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Future Trends for a First Course in Control Engineering

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This review summarises recent thinking in the academic control community on the future of control as a topic and thus on the design and focus of control courses at university. It is notable that the current thinking is quite controversial and significantly at odds with traditional practice, and thus implementing such changes will require substantial effort and will from the community.

Keywords: education, control engineering, future trends, community vision, learning and teaching

1 INTRODUCTION

In recent years the international control community, supported by the IFAC and IEEE Technical Committees on Control1 and contol systems society (CSS), felt it was timely to have some active reflection on the control curriculum and delivery in Universities (Antsaklis et al., 1999; Murray, 2003; Dormido, 2004; Rossiter et al., 2018; Rossiter et al., 2020; Rossiter et al., 2023). What is particularly significant is the growing awareness that despite society at large and our use of technology changing vastly over the past 30 years (in essence following the advent of micro-computing, mobile phones, laptops, etc.), the control curriculum we teach has changed very little. Moreover, it is becoming increasingly evident that the module design and delivery which was necessary for a pre-computing age, was really rather dull and uninspiring to the modern generation, and thus not preparing them well for the careers they were going to enter. In summary, the need to modernise is increasingly urgent.

This mini-review will give a rapid overview of the surveys and discussions carried out by the community in recent years finishing with a summary of the current thinking and priorities. In essence this reduces to a call to arms for each of us to begin instigating change within our own institutions. **Section 2** focuses on provision and design of Learning and Teaching (L& T) resources and **Section 3** focuses more on curriculum content[1].

2 LEARNING AND TEACHING RESOURCES AND COURSE DELIVERY

2.1 Historical Background

Traditional control courses and associated textbooks (Dorf and Bishop, 2021) have centred around mathematical algorithms and techniques for analysing and designing system behaviours, for both open and closed-loop. Many of the traditional techniques discussed and commonly assessed in control courses, assumed there was no ready access to computing, so deployed insight, clever graphs and other tricks to infer expected behaviour from some simple analysis which was amenable to pen

[1]http://control-education.ieeecss.org/ and https://tc.ifac-control.org/9/4

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and paper computations. Historically, laboratory access was limited and expensive and thus, while valuable, often only comprised a relatively small time component of a course.

2.2 Potential Released by Technology

With the rise of computing capacity several core changes have occured so that, even assuming a conventional curriculum, the design and delivery of all engineering courses can be significantly augmented; this paper focuses on control where some important examples are summarised here (Rossiter et al., 2018).

2.2.1 Micro-computing

The advent of cheap micro-computing means that laboratory provision can be much cheaper and more accessible, thus providing opportunities for an increased presence in the curriculum. A notable innovation that is beginning to grow in popularity in the past few years is the concept of take home laboratories (Oliveira and Hedengren, 2019; Rossiter et al., 2019; Oliveira et al., 2020; Yerolla and Besta, 2021), that is cheap (often as little as $30 per kit) and transportable mini-kits that students can borrow for many weeks and use for independent learning and investigation. Having 24/7 access to real hardware with rapid runtimes and driven by a laptop allows students to get a real feel for authentic issues. Indeed this can also inspire them and thus gain more enthusiasm for a topic.

Even in the case of more expensive and larger kits that would only be available in University laboratories (Quanser, 2022), these have become notably cheaper per unit and thus available in larger quantities.

2.2.2 The World Wide Web and Remote Access Laboratories

The creation and development of the world wide web provides opportunities for 24/7 access to both information and in some cases, real hardware. There is a recognition that University timetables limit the times that students can be physically present with expensive laboratory hardware, but allowing access via the web, potentially opens up the timetable to the full day and weekends.

A large number of remote access activities have been publicised in the control community, for example (Brinson, 2015; de la Torre et al., 2019; de la Torre et al., 2020; Egerstedt, 2022) and clearly this is just a small subset of those available. A core point to make here is that such laboratories are likely to be far more authentic and flexible than take home kits, thus providing students with the potential to further increase their insight and understanding of important engineering challenges and solutions.

Of course, there also some challenges for teaching staff in that: 1) as the numbers of kit are limited, efficient queueing of student access is needed, so access is still not totally free and 2) substantial local expertise is needed to set up the software to enable efficient, reliable and effective web access.

