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On an IFAC Online Pilot Survey for a First Course on Control

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***Abstract*— The paper introduces aims and objectives of the IFAC survey for a first course on control and discusses some its basic features.**

Keywords*— *engineering education, automatic control, online survey, core competencies, key skills

I. Introduction

For more than half a century, automatic control has become a recognized discipline in the field of engineering education. Although the study plans that were created in the period of its fierce flourishing belonged to the most modern designers, nevertheless in view of the ever increasing amount of new information and knowledge, these plans also need to be reviewed and updated regularly. For example, students studying 50 years ago used for calculations mostly pen, paper and a logarithmic ruler, they mostly did not experiment on real plants and they did not have access to computer support (like Matlab/Simulink, Mathematica or Maple). While analog controllers originally dominated time applications, these have now been overshadowed by their digital counterparts and much more frequently are embedded controllers hidden in nearly every modern family house, vehicles and, of course, in control of different dynamical processes. This development obviously requires a corresponding change in the control education and preparation of our students.

In 2018 the IFAC Technical Committee 9.4 (EDCOM) leadership together with IEEE Technical Committee on education decided to develop and run an online survey related to the expected curriculum of the first and often only control course taken by engineering undergraduates. A major goal of the survey is to establish core competencies and key skills that industry expects for entry-level control competency for graduate engineering positions at the baccalaureate and masters levels.

In the first piloting phase, feedback was sought both on the topics to be included and on the design and administration of the survey itself. Preliminary findings of this phase (achieved by the questionnaires at http://iolab.sk/ifac/index.php) will be discussed at IFAC Symposium on Advances in Control Education (ACE'19). They will be used to refine the survey before distribution to a broader control community. The extended results should be published at the IFAC World congress in 2020. The main contribution of this paper is focused on the design of the survey.

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II. Why and How?

From the point of view of establishing what are the core control competencies and key skills required by industry, the survey aims seem to be positively accepted by whole control community. However, once going into details we may see that there exist numerous obstacles and yet to be resolved problems which make the application of the possible outcomes questionable. More specifically, the design of the survey is not simple and the value of the resulting data is tightly aligned to the survey design; what do we ask?

A. Survey – for Whom?

When trying to establish a bridge between academic and industrial views, a vitally important observation is the diversity of industrial partners, and consequently industrial viewpoints. In the preliminary phase, the survey enabled the respondent to identify themselves with 15 important fields of control applications (Table 1) combined with 6 different roles (Table 2).

TABLE I. Fields of Control Applications of respondents

Aerospace	Automotive	Bioengineering
Civil	Computing	Control
Electrical	Electronic	Chemical/Process
Manufacturing	Materials	Mechanical
Mechatronics	Multi-disciplinary	Systems

TABLE II. Roles of RespondeNTs

Academic (not taught introductory course recently)	Academic (taught introductory course recently)

Industrialist (does not regularly interact with recent university graduates)	Industrialist (regularly interacts with recent university graduates)
Researcher (not university based)	Researcher (university based)

The options regarding the possible status of people in industry are surely far from being complete: we could also think about control experts responsible for staff recruitment, staff training, product marketing, equipment maintenance, technology, production, and so forth and of course also include engineers active in development and research. Each of them may see the requirements of a first control course from their own perspective.

Many practicing engineers, especially those who graduated a decade ago or more, may find work permanently overloaded by everyday tasks and thus find it challenging, although important, to keep track of the newest developments within their profession. Such industrialists may read this survey with the desire to see, what's new in control? They will expect useful information and insight from an academic survey, and not one over biased towards current practice.

Of course, the various roles of people working within the university sector may also bring numerous differing views. As a course designer one may ask: do the survey results respond to all my questions and enable me to enter all the views I wish to include? Similarly, does the survey deal with all the important points I have in my own course design duties? How far are the opinions of colleagues in industry, or at other universities, compatible with or in contradiction to mine?

In other words, a curriculum update should neither be a one-way process (from industry to academia, or vice versa), nor lead to the discussion "Which came first: the chicken or the egg?" Instead, a series of interactions may be beneficial for all members of the control community. Facilitating effective interaction may enable a positive and mutually enriching solution. The leaders of this survey have sought to encourage such interaction during the design phase of the final survey (to be released in the summer of 2019). Some examples of these are: email discussions amongst TC members, roundtables and panel sessions at conferences during 2018, lifelong learning courses offered by universities for industrial partners, invited professors from industry to lecture at universities, etc.

