

Vision article



Control education for societal-scale challenges: A community roadmap

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ARTICLE INFO

Keywords:

Control education
Outreach
Industry
Curriculum

ABSTRACT

This article focuses on extending, disseminating and interpreting the findings of an IEEE Control Systems Society working group looking at the role of control theory and engineering in solving some of the many current and future societal challenges. The findings are interpreted in a manner designed to give focus and direction to both future education and research work in the general control theory and engineering arena, interpreted in the broadest sense. The paper is intended to promote discussion in the community and also provide a useful starting point for colleagues wishing to re-imagine the design and delivery of control-related topics in our education systems, especially at the tertiary level and beyond.

1. Present state and future outlook

1.1. Background and context

Most researchers will routinely be asking themselves lots of questions and the most significant of these will be: what are the important problems in society today and can my work make a positive difference to tackling those? The way we ask questions is also very much influenced by our expertise, employer and personal opportunities; these set a context from which we contribute. Consequently this paper begins from a premise that the authors and readers work predominantly in the control theory and engineering arena, where that topic is interpreted in a broad sense to include multiple themes such as: modeling, classical and modern feedback, industrial applications, biological and health applications, aerospace applications, data handling and data security, fault diagnosis and detection, and clearly much much more.

The IEEE Control Systems Society (CSS) has set as one of its goals to support the wider community in answering such questions so that we can direct our research and educational efforts more wisely to help tackle societal-scale challenges. Towards this goal, the CSS set up a working group to provide and disseminate a report. One purpose of this paper is to ensure the findings of this roadmap report (Annaswamy, Johansson, Pappas, et al., 2023) can be disseminated effectively to a global audience. Moreover, this paper also aims to extend and interpret those findings to deliver a more holistic message, which the authors hope will be useful to all readers.

1.2. Scope of project

Many of us will at some point have been actively involved in the delivery of an introductory control theory course while others

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<https://doi.org/10.1016/j.arcontrol.2023.03.007>

Received 9 September 2022; Received in revised form 26 January 2023; Accepted 13 March 2023

Available online 17 March 2023

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may simply recognize the role and importance of such courses. An introductory course is focused on getting students to understand why the topic is so important. In simple terms, for numerous aspects of life, from controlling speeds of motors, temperatures in tanks, growth rates of plants, drug concentrations in patients and many more, the behavior of a system (equivalently its output/states) is often critically important. In control theory and engineering, we seek both to understand where behaviors come from and how we might influence them for the better.

Significantly, what has changed in recent years is the scope of control (Antsaklis et al., 1999; Lamnabhi-Lagarigue et al., 2017; Murray, 2003). Students from an older generation may have viewed feedback in a rather narrow sense considering largely traditional manufacturing contexts, PID loops and some exposure to frequency response methods. More significantly, a control theory course would likely have been much more focused on a mathematical formalism. However, it has become clear in recent years that feedback loops have far more extensive presence and impact and that we need to broaden our horizons to consider areas of significant societal importance such as: (i) climate change; (ii) efficient and sustainable agriculture/farming; (iii) space exploration; (iv) transportation; (v) underwater vehicles; (vi) biomedical science; (vii) economics and finance; (viii) pedagogy and, of course, this list could easily be extended far more.

One might call this a “change in awareness” but it calls for a significant change in many respects including a proper discussion on curriculum design and delivery (Rossiter, Zakova, Huba, Serbezov, & Visioli, 2020), as well as the focus of academic research. One core aim of this paper is to give academics the evidence and confidence to argue for change in their own institutions and research funding bodies. We all need five-year plans for the control curriculum, but perhaps now is the time to think even longer term and consider more drastic changes; how do we develop students and researchers who will have the skills and awareness to make a difference in the 21st century?

1.3. Paper organization

The paper is organized into separate themes for clarity.

1. Section 2 focuses on mostly earlier work in the education area. What skills will control engineering graduates need and what are the repercussions on curriculum design and delivery? This section largely forms the background for the subsequent sections.
2. Section 3 includes the major contribution and talking points of this paper. It builds on the previous section to anticipate the skills and projects that students will be working on in the future and how we might prepare for this and indeed motivate students to engage with it? This section summarizes the key findings from the CSS roadmap report (Annaswamy et al., 2023) and readers will be particularly interested in the concise summary of Section 3.6 which gives a clear handle on things they can use.
3. Section 4 is also a major contribution in that it gives in substantial detail some case studies from institutions across the globe and evaluation of good practice that readers can use as templates for adoption in their own institutions.

For reasons of space and clarity of messaging, the authors have decided not to discuss the critically important aspects of outreach and the changing needs of and interaction with industry. It was felt that these topics would be better served in separate articles.

2. Control education in the 21st century

This section focuses on tertiary education and open-access learning resources. Reflecting on the needs of 21st century society, what palette of undergraduate and postgraduate courses should we be offering students? For simplicity and calibration, we take a short course to be something like a 20 lecture-hour block with associated assessment.

We have to take into account that modern engineers are asked to face more and more complex systems, which are often both interconnected and continuously changing. Thus, engineering education in general should provide a solid theoretical background but also those soft skills (e.g. problem solving, team working, adaptivity, learning capabilities, communication, etc.) that are essential to rise to the challenge. In this context, control can play an important role because in addition to being based on rigorous mathematical concepts, it also naturally takes a multidisciplinary perspective and has a wide variety of applications. Teaching modalities in control courses should therefore take into account these aspects and exploit new technologies for this purpose. This can be accomplished, for example, by suitably mixing face-to-face and online lectures, by assigning problems to be solved with take-home laboratory kits, by devising projects to be developed in teams, and more.

It is noted that this section focuses primarily on undergraduate provision, but as indicated in Section 4.5, many of the generic findings implicitly carry forward into postgraduate and further training and how we as a community support that.

2.1. Recent community surveys

The technical committees (IEEE, 2022; IFAC, 2022) on control education for both IFAC and the IEEE CSS recently carried out a global survey on what would constitute the ideal first course in control (see Rossiter, Hedengren, & Serbezov, 2021; Rossiter et al., 2020 where all the details can be found). Almost 500 answers have been collected from instructors from 47 countries around the world (China, Brasil, USA and Italy have been the most relevant contributors). One could argue that the mindset behind this survey was fairly traditional by being focused primarily on fundamental concepts and associated mathematical tools. Nevertheless, the most important conclusion was slightly controversial in that it argued for a reduction in the emphasis on detailed mathematics and proofs and, instead, more stress on conceptual issues such as: why is control important?

As such, that survey provides a useful foundation for the discussions in this paper which develop that argument further. Indeed, we also want to expand the question to say: how would you design the curriculum for a second, third and more courses in control and what learning would you emphasise and why? It is evident in the following that the vision being presented here cannot possibly be achieved in a single course and thus the prime findings of the original survey likely still hold. However, in order to encourage students to focus more on control in their later studies, what should we be doing?

In summary, it appears that the main topics related to an introductory course (that is, the main concepts related to system analysis and feedback control) are fully covered in the survey, although, of course, there is always the need to provide solutions that can be easily customized by the instructor according to their requirements.

2.2. An ideal first course in control (Rossiter et al., 2020)

As this is already published, we keep this summary very brief. A first course (Rossiter et al., 2021) should focus primarily on concepts, getting students to understand the critical role of modeling, feedback and behaviors in the world, using examples from a wide range of scenarios. While some mathematical content and rigour are important, these should not be over-emphasised at the expense of enthusing students. Software packages and laboratories could be used extensively (e.g., see the case studies in Section 4) to support the learning and reduce the requirement for tedious pen and paper computations. Detailed mathematical developments for topics such as frequency response, state-space models and analysis, z-transforms, signal processing and so forth, which are essential in the preparation of a control engineer, should be provided in a later (or larger) course.

To finish, it should also be noted that the first course would be early in the curriculum, which is enabled by slightly reducing the mathematical requirements, compared to a traditional mathematically heavy course. This increases the potential impact on the whole student body. This description is somewhat vague, but exemplars of what could be included in such a course are given in Section 4 alongside some aspects of how these broader aims might be delivered.

2.3. Broadening our view of what control engineering involves

One hope of this paper is to give greater visibility to views on the content of a first course in control theory and engineering. It is evident that modern engineers need to be more versatile and adaptable than in previous generations (Murray, 2003), and this extends to an awareness of how core insights and understanding may apply across a diverse range of disciplines.

As described in Murray (2003): “[a]t its core, control is an *information*, and includes the information in both analog and digital representations. Increasingly, control is carried out in a digital fashion, and the advances in computation and networking, combined with the role of data-driven techniques, is fundamentally changing what control engineering involves”.

Traditionally, control has been taught in aerospace, chemical, electrical, and mechanical engineering departments, often in a manner tuned to those disciplines. However, there is increasingly an audience for control insights and tools that goes beyond these disciplines. Perhaps chief among these is computer science, which is increasingly a key home to students who go on to work with a variety of feedback systems (e.g., robotics and autonomous systems, large scale information systems and networks, on-demand services). Computer science students typically have a much different mathematical background (focused on discrete, rather than continuous, mathematics) and an appreciation for the role that software plays in the modern world. Teaching control theory to this audience is likely to be different than teaching it to a mechanical (or electrical or chemical) engineer.

Other domains in which ideas from dynamics, modeling, feedback, and uncertainty are important include biology, ecology, economics, mathematical statistics, and physics. Biology is a particularly interesting case from an educational perspective, since the level of mathematics required in most biology curricula is less than that of a traditional engineering program. But the concepts and insights of feedback and control are incredibly relevant in modern biological systems, and we must seek ways to reach out to this audience if we wish to provide the tools that biological scientists and engineers need to be successful.

Related to the question of what audiences are trying to reach is what set of insights and examples we should use for any given audience. As articulated elsewhere in this article, control engineering is now done at multiple levels of abstraction and across multiple disciplinary domains. The core ideas of dynamics, uncertainty, feedforward, and feedback apply almost universally, but the details can be very different if one is implementing a scheduling system for on-demand transportation systems versus an autonomous vehicle versus a modern turbomachine. Whenever possible, one should seek to at least demonstrate key concepts in a way that transcends the specific domain of a given example, allowing students to take away the key ideas of using feedback as a tool to manage uncertainty and to design the (closed loop) dynamics of a system, along with some of the fundamental limits and tradeoffs that cut across all layers of abstraction and application domains.

