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A first course in feedback, dynamics and control: findings from an online pilot survey for the IFAC community

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Abstract: Undergraduate students in many engineering programs around the world take only one control course. The IFAC Educational Committee has developed and piloted to a limited audience a comprehensive survey for the topics to be included in such course. This issue is relevant to both academia and industry. The paper discusses the initial findings related to the design of the survey as well as the responses of the participants. The findings will be used to refine the survey and distribute it in the near future to the global control community.

Keywords: Control curriculum,

1. INTRODUCTION

Undergraduate students in many engineering programs around the world take only one control course. The instructors teaching this course are faced with a challenging task to design a syllabus that provides the right balance between fundamental theory and practical applications, and fosters technical skills relevant to entry-level control positions. An additional constraint is that this has to be accomplished in a very limited time span, typically 40 contact hours of lectures, labs, and exercises.

Although some recent work on control curriculums exists (Cook and Samad 2009, Silverstein et al.,2015), that work has a very narrow scope by comparison with the needs of the control community. IFAC Technical Committee 9.4 (EDCOM) and IEEE Technical Committee on education felt that we could best serve our constituents by facilitating a discussion on the curriculum of the first and often only control course taken by engineering undergraduates.

In 2018 the EDCOM leadership designed an online survey and piloted it to a limited pool of control professionals. Feedback was sought not only on the topics to be included in the first control course, but on the design and administration of the survey itself. In this paper we discuss the initial findings of the survey. The findings will be used to refine the survey before a launch to the global control community. The results of the refined survey will be published at the IFAC world congress in 2020.

2. SURVEY DESIGN

The survey can be accessed at http://iolab.sk/ifac/index.php It has four main sections. Readers are encouraged to complete the questionnaire and add their input to the data being collected once the new version is online.

2.1 Responder Background

The respondents were asked to identify the basis for their views on the curriculum. They were given the following choices to select field and role:

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

Academic (not taught intro course recently)	Academic (taught intro course recently)
Industrialist (does not regularly interact with recent university graduates)	Industrialist (regularly interacts with recent university graduates)
Researcher (not university)	Researcher (university)

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In the general field of control, there are a number of specialty areas. The survey provided 15 different selections. For individuals whose careers span multiple areas, the survey provided two options: select multiple areas and take the survey one time, or select one area at a time and take the survey multiple times from the vantage point of the selected area. The presumption is that the same set of course topics might not be the best fit for every area. The anticipation is that the final survey results could be dissected based on area of specialization.

A major goal of the survey is to establish core competencies and key skills that industry expects for entry-level control positions at the baccalaureate level. To properly interpret the survey data, it is important to know if respondents have first-hand interactions with recent university graduates. Another goal of the survey is to identify differences in perception between industry and academia.

2.2 General Guidelines for the Curriculum of the First Control Course

In this section, respondents were asked to provide opinion on the general guidelines for the course. The following questions were rated on a 5-level Likert scale between "Strongly Agree" and "Strongly Disagree":

- *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.*

The last question in this section solicited input on the total lecture hours for the first control course. The available choices were 10-20, 20-25, 40-50, and >50.

- *I would expect all engineering students to attend at least N hours of lectures on control related topics (equivalently a 1st course) during their degree programme*

2.3 List of Topics with Time Allotment Options

In this section, a list of 82 topics typically included in introductory control courses, was provided. The topics were grouped in seven sub-sections:

- Basic control concepts
- Advanced control concepts
- Control design
- Classical control approaches
- State space approaches
- Discrete control
- Generic issues in control

For each topic, the following choices for lecture time allocation were available:

0 hrs	0-0.5 hrs	0.5-1 hrs	1-2 hrs	>2 hrs	Include Lab activities	Cover in 2nd course

3. INITIAL FINDINGS

3.1 Responders Information

A total of 43 individuals form 19 countries responded to the survey at this initial stage. Of them, 31 (72 %) were affiliated with academia and 12 (28 %) with industry. The details are shown in Fig. 1. For the next iteration of the survey, a significant effort will be made to increase the industrial participation although in addition we also want far more academic responses.

