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A first course in feedback, dynamics and control: Preliminary findings of a survey for the IFAC community

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Abstract— **This paper introduces a survey for the global control community on the most important topics that should be covered when engineering students take just a single control related course, a situation typical for many undergraduate engineering programs. There has been a rapid increase in the availability and power of both computing and internet resources which has an inevitable affect on both what content and how university education is delivered. This paper provides some context and discussion of a preliminary survey with a limited exposure; the intention is that feedback on this paper and the initial survey results will be used in planning for a more comprehensive survey of the entire IFAC community.**

I. Introduction

The paper begins with a brief introduction to the EDCOM committee (IFAC TC 9.4, [8]), its remit and recent priorities. There are also strong overlaps with the remit of the IEEE TC on control education [10]. Their scope is summarised concisely as:

1) University education and continuing education issues in control engineering.
2) Methodologies for improving the theory, practice and accessibility of control systems education.
3) Control engineering laboratories.
4) General awareness of the importance of systems and control technology and its cross-disciplinary nature.

In general terms these two committees have focussed on providing activities, largely at IFAC/IEEE conferences, whereby delegates and school children can engage with control education and novel pedagogies facilitated by new technology and understanding [14], [16].

Nevertheless, there has been an obvious and substantive shift in the last 20 years in terms of the way academic staff develop and deliver control courses, e.g. [1], [4], [7], [9], [15]. For many years there has been an on-going discussion of whether the topics covered in introductory control courses are relevant to the industrial practice of control. Some control professionals argue that the gap between what is taught and what is practiced has been a growing, [3], [17]. In a control education curriculum survey conducted by IEEE [5] only 32% of industry respondents rated the capability of new graduates as good to excellent. In a study by the American Institute of Chemical Engineers [2], only 31% of the industrial respondents considered that the academic preparation of current Chemical Engineering graduates in US adequately addresses the topic of control theory and implementation.

Thus the two committees felt we could best serve their remit by trying to bring together the thinking in the community on both how we should educate modern students but also, what we should include in the curriculum? Although some recent work on this exists [18], that work has a very narrow remit by comparison with the control community needs and the two committees are not aware of other substantive surveys providing this information.

One obvious example of the need for change were recent committee discussions at the IFAC world congress in 2017 on education prizes that historically had been focussed solely on text book contributions (e.g. the Harold Chestnut Award). EDCOM have subsequently proposed to IFAC that either a new award is instituted or the existing award has modified terms to recognise the changes in modern education, to quote some contributors to the discussion:

- *I full-heartedly support your application for a prize for non-textbook contributions. My students educate themselves on the internet - with very good results.*
- *I completely agree with your proposal of a new Control Engineering Education prize. I believe this new award will encourage the development and the application of new pedagogical practices for the benefit of future engineers.*
- *Current students demand new teaching and learning methodologies. So, a relevant question for the majority of staff is: which teaching approach to use to improve student learning [11]?*

These sentiments were echoed at the 2017 IEEE TC meeting in Melbourne where there was a clear recognition of the need for the community to be more cohesive in how it provides good quality materials for supporting undergraduate studies of control topics, as well as guidance on which of those topics should be prioritised within the curriculum. Moreover, in conjunction with EDCOM, it has been noted that the current sharing arrangement for learning resources [12] has not been designed optimally for academic or student users. Nevertheless, it would be churlish to criticise the current site design because more worryingly, the arrangement is entirely reliant on the current provider and manager Francisco Candelas who provides this service on a voluntary

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basis. Indeed, IFAC has long recognised this with minuted discussions certainly going back to 2008 (then led by L. Vlacic). Encouragingly, the IFAC council has now decided this needs action and has very recently set up a task group led by Jacquelien Scherpen (Groningen) to come up with a sustainable and effective long term proposal; it is to be hoped that they will engage the IEEE in delivery of the final solution.

EDCOM organised an education panel session [11] at the the recent IFAC PID event in Ghent in order to kick start some of the required discussions and to lay a foundation for a long term project. A simplistic questionnaire was also distributed to attendees as a means of getting some feedback on questionnaire design and intial impressions. Subsequently, the committee meeting there agreed to full support for a study involving the global community; development of the associated questionnaire is ongoing. It was also noted that there are stong overlaps with the priorities of the grouping of IFAC TC vice-chairs for industry and thus there is a need to fully engage with them in the final questionnaire design and delivery.