A key question in both reaching out to new audiences and describing control in a broad way is whether to try to teach a single course that is accessible to all students (as was advocated in Murray, Waydo, Cremean, & Mabuchi, 2004) or to develop specialized courses that are tuned for a given audience/approach but still provide a broad perspective that demonstrates the utility of control concepts across multiple domains. To a large extent, the approach will likely depend

on the organizational structure institution, the background of the students, and the desired size and breadth of classes. But *any* course in control should make sure to convey the broad view that we describe here, illustrating the power and limitations of feedback in modern applications.

2.4. Open access resources

While running the first survey (Rossiter et al., 2020), it became apparent that one thing the community could do better is share resources with each other. It makes no sense for individuals around the world to re-create each other's work, especially when one individual may have created excellent resources that we all could use, e.g. Albertos (2017), Douglas (2022), Egerstedt (2022) and Rossiter (2022). Obvious examples include inexpensive take-home kits (Oliveira, Hedengren, & Rossiter, 2020; Rossiter, Pope, Jones, & Hedengren, 2019; Taylor, Jones, & Eastwood, 2013) and virtual/remote laboratories (Brinson, 2015; de la Torre, Sanchez, & Dormido, 2006; Heradio, de la Torre, & Dormido, 2016), but clearly this argument also applies to lecture slides and other supporting materials like MATLAB, Python and Julia code (e.g. Julia, 2022; Koch, Lorenzen, Pauli, & Allgower, 2020; MathWorks, 2022; Python, 2022; Rossiter, 2017) and more.

As part of the IFAC 50-year celebrations, a temporary control education resources website was created and subsequently a member of the Spanish community offered a website as the base for a more formal repository (Control, 2022). However, neither of these was particularly effective in achieving high visibility to the community or gathering a wide range of resources.

In recent years, the IFAC council also ran a pilot project on the potential for developing and maintaining a control repository, but sadly decided that the economic costs of doing this well were beyond their means and thus, at least for the time being, have paused any work on this. Hence, in the last 2–3 years (Rossiter et al., 2022) the Technical Committees on Control Education of both the IEEE CSS and IFAC have been working together on a vision of what form of repository they can provide, which is sustainable and, critically, highly visible and useful to the community.

The main idea that has emerged is that creating and maintaining a website with all the resources hosted in it is not sensible because it would require too much effort for one or more individuals who act on a voluntary basis. It is more feasible to have a website with links to the different resources, which remain in their original position and are maintained by their creators. Further, the single resource is not validated, but its assessment is left to the user. There is, therefore, the need to constantly check that the links are working, which requires a much more reasonable effort. The main challenge in this context is to organize the website so that the users can easily find the most suitable tool for what they are looking for and do not get lost in it Douglas (2022). For example, the resources can be categorized according to the topic, to their level (introductory, advanced) or to their format. Providing a search engine is also challenging because it requires a well-defined taxonomy of the topics.

The first step toward this goal has been a survey to collect freely available resources related to the first control course. Preliminary results of the survey indicate that the main type of resources are videos, virtual or web-based interactive tools and remote/take-home labs. Regarding videos, it is worth mentioning that there are many open online modular courses and channels on youtube. There are also holistic resources that aim to cover almost all the topics related to a first control course. Finally, there is an increasing interest in providing apps (Quanser, 2022) that can be easily accessible by the students through their smart phones.

A control repository is really essential for diversity and inclusion. The availability of open access web resources would allow a significant improvement in the learning process of people with specific learning disorders or disabilities. Further, they can serve as a social elevator for students who have low incomes to increase the level of their education and therefore to boost their career.

3. A roadmap for the future of control and repercussions on education

This section describes and slightly extends the main outcomes of the CSS working group (2019–2022) (Annaswamy et al., 2023).

3.1. Present state and future outlook

As outlined in the introduction, a core aspect of control is a proper understanding of system behaviors. How do different systems behave and why do they behave that way? Building on an understanding of behavior, the next critical question is: what behavior would we like and what controls do we have to enable the desirable behavior? Of course, the natural follow on is: how do we use these to control degrees of freedom in a systematic way?

What is changing in the modern world is our realization of which systems or system behaviors we as engineers can work on. As our theoretical understanding has developed alongside a huge increase in computational power at relatively low cost, it is now feasible to tackle far more complicated problems than considered even just a decade ago. In parallel, we can equally demand far better performance than it was possible to deliver with more simplistic or traditional control strategies. Finally, engineers are increasingly noticing the synergies between the classical view point of control engineering and numerous societal problems which are amenable to similar solutions. Examples include: (i) Feeding the world and digital farming (Cabrera, Pedrasa, Radanielson, & Aswani, 2021; Caceres, Millan, Pereira, & Lozano, 2021); (ii) climate change (Satue, Castano, Ortega, & Rubio, 2021); (iii) space, the final frontier (Negri & Prado, 2021); (iv) underwater exploration (Rentzow et al., 2021); (v) biomedical and disease control (Cassany et al., 2021; Estigarribia, Bliman, & Schaerer, 2021); (vi) the sharing economy (Persson, Andersson, Fattouh, Ekstrom, & Papadopoulos, 2021) and indeed the reader could easily expand this list in many different directions. The realization above sets a critical challenge to universities and the control engineers within them: How do we prepare the engineers of the future for this changing world?

It is clearly apparent that the classical control courses focused on electro-mechanical or chemical processes and PID control are far too limited. We need to expose students to the huge breadth of potential applications and to the skills and techniques they will need. Following on from the above challenge, some recommendations of the CSS roadmap working group are:

1. Existing first courses in Control Systems should emphasise and discuss the broader applicability of control.
2. Courses in Control Systems should be introduced earlier in the curriculum and, where local conditions allow, teach fundamental control concepts to a broader class of students.
3. Modular organization alongside open-access (creative commons) availability of teaching material allows more flexibility in course design and delivery. This facilitates better targeting of content and delivery to different cohorts.

The following sections explore these recommendations in more detail.

3.2. Updating the first course in control for broader applicability

As noted above, we are now able to deal with far more complicated systems, which include non-linear dynamics, event-driven dynamics, hybrid dynamics, cyber-physical systems, and much more. This variety of applications needs to be properly represented, even in an introductory control module, so students can see where their skills will be needed. Moreover, there is a need for different mathematical skills and approaches that go beyond the traditional linear ordinary differential equations.

3.2.1. Frequency domain vs time domain

The recent survey (Rossiter et al., 2020) already made the point that frequency domain, while still a useful tool, could be considered somewhat of a “niche” and less appropriate to a first course seeking to motivate students and expand their horizons. The working group re-emphasised this point and argued that it would be more beneficial to students to expand their awareness of a broader range of modeling and analysis tools (see Section 4 for examples). Frequency response and indeed root-loci methods apply to linear models, but many of the challenges to society involve non-linear or discrete event or hybrid models, where linear approximations are not appropriate. As academics, we need to forge a balance in what we teach, so while traditional design methods, including frequency response, still have a role (and indeed PID approaches will still dominate many applications), these are relatively straightforward to pick up as required. Control education should strive to expand the student’s horizons rather than solely preparing them for the mundane.

Many frequency response insights and approximations were required in a pre-computing era, whereas now it is more productive to spend the time ensuring core concepts are understood and perhaps to use modern computing tools (Lynch & Becerra, 2011; Rossiter, Giaouris, Mitchell, & McKenna, 2008) and optimization to short-cut unnecessary details; no doubt students who choose to become control engineers will study and learn the fine details and coding when required.

Recommendation: Students are often not interested in mathematically elegant approaches and these are less important to the current average student.

3.2.2. Adapting to our students

Current students have grown up in an age of smart phones and tablets with intuitive software interfaces and the ability to search the web for any topic, anytime, anywhere. This has colored their perceptions of learning and indeed, more importantly the way they can learn. If we try to painstakingly develop complex and abstract mathematical foundations under the justification that it will come together by the end of the course, students can easily become disengaged and choose another course at a loss to our community.

Recommendation: Although it may go against our historical principles, it is better to begin with applications to motivate, computer tools (like MATLAB and/or Python, which both offer a great catalog of ready-to-use control applications and examples) to solve some interesting problems and only then gradually introduce the mathematics and physics that students will ultimately need.

3.3. Introducing a control systems course earlier, for broader audiences

Consider the titles: “Control systems” and “Building autonomous systems” or “Introductory AI for engineering systems”. While it sounds trite, the buzz words of “AI” and “autonomous systems” are more likely to garner interest so that students investigate further. Moreover, even where a module is core, a title that communicates modern and personal relevance will impact student attitudes and expectations as they begin lectures; indeed, one author’s experience is that the exact same course/delivery gets very different student evaluations from different engineering cohorts even though they sit in the lecture together; perceptions of relevance impact experience! An enthusiastic student is more likely to thrive and study hard.

Recommendation: It is timely for institutions to reflect on their choice of course titles.

It is important to recognize the different educational systems worldwide. For many engineering programs, exposure to a single control theory course is mandatory, but this may or may not be a separate course or embedded in other larger courses; moreover, it may not be until year 2 or even year 3. Later exposure is an obvious disadvantage should one want to engage interest in the many possible electives that

could follow and thus there is an argument that the first course should be in year 2 at the latest.

Given the importance of control and, in modern parlance, topics such as AI, it would be hard to defend many engineering courses where control was not included early enough and we have a duty to argue for this with our colleagues. However, more critically we need to ensure these courses are well-received and relevant to the modern world. It is more important that a first course enthuses and motivates students using a broad range of scenarios rather than dealing with detailed mathematics. Without a broad range of motivated students, where will the future control engineers come from?

3.3.1. Key concepts to emphasize

To some extent, control is about managing system behaviors and thus the fundamental part of a first course is to engage students with an understanding of what are “behaviors” and how are these classified for convenience and comparison/evaluation? This view leads naturally into the topic of modeling, as behaviors follow the model. Thus, a good amount of time needs to be spent unpacking the different types of models that can represent real systems and scenarios; these could be linear ODEs, PDEs, discrete event or hybrid systems, data driven systems, and more. Naturally, there is no time to introduce such a wide range of models and associated behaviors in detail, so decisions need to be taken as to the extent to which detailed mathematical analysis is used as opposed to or in addition to the use of computer simulations and/or hardware experiments. Also, the institutional context is critical here, as there may be many interesting electives students can be pointed to covering these topics.

Some mathematical precision is likely to be essential. There are many core concepts in behavior such as stability, transient behavior, speed of convergence and damping, which need quantifying so that we can define meaningful criteria for comparing and contrasting activities and design.

