

## Typical control curricula and using software for teaching/assessment: a UK perspective

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**Abstract:** This paper describes some of the preliminary outcomes of a UK project looking at control education. The focus is on two aspects: (i) the most important control concepts and theories for students doing just one or two courses and (ii) the effective use of software to improve student learning and engagement. There is also some discussion of the correct balance between teaching theory and practise. The paper gives examples from numerous UK universities and some industrial comment.

Keywords: Control teaching, control curricula, software, assessment, survey

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### 1. INTRODUCTION

Recently there has been a growing interest in how to improve the educational experience of engineering students, the increased activities of the IFAC control education committee EDCOM [2007] being a case in point. In the UK there has been a rapid increase in activity in recent years, supported by the Higher Education Academy HEA [2007] and its numerous subject centres. Universities are also trying to encourage more professional attitudes to the delivery of undergraduate education by providing career incentives to staff who take up this banner with the inevitable reduction in their research activity.

Universally, the increasing reflection on what constitutes quality teaching, perhaps coincidentally, is happening with a short time lag behind the improvements in technology. Academic staff are being encouraged to ask how modern technology might enable more effective learning and teaching. Simple examples include using virtual learning environments (VLE) as repositories of resources such as notes, podcasts and tutorials or to provide more structured pathways through material. VLEs also include numerous other tools such as discussions boards, group work functionality, computer aided assessment (CAA) and more. The potential to develop and deliver teaching resources of many different types efficiently is beneficial to learners who all have different preferences and requirements.

However, a major premise of this paper is that there is huge inefficiency in the efforts staff are making. It is well accepted that high quality education resources for blended or distance learning take significantly longer to develop and require more expertise than traditional lecture notes and tutorials Khan et al [2006]. Despite this, for many subject disciplines there has been insufficient effort put into sharing of good ideas and resources (e.g. Foss et al [2006], Guzman et al [2006]) between universities. There are many topics that are common across degree

programmes in all universities and not susceptible to the local variations or flavours that distinguish us. One obvious example is 1st year mathematics for engineers where almost all students will do some basic calculus, basic algebra, trigonometry, matrices, vectors, curve sketching and complex numbers. With this in mind, the UK funded some national projects e.g. HELM [2007], MATHTUTOR [2007] with a remit of producing resources which could be used, free of charge, by all UK educational institutions. One key advantage of this approach is that communal buy-in provided much more rigorous validation of the materials as well as ensured staff input orders of magnitude above what a single institution could supply with a consequent improvement in quality and coverage. It is now common place for UK engineering departments to base all 1st year engineering mathematics on the HELM workbooks and CAA; academic staff can then focus on motivating and supporting the students learning.

With this experience in mind, a group of UK control academics Rossiter et al [2006] [Special interest group (SIG)] asked the question whether, albeit on a smaller scale, similar benefits and sharing could take place for control engineering. Specifically:

- (1) Is there some commonality in what UK engineering departments teach in control?
- (2) Is there agreement on priorities?
- (3) Is there a will to consider more effective sharing and normalisation?

There are good summaries of priorities from a more global perspective Astrom [2006], Falsetti et al [2006], ACE Panel [2006], however the depth and breadth of material in some of those proposals is far beyond what would fit into typical UK engineering programmes. It was felt that the UK needs may be slightly different and we should first start with a survey of the current status.

Hence this paper summarises the principal outcomes of the project to date SIG [2007]. Section 2 looks at the discussions on syllabus and priorities and section 3 looks more at the potentially controversial issue of the extent to which we teach theory or use software to avoid this Atherton [2006], Rossiter *et al* [2006]. The paper is supplemented with comments from and experiences of several institutions and industrialists.

## 2. CONTROL EDUCATION PRIORITIES WITHIN THE UK

This section looks at the initial work of the SIG, a survey of the UK community to discern whether there are common needs and priorities. It is organised into academic and industrial subsections to reflect the potentially different perspectives.

The reader should note that courses within the UK are likely to be 10, 15 or 20 credits where a full academic year is 120 credits. Depending on the department, control will typically occupy between 20 and 30 credits in total over all basic courses.

### 2.1 The academic perspective of typical curriculae in UK universities

This section summarises what can be considered to be the most important control topics to teach to undergraduates typical first and second courses. Obviously there is variation in the opinions. The summary is based on a broad brush overview of 1st and 2nd courses at Reading, Imperial, Sheffield, Leicester, Newcastle, Manchester and Glasgow Caledonian and seems to have broad similarity with the recent Italian survey Falsetti *et al* [2006].

