels on the spacecraft that traditional approaches could not achieve. Rosetta was launched in 2004 and rendezvoused with Comet 67P/Churyumov–Gerasimenko in 2014 and also deployed the lander Philae onto the comet's surface. After 10 years in space to reach the comet and some avionics deterioration a retuning was needed. The industrial choice was to use structured H-infinity as an add-on controller; the flight software was successfully patched with the new algorithm. Rosetta completed its mission by descending to the comet on 30 September 2016.

Robust control was also successfully used for the ESA Automated Transfer Vehicle (ATV) for the International Space Station, resulting in about 2-cm accuracy in automatic rendezvous and docking, compared to 8–9-cm for the Russian Progress/Soyuz, the only other spacecraft capable of automatic docking. The ATV uses a six-degree-of-freedom linear multivariable robust controller and optical time-of-flight sensors (Personne, Lopez-y-diaz, & Delpy, 2005). Five ATV missions to the International Space Station were conducted during 2008–2015. The recently approved Mars Sample Return mission, a joint ESA/NASA program, will base the complete guidance, navigation and control system on advanced robust control techniques.

5.9. MPC for automotive turbocharged gasoline engines

The automotive industry has been faced with increasingly stringent regulations for emissions, fuel economy, and safety. In response to these trends, the complexity of automotive control systems has also increased, both in terms of requirements and actuators to satisfy them. The capability of coordinating multiple actuators to achieve multiple, possibly conflicting, objectives while enforcing constraints has made MPC appealing for such applications. In an industry first, General Motors now has MPC implemented for torque tracking in turbocharged gasoline engines. The technology, developed in a collaboration between ODYS, originally a university spinoff of IMT Lucca, and General Motors, is in high-volume production in global platforms.

In a paper announcing the technology scheduled for production (Bemporad, Bernardini, Long, & Verdejo, 2018), the following benefits were stated for the MPC control system: the ability to coordinate scheduling of multiple actuators; the ability to handle significant variation in time constants across the actuators and operating conditions; the ability to seamlessly manage constraints on inputs and outputs; and the provision of a future-ready framework as new requirements are imposed, new technologies adopted, and additional degrees of freedom made available.

We expect to see more and more applications of MPC in the automotive industry in the next few years, especially in the highly active areas of electric/hybrid-electric vehicles and advanced driver assistance systems/autonomous driving.

6. Three important caveats

Through efforts such as authoring this article, the IFAC Industry Committee aspires to contribute towards bridging the gap between the research and practitioner communities in control. That there are both a gap to bridge and insights to help bridge it should be evident from the discussion above. Although we hope that all control scientists and engineers will be interested in the contents of this article, our primary advice is to a subset of this community—those control researchers who are seeking to impact practice and the practitioners who are seeking to better exploit research developments. Here we offer three "caveats" to the main emphasis of this article; these are intended as reminders that there is more to control research than industry applications and that there is more to control collaborations than research.

6.1. The value of basic research

Our emphasis in this article on how the research community can facilitate the real-world impact of its output should not be construed as implying criticism of more basic research. There is considerable value in such research and indeed more of it needs to be encouraged as well, especially in light of the emphasis on near-term economic returns and "innovation" that is pervasive today (see also below).

Outside of the control community, the short-term orientation of many activities that are putatively research belie the labeling. Better apps and fintech may be easier to develop but they are unlikely to alleviate the societal challenges facing humanity today. Some of these disciplines may be more in favor—by funding agencies, venture capitalists, corporate partners, and even students—today, but control theorists should be wary of shortening their horizons as a competitive response.

Besides, science can be pursued as a purely intellectual activity and for the sake of fundamental understanding. Not all researchers in control science and engineering are motivated by industrial or other practical applications. Much work being done by control researchers is advancing dynamical systems theory and applied mathematics, worthy goals regardless of their practical implications.

In addition, the practical relevance of a basic research undertaking is not (or cannot be known to be) zero; it is just uncertain and unpredictable. Many decades can elapse before a fundamental scientific advance is harnessed for practical ends, and sometimes the more revolutionary the advance the longer its gestation period—and the greater its ultimate impact. A relevant example: the Laplace transform.