Nevertheless, a key aspect of modeling is the realization that models are always approximations and thus the quantifications of behavior are likewise approximations. A closely related characteristic of behavior is adaptability/resilience or, in more traditional terms, the ability to retain its behavior in the presence of unknown factors such as disturbances and faults (parameter changes). A core motivation for the use of feedback is to deal with uncertainty so there should be a seamless story. The challenge is to communicate the core concept of feedback, and its critical presence in numerous diverse scenarios, without being too occupied by detailed mathematical analysis whereby students lose the connection to the core concepts. One could further argue about whether true adaptive control is a seamless extension to this and could or should also be discussed as a motivational device, obviously using computational tools rather than detailed analysis which is more suited to a later elective course.

3.3.2. Modeling and simulation methodologies

It seems more reasonable for the modeling aspect of a first course to be focused on the time domain using, for example, component equations and balance relationships. Typically, simple examples lead to low-order ODEs and simple state automata, while more complicated examples are best handled using simulation packages that generate trajectories from more complicated ODEs or state automata rather than developing modeling equations whose explicit solutions may not be feasible to obtain. While it may be appropriate to use Laplace transforms to support behavior analysis in some institutional contexts, as a general rule, frequency response would be avoided in a short first course and left for an elective.

A core point here is that solving ODEs (or Laplace transforms) by hand is tedious and one would expect appropriate use of computer packages to support visualization of behaviors across a broad range of scenarios and parameters. Indeed, this also allows easy extension to higher order systems and potentially more interesting examples which

the lecturer can provide pre-packaged for the students to use. Such pre-packaged scenarios can also include a variety of important and realistic issues such as uncertainty, faults and disturbances. One of the authors has a number of these coded on MATLAB (e.g. Koch et al., 2020; Rossiter, 2017) which students seem to appreciate and other authors have found Python and Julia popular (Julia, 2022; Python, 2022), the last two presenting the advantage of offering a free and open-source solution.

3.4. Modularizing the teaching experience

As discussed in Section 2.4, a clear benefit of an effective repository of teaching aids is that high-quality resources will be readily available to the global community, both staff and students, and in a plug-and-play form. This vastly increases the flexibility to develop new courses with a reduced workload, or indeed, to produce micro-courses which cover only 2–4 lectures of content. Naturally, this type of concept has long been popular on YouTube and similar platforms (e.g. Khan, 2022; Rossiter, 2022), but it is something we, as a community, should take the opportunity to exploit better.

The COVID-19 pandemic, forced many lectures to be held online, has given a great boost to teaching modalities that differ from the traditional frontal teaching. In fact, students have perceived some clear advantages of the increased availability of video lectures and web resources at a very large scale. They can facilitate a new learning paradigm where the students select by themselves courses based on their own needs and preferences (for example, a teacher who explains a topic in a clear way with the required level of details). On the one hand, this personalized education might be beneficial for a person who can select their best path for their learning process, but, on the other hand, there is the clear risk that the student becomes lost in the vast ocean of available resources. The real challenge is, therefore, to organize the resources in a proper way, for example by providing selected “journeys” (Douglas, 2022) and by classifying them according to the required background, their goal, the system requirements in case of software tools, etc. There are also big issues that need to be addressed, such as the option to give comments/feedback from the user and the option to modify/add some material (in a wiki-style fashion). At this point, instructors should also possess the new ability to provide the right suggestions to a specific student in order to complement their teaching activity as well as possible.

There are two obvious scenarios we may wish to prioritise:

1. A lecturer wishes to redesign their course from scratch, but has limited time.
2. Continuing professional development (CPD) where a practicing engineer wishes to upskill in a focussed area.

For the former, we can support teaching staff by providing suitable resources in plug-and-play form so that minimal editing is needed to modify for the local context. Some good examples of this will be given in Sections 4.1, 4.2, 4.3. Effective laboratories, either hardware or software-based, take significant time to develop so it is even better if we can pick up and use resources developed elsewhere which cover in a high-quality manner the learning outcomes we are interested in. Better still if these resources are free or very low cost. For the latter scenario, Section 4.5 gives an excellent exemplar of how we can support CPD.

Naturally, teaching resources could also extend to Powerpoint slides, short videos, code snippets, jokes and more. A core point here is that if those resources are modularized effectively into small chunks so that they can be adopted standalone, then they are much more useful for sharing. Moreover, they are also much more useful to the end user who may need to upskill in a narrow topic area and wish to do this efficiently without having to engage with a whole course worth's of material first. In the authors' view, this modularization of learning is likely to become far more prevalent as the 21st century progresses and we should prepare for this.

Recommendation: The essential thrust of the arguments in this section imply that the role of historical textbooks needs to change. Staff and students will not want to purchase a 400-page tome covering everything; rather, they will want to be able to select from a range of 10–20 page resources with far greater focus. The change to mainly online access of textbooks has probably already occurred, so this slight adaption should be straightforward.

3.5. What resources do we want and why?

Having argued that modularization into relatively small chunks is the future, the control community will need to decide how they support and facilitate this, and indeed how material is clustered and stored effectively. The discussion on this is ongoing in the Technical Committees of the IEEE CSS and IFAC (Rossiter et al., 2022) and so now is timely for colleagues to support and direct this initiative.

It is likely that the modules will need to be separated. It is important to have some motivational, and perhaps more superficial, content such as: (i) the power of feedback and (ii) simple AI techniques. There will also be a need for modules with more in depth technical and mathematical content. This will need to be separated into themes such as (this list is not exhaustive but rather illustrative):

1. Modeling: (i) linear system modeling; (ii) non-linear system modeling; (iii) an introduction to hybrid systems (time-driven and event-driven dynamics); (iv) computational models; (v) data-based models; (vi) adaptation and learning; etc.
2. Behaviors: (i) how do linear systems behave; (ii) managing behavior; (iii) non-linear behaviors; etc.
3. Feedback: (i) Why is feedback important?; (ii) Practical feedback implementations; (iii) Common feedback design; etc.
4. Applications: (i) Automotive; (ii) Aerospace; (iii) Biomedical; (iv) Energy; etc.
5. Emerging topics such as system of systems, security, etc.
6. Control modeling and design tools: (i) PID; (ii) MPC; (iii) Supervisory control; etc.
7. Hardware: (i) sensors; (ii) actuators

It is implicit that within each theme or topic, resources should take a variety of forms such as:

1. Notes, handouts and slides.
2. Tutorial sheets, exams, assignments and online self-assessment tools if possible.
3. Simulation tools, scenarios and code to support independent investigation.
4. Laboratories (virtual, hardware and take home) with relevant staff/student information packs.
5. Videos, audios and other learning resources.

3.6. Summary: Adapting education delivery to the 21st century and its students

This section has made a number of recommendations which are summarised here for clarity.

1. A first course would be better to begin with motivating applications and with computer tools to solve diverse problems from a wide range of modern challenges and only then gradually introduce the mathematical tools and analysis.
2. Modern students are often not interested in mathematically elegant approaches and perhaps teaching staff should adapt to the students rather than the other way.
3. Institutions should reflect on their choice of course titles and use these to communicate relevance and excitement.
4. Learning and teaching resources should be modularized into small chunks for ease of sharing, use and adoption.

5. Future courses are more likely to be arranged around a diverse range of online resources rather than a single textbook. These could be wrapped into “journeys” (Douglas, 2022) for ease of use.
6. Modern technology has opened the door to cheaper and easier access to hardware/laboratory experiences which should be exploited.
7. While not discussed in detail here, the community needs to consider far more carefully the likely context and skills requirements of the future engineers and redesign our courses accordingly. We can expect that while mathematics and rigor will remain important, the focus and timing of the methods is likely to change.

4. Case studies

Some readers may view this section as the most important. The aim is to give concrete examples of how our curriculum can be brought into the 21st century in terms of:

- The topics we teach and the emphasis different aspects are given.
- How delivery and student engagement is managed.
- How we use laboratory exercises to support student development.

The section provides exemplars of good practice from several different sources, and many of these resources are already open access, hence easy for staff to adopt. The first focuses on the holistic design of a *large* first course, student motivation and engagement, alongside modernizing the curriculum. The second focuses on the expanding area of *take home laboratories* (Oliveira et al., 2020; Rossiter et al., 2019; Taylor et al., 2013) and how these give students opportunities to develop independent learning skills and a deeper understanding of core principles. The next two exemplars continue on the theme of laboratory-like exercises and look at the role of virtual and remote laboratories in supporting holistic student learning and also the key factor of student engagement and enthusiasm. The final case study considers postgraduate education and the researchers of the future and how we, as a community, can better support them.

4.1. Exemplar large first control course from University of California, Berkeley

EECS16AB “Designing Information Devices and Systems” is a two-semester course sequence designed to be taken by first-year students at Berkeley, and offered by faculty from the Electrical Engineering and Computer Sciences department. As will be clear, this is a substantial commitment, but that provides opportunities to achieve much more holistic learning and development. Students typically take two or three technical courses a semester at Berkeley so this course would comprise a third or more of their year’s studies. A typical schedule for a student in their first semester would include EECS 16A along with an introductory programming course (CS 61A). EECS 16B would be taken in their second semester along with a more advanced data-structures/software class (CS 61B).

The course requires students to have taken Advanced Placement (AP) calculus (AP, 2020) (or an introductory college calculus class) and has no physics prerequisites. It is designed to be taken concurrently with an introductory computation/programming class (such as CS 61A at Berkeley). EECS 16AB provide a strong foundation in linear algebra, as well as an introduction to machine learning, circuit design, control and signal processing. A series of hands-on labs showcases how the mathematics has concrete impact through engineering applications. By the end of the two course sequence, i.e. the end of 16B, the students complete a final project (in groups of 2–4 students) where they build their own robot car that responds to voice commands (see Fig. 1 for a student showing off her final project). This is an integrative project that combines ideas from all the areas mentioned earlier. It showcases



Fig. 1. A proud student showing off her final project, the voice-controlled robot car in EECS16B at UC Berkeley at the end of her first year. The project uses principal-components-analysis to learn the voice commands and pole-placement for control of the car.

the full stack of modern data-driven design to students — from doing experiments and collecting the data, to learning a model based on it, to designing a decision-rule/control-law based on this model, implementing it, and observing how it behaves in the physical world. For all of this, they have built circuits, programmed a microcontroller and used Python to identify system dynamics (learn the model) and build a classifier.