For many degrees, particularly those with a greater emphasis on control and/or which result in an MEng qualification, there will be more advanced courses in control following on from these first and second courses. These advanced courses will often reflect the research interests of the staff involved, and hence there is less scope for sharing material and so are not discussed here.

*1st course in control* A first course tends to cover core mathematical skills required for control and thus might be called Signals and Systems. It covers Laplace transforms, transfer functions, poles and zeros, responses of 1st and 2nd order systems, damping and resonance, basic block diagrams, Fourier series and transforms (useful for signal processing). Introduction to feedback (no analysis). Modelling and dynamics.

There are of course minor departmental variations in emphasis, organisation and the other topics covered within this module.

*2nd course in control* The 2nd course would be the course that covers key principles of control and maybe the only control course many engineers take. It is offered in year 2 or 3 depending on institution. Typical content is listed next.

Why feedback? Open and closed-loop, block diagrams, 2nd order systems (step responses, damping, overshoot,...).

Steady-state errors, the effect of disturbances, position of the integrator in the loop, poles and zeros and stability, characteristic equation and root loci, frequency response, Bode, Nyquist, nyquist stability, gain and phase margins, lead and lag compensators, PID. Velocity feedback.

Control design is usually not covered in this module beyond illustration. Laboratories are core to many modules, but typically based on MATLAB and SIMULINK.

*Remark 2.1.* : Although Routh-Hurwitz, Nichols charts, Zeigler Nichols are still in many syllabi, the authors of this paper are debating whether they are a useful (efficient use of time) given modern computing. Could we add value more with other topics, effective use of software, etc? Similarly, do we teach topics like Nyquist as a tool or expect students to derive the diagrams from first principles?

*Remark 2.2.* There are many notable omissions or topics that might be included in a 2nd course elsewhere Astrom [2006]. In the UK there appears to be less emphasis on sensitivity and thus fundamental arguments as to why control is important. First courses also do not tend to tackle, at least in any detail, control design via lead, lag, PID, root-loci and pole-placement, digital control, state-space approach to control, Kalman filters, sensitivity (noise and disturbance rejection) and robustness, feedforward, relevance or significance of zeros, PLCs, measurement (sensors and transducers) and time delays.

### 2.2 Some academic feedback on the above summary (not verbatim)

The general consensus from those responding to a survey is that the proposed syllabus is broadly correct. It is interesting to note that the emphasis on digital control is perhaps lower now that it would have been a few years ago with many assuming that with fast sampling, continuous and discrete implementations are similar enough. The need to emphasise the understanding of key concepts before going into mathematical detail was also an important point. Typical comments are listed next.

- First the digital control question. In some ways it is less important now as restrictions on sampling rate rarely apply. I think it is best to teach continuous systems first because of the strong link it provides to courses being done roughly at the same time on topics such as, circuits, dynamics, measurements and sensors, and modelling. A DSP course is the best for the first introduction of digital techniques and it can be taken up later in, say, what would be the third control course.
- I believe it important to first introduce feedback systems simply with very little mathematics. This should include simple block diagram analysis, where blocks contain just constants. In effect this can show steady state responses to step signals. The concepts of dynamics and thus transients can then be done by first introducing an integrator block, stating that if its input is a constant then its output changes at a constant rate; feedback is then connected around the integrator. The input is found at discrete times, and the exponential lag response is then argued. This approach has been used successfully for some years

and is not inconsistent with the approach described in Cortes et al [2007].

- A repository of graded formative questions would be very useful in order to produce tutorials and worked examples. Core syllabus concepts are good, but I wouldn't want to see a uniform syllabus set across the UK. Specific examples would be more useful than complete lecture series.
- I think there is just one major omission in the draft syllabus; that is, performance specifications should be included.
- The debate about digital control/continuous control is indeed interesting given the current processor speeds. Although we teach some digital control techniques, the control design of all our current lab practicals which involve real time control is done in the continuous domain, and the Simulink implementation is also done with continuous blocks. The discretisation is done automatically behind the scenes.

### 2.3 The industrial perspective

The industrial view point was gratifyingly very close to the academic one. Once again the emphasis is on deep understanding of, and the ability to use, basic traditional concepts rather than the need to be broad. It is interesting that there was no demand for introducing state space methods into first courses, despite the obvious arguments that might support such a call. Nor was there a call for a greater emphasis on loop sensitivity at this level

*From a group leader in a major international systems engineering company* Your question concerning a basic control course is one that I have often thought about, partly because I started out having done just two control modules and had to go back and do a Masters before I felt confident - the main problem for me even then was there were too many methods (but also no computers). Many engineers have a single control course but don't really appreciate it and generally resort to some crude hand-tuning and a lot of conditional logic to stop things going wrong.