B. *When Two Do the Same, It's not the Same Thing*

An important aspect regarding the definition of a unified curriculum for a one semester course on control is the entry skills and knowledge of the students. It is not possible to define and guarantee a unique starting position of all course participants, certainly across different institutions, departments and countries. Student grounding in mathematics, physics, numerical and computer algebra tools (Matlab/Simulink, Mathematica, etc.), and indeed experimental skills will vary dramatically from one university to another and indeed from one study programme to another. Moreover, the learning skills and environment will differ: for example the students' ability to attend, listen and comprehend lectures, to participate in active learning, project work and discovery based learning, to work in teams and to present their results. All these factors strongly influence the scope of material and learning that it is possible to include in a course. Some material may not need to be covered by defining entry requirements carefully, leaving space for novel material, but no matter how well such a curriculum is designed, its application at different universities will inevitably lead to different outcomes.

The basic assumptions which can or should apply are also linked to the available course and lecture hours. In the preliminary survey completed by 43 individuals from 19 countries, expectations on the 'size' (total student study hours) varied, as seen in Fig.1. The most common response required approximately to 4-6 weekly study hours over a 12-15 week term, but some expectations are also higher.

C. *The Main Problem – What to Include and How?*

As was already mentioned in the introduction, one of the main tasks of the survey is to specify the most important content to be covered by an introductory control course.

When you consider classical provision with a 2 hr lecture and 3 hr exercise, one possible analysis tool would be to try to estimate the number of keywords which it is realistic to be covered by the course. For example, with 5 new keywords per

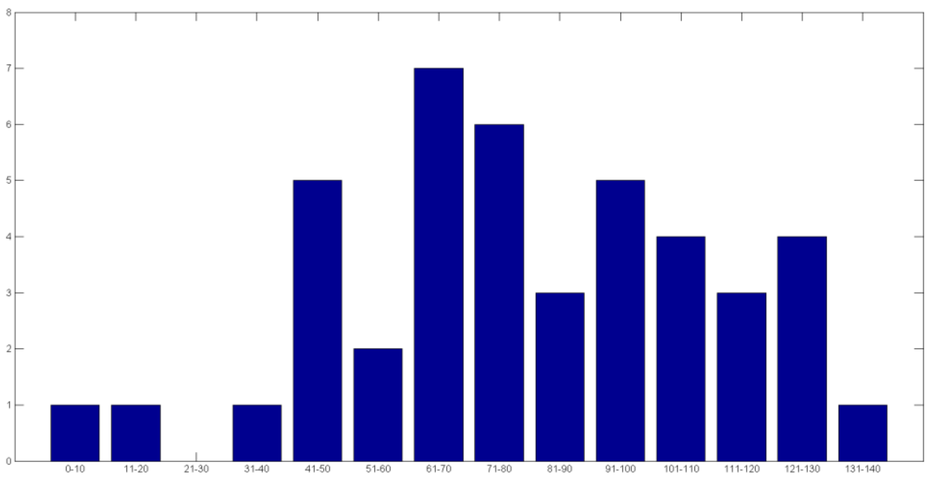

Fig. 1. Number of responders vs. number of indicated hours in the control course.

week you could consider up to 60-75 keywords per course. If you double this number, it is 120-150 keywords. Now, you may try to think about, how many keywords you need to cover a new concept, say, in control design. Nevertheless, the amount of content and learning linked to different keywords will vary, so while this analysis is useful, it will not tell the whole picture.

D. Educational Frameworks

The educational framework has changed significantly in the last few decades. This change is not constrained to just the replacement of a ruler by computers, but rather the impact of new technologies is much deeper. Let us mention just different electronic media and new learning technologies including different forms of synchronous and asynchronous communication, remote access to experiments, Massive Open Online Courses with hundreds thousands of participants, or virtual, mixed and augmented reality. These new technology enabled tools are supporting course delivery in many formats, but also need some time to be mastered, both by staff and students. Since many of these tools are specific to control, you need to allow for student preparation and familiarization and this takes time that previously may have been used on additional content; hence this introduces a possible trade-off between analytical depth and application skills/insight. Consequently it is important to note that, with the exception of some questions related to remote access to experiments, in the first pilot phase of this survey the educational aspects that may occupy a significant amount of student study/contact time and thus effort, remained out of the survey scope.

Constraints on realistic course content planning become yet more visible in the context of course delivery based on a learning objects methodology (underpinned by Learning Technology Standards, https://www.ieeeltsc.org/, see also https://en.wikipedia.org/wiki/Learning_object), or a methodology denoted as Competency-based learning or competency-based education and training (see e.g. https://en.wikipedia.org/wiki/Competency-based_learning). These represent a modular approach to teaching and learning used preferably in learning concrete skills as opposed to abstract learning. Every individual skill or learning outcome (denoted as a competency) represents a single unit of a larger hierarchy of learning goals. The students (studying preferably at their own pace) can only move on to further competencies after they have mastered the current skill being learned. After that, higher or more complex competencies are learned to a degree of mastery and are isolated from other topics. Since the competency-based learning requires mastery of every individual learning outcome, such an approach requires new forms of class organization and synchronization, which again may significantly limit the course content.

