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Opportunities and good practice in control education: a survey

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Abstract:
The ways we can and do educate University students is changing rapidly and thus the paper gives a concise survey of opportunities and good practice within control and systems engineering. Rather than focussing on generic issues, more focus is given to specific approaches which are highly relevant to control topics. Hence, much of the paper discusses laboratory provision, locally, remotely and virtually. Nevertheless, there is also some discussion of general good practice and resources which have been used and evaluated in the control community.

Keywords: Education, Independent learning, lecture videos, technology, problem solving.

1. INTRODUCTION

There have been huge changes in approaches to education over the past 20-30 years, although the penetration of this thinking into higher education has been relatively slow. It is also notable that among all diverse topics, control engineering lends itself to a great variety of innovation because it can be mathematical (formal or informal), experimental, based on writing (reports), explicitly linked to industry and enterprise, and so on. Consequently, the IFAC education committee felt it was both timely and useful to present a concise survey, with evidence, of good practice in the community to help all lecturers out there reflect on how they could improve their current practice and where they could get support and guidance to do so.

This survey will discuss a wide range of scenarios and concepts and thus each will be dealt with relatively briefly (Readers are referred to the references for more details.);

(1) What is accepted good practice?
(2) What is the evidence and context?
(3) How and why should I try this?

1.1 Historical context

As recently as the early 1990s education was markedly different; this is significant because many current University staff were educated in the 1970s-1990s. Staff training in education and pedagogy would have been minimal and thus academics who obtained a post based on excellent research would be expected to 'get on' with teaching with little or no guidance on good practice. Moreover, academic staff are not representative of typical students as it is likely they were top of the class, or near to that, and thus very atypical in ability, motivation, learning and discipline. In a historical context students received lectures of varying quality, often without handouts, and made the best of deciphering the lecturer's writing on the backboard using books and other tools later. Independent learning was implicit. Although exam questions were largely predictable (little problem solving), a student who was able to work there way through a complex syllabus with relatively little help could probably problem solve anyway!

In terms of technology, readily available computing for undergraduates did not come in until around the mid 1990s. Hence paper and pen exercises would have been the norm and wide scale integration of software packages such as MATLAB into teaching and assessment was not possible. Consequently a lot of value was placed on derivations, proofs, number crunching and mathematics.

In terms of laboratories, access would have been restricted to a few visits each term due to a combination of timetable, space and equipment restrictions. Virtual laboratories and remote laboratories would simply not have existed. In a similar vein, the content would have been largely traditional, focussed around electro-mechanical topics with a smattering of process engineering for some.

1.2 The modern context and opportunities

There are huge new opportunities to offer students a higher quality learning experience, which also benefits employers. Universities accept the need for academics to be properly trained in education. For example, in the UK a two year part-time course leading to a formal qualification and accreditation by the higher education academy (HEA) is mandatory for new staff. A key part of this is that staff are required to reflect in detail on learning outcomes, for example: (i) what do I want the students to be able to do, and why? (ii) how can I be sure they achieve this? (iii) what effective good practice is there?; etc. In summary, staff have support and incentive to pursue good practice.

A key point of contention from the increased focus on pedagogy is whether the use of a didactic lecture and/or the blackboard is useful (Mazur, 2012) and equally 'death by powerpoint' has bad press. However some can be too quick to reject chalk and talk techniques without a careful consideration to their role in a overall delivery plan.

The most exciting developments are where modern technology can make a difference making things achievable (in reasonable time and cost) that were not just 3-4 years ago. The internet is increasingly more powerful and faster allowing real time access to data, laboratories (Gustavsson et al, 2009) and resources. Software has also improved so that the average academic can author relatively advanced simulators ((Cameron, 2009), (Guzman et al, 2006),(Khan et al, 2006),(Goodwin, 2011)) quickly and without the need to be expert in coding. These have led to many innovations such as remote access laboratories, virtual laboratories, computer aided assessment, online videos and audios and text files and so forth: (Jong et al, 2013; Mathtutor, 2012; Rossiter, 2012; Murray, 2013).

The rapid advances in computing technology mean that departments now have the potential to develop very cheap equipment. No longer does each experiment need an expensive IO card or similar; instead one can plug into the computer directly via USB port. This opens up the possibility of producing and distributing real equipment in multiple copies, and thus which can be taken home by students (Taylor et al, 2013),(Eichler et al, 2013).