My approach is always to understand the problem or task first, and then I'll understand the tools I can use to solve or complete it. Teaching fundamentals first is an attempt to make teaching easier but may not motivate well. Hence I would not start with fundamentals such as Laplace. Now we have Matlab, I've often wondered about how I would teach control so here are my thoughts:

The basic structure of a first control course would be:

**Stability:** 1) Feedback analysis  $G/(1+G)$ , with enough block diagram manipulation skills to write equations for feedback and forward configurations<sup>1</sup>. 2) Nyquist diagram to represent the frequency response, and to understand the feedback equation as a mapping from  $G$  to  $G/(1+G)$ . 3) Bode diagram and Bode analysis.

**Performance:** 4) Laplace transforms, relationship to  $d/dt$ , Rads/sec vs. Hz, time constants and poles and zeros.

<sup>1</sup> We should note that there is not always unity gain in the feedback path, for instance, in electronics  $G/(1+GH)$  would be much better; our teaching should reflect this.

5) 1st and 2nd order systems, introducing root locus. 6) Root locus, relationship to Nyquist plots and stability margins. Bring in gain and phase margins.

**Controller and compensator design:** 7) PID Control and pole-zero placement 8) Lead-lag compensation.

It would be good to get more z-transforms in but I suspect it's too much for a 20 hour module.

*From an industrial power systems control engineer* These notes are based on and prejudiced by over 30 years experience of working on predominantly boiler control systems on large (500MW) coal fired generating plant. The dynamics of the plant are relatively slow (typical time constants of the order of minutes), non-linear and time variant. Originally control was by electronic 3-term analogue PID controllers. Since the 1980's digital control has largely replaced the analogue controllers and has allowed the use of other control techniques (Fuzzy logic, Kalman filters, MPC).

**PID controllers:** PID controllers are the main form of controller used in industry. Therefore it is important that the theory of the PID controller is taught and students know how to determine controller settings for a PID controller.

**Bode/ Nyquist:** I think there is great value in teaching the theory of Bode diagrams and Nyquist plots. This provides the basis of understanding the plant dynamics and the effects of closed loop control and the controller settings. However, although I think students should understand the mechanics of calculating the frequency response of a system, the use of Matlab should enable the calculations to be done quickly so that time can be devoted to controller design. It would also allow higher order systems to be investigated.

**Signal Analysis:** To obtain the dynamic response of unknown plant testing must be undertaken. There are packages available but these are not always accurate. I feel there is a need to understand signal analysis such as Fourier Transform, the problems with a finite sample length rather than the theoretical infinite sample length, the use of Hanning and Hamming windows and other such techniques.

**Zeigler Nicholls Criteria:** The Zeigler Nicholls criteria is much used and misused technique for obtaining PID controller settings. Again I think an understanding of the underlying theory, rather than blind application is important. It is, remarkably robust for at least getting into the right ball court but can be sensitive or imprecise when response data is noisy.

**Digital control:** Because the dynamic response of the plant I have dealt with is relatively slow compared with the sampling rates of data available using digital computer I/O, it has always been possible to treat the systems as effectively analogue systems rather than as digital systems.

### 2.4 Summary

There seems to be common ground between academics and industrialists on the most important content for introductory control courses which may be the only courses taken

by many engineers. The main apparent tension is the industrial desire for students to have enough understanding to do design whereas this will often not be taught until a later optional module. Typically students will be exposed to analysis and are expected to understand the impact and role of different controller types, but may not do an independent design.

### 3. USING SOFTWARE FOR LEARNING AND ASSESSMENT

Those staff contributing directly to the SIG were unanimous in proposing that software be used actively within the teaching and assessment of 1st/2nd course in control. The most significant argument is that many of the theoretical methods and rigor used 30 years ago were in a context where only paper and pen designs were possible. It was essential to have a thorough grasp of detailed plotting in frequency response and root-loci, of Routh array techniques and more in order to make any reasonable progress.

Today however the scenario is different. Students need to have an understanding of how to sketch Bode and Nyquist plots and root-loci, but need to have less concern for computing the numerical details; software can be used for this. Consequently we can put more emphasis on interpretation and design, using simple rules that work for the straightforward problems tackled in introductory courses.

#### 3.1 Summary of SIG proposal

Staff and students should use interactive software to illustrate key points. We recommend that staff remove the hard work of unnecessary paper calculation and use software so that the focus can be on concepts, implementation and understanding the bigger picture<sup>2</sup>. There is a need for students to have the ability to do computations by hand, but the time spent on this skill must be tempered with other needs.