6.2. Control science as the standard-bearer for rigor and analytical thinking

Along with and related to its theory-centricity, rigor is a hallmark of control research, and one that also stands in contrast to some other disciplines. Faster design cycles, agile development processes, calls for rapid returns on investment, short-term reward structures, celebrations of failure . . . these features of innovation ecosystems today are indicative of a mindset that is in some respects diametrically opposed to control. The rigor and analysis emphasized in the latter can be viewed as "old fashioned" and ill-suited to today's fast-paced, ever-changing business world.

One rebuttal to this view is that what may seem a new world today in terms of its pace of progress is not in fact so new. One book on innovation from more than a half-century ago espouses a similar theme:

> Technical innovation is essential to corporate growth and is the principal means of corporate competition. Companies must innovate at an increasing rate. New products and processes have progressively shorter life cycles. Whereas in the twenties, thirties, and forties a company could count on a product to keep its share of the market for ten to twenty years or more, a product in the fifties was and in the sixties is lucky to last five years, and in the case of some consumer product fields, six months. For these reasons a progressively larger share of corporate income comes from products introduced within the last ten years. (Schon, 1967)

In any event, trial-and-error innovation may be appropriate for some applications, but control technology is, in most cases, applied to domains that are safety- and mission-critical—the cost of poor control can mean lives or billions of dollars lost. An aircraft control system is not a video game and a refinery control system is not a consumer app.

Thus, even as control scientists seek to enhance their relevance to industry, the rigorous, systematic methodology (and "mindset," as briefly noted earlier) they personify through their work should be sustained, and even celebrated—it serves as a necessary antidote to some contemporary trends (that perhaps are not so contemporary).

6.3. Industry engagement by academia is about more than research

The principal purpose of academia is not research but education, and the principal benefit that academia can provide to industry is well-educated graduates, not breakthrough research results. Although enhancing research collaborations is an important goal, all stakeholders involved in that pursuit should keep the educational priority in mind. Faculty, research scientists, and students in academia, as well as research staff and practitioners in industry, can all help ensure that research collaborations support the educational mission of universities and are not conducted at its expense.

As noted above, faculty and industry personnel have different perspectives on one specific aspect of control education; we expect that more differences will surface in other aspects too. Industry input is valuable for furthering academic education especially because it may be at odds with academic practice. But this is not to imply that industry perspectives focused on product and solution needs should take precedence in formulating all facets of academic curricula. Universities do not exist solely or primarily to train students for industry; they must also provide them with a broad-based education and enable them to succeed in a fast-evolving, technology-driven world. Academic curricula and experiences should certainly be designed with an eye to making graduates employable and useful to industry, but also, and more importantly, to instill values for the betterment of humanity and of the ecosphere that sustains it.

Table 6
Ten messages for the control research community.

1. Advanced Control Technologies Vary Significantly in Their Impact and Perceptions Thereof
2. The Control Research Community is Broadly Unaware of the Impact of Advanced Control
3. Real-World Success Requires Domain Understanding
4. Control Technology Implementation Infrastructures and Architectures Are Industry-Specific
5. Advanced Control Is More than Feedback Control . . . It's a Systems-oriented, Rigorous Mindset
6. Control Science Has Broad-Based Relevance for New and Emerging Technologies
7. Corporate R&D Can (Sometimes) Serve as a Bridge for Technology Transfer of Academic Research
8. Cost Reduction Is a High-Priority for Industrial Innovation in Control
9. Economic Expectations Influence Industry Investment in Research
10. The Industry-Academy Disconnect Extends to Education

7. Conclusion

The IFAC Industry Committee was created in response to concerns about the lack of industry engagement with IFAC and the control research community. The disengagement is to the detriment of both sides of the divide. Research is not as valuable for applications as it might be (a lost opportunity for better products and services for society) and practitioner perspectives are not sufficiently informing research (a lost opportunity for more relevant theoretical contributions).