In summary, both EDCOM and the IEEE TC on education have recently decided that the topic of control learning resources and the curriculum is a sensible priority for the short term. This paper presents the early findings in the associated project gathered from the panel session and pilot questionnaire in Ghent. Later and more complete studies will be published at the IFAC ACE 2019 and the IFAC world congress 2020.

II. Panel session findings

A panel session was arranged at the IFAC Conferences on Advances in PID, Ghent, 2018 with the title: **What is an ideal undergraduate control curriculum?** and panellists representing the global community: Ferdinand Kieckhafer (Hamburg University, Germany), Tore Hagglund (Lund University, Sweden), Paulo Moura Oliveira (UTAD, Portugal), Guy Dumont (The University of British Columbia, Canada), Tao Liu (Dalian University of Technology, China). This section summarises some of the major points that were raised by both the panellists and other delegates.

For simplicity, these are presented as number of bullet points and moreover, readers will find some conflicting points of view. This is inevitable and recognises the different priorities and assumptions that may be present in different institutions. Nevertheless, it serves as a good start point as there is clear consensus on most issues.

- Motivation is essential. Can we convince students that the material is fundamental? Build interesting experiments.
- Start from real life problems and interesting examples in first lectures. Let students identify which mathematics they need to tackle these problems.
- IFAC should have a role in defining the ideal control curriculum to help the community.
- Classical control needs to be taught in a different way to historical methods and make more use of computers.
- We should define and provide some benchmark problems for use in teaching.
- PI should be included in an introductory course. The efficacy of integral action, even with NL system is essential.
- Some felt PID tuning rules should be taught so students can see the link between behaviours and tuning and the benefits of good tuning rules. Also this is an invaluable skill in employment. Others felt this was too advanced and should be in a second course.
- Digital technology is growing and almost pervasive so ideally we should include this.
- Some countries, such as China, may have clearly different requirements, for example due to assumptions of students having higher initial background competence in mathematics or as they offer many more programmes with a major in control.
- The effective use of computer simulations for both training and testing are important.
- The community would benefit from the sharing and understanding of tests for concept understanding (a concept inventory is needed) and also effective pedagogies for the intended learning outcomes. The community must value and utilise the research on Teaching & Learning.
- From an introductory course, students must understand the capabilities and limitations of control loops and core components. The focus should be on concepts and should enthuse and excite rather than focus on specific design methods or number crunching/algorithmic problem solving.
- Must include modelling and process dynamics to support the use of transfer functions and to understand the roles of poles and zeros on behaviour.
- Appreciation of the power of and need for feedback. Good systems from bad components, reduce effect of disturbances/uncertainty, shape behaviour (stabilise unstable planes), but also introduces a risk of instability and over-reaction to measurement noise, trade offs between performance and robustness.
- Ideally include a brief introduction to state space.
- De-emphasis things like plotting of root-loci, instead do *back of envelope* sketches to aid understanding.
- Give students realistic environments in hardware or virtual laboratories so they can play around and also recognise that friction, stiction, non-linearity, uncertainty, and more exist and have an impact. Must have real hardware laboratories if possible.
- Use a variety of everyday examples to inspire multi-disciplinary cohorts.
- Do not include too many concepts as students cannot absorb them. Must be judicious about what we include and ensure that we cover the basics well and also those concepts which how easy to generalise and thus have most value.
- About 50% feel non-linearity should be included in the introductory course.

- How deal with colleagues who do not want to change? It would help to have an IFAC accredited typical curriculum which we can give to colleagues. Need a community to build this picture, develop course/materials and share.
- University needs to provide students with skills they cannot easily get on the job to supplement the application knowledge that comes later.
- Danger that students can do mathematical analysis with for example Bode, root-locus and Nyquist but yet have no understanding of control? Application of control illustrates the differences between theory and practice; this is important.
- Students need to have an understanding of requirements before engaging with control design.
- Should avoid over emphasising linear and SISO examples in a 1st course. State space gets around this and can be used to introduce important concepts (MIMO, observers, time domain, NL, ..).
- Modern students expect to be stimulated more than in the past. Need different teaching methods. Empirical evaluation is essential to judge efficacy.
- A standard curriculum would be useful and shared benchmarks.