If one accepts the need to make use of software to help with developing insight and design skills, the move also raises questions of how best to examine control? There seem to be agreement that one should balance assessment between traditional exams and some laboratory based work where students are expected to be fluent in the software and demonstrate aspects of control that would be too time consuming or unrealistic in a paper based exam.

As a community we could usefully share our experiences of developing software based assessments. The practice and experience of several institutions are thus summarised next. The feelings of several of us are that it is logical to base ourselves around MATLAB and sisotool. These are widely used in industry and it effectively ensures that the students are immediately employable.

#### 3.2 Descriptions of and experiences in assessments using software

The case studies given in this section repeat several main themes.

<sup>2</sup> This also avoids the huge blockages caused by typos in paper/pen computations.

- (1) Careful preparation, technical support and a back up strategy are essential when arranging formal exams within a PC laboratory.
- (2) Do not expect the use of software to save time; in many cases introducing this form of assessment puts a substantial extra tutoring and/or marking load on the staff.
- (3) Student feedback is very positive with typical comments suggesting that the laboratory really helped with their understanding of key concepts. Above anything, this is a good reason for continuing.
- (4) Increased familiarity with MATLAB/SIMULINK software can be used to benefit in later modules.
- (5) Most departments still retain a larger percentage of the assessment for a formal paper and pen exam.
- (6) Ensure the students keep suitable records of their work during the laboratory. Critically, they should include notes that demonstrate understanding of concepts.

*Academic 1* Reliance on the network can be crucial in an examination situation. We tend to set open ended coursework assignments for the students to tackle often with data logged from an industrial process.

It is important that the students understand the principles before they fly off to use computer software packages; care is needed to get the balance right.

*Academic 2* A split of about 30:70 practical assessment to examinations is appropriate. Control is easier to teach when people have physical experience of the systems (not just software).

We used MATLAB as a tool, including SIMULINK and Quanser experiments. Simulating a system is useful, but not a substitute for physical experience.

*Academic 3* Our Matlab based control module and related assessment are popular, but:

- (1) Extremely time consuming from my side to produce appropriate questions.
- (2) As I need to guard myself from possible computer problems, I must have spare PCs and also I have at least one computer technician present. Even the invigilators must be "Matlab experts" to cope with possible problems.
- (3) I have to make sure that there is no internet/network access as I can imagine students emailing the answers to their best friends. We have a software that does that but once again we need a computer/network expert to be present.
- (4) Some students find it difficult to adapt (slow in typing...).
- (5) I need a lot of time for marking.

*Academic 4* Regarding the Matlab use in examinations, when we used the Control Kit we had no problems and I think this should be the case with sisotool. From the Control Kit experience:

- (1) No more time was required to set exam questions—probably less. Most exam questions I set now I usual check by using the Control Kit.

- (2) We had a technician available as well as one demonstrator if students complained about the software.
- (3) All the machines were set up as stand alone so no communication was possible. Obviously there is a limit to the class size. A few spare computers should be available. No printing or graphing of results was required. Even though the students get graphs on the monitor you ask for numerical answers to be written down or for them to do a sketch. There is no difficulty whatsoever in designing questions for numerical answers to show the students will have carried things out correctly.
- (4) No typing is required. The students fill in an answer book in writing in the normal way. Incidentally this is good practice for working with control software - you should always keep a hard copy of what you have done- it can be very brief.
- (5) Marking definitely took no more time - again probably less as one does not have to try and find where students have made errors in calculations to decide on how many part marks to award.

*Academic 5* We have found the biggest battle is with student attitudes. On the one hand the majority of the class is very positive about the laboratory based assessment and comment that this aspect has been far and away the most useful in helping them understand the module SIG website [2007], including the more theoretical aspects. However, a sizeable minority find the assignment very challenging and complain about the need to learn the software tool (support is provided in advance of the assessment) in addition to the theory. Those who do not prepare adequately will typically score less than 20% on the laboratory assignment and this is clearly a cause of some student disquiet. Conversely of course the well prepared can get very high marks.

The issues raised by other academics are also critical. Due to the large cohort, we run assessments with upto 40 students at a time, but this can cause the software to run slow and also makes demonstrator help a precious commodity. Also, there is always vulnerability to network problems and a contingency needs to be in place - we have had two network failures (central university issues) during assessments and this does cause major discontent. We get around the issue of students demonstrating understanding, as well as using the software to give correct numerical answers, by awarding many of the marks for the interpretation and/or justification of the results. In our case, we also viva the students on their report. This is clearly optional and very demanding on time, but seems to be of huge benefit to and appreciated by the students.