This state-of-affairs is not exclusively a problem for the control community. An eloquent discussion with references to numerous disciplines from science and engineering but also from sociology, journalism, education, and other fields, can be found in (Wolfenden, Sercombe, & Tucker, 2019). The authors cast the challenge as one of "epistemic translation," concluding with the following:

> The failure to facilitate a creative interface between practitioners and academics results in waste: the waste of academic work that lies untranslated for practice, the waste of practitioner knowledge that lies untheorised. It impoverishes discourse in both places, leading to a situation where bakers bake bread only for other bakers. In their attempts to promote research, universities have also created the conditions for anxiety, insecurity and inferiority for skilled and capable staff from practice backgrounds. In recognition of the integrity and validity of multiple epistemologies, we need a new focus on the skills of epistemic translation, and new structures which enable the kinds of conversations that will change the world.

The principal objectives of the Industry Committee can be characterized as translating between the perspectives and values of researchers/academics and practitioners/industrialists. In this article, our focus has been on broadening the understanding of academics and researchers in control about how industry works vis-à-vis the development, productization and commercialization of advanced technologies. Our key "takeaways" are the "messages" discussed earlier. We reiterate these in Table 6; it is notable that the messages all reinforce the need for a more holistic perspective on the part of researchers in control.

There are positive developments to emphasize too, such as the many successful advanced control applications across industry sectors. We have summarized a number of these. We expect nearly all of them will have been news to our readers, evidence itself of one of the challenges for our community.

The work of the Industry Committee continues. There is, for example, work to be done in the converse direction—messages for practitioners to better avail of and connect with researchers. Ultimately, we hope to develop, and where possible begin to implement, specific recommendations for researchers and practitioners. The goal of a seamless community in which specializations are not siloed but part of a synergistic whole is distant today—but that suggests opportunities for transformation abound.

Declaration of conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Katharina Willixhofer of the IFAC Secretariat for her invaluable assistance to the Industry Committee, including with surveys and compiling data for this article. Our thanks are also due to many other members of the Industry Committee who provided comments: Daniel Abramovitch, Ankur Ganguli, Carlos Guardiola, Vladimir Havlena, Arthur Kordon, Zdzisław Kowalczuk, Michael Lees, Bran Selic, Takashi Yamaguchi, and Georg Weichart. We also acknowledge the help of the members of the Industry Committee's Executive Subcommittee—within which group additional discussions about this article occurred—who are not listed as authors: Kevin Brooks, Roger Goodall, Steve Kahne, Silvia Mastellone, Carlos Pereira, and Alex van Delft. Comments from an anonymous reviewer helped improve this article. Finally, the first author would like to thank Rolf Findeisen, for an advance count of the 2020 World Congress accepted papers for Fig. 1, and Françoise Lamnabhi-Lagarrigue for suggesting this article and for providing valuable feedback.

References

Abramovitch, D. Y. (2019). Thoughts on furthering the control education of practicing engineers. *IFAC-PapersOnLine, 52*(9), 85–90. https://doi.org/10.1016/j.ifacol.2019.08.129.

Åström, K. J. (1999). Automatic control–the hidden technology. (Ed.) P. Frank (Ed.), *Advances in control–highlights of ecc '19*. Springer Verlag.

Åström, K. J., & Kumar, P. R. (2014). Control: A perspective. *Automatica, 50*(1), 3–43. https://doi.org/10.1016/j.automatica.2013.10.012.

Bay, J. S. (2003). So what. *IEEE Control Systems Magazine, 23*(3), 10–11.

Bemporad, A., Bernardini, D., Long, R., & Verdejo, J. (2018, April 3). *Model predictive control of turbocharged gasoline engines for mass production*. https://doi.org/10.4271/2018-01-0875.

Bernhardsson, B. (2014). Control in mobile phones. in *The impact of control technology, 2nd ed*. IEEE Control Systems Society.

Bernstein, D. S. (1999). On bridging the theory/practice gap. *IEEE Control Systems Magazine, 19*(6), 64–70.

