Technical Committee on Control Education

A First Course in Systems and Control Engineering

In recent years, the IEEE Control Systems Society (CSS) Technical Committee (TC) on Control Education focused on two main tasks: 1) supporting the partner International Federation of Automatic Control (IFAC) community in a survey of the worldwide community concerning priorities in university engineering control courses [1] and 2) outreach activities. The latter of these activities is currently undergoing a major refresh under Daniel Abramovitch and will hopefully be reported in a later submission. Thus, this contribution is focused on the former project. Moreover, we extend this slightly in light of the current COVID-19 pandemic to reflect on effective teaching practices.

BACKGROUND ON SURVEY

Most engineering undergraduates take at least one course on control engineering. However, historically, there has been significant variety in the focus of these courses, both across different institutions and countries. The TC felt that it would help both academics, students, and employers if there was some international consensus on what the priorities should be (while, of course, accepting that there would be some discipline and institutional differences). The survey demonstrated a remarkable consistency of views across the community for what could be considered 60–70% of the content, with differences largely being about what topics would be included in the last few weeks. As the results are already published [1], here we focus on summarizing some of the core conclusions and develop this by reviewing some of the repercussions on delivery. Specifically, we focus on developments in the community that support the survey outcomes while also being pertinent to the distance learning scenarios that are increasingly commonplace (and indeed necessary during COVID-19).

MAIN SURVEY OUTCOMES

There was an overwhelming consensus that a first course should focus on concepts, case studies, motivation, and context, as shown by the responses in Figure 1. It is more important that students understand why feedback is important and understand its impact, rather than become fully mathematically literate with a range of analysis and design tools.

Although some mathematical depth/rigor is ultimately important, students can develop this in time as they need it. Thus, this is initially included where necessary but not as an end. Consequently, anything requiring more advanced mathematical tools should be part of a second, rather than a first, course. The assessment of a first course is that it should not include too much algebra and proofs. Instead, it should focus on understanding concepts, perhaps supported by software for number crunching and experiments, as illustrated by the responses in Figure 2. Both academic and industrial responses agree on these points for a first course.

There was also consensus about the importance of first principles modeling, dynamics, and quantification of behaviors. However, only some disciplines were keen on including state-space approaches, with most believing

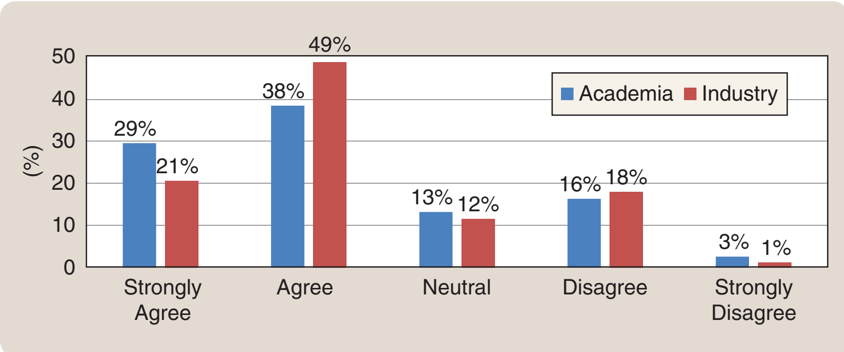

FIGURE 1 Survey responses focusing on concepts, case studies, motivation, and context.

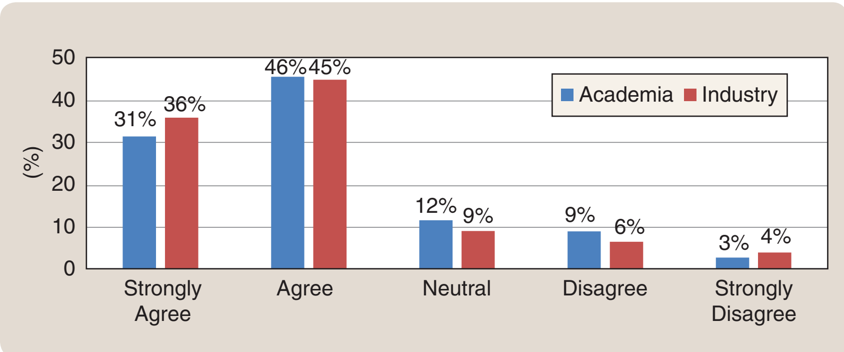

FIGURE 2 Survey responses on a first course, with simulations and experiments for conceptual understanding.

Digital Object Identifier 10.1109/MCS.2020.3033106
Date of current version: 18 January 2021

these models could come in a later course. Although not an overwhelming consensus, there was still a majority view that Laplace transform tools were appropriate for a first course, as depicted in Figure 3.

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It was taken for granted that not only should exposure to hardware be incorporated, but also (as much as possible) a first course should introduce students to authentic issues and challenges that will be encountered on industrial systems. A specific example that split the respondents was whether digital control should be included. This is obviously increasingly relevant. However, its inclusion potentially comes at the price of excluding something else.