III. QUESTIONNAIRE RESULTS

In parallel with the panel session, a pilot questionnaire was distributed to the delegates at IFAC PID 18. The prime role of this was to get feedback on the questionnaire design so that an improved version and delivery could be planned. Nevertheless, the results are still interesting and are worth sharing as they represent the views of around 60 people from a good range of international countries. It is not possible to display all the data here, so a selection is presented to give a clear view on the thinking of the delegates.

A. Likert scale questions

For reasons of space the full questions are not included here but it is hoped that the sentiments of the implied questions are clear. A reader wishing to see a slightly updated version of the quiz and questions can visit the website (http://iolab.sk/ifac/index.php). Indeed, you are encouraged to complete the questionnaire and add your data to that being collected.

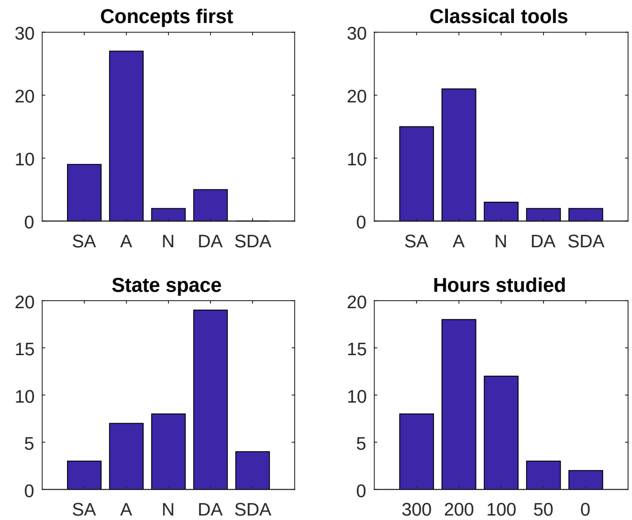

Fig. 1. Questions on a Likert scale: SA (strongly agree), A (agree), N (Neutral), DA (disagree), SDA (strongly disagree). The vertical axis is the number of respondents.

Figure 1 uses a Likert scale and indicates a strong priority for classical methods over state space, a desirable focus on concepts in a first course and a preferred course length of about 200 hours (circa 40-50 lectures).

Figures 2-7 simply asked delegates whether they felt these topics should be included in a first course. Obviously this is distorted somewhat by the fact that they may have entered a different size of module (number of lectures), but given the number of responses this still presents some interesting preliminary findings.

1) Some topics are clearly indicated as being expected in a first course (or pre-requisite knowledge). These include system dynamics (1st/2nd order responses), Laplace, PI, concepts of stability, disturbance rejection, regulation and tracking and laboratories. It is interesting to note that there was also a strong demand for the classical topics of frequency response, Bode and margins.
2) Topics which still had a strong, but not so overwhelming vote include generic concepts, 1st principles modelling, Nyquist, simulation, offsets and delays.
3) Topics where the response was more mixed although still with some dominance towards inclusion are: introduction to state-space, root-loci, industrial control diagrams, emperical models, pole placement.
4) Topics which had some support but more people less convinced about inclusion are: lead and lag compensation, low-pass filters, industrial software, controllability, observability, state feedback, times series, discrete control, z-transforms, c2d transforms, unit circle, PLCs,
5) Topics where there is a good consensus that these should not be include are: optimal control, Kalman filters, observers, DFT, signal prcoessing, signal flow graphs, state trajectories, MIMO systems, integral action in state space, eigenvalue/vectors in state space.

B. Textual comments

The following data was taken from written comments provided by delegates at IFAC PID in Ghent, May 9-11 2018, some prompted by the panel session on the 10th.

Which core control and systems skills would you expect engineering graduates to have?

1) Understand the concept of dynamic system and its mathematical representations (model).
2) Obtaining models from first principles and from data (from first principles it is useful if they approach

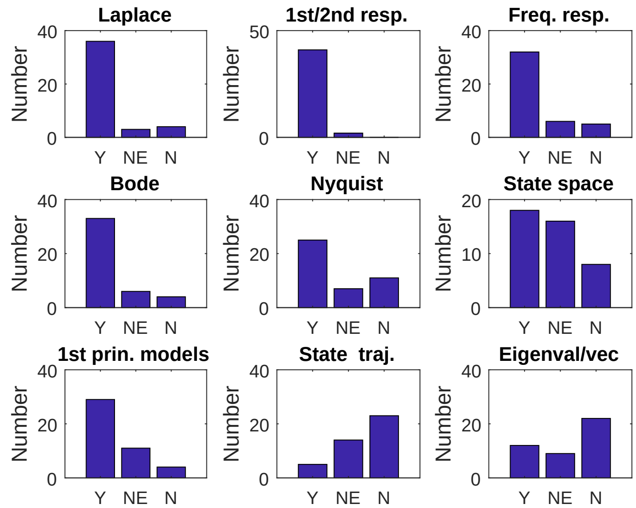

Fig. 2. Questions on a three point scale: Yes (Y), NE (Neutral), N (No). The vertical axis is the number of respondents.