Blondel, V., Gevers, M., & Lilndquist, A. (1995). Survey on the State of Systems and Control. Retrieved from https://hal.inria.fr/inria-00074195/document

Cantoni, M., Weyer, E., Li, Y., Ooi, S. K., Mareels, I., & Ryan, M. (2007). Control of large-scale irrigation networks. *Proceedings of the IEEE, 95*(1), 75–91.

D'Andrea, R. (2014). Mobile-robot-enabled smart warehouses. In Tariq Samad, & A. Annaswamy (Eds.), *The impact of control technology*. IEEE Control Systems Society *2nd Ed.*.

Di Cairano, S., & Kolmanovsky, I. V. (2018). Real-time optimization and model predictive control for aerospace and automotive applications. In *2018 Annual American control conference (ACC)* (pp. 2392–2409). https://doi.org/10.23919/ACC.2018.8431585.

Falcoz, A., Pittet, C., Bennani, S., Guignard, A., Bayart, C., & Frapard, B. (2015). Systematic design methods of robust and structured controllers for satellites. *CEAS Space Journal, 7*(3), 319–334. https://doi.org/10.1007/s12567-015-0099-8.

FDA. (2019). FDA authorizes first interoperable, automated insulin dosing controller designed to allow more choices for patients looking to customize their individual diabetes management device system. Retrieved from U.S. Food and Drug Administration website: https://www.fda.gov/news-events/press-announcements/fda-authorizes-first-interoperable-automated-insulin-dosing-controller-designed-allow-more-choices

Foss, A. S. (1973). Foss-TAC-1973. *IEEE Transactions on Automatic Control, 18*(6), 646–652.

Gao, Z., & Rhinehart, R. R. (2004). Theory vs. practice: the challenges from industry. *Proceedings of the American Control Conference*, 1341–1349.

Goupil, Philippe (2010). Oscillatory failure case detection in the A380 electrical flight control system by analytical redundancy. *Control Engineering Practice, 18*(9).

Grosman, B., Ilany, J., Roy, A., Kurtz, N., Wu, D., Parikh, N., & Cohen, O. (2016). Hybrid closed-loop insulin delivery in type 1 diabetes during supervised outpatient conditions. *Journal of Diabetes Science and Technology, 10*(3), 708–713. doi:10.1177/1932296816631568.

Holley, P. (2019). Amazon's one-day delivery service depends on the work of thousands of robots. *Washington Post*.

JDRF. (2019). FDA grants breakthrough device status: ilet bionic pancreas. Retrieved from JDRF website: https://www.jdrf.org/blog/2019/12/23/fda-grants-breakthrough-device-status-ilet-bionic-pancreas/

Joshi, S. S. (1999). The need for a systems perspective in control theory and practice. *IEEE Control Systems Magazine, 19*(6), 56–63.

Kim, E. (2016, June). Amazon's $775 million deal for robotics company kiva is starting to look really smart. *Business Insider*.

Lamnabhi-Lagarrigue, F., Annaswamy, A., Engell, S., Isaksson, A., Khargonekar, P., Murray, R. M., & Van den Hof, P. (2017). Systems & control for the future of humanity, research agenda: current and future roles, impact and grand challenges. *Annual Reviews in Control, 43*, 1–64. https://doi.org/10.1016/j.arcontrol.2017.04.001.

Lu, J., & Nath, R. (2014). Ethylene plantwide control and optimization. *The Impact of Control Technology*. IEEE Control Systems Society *2nd Ed*.

Meadows, D. (2008). In D. Wright (Ed.). White River Junction, Vermont, U.S.A.: Chelsea Green Publishing Company Ed..

Panetta, K. (2018). 5 trends emerge in the gartner hype cycle for emerging technoloties, 2018. Retrieved from Smarter With Gartner website: https://www.gartner.com/smarterwithgartner/5-trends-emerge-in-gartner-hype-cycle-for-emerging-technologies-2018/

Panetta, K. (2019). 5 trends appear on the gartner hype cycle for emerging technologies, 2019. Retrieved from Smarter With Gartner website: https://www.gartner.com/smarterwithgartner/5-trends-appear-on-the-gartner-hype-cycle-for-emerging-technologies-2019/

Personne, G., Lopez-y-diaz, A., & Delpy, P. (2005). ATV GNC synthesis: overall design, operations and main performances. *6th international esa conference on guidance, navigation and control systems*.