There was a fairly universal desire for some exposure to proportional-integral-derivative tuning to be in a first course, given that this still dominates industrial practice (and thus, employers would expect some awareness at minimum). In terms of importance, this topic ranked third and fifth, respectively, for industrial and academic respondents, thus it is more important than most topics (for example, block diagrams, delays, and signal processing).

Although there is some evidence of national and discipline differences, that discussion is not pertinent to this article. However, what is more important is the recognition that, having agreed on a generic curriculum for a first course, the community must be better placed to curate and share effective and relevant learning resources and practices with each other.

TEACHING PEDAGOGIES

Good practice in education is constantly evolving. Hence, it is useful for academic staff members whose prime role is research to have a concise summary of good practice with which they can engage and implement courses. The engineering control community tends to be quite pragmatic in its approach, and numerous proposals have been published [2] in recent years (such as at the IFAC Advances in Control Education Symposiums and special sessions at major conferences).

The results from the control curriculum survey [1] support the argument for more project-based learning in control education. Traditional control curricula start with rigorous mathematical models and spend several weeks on mathematical manipulations before arriving at simple transfer functions for practical applications. During this time, students lose motivation and fail to see the connection to real-world practice. Project-based learning flips this progression. It starts with a relatively simple practical control problem, such as temperature control, and students develop control concepts and control intuition in the context of the specific problem (in many cases, by trial and error). Students then develop a much greater appreciation for the practical importance and relevance of the mathematical analysis. An essential prerequisite for project-based learning is the access to control laboratories.

One area of expertise and interest within the control community is how best to support student engagement with laboratory activities that are largely hardware based (but also software based). The community in Spain has been particularly active in developing and promoting online access to virtual and remote laboratories [3]–[7], and their work provides resources that are both accessible

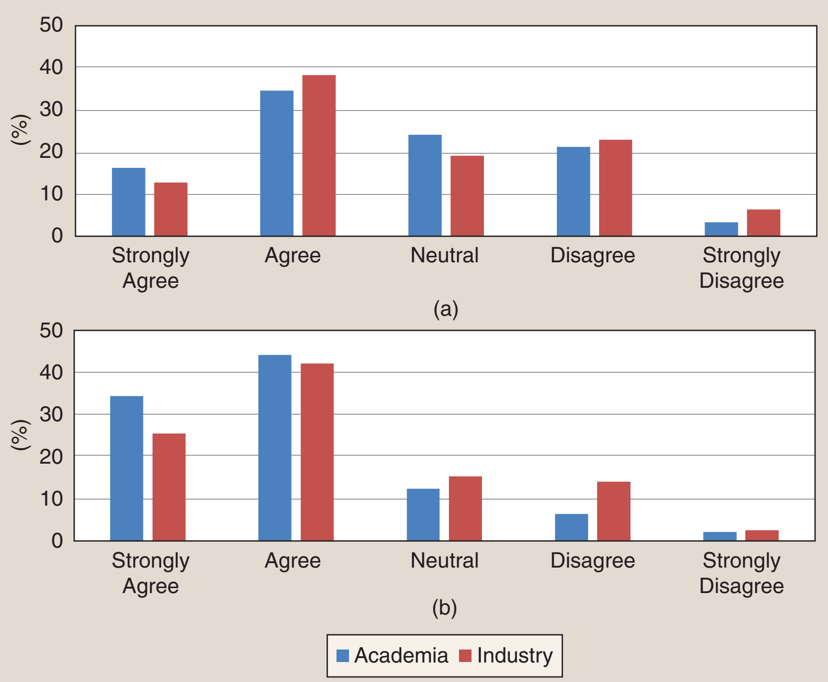

FIGURE 3 Survey responses: (a) state space and (b) Laplace/proportional-integral-derivative control.

A core skill for graduate engineers is the ability to learn independently and be confident in applying that learning to unseen scenarios (for example, through problem solving).

across the globe and offer templates for those who may wish to develop an in-house equivalent. Further evidence of pragmatism has also appeared in several recent publications [8], [9].

In parallel, a number of researchers have pursued the concept of take-home laboratories [10], [11], that is, real hardware that students can take home and thus access and experiment with using their own laptops. It is now accepted that such equipment can be built for as little as US$35 per unit, cheap enough to purchase and lend out to the entire cohort, thus incorporating interesting open-ended assignments and activities. A very successful and widely adopted kit is the one in [10], which includes a large number of prepared files in Python and Matlab, so that students can focus on the application of their learning. The first author's department developed a take-home static helicopter kit [11] (see Figure 4), which fits in a small toolbox to support more advanced control modules. This does, however, cost approximately US$300 per unit.