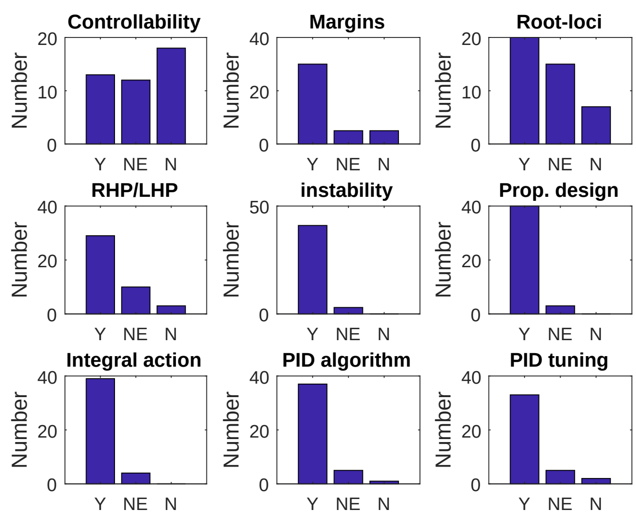

Fig. 3. Questions on a three point scale: Yes (Y), NE (Neutral), N (No). The vertical axis is the number of respondents.

examples from different engineering fields).

3) Be aware of the importance of feedback related to model uncertainties, disturbances, delays.
4) Design at least basic control loops (PID, feedforward, cascade, predictors and basics of MIMO systems).
5) Implementation issues: simulation, control implementation,

What role do you feel IFAC TC9.4 and the IEEE TC on control education should play?

I like the repository, but I think in general people are not aware of its existence. It should act, at least in the first years, as an inventory of different initiatives, to use them to force

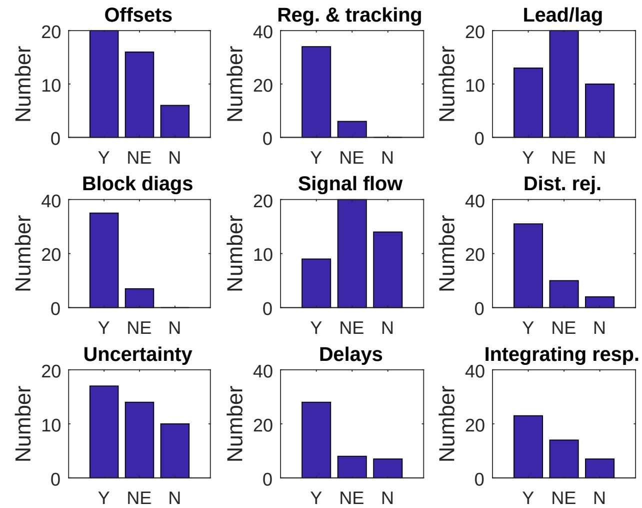

Fig. 4. Questions on a three point scale: Yes (Y), NE (Neutral), N (No). The vertical axis is the number of respondents.

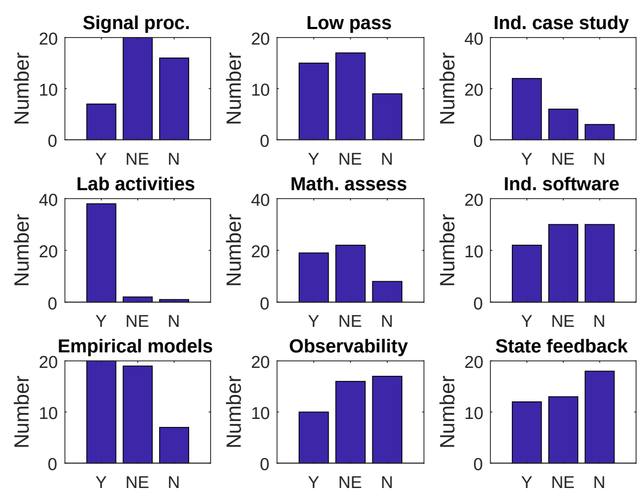

Fig. 5. Questions on a three point scale: Yes (Y), NE (Neutral), N (No). The vertical axis is the number of respondents.

collaborative works using the most interesting ideas from the different groups.