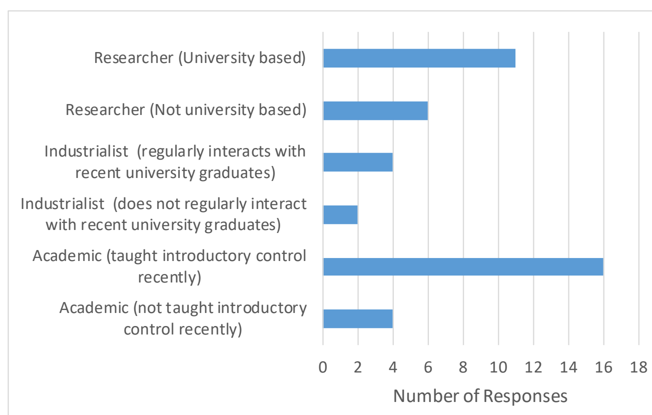

Fig. 1 Responders Affiliation Breakdown.

Most responders selected multiple engineering sectors for their background. Aerospace, mechatronics, computing and electronic are the most frequently checked fields. The results are summarized in Table 1. There are very few single area selections, which is an indication that there is a significant overlap in the choices provided to the respondents. Due to the large number of permutations, there are only a few repeated selections, which makes the analysis of results by specialty area impossible within this limited pilot survey.

For the next iteration of the survey, the area list will be revised to avoid overlap and confusion between choices. The total number of options will be reduced and only one selection will be allowed. Moreover, we hope the increased number of responses will allow greater precision of analysis.

Table 1. Area Specialization Response Results

Area	Number of Selections	
	Single Selection	With Other Selections
Aerospace	1	11
Automotive	2	8
Bioengineering	0	2
Civil	1	0
Computing	1	10
Control	5	24
Electrical	0	9
Electronic	0	10
Chemical/Process	0	5
Manufacturing	0	6
Materials	1	0
Mechanical	0	5
Mechatronics	1	11
Multi-disciplinary	0	5
Systems	0	13

3.1 General Course Guidelines

For the general guidelines of the course, the majority of the respondents agreed that the course should be structured around classical tools, such as closed-loop transfer functions, and should put more emphasis on concepts rather than mathematics, Fig. 2. Opinions were split on whether to avoid frequency domain analysis. This will be further discussed later in the paper in conjunction with the analysis of the course topics.

3.2 Course Lecture Hours

Opinions were split on the number of lecture hours dedicated to the course, Fig. 3. The option 40-50 hours was favoured, but by a very small margin, followed by the two extremes, 10-20 and >50. The answers to this question, however, are not consistent with the suggested time allotment for individual topics. The responders were asked to allocate lecture time for each of the 82 course topics. For each individual responder the allocated lecture times are added together and shown in ascending order in Fig. 4. There is a definite discrepancy between the general lecture guidelines (Fig. 3) and the actual lecture time allocation (Fig. 4).

An explanation can be provided based on the fact that most of the respondents, 27 out of 43, have not taught a control course and overlooked the total hour constraint. Only 6 responses satisfied the constraint of a total of 40 lectures. It is clear that the total hour constraint was not incorporated well in the survey and its presence in the next iteration of the survey needs to be reconsidered.