A core skill for graduate engineers is the ability to learn independently [12] and be confident in applying that learning to unseen scenarios (for example, through problem solving). A traditional didactic lecture format may not support this, as it can encourage students to perceive the content as given/fixed, rather than something they have a role in creating and understanding. Hence, the delivery must put sufficient onus on students to self-assess and reflect upon their own progress and actively manage their learning. Staff can scaffold this by providing students with guidance and support on how to develop their independent learning and self-assessment skills. Simple examples include computer quizzes and using Matlab tools to check their work. More advanced pedagogies such as flipped learning [13]–[15] take this one step further and can be very effective in helping students engage with their progress and develop confidence. A number of tools such as lecture response systems are now widely available to support these types of sessions.

It is interesting that the increasing focus on independent learning within higher education was accelerated by the recent COVID-19 pandemic, which is actively forcing many lecturers to update their delivery and resources accordingly. There is pressure to provide many more standalone resources [16], [17], including notes and short videos on core topics, quizzes, problems, and web-accessible laboratory activities. Such advances allow the contact time to focus more on the flipped learning model and active engagement, that is, the more challenging aspects in a course: group discussions and problem solving.

A BENCHMARK CONTROL COURSE IN THE POST COVID-19 ERA

A benchmark control course [18] should aim to contain many core components.

- Laboratory activities should be included such as quality hardware, if possible, and virtual and/or remote laboratories and/or take-home kits to reinforce and support further and deeper learning. These activities should be embedded into assessments to encourage engagement.
- Self-assessment resources are needed such as computer-based quizzes that students can use independently to assess their progress. Again, embedding these into assessments will encourage better student engagement. Projects at the one of the author's institution are looking at the potential role of such quizzes to form a baseline assessment for accreditation

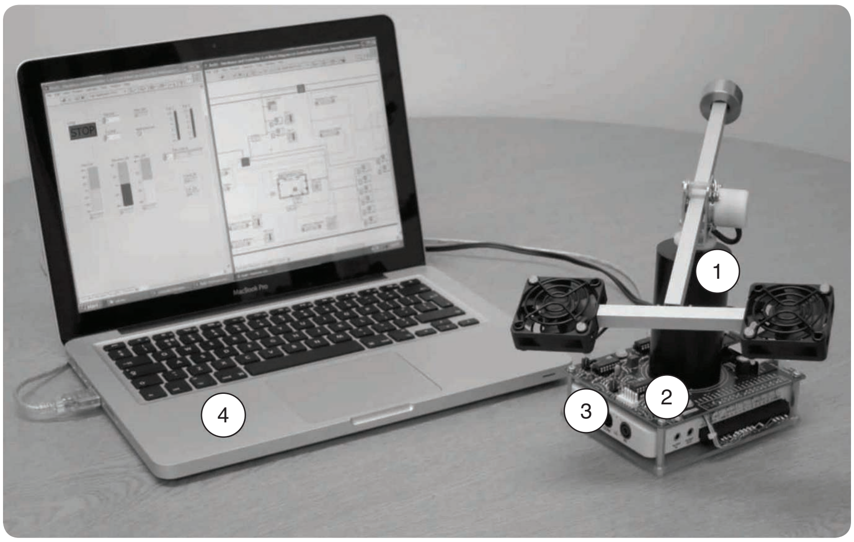

FIGURE 4 An example of a take-home helicopter kit [11] that students can connect to their laptops via a USB.

purposes [12], thus enabling end-of-year exams/assignments to focus solely on more challenging and interesting aspects.

- Appropriate learning tools should be provided on modern virtual learning environments (VLEs), such as discussions forums, file sharing, quizzes, assignments handling, and feedback tools.
- Learning outcomes for accreditation [12] are need that go beyond simple technical learning, such as presentation skills, problem solving, and independent learning.

A simple example of an introductory course covering modeling, behavior, and an introduction to feedback in Rossiter's department is summarized next. In general terms, the course received excellent feedback for its resources, design, and delivery:

- two 50-min interactive lectures per week
- weekly drop-in tutorials where students can get one-to-one assistance
- three pass/fail (easy-to-mark) hardware laboratories, supported by many optional virtual laboratories [due to very large numbers (~400), take-home laboratories cannot currently be used] to apply learning (students not adequately completing the compulsory preparation are refused entry)
- regular, short computer quizzes on threshold learning elements, with the students passing all the quizzes and laboratories achieving a bare pass; higher marks are available through end-of-year exam/assignments
- the use of a VLE to deliver all aspects of the course and including a discussion board that is checked daily.

It is useful for academic staff members whose prime role is research to have a concise summary of good practice with which they can engage and implement courses.

SUMMARY

The community has clearly established [1], [19] the type of content that should be in a first course, and there is also a developing appreciation in the community of good pedagogy in a blended approach to course design and delivery. This article summarized some of those aspects. The main call for the community is to improve the efficacy of how to design and deliver such courses and, moreover, share quality teaching resources to enable colleagues to both find and use such resources efficiently. This will be a main focus of the TC on Control Education going forward.

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