2.2.3 Virtual Laboratories and Interactive Tools

Along the same lines as the discussions above, the increasing power of modern computers means that student access to realistic model simulations and other interactive tools are now available through personal laptops, either as a local file running on cheap software (or available through a university license) or through a web server (Guzmán et al., 2013; Guzmán et al., 2016; Heradio et al., 2016; Rossiter, 2017; de la Torre et al., 2020).

A number of points can be made as an encouragement to teaching staff to consider deploying such virtual laboratories and interactive resources in their teaching.

1. Being software based, these may allow an unlimited number of students (in the author's case a typical class size is around 400) to access the activity simultaneously. This also allows their use for interactive segments during lecture slots.
2. With suitably visual affects, these allow students to engage with core concepts and learning very cheaply, and thus to optimise the use of their time on actual hardware. Also simulation times can be instantaneous or much faster than real-time!
3. Modern coding tools mean that effective GUIs/activities can be coded in a half-day or less, thus cheap on staff preparation time.

2.2.4 Using Computers for Assessment

The recent COVID pandemic forced many academics' hands in adapting the way they assess, most notably the move away from closed-book exams to open-book assessment with students sitting the test at home on their computers. An interesting discussion to be had over the next few years is whether staff feel this new model has some advantages and should be retained; anecdotal evidence in the author's institution is that many staff liked the new model and may wish to retain it, notwithstanding issues with handling potential unfair means.

It is worth noting that there has been a quiet trend (Lynch and Becerra, 2011; Rossiter, 2011; Rossiter, 2022b) within the community for many years proposing that assessment of control computations using paper and pen exercises is somewhat ludicrous; no-one would do it this way in a job and number crunching should not be a university level assessment. We should give the students access to a computer to do the number crunching and check they can make the appropriate decisions on what are appropriate computations and design steps and indeed spot obvious errors and so forth. The author uses threshold assessment (Rossiter, 2022b), thus worth pass/fail marks only, to ensure students have base level competence in core analysis tools and this is very fast to mark using computer quiz engines.

2.2.5 Online Courses and Resources

Another area which has undergone rapid evolution in recent years, but one could argue, certainly for control topics, is developing in more of an ad hoc sense rather than systematically, is the concept of online courses and learning resources (Albertos, 2017; Rossiter, 2022a; Douglas, 2022; Egerstedt, 2022; Khan, 2022).

There is no doubt that there is a plethora of superb online resources which students can use to learn from, but a simple search on the web could return thousands of options and leave the user confused. Consequently, a current urgent project within the community (Serbezov et al., 2022) is to collate the available resources and disseminate these in a digestible manner (Douglas, 2022).

Perhaps, what is more pressing for the academic community, is the need to share resources Serbezov et al. (2022) in a manner that allows each of us, and our students, to benefit from the excellent resources others have developed. Thus the encouragement to share with suitable creative commons licenses is equally important.

2.3 COVID, Student Expectations and Summary

The recent COVID pandemic is likely to have speeded up the transition to new ways of learning and delivering learning in many institutions, especially the increasing use of online resources, lectures and assessment. The brief examples of this section serve to illustrate that much good practice already exists which staff can therefore adopt and apply relatively rapidly.

What perhaps has not been discussed, and indeed there is little space for the issue here, is the concept of student expectations and the modern student. Certainly anecdotal evidence is fairly strong that the students of today appreciate and expect different support and resources to those of students even just 10 years older. If we are to engage these modern students, we need to meet them in the right place, and it is apparent that they have grown up with digital technology and thus expect L&T methods at university to make extensive use of such technology. Indeed, as a minimum, they may expect all the resources to be available via their mobile phones.

3 CURRICULUM CONTENT, DESIGN AND DELIVERY

The previous section has focussed largely on L&T resources and accessibility, but sitting alongside this is the core content and delivery of a first course in control. It has become apparent from recent work (Murray et al., 2004; Rossiter et al., 2021; Rossiter et al., 2023) that two fundamental changes are timely:

1. A first course needs to cover a wide range of scenarios, certainly far beyond traditional engineering.
2. A first course should be less concerned with mathematical elegance and proof and focus more on application of the core concepts.

Some interesting exemplar case studies from three varied international institutions are available in (Rossiter et al., 2023) and we hope more will follow from the respective IEEE/IFAC Technical committees in the very near future.