An interesting aside is the recent trend to recognise the pervasiveness of systems and control in many disciplines outside of engineering. Hence there are opportunities for engineers to recognise how their skill sets can be more broadly applied and conversely, opportunities to introduce novel 'systems' modules into other areas (Murray, 2013).

1.3 Summary of contribution

This paper will summarise best practice, as evidenced in the control community in a number of areas. Section 2 will cover briefly (as common to many topics) the lecture itself (Mazur, 2012). Section 3 will focus on laboratories and equipment. The focus is on cheap, fast, reliable and safe to improve accessibility. Section 4 will discuss the potential for students to have a real laboratory at home. Section 5 will discuss on-line learning tools and the evangelisation of systems and control to disciplines outside engineering. Due to space limitations, this paper will not discuss issues linked to accreditation (UK-SPEC, 2011) and overall curriculum design/holistic student development.

2. THE ROLE AND DESIGN OF A LECTURE

This section will give a brief discussion on what makes a good lecture, in particular in the context of something like control. Of course the first thing to note is that diversity is usually good and thus lecturers are encouraged not to adopt a single technique; sometimes a variety of approaches within the same course is best.

2.1 Didactic lectures

Employers are interested in students ability to abstract, see the big picture, analyse real world problems, learn independently, include issues such as risk and reliability and design, etc. (PANEL SESSION , 2013). A didactic lecture can encourage students into a memorise and regurgitate approach to learning which does not prepare them for real world scenarios. Students must not see the lecture content as the totality of what they need to know (Rossiter et al, 2010) nor should they view the ability to do simple exercises as sufficient to be capable engineers (Kawski, 2013). Hence, the overall portfolio of lectures must not be overloaded with didactic presentation techniques which convince students, by example, that this is what is valued. Nevertheless, didactic presentation modes still have an important role and should not be removed entirely.

(1) Many students do not parse formulae correctly; what they 'say' does not match what they write. Watching a lecturer carefully write/talk out a solution on a blackboard with the correct language will help them learn the correct associations and approaches.
(2) A screen dump of a solution with several steps can confuse or switch students off. By writing a solution out during the lecture, a lecturer is forced to go slower, at a pace where students can clearly identify the steps and thinking and thus follow the argument.
(3) There are some important messages which the lecturer wants to be sure are presented correctly.
(4) Good practice suggests lecturers should face students and thus use an overhead projector, or pen-enabled laptop (Wilson and Maclaren, 2013) or smart screen.

2.2 On-line lectures or no lectures

A common challenge at many Universities is the diversity of nationalities in the student cohort. Apart from the differences in expectations of learning processes and backgrounds there is a huge variance in language abilities. Poor language skills in combination with the poor acoustics, the novelty of words and speed of speech, it is not surprising that many students struggle in lectures; in these cases there is substantial evidence that the recording of lectures is hugely valueable (Middleton, 2013). Students can listen again later to the lecture and correct any initial misunderstandings, reinforce the sounds and interpretations of keywords, update and correct their notes and so on.

A natural progression of this is the development of fixed lecture resources for key topics (Mathtutor, 2012),(Khan Academy, 2013), (Rossiter, 2013), (Saunders and Hutt, 2012), (Williams and Fardon, 2005). Such resources give students the freedom to study in their own time and thus to acquire key skills. Moreover, the availability of didactic resources online removes the pressure on the lecturer to cover everything in lecture time; now they have freedom to use the lecture time for more engaging activities (Mazur, 2012). There is growing evidence that, given suitable online/preparatory resources, lectures can be replaced by workshop type sessions in open classrooms (e.g. yaledailynews.com/blog/2013/01/14/tech-savvy-classroom -aims-to-transform-learning/, web.mit.edu/edtech /casestudies/teal.html) where students work on problem solving in small groups. Such sessions ensure students are active in the learning process and thus evidence suggests they learn much more than they would just listening to a lecturer.

Student evaluations indicate this is popular and effective. Perez et al (2011) reported on the outcomes from incorporating on-line animated and interactive tutorials into the traditional classroom teaching settings. These tutorials (addressing numerous control system examples, from the tank level and welding machine control to cooperative robot arms, space telescope and supersonic jet control have been developed, animated and made available to students), and being supported with interactive and an easy-to-use user interface, have been introduced from early 2005. Student feedback from the course evaluations clearly showed the improvement attained reflected in increased average scores over the period 2005 to 2010 as well as more positive student responses to the question: *Overall, how effective was this course in helping you to learn?*.