*Academic 6* The initial goal, as it was requested by the head of school, was to introduce a new teaching style that would take traditionally taught modules and would transform them with the use of state of the art software/hardware. At the first joint meeting it was decided to use Matlab and a stage II module that is introducing control systems to electrical engineering students.

I designed a module based on how an engineer would use various control concepts to design a system or controller. So for example I will draw the Bode plot using Matlab

rather than with a hand sketch. So a two hour session will typically include 20-40 min lecture and then tutorial exercises which can be answered using Matlab.

The material that is presented is more or less the same as other universities although I do not cover topics which I think that are obsolete, like the Routh test. The final mark is composed by the normal lab (15%), a 3hr open book Matlab assessment (65%) and an 1hr normal unseen examination (20%). The 3hr paper is similar to the tutorial exercises and the students have to write there answers/comments/figures in a MSWORD file which at the end of the exam I print. To ensure that there is no improper behaviour the network is disabled.

The results of this new teaching method were more than satisfactory. The students engage and interact with the facilitator. Hence the students remain 100% focused. The students have the opportunity to build their own systems and controllers and hence to materialise what they have been taught! The student feedback was very good and therefore we expanded this scheme to at least 2 more modules (stage III-IV and MSc) which are now attracting more student interest and registrations.

The biggest problem is that students are not used to this new teaching style and some got the impression that this is another "programming language" module (like C, C++). Some extra sessions were arranged to overcome these problems.

*Academic 7* For many years we have run an assignment designed to reinforce the Laplace analysis of systems and demonstrate the success of simulation. Students are first required to derive the theoretical step response for various first and second order systems. They then use MATLAB to both simulate that system and generate graphs with the simulated response superimposed on a plot of the theoretical response. The close proximity to the plots, it is argued, allows the students to have confidence in simulation. Students are then provided with other example systems, some higher order, where they have to form the block diagram, generate the transfer function and then simulate the response using MATLAB. This form of assignment has proved to be successful in helping students understand such systems.

#### *Miscellaneous additional comments from other staff*

- Computer assessment using MATLAB looks interesting and I would welcome more discussion/info on this - though still have a hankering after asymptotic Bode sketches as a first start - confirm with MATLAB once or twice then leave it to computer.
- We use MATLAB in exams for the Part 4 advanced control module (a small number of students - so it is manageable). Here they both write in the answer books, but can also save documents / graphs, the printed version of which is examined. This may well be appropriate at this level, but if we were to use MATLAB in Part 2 or 3 exams then I rather agree that the students should record what they do in the answer book including sketches of graphs.
- Our experiences (and precautions) with the computer based exam are very consistent with the others

recorded here. Although we ask the students to save plots and other information (such as identified model matrices) in a Word document, it is certainly a good idea to get the students to sketch graphs on the answerbook in the year 2/3 exams.

- We expect students to save all key MATLAB figures directly into a word document as they go, next to any numerical answers. This document should be printed off and brought for marking a few days later. Sketching and associated skills are assessed in a separate written exam.
- I feel that we need to discuss more carefully the proportion of assessment that should be software driven and conventional written. My fear about having a completely software design approach is that the students will not gain an appreciation of the underlying theory behind the techniques and thus become software design techs. Another problem is the continual occurrence of errors in software packages e.g. Matlab. Without an understanding of the maths the student will not be able to ascertain whether or not the software is producing a reasonable design. Practical skills are very useful for design based engineers, but wouldn't it be better to have a physical system coupled with software design? Thus covering the full design spectrum in a problem based learning environment.
- Once students know about the MATLAB environment it is possible to set them more interesting assignments where they programme using MATLABs own language. This can be used in assignments associated with other control modules.

#### 4. CONCLUSION

There are two clear conclusions in this paper.

First, there does seem to be general agreement within the UK control community about what topics are covered during introductory control modules. These include many topics that would be expected but also, do not include a number of topics that colleagues might argue are equally critical. The likely response is that within the time allotted, it is not possible to do more. If more is wanted, the engineering institutions would need to put pressure through accreditation requirements for control to take a higher priority. Nevertheless, there may be some frustration that students not taking optional modules in later years will, as a rule, neither be proficient in control design nor have had exposure to robustness issues or state space methods.

The second conclusion is that there is a significant move towards using software, specifically MATLAB/SIMULINK, both for teaching and assessment. In parallel, many traditional topics, such as Routh arrays and Nichols charts, are gradually being dropped and more emphasis is being placed on interpretation. The student feedback available seems to indicate that students come out more confident in basic principles and thus potentially are more ready to re-engage with the topic later in their studies. A number of minor conclusions on best practise in using computer based assessment also seem to be widely shared.

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