The course sequence is built around six modules as below:

- (16A) Introduction to systems (tomography/medical imaging, matrices, inverse problems, PageRank)
- (16A) Introduction to circuit design (touchscreen design, circuit components, basic feedback using op-amps)
- (16A) Introduction to machine learning (GPS design, least squares, sparsity, Orthogonal Matching Pursuit)
- (16B) Introduction to differential equations (Transistors, CMOS, RLC, time constants, filters)
- (16B) Introduction to robotics and control (Stability, controllability, feedback)
- (16B) Introduction to unsupervised machine learning and classification (singular value decomposition, principal components analysis, linearization, classification)

4.1.1. Course philosophy

Here we try to explain some of the objectives behind the design of these courses.

- **Inclusive:** 16AB students have different backgrounds, personalities, and a-priori interests. It is often unclear to students what practical problems can be solved by an engineer. Our goal is for each student to find *something* in the course that resonates with them. While some students may have access to family in STEM fields, many have not. Many students come to us without fully knowing what the words signal processing, machine learning, or design even mean. Our goal is to demystify this jargon, all while providing tangible examples of what engineers can do with mathematics (and allow students to immediately achieve these in the lab.) We try to reflect the diversity of intellectual work in

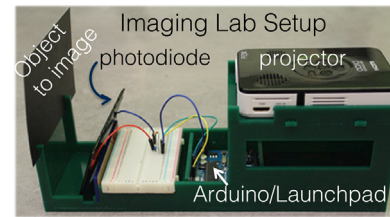


Fig. 2. Illustration of the Imaging Lab in EECS16A. The projector illuminates the object to image, and the reflected light is collected by the photodiode, which is connected to the Arduino. By using different illumination masks, we collect different linear combinations of pixels from the image, and can use matrix inversion to generate the image.

an engineer's life: students are exposed to modeling and mathematical work, debugging in hands-on labs and writings software. The diversity of perspectives allows students to find their niche — what is the application that motivates them or the skill they excel at? In a STEM environment where many students are exposed to negative stereotypes such as 'brogrammers', this diversity can allow students to find an intellectual home and feel they belong.

- **Supportive:** The course provides high-touch instructional resources to help students be appropriately supported with the challenging material so they can all succeed as individuals. We use a non-curved grading policy to this end, and provide many different, non-traditional avenues for students to engage with the material, ranging from social dimensions, diverse applications, diverse role models, teaching opportunities. Students can earn extra credit through art and media projects related to the course (we have had students writing songs or making videos about the course).
- **Motivating, Empowering, and Inspiring:** Since we want to reach all students, even those who are not necessarily committed to engineering, we try to have every concept be motivated by a concrete application. A student may not be a-priori motivated to memorize the formula for a matrix inverse. However, using the concept of inversion to build a camera and understand medical tomography provides a concrete motivation to study mathematics that might otherwise seem esoteric (see Fig. 2 to for the hardware setup of the tomography lab). As a concept is developed, we aim to empower students to do something that they could not do (or even conceive of) before. With this in mind, homeworks connect to a wide range of applications even beyond the lab (ranging from biomedical applications to home appliance design). While programming is required for the course, all assignments are Jupyter notebook-based and require minimal coding with skeletons largely provided, and the students only do the mathematical parts of the programming.
- **Foundational and Rigorous:** The goal of this course is to prepare students at the level of a single-semester lower-division linear algebra course in the Mathematics department, and maybe a little beyond. Based on a backbone of linear algebra, we build out the foundations of linear circuit analysis, control of dynamical systems and learning from data. Definitions are motivated and then results are derived, albeit often in simplified models. The idea behind modeling and how to use this idea is explicitly discussed. We try to get students to question assumptions, explicitly introduce proofs and talk about design and debugging. The course goes significantly deep and is not intended to be a survey class.

Admittedly, the goals for the course here are a bit ambitious, and achieving them comes with some trade-offs. First, in order to be able to discuss applications in detail, we spread out the content of a one semester linear-algebra course over two semesters. We also rely on

students having taken calculus in their high-school or community college.¹ We also require that students take a Python-based introductory CS course as a co-requisite to be adequately prepared. The course workload is quite high, with a total of eight minimum contact hours per week (three lecture + two discussion section + three lab) and additional time spent on homework. In order to be able to get to some of the more advanced topics that may traditionally have been taught in upper-division courses, we must follow a very careful path through the course, with less time to explore tangential paths that might otherwise be interesting. The circuits material is taught with limited exposure to the physics aspects, given the short time. UC Berkeley has been teaching this course at scale with approximately 1500 students taking the course sequence every year. One faculty member works with about 30 teaching assistants (largely undergraduates working 8 h/week) and 60 tutors/graders (all undergraduates working 4–6 h/week).

4.1.2. Further details

Each of the applications from the course is discussed in more detail below. Even though we organize modules around applications, the course emphasizes interconnections across areas and integrative mathematical thinking.

- **Tomography and Imaging (Modeling):** The course starts with an introduction to linear algebra and inverse problems, motivated by the application of medical imaging. The lab consists of building and programming an imaging system using structured illumination from a projector and measurements using a single pixel sensor to reconstruct an image.
- **PageRank (Systems):** We introduce the idea of state and use the example of interconnected webpages and their state (in terms of the number of people visiting the webpage) to understand the idea of linear transformation. The motivation here is figuring out the most important web-pages in a graph of interconnected sites. This brings in concepts of eigenvalues, eigenvectors, as well as connecting to recurrence relations.
- **Touchscreens (Design/Circuits):** This module introduces basic linear circuit theory motivated by the problem of sensing touch in the real world. The analysis is grounded in a linear-algebraic perspective where both circuit elements and the topology introduce linear equations relating basic current and voltage variables. In addition to analysis, the module shows how having interpretable building blocks and understanding their interconnections is useful for design. This especially comes out when discussing op-amps and basic feedback. The lab consists of building resistive and capacitive touchscreens.
- **Positioning (Machine Learning):** This module introduces optimization as a way to extract information, motivated by the problem of figuring out where you are in the world, i.e. the problem of GPS. This brings in linear-algebraic concepts of inner-products, norms, orthogonality, projections, and linear regression, as well as the signal-processing idea of correlations. The lab consists of programming a receiver for an indoor localization system based on listening to acoustic beacons being transmitted by speakers at known locations.
- **(16B) CMOS (Differential equations, system modeling):** The first module in the second semester introduces basic CMOS and an understanding of differential equations, motivated by the problem of understanding why digital computations are limited in speed. The approach to ordinary differential equations connects to the eigenstructure of the matrices involved. The lab consists of making an analog-to-digital converter and vice-versa.

- **(16B) RLC circuits (Differential equations):** RC circuits are introduced as a way to model the CMOS earlier, and we build on this to discuss the application of filtering (using RLC circuits). We motivate this by the practical problem of rejecting ambient signals, like 60 Hz noise, while trying to sense neural signals. By thinking about what happens to linear constant coefficient matrix differential equations driven by complex exponential inputs, we arrive at transfer functions. The lab consists of building filters for audio input for the robot car.
- **(16B) Robotics (Control):** This module introduces basic state-space linear control theory in the context of following a desired trajectory for a robot (linear plant) while rejecting disturbances and model errors. We introduce the ideas of stability (connected to eigenvalues and differential equations) and controllability (connections to subspaces and rank). We introduce the key idea of feedback and how this can change the eigenvalues of a closed-loop system. Linearization is taught to get an approximate model in the neighborhood of a trajectory and system-identification from data is connected to the least-squares approaches they learned in 16A. The lab consists of making a robot car drive straight.
- **(16B) Spike-sorting/Classification (Unsupervised Machine Learning):** This module introduces the ideas of principal component analysis and clustering in the context of classifying signals from distinct neurons. Here we introduce singular value decomposition (via the spectral theorem for symmetric matrices). Singular value decomposition (SVD) allows us to identify the principal components and classify data. We also use the application of image compression to introduce low-rank approximations to data. The lab consists of doing simple speech recognition for the robot car.

Throughout these modules we try to highlight the similarity in the modeling and mathematical approaches that span the areas of control, signal-processing, machine learning and circuits. Our goal is to build versatile students who cross traditional disciplinary boundaries, and who are aware that each of these application areas are not intellectual silos.

4.2. Exemplar use of hardware to engage students

With the recent shift to remote learning during COVID, many instructors had to find alternatives to large campus-based experimental activities. This has probably accelerated the adoption of home-based learning modules/equipment and assessments of learning outcomes for these miniature labs (de Moura Oliveira, Hedengren and Boaventura-Cunha, 2020; Oliveira & Hedengren, 2019; Oliveira et al., 2020). Such low-cost and compact hardware enables students to have substantial hands-on learning at home and plan individually motivated experiments to reinforce key concepts; here we focus on their usage for a process dynamics and control course.

4.2.1. Concepts and learning outcomes of a basic control course

A typical process dynamics and control theory course has elements of transient system analysis and regulatory control design as shown in Fig. 3. Control design includes selection of an actuator and measurement. If a physical system is available for data collection, the actuator is moved with a step or other type of move plan to excite the measurement for model identification. If a physical system does not exist, a simulated system as a physics-based digital twin can be substituted to either generate data or linearized to produce a standard model for controller development. Some of the standard models include first-order, second-order, and state space forms.

Controller development begins with an assessment of any additional measured disturbances that can be included as a feedforward or cascade controller. The selection of P-only, PI, or PID control is based on the system characteristics as integrating (P-only) or non-integrating (PI

¹ The two-course structure allows students to take calculus in parallel with the first-semester 16A, though we prefer students have completed one semester of calculus before.