2.3 Summary

(1) Lecture time should not be dominated by didactic delivery; rather students should be active.
(2) Provision of lecture recordings and pre-prepared videos gives support to students who benefit from seeing something through several times and frees lecture time for more engaging activities.
(3) There is an opportunity for IFAC to offer some form of quality mark and sharing of resources.

3. USING TECHNOLOGY TO IMPROVE THE EFFICACY OF LABORATORIES

Laboratories play a key role in student learning as they provide a tangible experience of engineering in real life and the ability to learn by trial and error. This section summarises some of the good practice in the literature:

(1) How to ensure that students make the most of time with hardware, that is through effective preparation.
(2) There is a focus on simulated and remote laboratories which provide new possibilities for improving access (24/7 and from anywhere). A simulated or virtual laboratory provides an *authentic* representation of or interaction with a real scenario whereas a remote laboratory gives access to and control of actual equipment (Dormido (2004)) as if you were present.

3.1 Integration of face-to-face and on-line learning

In order for students to benefit fully from access to hardware, it is important they prepare adequately. Hence, the requirement for students to do pre-lab activities closely related to the laboratory (Abdulwahed, 2010), (Jong et al, 2013) is relatively wide spread good practice. Nevertheless, a substantial amount of time at the beginning of each lab session could be dedicated to marking and feedback of preparation; this is both inefficient and using valuable time that should be spent on the hardware. Consequently, academics in Griffiths have been working on incorporating on-line teaching tools into laboratories.

Both the Control Systems course and Digital Control Systems Engineering course are lab intensive with lecture and lab topics closely related and sequenced. Typically, the lecture topic taught in the current week is explored and examined during the lab session held in the following week. To give them a strong motivation for engagement, students must submit their Lab Preliminary for assessment. From 2011, the Lab preliminaries are given to students as an on-line assessment which includes both theoretical questions and analytical problems. Analytical problems are decomposed into a sequence of steps and sub-questions and thus in a sequence reflecting a logical progression typical for worked analytical problems. Students submit their results on-line well before the appropriate lab session.

To further support effective engagement, an adaptive release tool is used to provide students with detailed step-by-step explanation of the worked analytical problem, only after their preliminary work is submitted. Similarly, the laboratory manual is not released until this point.

The authors have noted several benefits from this new approach. Since students preparation is marked, this was designed to encourage deep understanding, and moreover they have access to the correct answers, the questions received from students are both fewer and more meaningful. Consequently, the observations are of an increased understanding of the lab experiments evidenced by higher quality lab reports. Further, since the introduction of this system, there has been a marked improvement of around 20% in student responses to the question: *Overall, how effective was this course in helping you to learn?*.

Plans for yet more improvements overlap with the previous section on lectures. There is evidence elsewhere (for example see recent work in Southampton on how quality video and animation could improve student preparation (Memoli, 2011)) that including familiarisation 'lectures' for anything new, such as an online quiz environment, helps improve student engagement/learning and reduces the 'fear factor'. In this case, for example, modern technology enables the cheap production of video and thus authors in both Griffiths and Sheffield are planning to introduce mini-lab introductory lab lectures (of 5-7 minutes each) to help students better prepare for the incoming lab session. This enables students to become familiar, in advance, with the hardware set up and activities required.

3.2 Remote laboratories

Remote experimentation for engineering education can be considered a mature technology (widely implemented), e.g. (RELOAD, 2010; Qiao et al., 2010; Ma and Nickerson, 2006). They enable access to real hardware and thus an authentic learning experience outside the timetable and without requiring physical attendance and thus can be cheaper to provide than a multiplicity of kits should students need to attend in person. However, the process of transforming a classic control experiment into an interactive web-based laboratory is not yet an easy task (Vargas et al., 2011): (i) Hercog et al (2007) used a framework based on the use of MATLAB/Simulink for the control algorithm development and on LABVIEW for the user front-end; (ii) Stefanovic et al (2011), uses LabVIEW in both the server side and as the user graphical interface; (iii) the work in Barrios et al (2013) describes the development, implementation of a multi-user network architecture based on the use of Graphical User Interface (Applet) developed with Easy Java Simulation (EJS) and MATLAB and/or LABVIEW for controlling the devices. In this sense a singular project was the AutomatL@bs network (http://lab.dia.uned.es/automatlab), a consortium of seven Spanish universities working on virtual and remote laboratories: a)enabling students to access experiments not available locally. b) increasing the quality and robustness of the network of virtual and remote laboratories (Dormido et al (2012a, 2012b)).