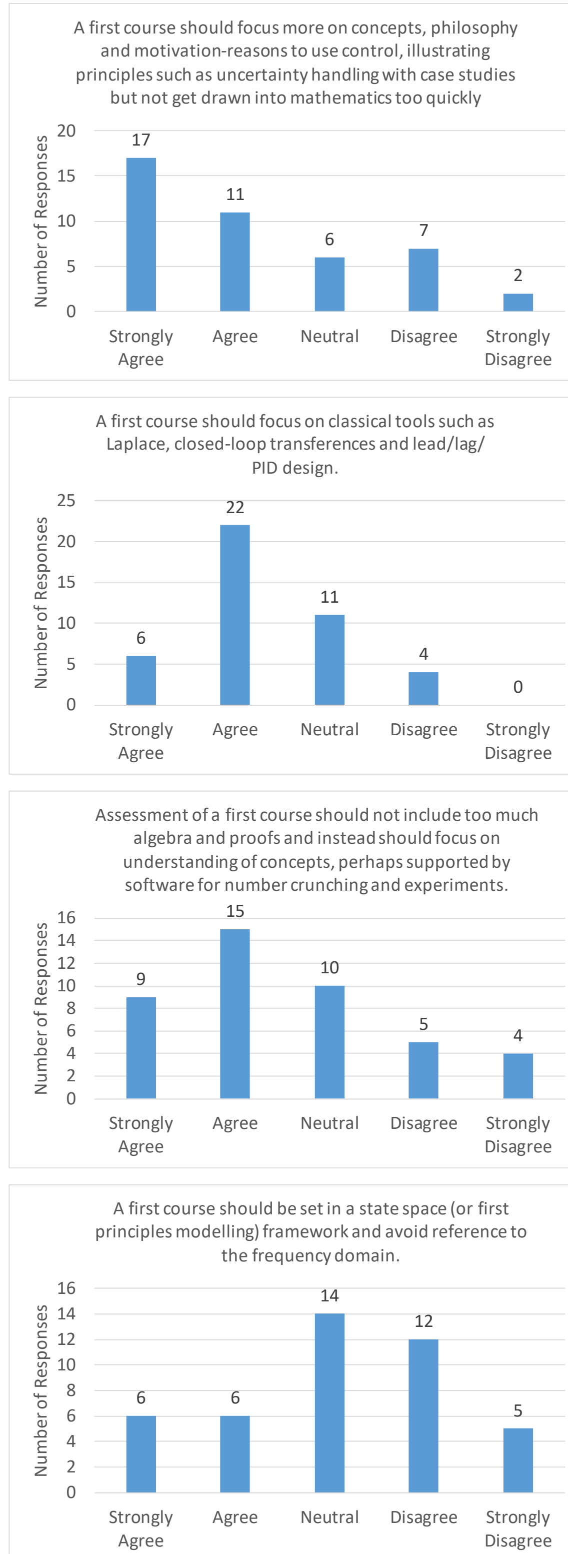

Fig. 2 Responses for the general guidelines of the course.

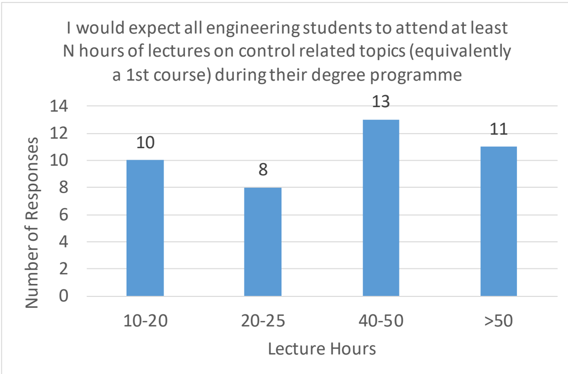

Fig. 3 Lecture hours expectations for the course.

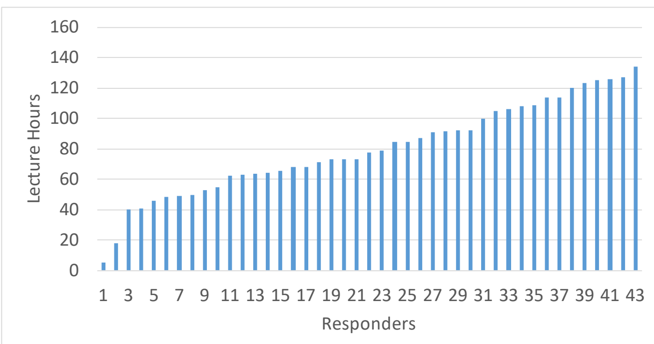

Fig. 4 Total lecture hours from all 43 individual responses arranged in ascending order and calculated as the sum of lecture allocation times for the specific course topics.

3.3 Course Topics Ranking

Weight factors are defined based on the lecture hours suggested for a given topics.