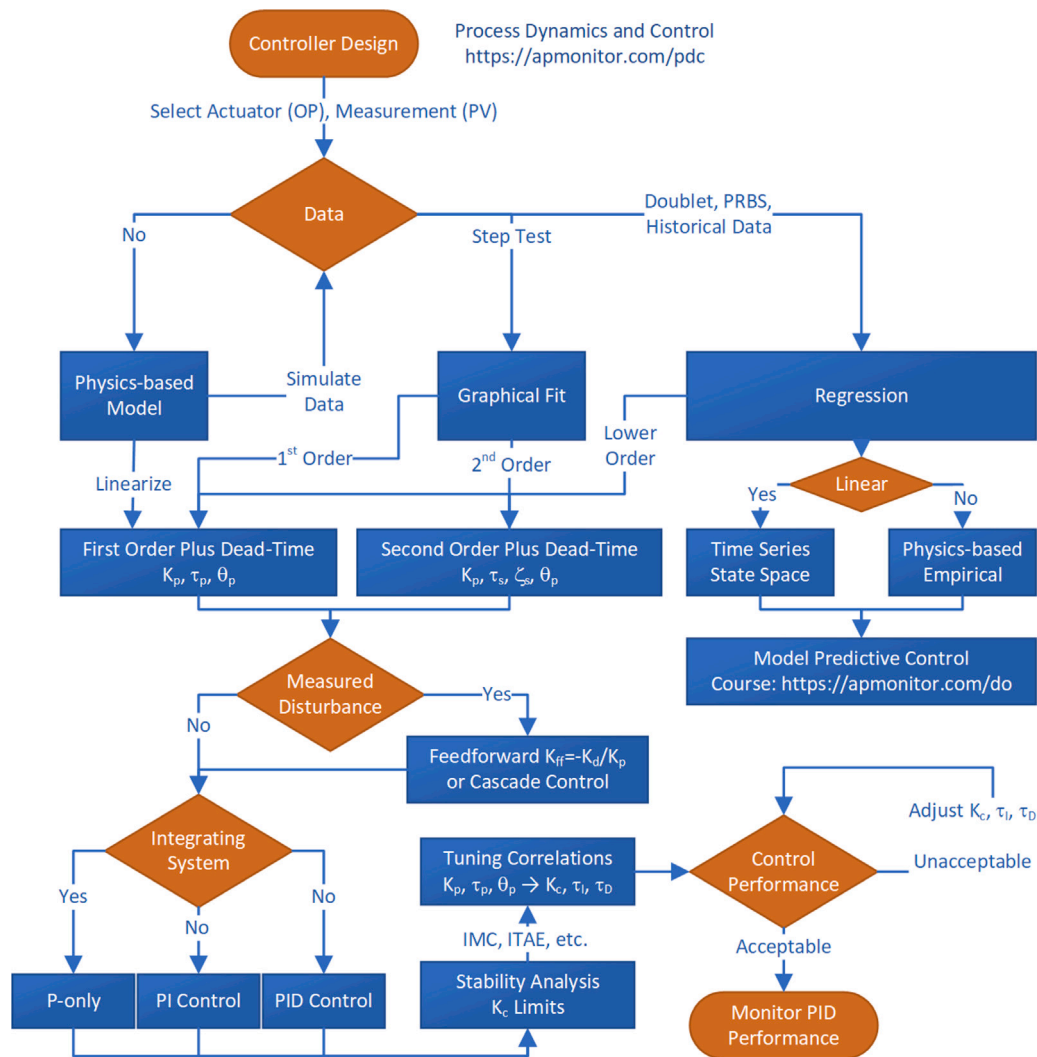


Fig. 3. Course overview and flow of concepts for dynamic modeling (top half) and controller development (bottom half).

or PID). The tuning of the controller begins with a stability analysis to determine the range of acceptable controller gain (K_c) values. Internal Model Control (IMC) tuning correlations are used to convert the standard model forms into candidate values for PID parameter implementation. The controller is tuned to achieve acceptable metrics such as rise time, overshoot ratio, and settling time over a range of setpoint changes.

Many control courses include a laboratory element to reinforce theory and expose students to issues with real data such as measurement noise. An example of the stark contrast between theory and practice is with model mismatch of a physics-based simulation and measurements. Students discover uncertain parameters in physics-based equations or limitations of assumptions such as input constraints and computing delays that lead to the mismatch. Another example of the value of real data is that each physical system is slightly different. The differences are created from variations in manufacturing and ambient conditions at the time of the test. This lack of exactly reproducible results discourages plagiarism and encourages adaptation of the methods for each device. Moreover, students have reported that the hands-on and long-term nature of a laboratory which can be accessed regularly and easily throughout the course helps to solidify key theoretical concepts.

4.2.2. Description and usage of the TCLab take home equipment

The temperature control lab (TCLab) is a very cheap (circa 40 dollars) take-home micro-controller with two temperature sensors, two

heaters, and an LED indicator (see Fig. 4). The device connects to a local computer via a USB and uses a simple domestic power source. Critically therefore, each student can borrow for the entire semester a TCLab device and thus use these safely at home to reinforce each concept in a dynamics and control course. An open source website (Temperature, 2023) provides 23 lab modules that reinforce major topics of a typical dynamics and control course with source code in Python (interactive Jupyter notebooks) and MATLAB (interactive live scripts and Simulink). Instructors at 70 universities have adopted the TCLab as a take-home lab experience with several adaptations of the content based on experiential learning time (typically 1 week to 12 weeks). The TCLab is also a benchmark for research in control algorithm development (de Moura Oliveira, Hedengren and Solteiro Pires, 2020; Mejía, Salazar, & Camacho, 2022; Park, Martin, Kelly, & Hedengren, 2020; Sharma & Padhy, 2022; Yerolla & Besta, 2021).

As noted in Section 4.1, the provision of transparent and simple template code in popular software to perform many different standard tests (open-loop step, PID, etc.) means that students (and staff) can focus on learning and applying the core concepts rather than being bogged down by writing code to interact with the hardware.

At Brigham Young University, students complete a TCLab exercise with each assignment throughout a 14 week course. Homework is due 3 times per week as micro-modules that include theory, simulation, and the lab exercise. Each assignment is designed to be completed in 1–2 h. In addition to the learning modules, a course project extends their



Fig. 4. The Temperature Control Lab (TCLab) connects to a computer for Python or MATLAB hands-on exercises.

understanding to interacting control. Students create a 2 heater x 2 temperature model with two interacting PID controllers with feedforward elements. The TCLab project is a precursor to small team projects where they design, build, and tune a physical system that includes an actuator, sensor, and controller. This progression from homework exercises, to TCLab project, and finally to an open-ended project is motivating for students. Students gain hands-on experience that reinforces dynamics and control theory.

As a complementary example, at the University of Sheffield the equipment is used as the base for an open-ended assignment in lieu of an exam; students are asked to demonstrate the importance of feedback, the impact of different practical issues (e.g. delay, uncertainty, constraints, sampling) and how to tune PI effectively. It is notable from this how much more effectively and confidently the students understand the course content as compared to when they had an end of year exam instead.

4.3. Exemplar use of virtual and remote laboratories to support learning and understanding from Spain

While the approach presented in the last section presents several advantages, there are many cases where the hardware, or lab equipment, cannot be taken home by the students, either due to its scarcity or to its size and weight. A solution to also provide off-campus lab activities are the so-called virtual and remote labs (Dormido, 2004). While virtual labs work with simulations based on mathematical models, remote labs use physical devices to perform real experiments. Other related solutions are hybrid laboratories (which usually use a virtual model but a real controller) (Zapata-Rivera, Larrondo-Petrie, & Weinthal, 2019) and digitized laboratories (which store real measurements and serve them on-demand through an interactive app) (de la Torre et al., 2020). All these approaches present their own advantages and limitations, but it is generally accepted that using a combination of virtual and remote labs is a good approach when delivering a complete lab experience (Heradio et al., 2016). As such, while this section applies primarily to a first course, it also crosses over to more advanced courses.

This section presents a course overview, run in UNED as part of one of its Master Programs, that uses the above lab resources to facilitate experimental work to their students in a distance education context. However, similar approaches also exist in traditional universities, such as Lei, Zhou, Hu, and Liu (2022), offering virtual and remote labs as a complement to their hands-on lab activities.

4.3.1. Brief overview of the virtual course

The online course consists of ten practice units²; each of them focused on a particular system or process (de la Torre, Chacon, Chaos, Dormido, & Sánchez, 2019). Every practice offers a virtual lab that models and represents a simulated version of the system, as well as its corresponding real remote laboratory. These units also contain documents to introduce the students to: (1) the theoretical background and the model of the plant; (2) the user interface for the virtual and remote lab applications and (3) the experimental tasks they are asked to perform.

Fig. 5 shows a screenshot of one of these practice units in the course. In particular, students must follow these steps to complete each practice unit:

1. Read the document with the introduction to the theory.
2. Read the manual about how to use the user interfaces for the virtual and remote labs.
3. Read the document with the list of tasks to be performed during the practice.
4. Access the virtual lab and do the required experimental tasks.
5. Prepare and present a lab report using the measurements and knowledge obtained with the virtual lab.
6. Access the remote lab and do the required experimental tasks.
7. Prepare and present a lab report using the measurements and knowledge obtained with the remote lab.

Table 1 lists a selection of the virtual and remote labs in the online course and offers a brief description of the systems themselves.

When working with the virtual and remote labs, students can usually: (1) tune the parameters of already pre-built controllers to meet some specifications in the system response, and/or (2) code their own controllers in Javascript, among many other things.

4.3.2. A virtual and remote lab example

The Furuta pendulum (Fig. 6) is a device consisting of an inverted pendulum pivoting on a rotating base. The turn of this base allows control of the position of the pivot and thus, indirectly, the angle of the pendulum. This is a challenging device because it is unstable (when the pendulum is in the upwards position) and it also exhibits non-minimum phase behavior. Figs. 7 and 8 show the virtual and remote versions of this lab.

With this laboratory students can perform, among others, the following tasks and activities:

1. Develop a control law that keeps the pendulum in an upwards position while the pivot of the pendulum follows a reference signal. This control law is based on linearization around the unstable equilibrium point.
2. Implement a swing up control that is able to swing-up the pendulum from its stable equilibrium position (downwards) to its unstable equilibrium point (upwards) in order to apply the control developed on the previous step.

Both the virtual (Fig. 7) and the remote (Fig. 8) labs, present a visual programming editor that allows students to:

1. Define their own charts. The charts that appear in both figures are not present when the lab is loaded. They only appear when the user defines the chart. Thus, students need to think and decide what data they consider relevant to visualize and plot for each experiment they perform.
2. Code their own controllers. Students are asked to replace the built-in controller and test their own. This is done using the *replace function* blocks, which involves writing Javascript code to code the controller.

² <https://unilabs.dia.uned.es/blog/index.php?entryid=3>.