However, while the modern internet has made the provision of remote laboratories relatively straightforward in principle, there are still many practical obstacles (Rossiter et al, 2011). Where the activity has a relatively slow time scale, there is still a need to allocate students specific access times which mitigates against supposed 24/7 access. In fact, even for hardware which has fast time constants, students must queue to gain access when a single student requires say 10 min to perform all their tests; especially as many students have the same 'free' periods. With large class sizes, poor access leads to wide spread student frustration and disengagement! The alternative of arranging some form of booking system introduces ongoing management and coding complexity which can be difficult.

A further important issue is reliability. During key periods a remote access laboratory needs to be available and this has significant workload repercussions for technical staff who have to monitor for malfunctions, breakages and other unforeseen issues; often these may occur out of hours and thus may not be fixed until the following day which again mitigates against the supposed 24/7 access.

Other key challenges include reuseability, interoperability, collaborativeness and integration into learning management systems. A review (Chen et al, 2010) concludes: 1) *There are lots of virtual and remote laboratories developed with LabVIEW, Java Applet and Flash* and 2) *To develop a remotely accessible laboratory developers have to master computer hardware/software, data digitization/collection, data transmission/visualization, and network. An engineering education laboratory developer rarely has sufficient expertise. The development of a unified user friendly remote laboratory publishing tool is in great demand.*

3.3 Virtual laboratories

A popular alternative to remote laboratories is a virtual laboratory (Foss et al., 2006; Guzman et al, 2006; Khan et al, 2006), that is one which emulates real equipment and has the appearance of being authentic (Goodwin, 2010), despite being a simulation. These can be used in isolation, for example as part of a learning activity or assignment, or to support pre- and post-laboratory activities (Abdulwahed, 2010) (that is to emulate the activities, concepts and questions in an actual laboratory). An obvious advantage is that multiple students can access a virtual activity simultaneously, as well as anytime/anywhere.

A key requirement for virtual laboratories is good accessibility and thus one might favour laboratories one can access via the internet (Khan et al, 2006; Guzman et al, 2006). However, academics responsible for delivering virtual laboratories have other factors to consider:

- The better and more accessible the interface, the more likely that the development work is significant and/or requires substantial software skills. Staff with limited resource/skill may find that less accessible interfaces which allow simpler coding are pragmatic alternatives. [The 1st author uses MATLAB GUI tools; students need access to MATLAB.]
- Module leaders like to tweak their module activities regularly and hence there are advantages in being able to author/edit their own virtual laboratories rather than being reliant on a costly or unavailable expert.
- Off the shelf or free to access laboratories are cheap to implement and may be high quality, but the IFAC community does not have an effective mechanism for sharing these alongside independent evaluations.

4. TAKE HOME LABORATORIES

Computing hardware is getting cheaper every year and with it the potential to design and build meaningful hardware that costs just 50-100 pounds to make. In terms of education, this opens the door to a significant change on how students access laboratories; now it is possible for students to have their own hardware for many simple activities and thus access department facilities only where more expensive or limited equipment is required. For example, a few years ago access to hardware required an expensive IO board on the computer whereas nowadays one can drive hardware through the USB port with a simple interface such as Arduino on the hardware.

So far this potential has not been explored effectively, but this is beginning to change, particularly with the advent of low cost data acquisition and control units, such as National Instruments' (NI) myDAQ, which has begun to establish itself as a teaching aid in the educational sector, particularly on electrical and electronics engineering courses (Chesnutt et al, 2011; Walters, 2011; Meng-jun, 2011). The adoption of this hardware by the systems and control community has been slower, but is beginning to happen, particularly with the advent of so-called 'miniSystems' that utilise the myDAQ platform to provide a portable and low-cost replica of a range of real-world systems. Current examples include miniature vertical take-off and landing vehicles, power grids and flexible structures.

Inspired by these examples, (Taylor et al, 2013) have recently developed their own take-home hardware to provide systems engineering students with a challenging control problem. This hardware is shown in Figure 1 and consists of a miniature three-degree-of-freedom (3DOF) helicopter, interfaced to a PC via a NI myDAQ. The helicopter chassis consists of two independently controlled fans connected via a rigid link. This link is free to pitch around an axis that is pivoted at the end of a second linkage that provides mechanical assistance via an adjustable counterweight mounted at its far end. This linkage is free to rotate about the horizontal plane, and is mounted upon a vertical shaft that spins freely within a cylindrical housing. This housing connects to a signal conditioning board via a standard D-type connector. This allows easy assembly, and disassembly of the take-home kit, which is stored within a padded toolbox for easy and safe portation between home and campus. The entire parts cost of each kit was