General comments

- The focus needs to be on solely an undergraduate degree with a single feedback control course, as this is often the case.
- Need clarity on implied credit weighting of the course and how this affects reponsee answers.
- Should we clarify *pre-requisites* such as mathematical skills which we might expect to be covered elsewhere?
- Use the information gathered in the survey and one-to-one interviews to define the main topics to teach in the typical, reduced and extended cases. The idea is to

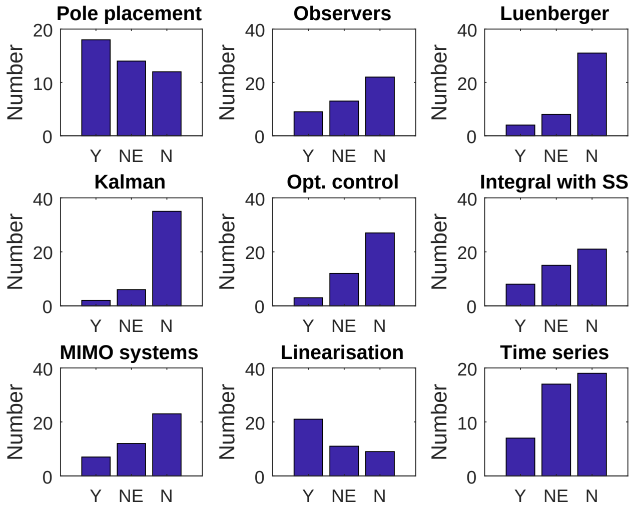

Fig. 6. Questions on a three point scale: Yes (Y), NE (Neutral), N (No). The vertical axis is the number of respondents.

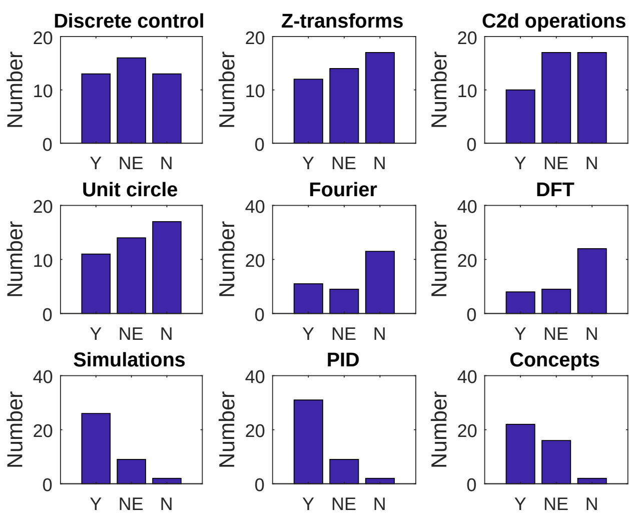

Fig. 7. Questions on a three point scale: Yes (Y), NE (Neutral), N (No). The vertical axis is the number of respondents.

establish a kind of standard.

- The questionnaire should include elements like industrial robotics, mobile robotics, path planning, discrete-event modeling, Petri nets, that is, related to automation and robotics.

IV. Conclusions

This preliminary study has indicated some clear conclusions that are immediately useful although it is also evident that a more careful and wider study is required before making final proposals to the community. In the short term, the following messages have broad support from those who were questionned; all are taken as being directed towards a first course in control and feedback for engineers.

1) A first course should focus on concepts and principles and be used to motivate an interest in the need for control.
2) If not covered previously, the course should cover some first principles modelling and system behaviours; this also serves as motivational groundwork for feedback.
3) Laplace transforms should be introduced or used, alongside concepts such as stability and performance.
4) Design techniques should largely be restricted to an introduction to PI with illustrations but not teaching of design methodologies. An understanding of the role of integral action is essential.
5) Laboratories and interesting case studies should be included.
6) Realisitic issues such as uncertainty, disturbances, delays and non-linearity should be introduced but largely dealt with as motivational topics.
7) Mathematical analysis and theorems should be kept to a minimum.
8) While the concept of a state-space model might be mentioned briefly, in general terms state-space methods should not appear in a first course.
9) Although seen as increasingly important, discrete control is unlikely to feature in an introductory course.

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