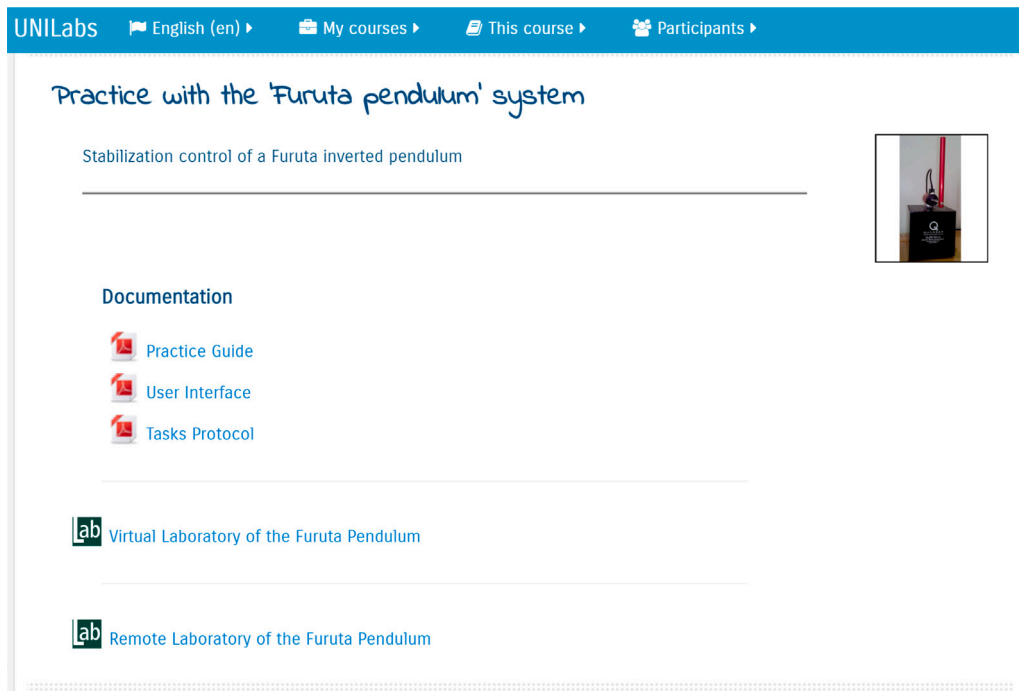


Fig. 5. One of the ten practice units in the online course, containing documentation and the virtual and remote labs.

Table 1

Description of a subset of the available laboratories for remote access at UNED.

Title	Description
Tension and velocity control of a belt on a two coupled electric drives system	Two electric drives coupled with a flexible belt that passes through a pulley with a system that allows measuring its velocity and tension. The main control problem is to change the torque in the motors in order to regulate the tension and the velocity of the belt. This can be done either individually or simultaneously.
Level control in a four tanks system	At the bottom of each tank, there is an outlet of known section and another one with an unknown section, regulated by means of a valve that enables or disables the corresponding perturbation. The system also has two three-way valves that allow regulating the flow, coming from two pumps, that enters in each of the tanks.
Control of the ball and hoop system	An electromechanical device consisting of a ball rolling on the rim of a hoop. The hoop is mounted on the shaft of a servomotor and can rotate about its axis. The rotation of the hoop causes an oscillatory movement of the ball around its equilibrium point. The behavior of the ball is similar to the dynamic of a liquid inside a cylindrical container, being the main objective to control these oscillations.
Control of the ball and plate system	This system consists of a ball rolling on a rigid square plate. The main purpose of this system is to control the position of the ball by manipulating the slope of the plate in two perpendicular directions. This system is employed in the aeronautical industry for the development of vehicles simulators.

- Control the execution flow of the lab. More options, such as running, stopping or resetting the experiment are available through the blocks, as well as reading and or writing variables from the lab. This, in combination with the previous features, offers students an open sandbox to work with the lab.

4.4. Control systems course at Imperial College London: On-site and remote quadrotor test-bed experiment

Continuing the theme of laboratory activities in engineering education, here, we discuss a hybrid implementation which mixes remote and face to face access. The section discusses the integration into the second-year basic Control Systems course at Imperial College London of a laboratory test-bed developed to replicate the dynamic behavior and the control design challenges of an under-actuated multi-rotor Unmanned Aerial Vehicle (UAV) (Fig. 9). The test-bed ANT-X 2DoF Drone (ANT, 2020) is based on a quadrotor UAV fixed to a structure that allows only the longitudinal motion. Using specific open-source firmware developed in Simulink, the drone can be directly operated from MATLAB, relieving students from coding implementation issues. Moreover, the equipment can be operated remotely.

In the following, we summarise some of the available experiments and how the equipment was integrated into module delivery to optimise student learning and engagement, alongside an evaluation of student experience (Panza, Invernizzi, Giurato, Yang et al., 2021).

Comment: The reader will note that this case study, as indeed does Section 4.1 goes slightly beyond a simple and short 20 h course in control in terms of its content and specifically also includes use of some elementary frequency response methods. We feel the good practice here is nevertheless interesting and useful, indeed more so for indicating how longer courses can go beyond earlier generic recommendations.

4.4.1. The test-bed

This section gives a concise test-bed description with more details found in Panza, Invernizzi, Giurato and Lovera (2021). The ANT-X 2DoF Drone has been designed to replicate the longitudinal motion in near-hovering flight conditions when the multi-rotor dynamics can be approximated by four decoupled sets of differential equations describing, respectively, the yaw, the altitude, the pitch/ x -translation and roll/ y -translation dynamics (Ghignoni, Buratti, Invernizzi, & Lovera, 2021). The linearized longitudinal dynamics are described by:

$$\begin{aligned} \dot{\theta} &= q \\ J_{\theta} \dot{q} &= M_c + M_e \end{aligned} \quad (1)$$

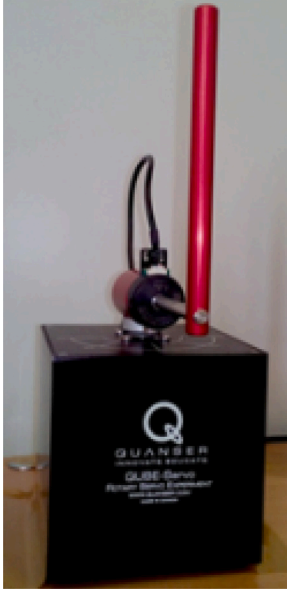


Fig. 6. The Furuta pendulum system.

$$\dot{x} = v_x, \quad m\dot{v}_x = -mg\theta + f_e \quad (2)$$

where (θ, q) are the pitch angle and rate, respectively, (x, v) are the position and velocity along the x -axis, respectively, m is the quadrotor mass, J_θ is the pitch inertia moment, g is the gravity acceleration, and M_e, f_e denote the torque and force disturbances, respectively. While the pitch dynamics (1) is actuated by M_c , the translational motion (2) can be controlled only indirectly, by changing the pitch angle. The longitudinal dynamics (1)–(2) captures the relevant challenges of the underactuated dynamics of co-planar multi-rotor UAVs, which is an appealing feature from the educational point of view.

The test-bed comprises three main components:

1. The drone is a fully functional quadrotor with additional features to operate in safety.
2. The main structure comprises an aluminum frame and two steel bars to constrain the translational motion.
3. The ground control station is any suitable computer from which the user interacts with the drone.

There are two operational modes for the drone: (i) *attitude mode* (1 DoF) is achieved by constraining the linear displacement DoF through removable mechanical constraints (1DoF rings) and (ii) in *position mode* (2 DoFs) the drone is free to move along the bars with two DoFs (translation and rotation).

The 2DoF Drone software architecture is based on PX4, an open source flight stack for drones, widely used in academia and industry, and on ROS, which provides a communication infrastructure. Moreover, there are two proprietary software tools. The first allows automatic integration of attitude and position controllers, designed in Simulink and customizable by the user, into the PX4 firmware. This tool does not require programming skills and allows the user to focus on the design of control laws, although the PX4 firmware can be modified directly, if needed, by advanced users. The second software tool is a MATLAB API providing the capability to communicate with the drone, send commands, and receive information.

4.4.2. The educational material

A set of experiments complemented with educational materials has been prepared to support teaching activities in the design of flight control laws. The possibility of doing repeatable experiments in safe conditions allows one to perform simple tests and to experimentally validate learning which gives a relevant value to the educational experience.

M1: Angular rate dynamics model identification (1DoF). The objective of this activity is to obtain a sufficiently accurate model describing the pitch motion of the ANT-X 2DoF Drone when the translational degree of freedom is constrained. A time-domain identification technique is proposed based on the following second order model:

$$G_q(s) = \frac{\mu s}{s^2 + 2\xi\omega_n s + \omega_n^2} e^{-\tau s} = \frac{q}{M_c^d} \quad (3)$$

where ω_n is the natural frequency, ξ the damping ratio and μ the gain and the term $e^{-\tau s}$ captures some of the many small modeling errors, including sensing, actuation and so forth.

The identification problem, especially for ω_n and ξ , can use standard second order dynamics observations linked to frequency of oscillation and decay. Due to the derivative term in the numerator, a doublet signal input can be used to estimate gain μ by ensuring the model (3) response matches the equipment. Finally, the time delay τ can be estimated by visual inspection of the response or by using the Matlab `delayest()` routine on the collected data. An illustration of the time-domain verification of the identified model can be seen in Fig. 10.

M2: Angular rate control (1DoF). Starting from the identified model in (3), the objective of this laboratory is to design and implement a PID controller for the pitch rate dynamics using the control moment M_c^d as input:

$$M_c^d(s) = \left(K_p + K_i \frac{1}{s} + K_d \frac{s}{\tau_f s + 1} \right) e_q(s) \quad (4)$$

where $e_q(s) = q_d - q$, $K_p, K_i, K_d > 0$ are the proportional, integral and derivative gain, respectively, and τ_f is the derivative filter constant. After inviting the students to manually tune the controller to understand the effect on the response of each individual PID gain, a loop-shaping approach is shown to achieve satisfactory robustness and performance guarantees in terms of minimum phase margin and crossover frequency. Since the identified model has two complex-conjugate low frequency poles, the model transfer function is approximated in the desired control bandwidth by $G_q(s) \approx \frac{\mu}{s^2} e^{-\tau s}$ and then, the loop function

$$L_q(s) = PID(s)G_q(s) \approx \frac{\bar{\mu}}{s^2} \frac{(\tau_1 s + 1)(\tau_2 s + 1)e^{-\tau s}}{(\tau_f s + 1)} \quad (5)$$

is shaped according to the following strategy:

- set the derivative filter pole sufficiently at high frequency with respect to the desired crossover frequency ω_c^d ;
- place one zero at low frequency $\left(\tau_1 = \frac{10}{\omega_c^d}\right)$ and one beyond ω_c^d $\left(\tau_2 = \frac{1}{2\omega_c^d}\right)$ to cross the 0 dB axis with -20 dB/dec slope;
- select $\mu = \frac{\omega_c^d}{\tau_1}$ in order to cross the 0 dB axis at the desired crossover frequency (note that $\|L_q(j\omega_c^d)\| \approx \bar{\mu}\tau_1/\omega_c^d$).