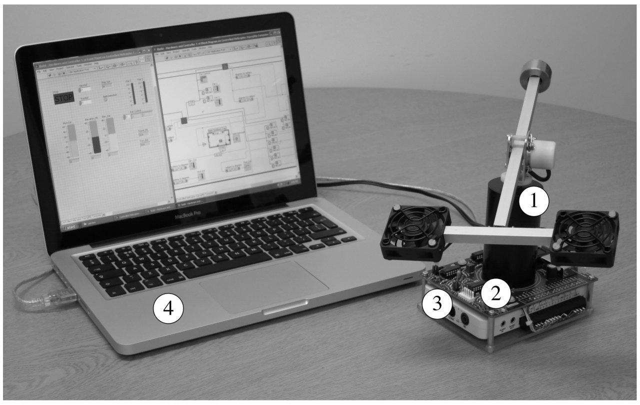

Fig. 1. Take-home helicopter set-up, showing (1) the 3-DOF helicopter, (2) signal conditioning and power electronics, (3) NI myDAQ interface, (4) PC running NI LabVIEW.

under £300, making it possible to provide each student on the course with their own kit, on a loaned basis.

The system is dynamically rich, containing a mixture of continuous and discrete-time dynamics. It is nonlinear and displays significant dynamic coupling between the inputs to each fan and each of the measured linkage angles. The system provides students with a challenging control problem, requiring mastery of techniques such as modelling, state-estimation and multivariable control, as well as basic data-acquisition techniques. Student feedback on the inaugural use of the take-home hardware has been extremely positive, suggesting the take-home paradigm has significant potential as a teaching aid.

5. VIRTUAL LEARNING ENVIRONMENTS AND SYSTEMS AND CONTROL OUTSIDE ENGINEERING

This section is brief and aims to raise the profile of some issues which are either generic or of growing importance.

5.1 Virtual learning environments

Virtual Learning Environments (VLEs) are ubiquitous by now so some brief comment is appropriate to emphasise that the community should make use of these tools. There are many papers in the literature which highlight the potential benefits of a VLE, such as: (i) incorporation of quiz environments for both student self-assessment and efficient summative assessment; (ii) date releasing and conditional releasing of information linked to student behaviour; (iii) maintains a database of student interaction which can be used for monitoring and support; (iv) integration of unfair means tools such as Turn-it-in; (v) easy single location for all module resources; (vi) and many more!

5.2 Broadening our students perspectives

The concept of what is an engineer is changing rapidly. No longer do employers want someone who has just attended traditional classes in engineering topics; today's engineers are expected to be multi-disciplinary, including disciplines such as finance, biology, the environment and so on. Consequently (Murray, 2013), there is a need to re-invent our traditional control courses. To what extent do these encourage students to think of their discipline outside the conventional boundaries? To what extent do we offer a control and systems module that is attractive to students from outside engineering? There is already some evidence in the literature (Murray, 2003, 2004) of successful models for achieving this. There is a need for a dialogue in IFAC about how we take this evangelisation forward and determining the correct balance between concepts/application and rigorous mathematical underpinning.

6. CONCLUSIONS AND FUTURE OPPORTUNITIES

This paper has given a concise survey of good practice in the area of control education. There was brief discussion in areas which are shared across all disciplines such as lecturing and then a more detailed discussion of topics in which are highly relevant to control, such as virtual and remote laboratories. A summary of the key points is:

(1) There is a growing acceptance of the potential of virtual and remote laboratories to enhance student engagement/learning and to supplement formal laboratory sessions. However, substantial expertise is needed to create an effective and reliable remote laboratory with numerous alternatives in the literature.
(2) Numerous excellent virtual laboratories are freely available on the internet, but could benefit from independent evaluation and coordination. Virtual laboratories require less expertise and time to develop with many good exemplars already in existence.
(3) There is a broad consensus that laboratories are more effective when there are good pre- and post-laboratory resources and activities.
(4) It is increasingly straightforward and cost effective to design, build and distribute cheap laboratory kits which consequently all students can own and use.
(5) There are many opportunities through Youtube/ itunesU and similar outlets for the IFAC community to provide learning resources which are easy to use and learn from and thus the opportunity to rethink the role of the lecture slot in education.

As a postscript, the rising usage of mobile devices such as tablets and smartphones creates an opportunity to provide resources which students really can access anytime and anywhere (Esquembre and Garcia, 2013).

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