3.1 Applications of Control

A historical control course would likely have focussed predominantly on mechanical, electrical and chemical engineering examples such as suspension systems, tanks, heat exchangers and motors. However, there are changes in society which are pertinent. First engineers are less likely to focus on a single discipline and employers expect them to be multi-disciplinary and moreover engage in life long learning to diversify and extend their skills as required. Secondly, there is an increasing awareness (Murray, 2003) of the prevalence of feedback loops and the need for control in a wide variety of application areas such as crop growth and irrigation (Cabrera et al., 2021), solar energy (Satue et al., 2021), modelling and control of disease (Estigarribia et al., 2021), autonomous bikes (Persson et al., 2021), underwater vehicles (Rentzow et al., 2021) and indeed this list could easily be expanded and broadened far more.

A first course in control needs to be multi-disciplinary and expose students to the huge variety of potential applications and indeed, potential benefits to society, of applying feedback effectively. If we accept that university is only the first step in a life long journey of learning, then it is less important to teach students lots and lots of dry information which they can easily pick up as required. Rather we need to focus on enthusing them and exposing them to core concepts and principles, so they are motivated to engage and learn. Moreover, most institutions will have higher level courses in years three and four where students can specialise and thus engage with greater technical depth and detail.

3.2 Reducing the Focus on Mathematics

One of the controversial points in the recent international survey (Rossiter et al., 2020) was the recognition that our historical emphasis on treating a first control course like an applied mathematics course is probably not appropriate in the 21st century. In general terms, apart from a small minority, historical graduates remember just that, control = mathematics, and they have little empathy or understanding of what the topic is really about? Thus, as teachers, we have failed them.

This is not to say that mathematical precision and rigour is not important, but we have to decide its place and priority. Most graduate engineers will not be control experts, they will not need to do detailed loop analysis, understand root-loci or indeed state-space methods. However, they will need to understand what a feedback loop is, why it is important and have some understanding of the links between behaviours and tuning? Hence, we need to propose a first course that focuses on the core principles and concepts such as: modelling and behaviours, uncertainty, performance measures, the role of feedback, simple PI designs and interesting case studies/laboratories; it is noted that current discussions (Rossiter et al., 2023) may end up proposing even more drastic changes, focussing on a range of modern applications and potential usage rather than on traditional behaviour analysis.

To summarise however, while some mathematics is important, we should de-emphasise that to ensure students finish the course believing they have learnt control and not mathematics.

3.3 Exploiting Software Tools and Virtual Labs

As a throw away and discussed in **Section 2.2.4**, given the plethora of computing tools now available, the author believes that it helps reduce the emphasis on tedious mathematical computations and number crunching if examiners exploit computing tools (Rossiter et al., 2008) for the mathematical computations. Thus students can focus their time and effort on understanding principles and applying these to interesting applications Egerstedt, (2022); Taylor et al. (2013); Park et al. (2020).

Moreover, as discussed in **Section 2**, the advances in technology allow staff to adopt lots of interesting and interactive laboratory activities which bring the topic to life in a way which attendance at one or two brief hardware laboratory sessions could not. These activities, be they virtual labs, take home labs, remote labs or indeed other activities are readily available and typically low cost. Moreover, they can be used in conjunction with concepts such as threshold assessment (Rossiter, 2022b) to reduce the implied marking and assessment burden on both staff and students so the focus is on enjoying learning.

Modern students expect all their resources and much of their assessment to be accessible online. It is straightforward to do this for nearly all aspects of the learning delivery and thus is a win-win if this means students also engage better.

4 CONCLUSION

Universities can be rather slow to change, partially driven by legal requirements which limit the time scales for radical changes in the curriculum, but also natural inertia in staff; we have always done it this way! Of course, researchers know we cannot stand still and education likewise needs to modernise and move forward to ensure we provide the engineering graduates needed by industry (e.g. https://accreditation.org/explore-accreditation/accords/washington-accord).

Recent community wide surveys (Rossiter et al., 2018; Rossiter et al., 2020; Rossiter et al., 2023) have made it clear that both the content and delivery of control courses needs modernising in many institutions. We need a concerted effort from all academics to push forward these changes, ensuring that:

- Students are enthused by a first course in control and seek to study more advanced options.
- Students are adequately prepared for the hugely diverse problems that face them in modern industry.
- Students develop an awareness that control concepts are far more broadly applicable and useful than in just conventional heavy engineering.
- Our teaching methods and resources are tailored to the students and context of today, not those of yesteryear.

AUTHOR CONTRIBUTIONS

The author JR has written this review paper alone, but as noted in the acknowledgements it draws substantially on collaborative work with numerous international colleagues.

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