The PID gains are then recovered using $K_i = \bar{\mu}/\mu$, $K_p = (\tau_1 + \tau_2)K_i - K_i\tau_f$ and $K_d = \tau_1\tau_2K_i - K_p\tau_f$.

The performance achieved when selecting $\omega_c^d = 30$ rad/s with $\tau_f = 0.01$ s is shown in Fig. 11. The students are then encouraged to test different performance requirements, compare the results, and discuss their findings. The last part of the activity is devoted to presenting digital implementation strategies and discussing possible issues, such as the effect of reduced sampling rates (see Fig. 12).

Further experiments. It is clear that this equipment lends itself to a number of other experiments which would usefully reinforce learning of control topics and enthuse students about the relevance of control to aerospace applications (e.g. attitude control, position and velocity control); these are included in the module delivery for Imperial College students. The details are omitted for reasons of space and overall paper focus.

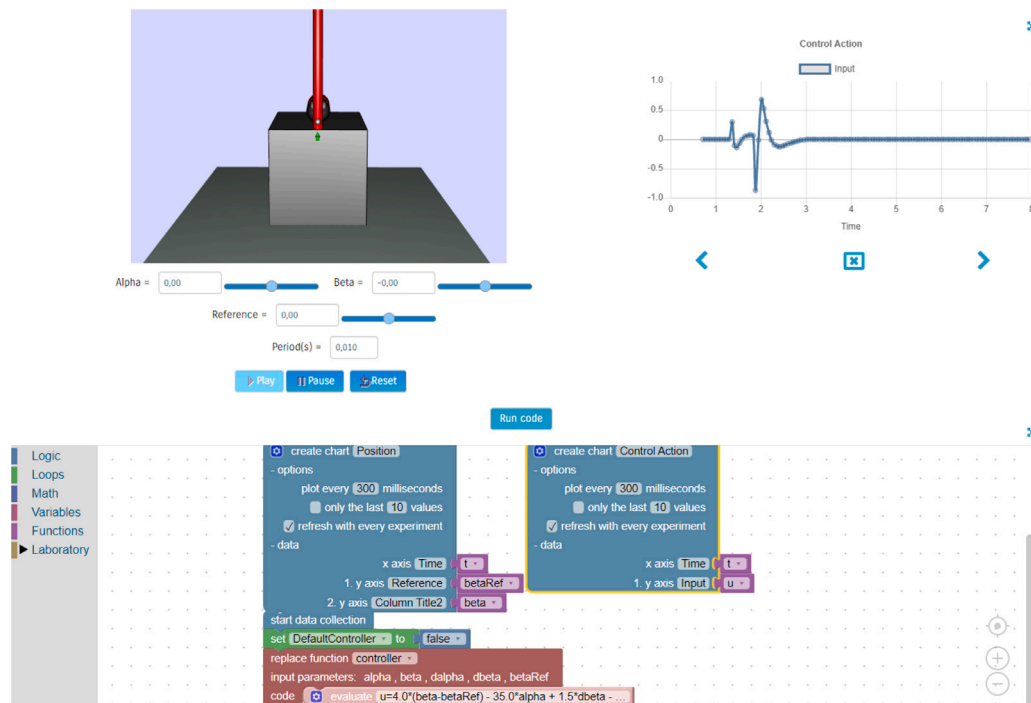


Fig. 7. The VL on the Furuta pendulum.

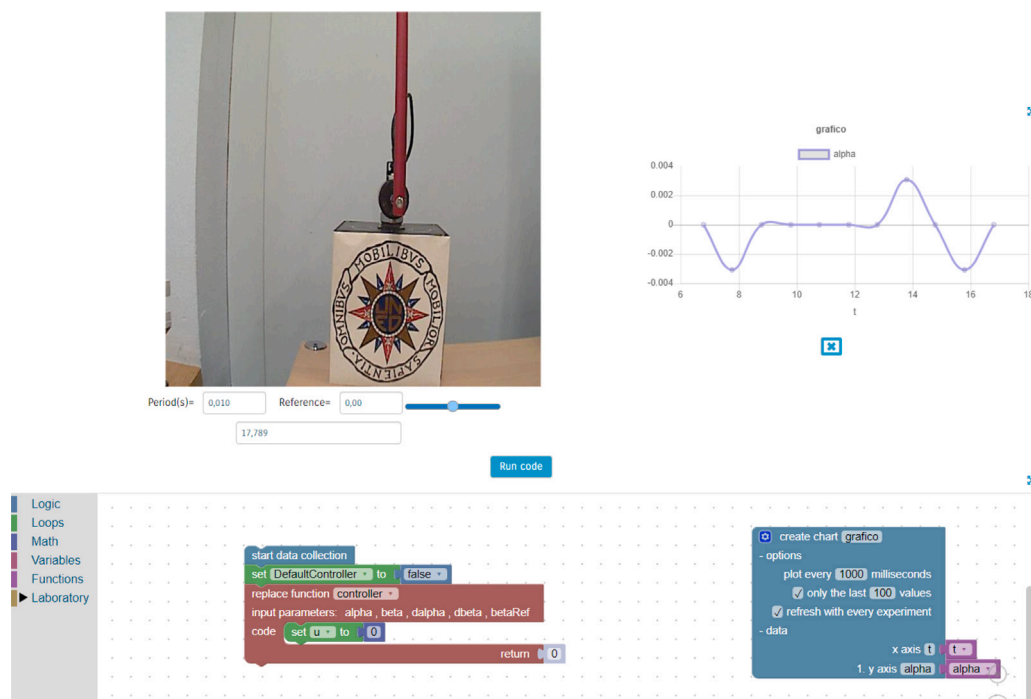


Fig. 8. The RL on the Furuta pendulum.

4.4.3. The student experience at Imperial College London

What is particularly important for this paper is evidence of good practice and how this benefits student learning and experience. The module content and its organization are largely traditional (e.g. system concepts, stability, feedback, control design), so here the focus is more on how the laboratory aspects enhance student learning, appreciation and enthusiasm for control.

The main ideas are to have both a large number of laboratory activities (8 in total) to reinforce the context for the core concepts

and moreover, a mixture of face-to-face and remote access (50:50 split) to optimise accessibility and facilitate ease of timetabling. In the four 3-h face-to-face sessions, 6–7 students share one UAV platform. The room can cater for 15 groups at once (less than half the class) and thus remote access is invaluable so that students who are not timetabled in the laboratory in any given week, can still access the activities.

An important observation here is that in the remote-mode sessions, both the students and the teaching team work remotely. The groups discuss and cooperate on their tasks via online meetings, while



Fig. 9. (Left) The ANT-X 2DoF Drone.

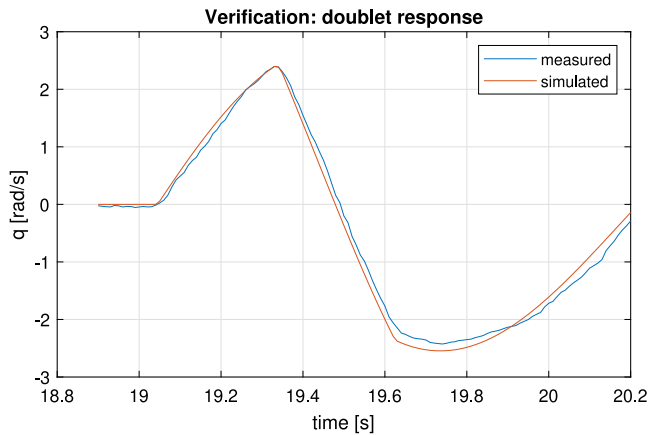


Fig. 10. Experimental verification of the identified pitch rate model.

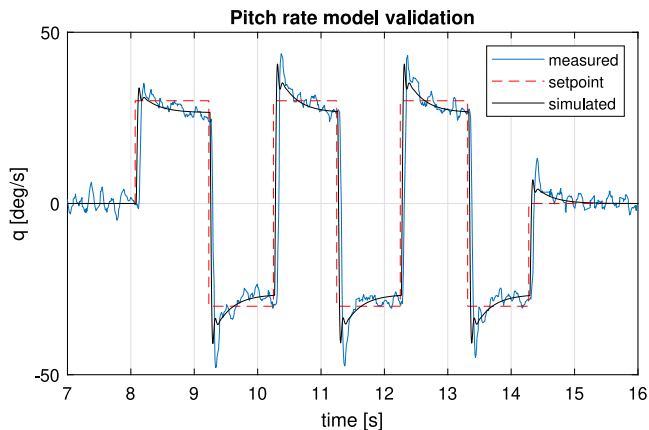


Fig. 11. Simulation vs measured setpoint tracking results for pitch rate control.

the teachers join the group meetings regularly to answer questions and have rapid access to the hardware where required. The hybrid-mode lab sessions exploit the aforementioned remotization of the UAV platform and are divided into a home part and a lab part, running simultaneously, as shown in Fig. 13.

4.4.4. Takeaways

A core aspect of the educational under-actuated multi-rotor UAV test-bed is that this is a real flying UAV, albeit with limited degrees of freedom and thus will engage and enthuse aerospace engineering about

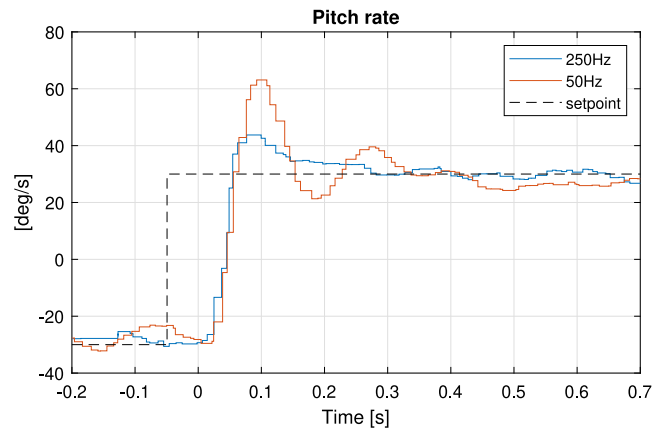


Fig. 12. Effect of sampling rate on pitch rate control.

the relevance of control. Moreover, it provides students with a real hands-on experience in the design and validation of flight control laws and includes important aspects such as authentic sensors and actuators.