E. Non Multum Sed Multa versus Non Multa Sed Multum

Depending on the context, a control course may focus on either a narrower scope of material but require deeper knowledge and mastery, or alternatively, the course could be broader but just give an overview offering an introduction to several control topics. In order to identify particular preferences, the survey begins with questions:

- A first course should focus more on concepts, philosophy and motivation-reasons to use control, illustrating principles such as uncertainty handling with case studies but not get drawn into mathematics too quickly.
- A first course should focus on classical tools such as Laplace, closed-loop transferences and lead/lag/PID design.
- A first course should be set in a state space (or first principles modelling) framework and avoid reference to the frequency domain.
- Assessment of a first course should not include too much algebra and proofs and instead should focus on understanding of concepts, perhaps supported by software for number crunching and experiments.

In the preliminary survey we have used more than 80 concepts split into 8 groups:

1) Basic control concepts (13)

- 1st principles modelling of simple systems (for example with ODEs)
- System behaviours (e.g. 1st and 2nd order responses)
- Laplace and transfer functions
- Convergence, divergence and stability
- RHP/LHP
- Feedback loop concepts and definitions (closed-loop vs open-loop)
- Block diagrams (simple case only)
- Offsets to steps
- Offsets to ramps
- Impact of disturbances on behaviour
- Integral action
- Definition of PID compensator
- Definitions of regulation and tracking scenarios

2) Advanced control concepts (18)

- Models with integrating response
- Dealing with parameter uncertainty
- Delays and dead-time
- Signal processing and impact of measurement
- Low pass filters
- Band pass filters
- MIMO systems
- Nonlinear models and linearisation
- Signal flow graphs
- Block diagrams (multi-input and possibly multi-loop)
- Constraint handling
- Wind-up and anti-windup
- Routh array/criteria
- Alarm management
- Hierarchies in practical control implementations
- Effect of measurement noise
- Sensitivity
- Non-minimum phase processes (and RHP poles)

3) Control design (10)

- Proportional
- PI
- PID
- Lead and lag
- State feedback (pole placement)
- State feedback (optimal control)
- On-off control
- Feed forward
- Analogue implementations
- Control loop requirements

4) Classical control approaches (7)

- Frequency response
- Bode diagrams
- Nyquist diagrams
- Nyquist stability criteria
- Analysis with Root-loci
- Design with Root-loci
- Design with Bode diagrams (and/or frequency response methods)

5) State space approaches (8)

- State space models
- First principles derivation of state space models
- State trajectories and phase plane
- Eigenvalue/vector decompositions within the context of state space behaviours
- Controllability
- Observability
- Concepts of state feedback
- Pole placement state feedback design

6) Optimal control (4)

- Optimal control state feedback design
- Luenberger observer
- Kalman filter
- Integral action with a state feedback control law

7) Discrete control (8)

- Z-transforms
- Time series models
- C2d operations
- Unit circle
- Aliasing
- Fourier transform
- DFT
- Continuous design with discrete implementation

8) Generic issues in control (13)

- Hardware laboratories
- Software laboratories (e.g. MATLAB, virtual laboratories)
- Mathematical/theoretical assessment
- Assessment focused on concepts
- Modelling from real data
- Industrial control diagrams and notation
- PLCs (introduction)
- PLC programming
- Industrial case studies
- Industrial control software (e.g. DCS systems, ...)
- Simulations and implementations too authentic scenarios
- Use of or exposure to global benchmark systems
- Implementation issues (practice does not match theory)

This overview shows that a one term course may cover just a fraction of this list and indeed this list could still be considered as being far from complete. For example, in the motion control area, the students should, besides traditional knowledge such as PID control (150 mil. items found by google), moreover ideally, they should know at least something about:

1. Internal Model Control (IMC, 29.2 mil. items found by google),
2. Disturbance Observer Based Control (DOB, 18.7 mil. items found by google),
3. Active Disturbance Rejection Control (ADRC, 7.8 mil. items found by google),
4. Model Free Control (MFC, 4.3 mil. items found by google),
5. Fractional Order PID Control (FO-PID, 41.3 mil. items found by google).

These additional topics also come with an implicit need for coverage of the relevant modelling issues, noise filtration, uncertainty impact, the role of constraints, optimal tuning, and so forth. Clearly, the amount of ideal content implied is beyond what could be realistically included in a first course and thus inevitably students will have a knowledge deficit somewhere.