Qin, S. J., & Badgwell, T. A. (2003). A survey of industrial model predictive control technology. *Control Engineering Practice, 11*, 733–764.

Reinsel, D., Gantz, J., & Rydning, J. (2018). *The digitization of the world: from edge to core*. Retrieved from https://www.seagate.com/files/www-content/our-story/trends/files/idc-seagate-dataage-whitepaper.pdf .

Ridgely, D. B., & McFarland, M. B. (1999). Tailoring theory to practice in tactical missile control. *IEEE Control Systems Magazine, 19*(6), 49–55.

Rossiter, J. A., Zakova, K., Huba, M., Serbezov, A., & Visioli, A. (2019). A first course in feedback, dynamics and control: findings from an online pilot survey for the ifac community. *IFAC PapersOnLine, 52*(9), 298–305.

Samad, T. (1997). Visions of control. *IEEE Control Systems, 17*(1). https://doi.org/10.1109/37.569727.

Samad, T. (2017). A survey on industry impact and challenges thereof. *IEEE Control Systems, 37*(1). https://doi.org/10.1109/MCS.2016.2621438.

Samad, T., & Annaswamy, A. (Eds.). (2014). *The impact of control technology 2nd Ed*. Retrieved from http://ieeecss.org/impact-control-technology-2nd-edition.

Samad, T., & Stewart, G. (2013). Perspectives on innovation in control systems technology: compatibility with industry practices. *IEEE Transactions on Control Systems Technology, 21*(2). https://doi.org/10.1109/TCST.2013.2240531.

Sánchez-Peña, R. S., & Chernavvsky, D. R. (2019). *The artificial pancreas: current situation and future directions*. Elsevier. doi:10.1016/C2017-0-02120-1.

Quevedo Casín, J., Sánchez-Peña, R. S., Puig Cayuela, V., & Quevedo Casín, J. (2007). *Identification and Control*. Springer. doi:10.1007/978-1-84628-899-9.

Schon, D. A. (1967). *Technology and change: the new heraclitus*. Delacorte Press.

Statista. (2018, August). Number of mobile phone users worldwide from 2015 to 2020 (in billions). *Statista*. Retrieved from https://www.statista.com/statistics/274774/forecast-of-mobile-phone-users-worldwide/ .

Sterman, J. (2000). *Business dynamics: systems thinking and modeling for a complex world*. McGraw-Hill Education.

Group, The Radicati (2019, January). Forecast number of mobile devices worldwide from 2019 to 2023 (in billions). *Statista*.

Ting, T. (1999). Bridging the gap between the theory and practice of control: aerospace perspectives. *IEEE Control Systems Magazine, 19*(6), 45–48.

Van Dooren, R. (2014, May). Global scientific output doubles every nine years. *Nature.Com.*. Retrieved from http://blogs.nature.com/news/2014/05/global-scientific-output-doubles-every-nine-years.html .

Wolfenden, H., Sercombe, H., & Tucker, P. (2019). Making practice publishable: what practice academics need to do to get their work published, and what that tells us about the theory-practice gap. *Social Epistemology, 33*(6), 555–573. https://doi.org/10.1080/02691728.2019.1675098.

Young, P. M., Morris, J. C., & Ho, H. T. (2003). Servo control of a dual-stage actuator for a high performance disk drive. Part 2: controller design and implementation. In *Proceedings of the 2003 American control conference, 2003: 3* (pp. 2529–2534). https://doi.org/10.1109/ACC.2003.1243457.

Zolghadri, A., Henry, D., Cieslak, J., Efimov, D., & Goupil, P. (2014). *Fault Diagnosis and Fault-Tolerant Control and Guidance for Aerospace Vehicles, from theory to application*. Springer.