The remotization kit is particular important for faculty who teach large classes. This allows students to access the system and perform experiments from anywhere. In this case Imperial College deploys a hybrid running of the lab, so students take it in turns to access the hardware in-situ, thus also adding more value to the occasions when they are remote.

In a nutshell, the Imperial experience has shown that a proper integration of challenging and intriguing experiments into a basic Control Systems course has been a great selling point for students, who thereafter are keen to learn more and more of systems and control thus getting engaged with subsequent years more advanced courses.

4.5. EECI International Graduate School on Control

While the earlier case studies focused primarily on undergraduate education, it is important to recognize that our PhD and postgraduate students and young researchers also need systems and control courses, especially with the rapid and increasing developments of this area. This case study provides an exemplar of how the control community is supporting this training on a global scale.

The International Graduate School on Control (IGSC) is organized every year where independent modules on different topics are taught; a single 21-h module per week. The best international experts are invited to teach recognized topical subjects in esteemed universities and institutes all over the world. A new program is proposed each year. The description of all modules with the summaries of the courses are available on the website (Lamnabhi-Lagarigue, 2022). Since its creation, the IGSC has covered a wide scientific domain, ranging from theoretical foundations of dynamical systems to industrial applications, and from very focused topics to fully interdisciplinary ones.

The scientific aim of IGSC is to complete the training in the multi-disciplinary field of systems and control, thus offering a complementary and essential education for PhD students, post-docs, young researchers and engineers. IGSC typically brings together about 400 PhD students each year from all over the world, see for instance Fig. 14 showing the nationalities of attendees in 2019. These modules are eligible for 2nd year master's degree credits and PhD thesis modules. Completion of a module obtains the equivalent of 3 ECTS (European Credit Transfer and Accumulation System).

In addition to the training aspect, students, most of them PhD students, have the possibility during their stay of one or more weeks, to establish collaborations with local research teams and with the visiting teacher. Some continue over the years, and even beyond, during their professional career.

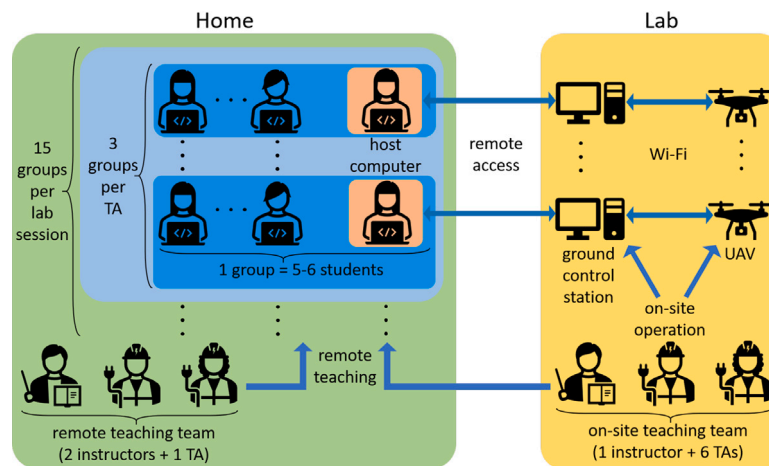


Fig. 13. Schematic of the hybrid-mode lab organization.

International Graduate School on Control 2019

Nationality of participants by continent

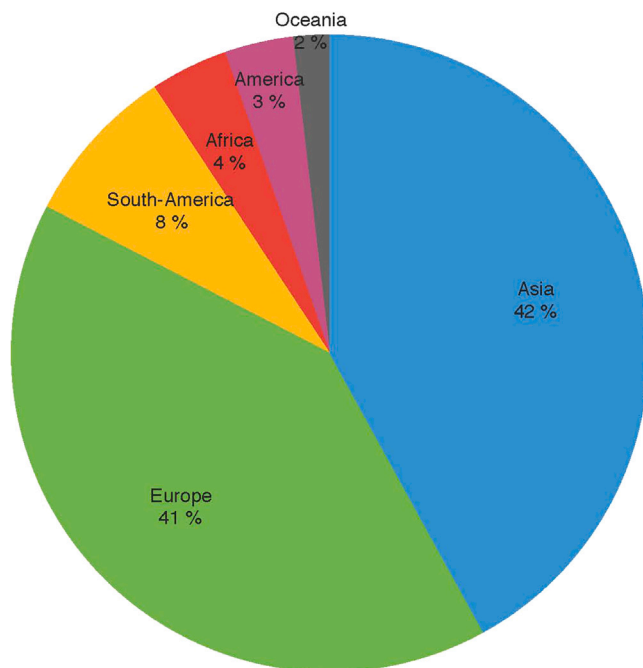


Fig. 14. Nationalities of attendees of IGSC in 2019.

The IGSC is organized by the European Embedded Control Institute (EECI). EECI was founded in 2006 in the framework of the HYCON Network of Excellence, a funded European Commission project from 2004 to 2014. EECI is a non-profitable association (under the French Association Law 1901), based on volunteer work by its members. The headquarters of EECI are in the premises of CentraleSupélec which is a public institution and a founding member of Paris-Saclay University. The IGSC has been technically co-sponsored by IFAC, since 2017 and by IEEE CSS, since 2019.

All the functional expenses of a module, such as the salary of the teacher, their travel and stay, secretariat, local taxes and miscellaneous costs, are financed totally by the registration fees. In order to attract the best PhD students, EECI applies each year for financial support grants from various local, national, European and international institutions.

This supplementary budget is dedicated to distributing grants to excellent students to support their attendance. Students may apply for such a grant by submitting a detailed CV and a letter of recommendation from their advisor. The IGSC scientific committee then examines and evaluates each of these candidatures, and distributes the available grants to the most deserving candidates. These grants not only make it possible to increase the participant scientific knowledge but also to meet a variety of students with different backgrounds, from different countries, with different knowledge and education. Since its creation, EECI strongly supports Diversity and Inclusion.

All the participants assess their course at the end of each week module. The collection of data is then published; Fig. 15 shows the overall evaluation of the modules taught in 2019.

5. Conclusions

This paper has reported and expanded on the findings of the IEEE CSS Roadmap 2030 working group (Annaswamy et al., 2023). The most important findings in Section 3.6 reinforce the conclusion that there is an urgent need to modernize our systems and control courses, especially for those institutions where such a change has yet to occur.

The traditional mathematically heavy focus of early courses is both under-appreciated by modern students who have a very different early education and experience than older staff, but also is much less likely to prepare them appropriately for the working world they are entering and the societal challenges they will need to confront. Modern computing tools, the web, accessible laboratory equipment, a focus on transferable skills are just some of the aspects that can be exploited far more effectively. Moreover, the recent explosion in our awareness of the potential applications of control gives a huge opportunity to motivate and enthuse students about the societal problems they could tackle and the wide range of techniques and models they will need to exploit.

The exemplar course in Section 4.1 gives an example of how, with sufficient support, an academic department can deliver an inspiring and wide-reaching introductory modular course on basic control concepts and methods, while simultaneously exposing students to numerous important and underpinning analysis tools. The take-home hardware discussed in Section 4.2 shows how easily we can exploit modern computing and cheap hardware to magnify students learning, facilitating them to experiment at home and to make modifications quickly and easily from template examples. The case study from Section 4.3 demonstrates that giving students remote access to authentic laboratory experiences is achievable and beneficial, and this significantly opens up opportunities for students to engage with hardware and realistic issues. Section 4.4 reinforces the messages on laboratory activities; moreover, it provides an exemplar of how to deliver in a hybrid fashion and also

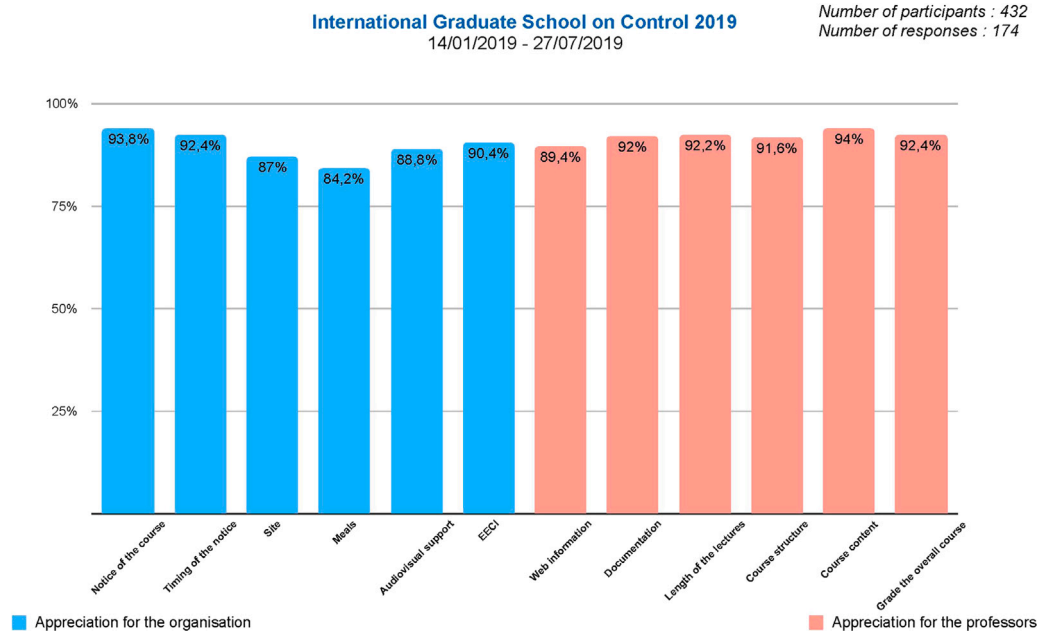


Fig. 15. Evaluation of IGSC modules in 2019.

to tailor activities to the cohort so as to enthuse them more effectively. Finally, Section 4.5 emphasises that education does not finish at the undergraduate level. As a community, we need to continue to support the training and development of our researchers so they can tackle the problems of the future and the IGSC is an exemplar of how we might do this.

Finally, we all have a role in supporting each other, as well as students and working engineers. There will be a far greater demand for high quality, free at the point of access, independent learning mini-courses of, say, 2–4 h lecture content. These would be accessible through the web and enable learners to pick up specific skills and knowledge as they need it. As a community, we need to both produce and collate these resources to facilitate easy access and search. The technical committees of the IEEE CSS and IFAC are working together on proposals for how best to handle these challenges.

Data availability

No data was used for the research described in the article.

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