In summary, although much of the required content may be found in the current survey list of topics (e.g. ADRC requires some items from state space design and Luenberger observer), nevertheless, one might argue that the survey forms are already too detailed. Consequently there is a tension between the need to be comprehensive and include several "fashionable" and "trendy" areas (documented by results of a google search) while simultaneously focusing attention to the core topics required in practice.

Everybody has to ask, how far it is important to become at least familiar with the keywords characteristic of the control domain and how far the study should relate to areas, in which safety, reliability, or high performance are also an issue. An optimal balancing of the granularization related to the course content seems not to be definitive in general. When considered as a step towards competence based learning and size of corresponding modules, the granularization levels considered in particular areas are obviously not equal. Therefore, it is very important to keep this survey open-ended where possible and to include a free space giving the responder sufficient space to add their opinions and thus to guarantee its timeliness and flexibility. With respect to this, we have included some additional questions, as:

- Also please give any other useful textual comment/reflections, including what the questionnaire could or should include?
- What role do you feel IFAC TC9.4 and the IEEE TC on control education should play in developing and sharing resources for the topics we identify as most important?
- Do you have vision for how this sharing could take place (we assume all resources should be under a creative commons license)? Is the current repository [https://tc.ifac-control.org/9/4/repository] fit for purpose or how would you improve it? To what extent do we want to support resources on other social media such as youtube, twitter, … ?
- In the near future this survey will be distributed to the global control community. Please provide comments on the structure, content, organization, and user-friendliness of the survey.

F. *Additional Activities to the First Control Course*

In the questionnaire respondents were asked to opt not only for the number of hours of lectures that such a topic should occupy, but also they could decide what topics should be included in laboratory activities and what topics should be preferably covered in a later, but optional course.

Table 3 shows that except for topics containing laboratory work directly in their title, respondents recommend the use of experimentation mainly for consolidation of knowledge in topics connected with basic controller design (e.g. more than 37% of responders supported laboratory activities for PID compensators), modelling and system analysis.

TABLE III. RECOMMENDED TOPICS FOR LABORATORY ACTIVITIES

Topic	Number of responders
Hardware laboratories	18
Software laboratories (e.g. MATLAB, virtual laboratories)	
Definition of PID compensator	16
PID	14
Impact of disturbances on behaviour	13
Integral action	
Implementation issues (practice does not match theory)	
System behaviours (e.g. 1st and 2nd order responses)	12
Definitions of regulation and tracking scenarios	
1st principles modelling of simple systems (for example with ODEs)	10
Offsets to steps	
Low pass filters	
Bode diagrams	
Modelling from real data	
Convergence, divergence and stability	9
Feedback loop concepts and definitions (closed-loop vs open-loop)	
Dealing with parameter uncertainty	
Signal processing and impact of measurement	
Wind-up and anti-windup	
Effect of measurement noise	
Proportional	
PI	
Lead and lag	
State feedback (optimal control)	
Feed forward	
Frequency response	
Simulations and implementations too authentic scenarios	

On the other hand Table 4 demonstrates that not each topic is expected to be taught in the first course.

TABLE IV. RECOMMENDED TOPICS FOR A 2ND CONTROL COURSE

Topic	Number of responders
Kalman filter	19
Optimal control state feedback design	18
Integral action with a state feedback control law	17
Optimal control	16
Non-minimum phase processes (and RHP poles)	
State feedback (optimal control)	15
Nonlinear models and linearisation	
Luenberger observer	
Dealing with parameter uncertainty	14
MIMO systems	
C2d operations	13
Z-transforms	
Aliasing	12
Continuous design with discrete implementation	
Industrial case studies	
Constraint handling	
Pole placement state feedback design	
Sensitivity	
Concepts of state feedback	
Fourier transform	
Unit circle	
DFT	
Time series models	
Controllability	11
Observability	
Implementation issues (practice does not match theory)	10
Effect of measurement noise	

III. CONCLUSIONS

As it was already mentioned, the discussion in this paper builds on a preliminary survey design for limited distribution of the questionnaire in the late summer and autumn of 2018. This paper is a step towards the design of the final version of the questionnaire which should be available after IFAC Symposium "Advances in Control Education 2019". Authors hope that achieved results will enable the control community to clarify and unify approaches used in control education around the world.

Table 3 showed that one also has to accept the newest trends in supporting experimental work in laboratories. Nowadays students have different attitudes to education in general compared to their predecessors. The methodology adopted in the future has to reflect their needs. The classical approaches emphasizing theoretical aspects of control procedures seem to some degree to be becoming obsolete and certainly are less popular. We need more interactive educational tools that can be available locally or even via Internet. Such tools are increasingly available and thus straightforward to integrate into a learning plan. Finally, there is some consensus that the most important aspect both for development of students' skills and their motivation, are control experiments on real plants and thus these activities represent an important item of the study.

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