Table *2.* Weight Factors Definitions for Topics Ranking

Lecture Hours	0	0-0.5	0.5-1	1-2	>2
Weight Factor	0	0.5	0.75	1.5	2

For each topic, the weight factors from all responses are added together to produce a ranking sum. The higher the sum, the higher the ranking.

The rankings are presented in Tables 3-7. The rankings based on responses from industry are in column I. The rankings based on responses from academia are in column A. Column Δ gives the difference in the rankings, Δ=I-A. Negative value in column Δ indicates that industry ranks the topic higher; positive value means the opposite.

Table 3 shows the rankings in the order of industrial selection. Table 4 shows the rankings in the order of academic selection. From the top 20 topics in the industrial classification, only 12 are among the academic top 20 list. The same is true for the bottom 20 industrial topics.

Table 5 presents topics with similar rankings between industry and academia. There is some agreement at the top, but most of the agreement is in the lower tier of the classification.

Table 6 presents topics ranked significantly higher by industry. Of note is the fact that optimal control concepts are among the top 10 for industry and much lower for academia.

Table 7 presents topics ranked significantly higher by academia. Of note is the fact that frequency response analysis is ranked very high by academia and relatively low by industry. Software laboratories received number 1 ranking from academia, but only 21 from industry. As expected, the academic ranking favours more fundamental topics, such as systems behaviours, while industrial ranking elevates implementation, such as modelling from real data and dealing with parameter uncertainty

4. PANEL SESSION

The questionnaire was advertised during a panel session at Control 2018 in Sheffield, and thus many of the respondents will have attended that panel session. This section gives a brief summary of some of the more interesting or challenging comments made at that session.

- *Easy to teach the analysis and maths, less so the engineering and application.*
- *Need balance: theory, implementation and integration (theory alone not useful). Integration is perhaps not done enough.*
- *Starting with transfer functions can be confusing – why not start with modelling such as state-space and dynamics. Perhaps transfer functions come later for sensitivity.*
- *Essential we excite students first so they decide to study more. Can be hardware or whatever – do not start with the maths.*
- *Danger of getting students spend too long on heuristics to solve practical projects before they learn the appropriate tools.*
- *Must encourage students to learn the value of systematic and rigorous analysis which they can then use elsewhere.*
- *Should start with signal and systems module – this will also explain why is control needed. Signal and systems is a much topic now than it used to be.*
- *Do we recognise the broadening focus of control given modern technology, mobiles, etc. Do we need different tools?*
- *How do we use/exploit modern technology effectively (mobiles, etc.). Must convince average/weak students that control is relevant (hidden technology) and link to modern issues/components/etc.*
- *Have students got a narrow perception of what is control and control related topics? Change module*

titles to change perception. Almost all topics are control related and we do not make enough of this. Use the title "feedback" but not the word "control" and show how wide spread this is.

- *Modern students have changed – we need to as well.*

5. CONCLUSIONS

One obvious conclusion from this pilot survey is that a far greater participation rate is needed to allow meaningful analysis of some aspects, as the current number of respondents means that the variance on any inference will be quite large. In particular, it will be interesting to explore the differences between industrial and academic preferences, while recognising that sometimes industrialists have rather ambitious expectations of how much content can be covered. Also, splitting responders into different engineering disciplines and examining data along those lines can only work where there are substantial numbers of responses for each discipline. It may not be possible to get this level of precision even with the final survey.

Textual comments suggest a higher focus on concepts and application than purely mathematics . They also indicate the need to modernise and thus ensure that what is understood as a classical approach is somewhat updated to recognise the needs of future engineers. This issue also will need exploring in a final survey.

It is encouraging that industrialists and academics largely agree on which topics are of secondary importance and thus differ mainly in the ranking of the more important topics. It would perhaps be useful to have a more concrete example of a typical module and ask what would be removed and replaced by what, as having an open-ended survey makes it hard for respondents to ensure their response is implementable in practice. For example, it was clear that some respondents were not careful enough about the time implications of including multiple topics.

In summary, the final survey may need to be a little simpler in design so that respondents give data which is useful and can be turned into concrete conclusions. The options provided will need to be posed in a 'deliverable mode' rather than an idealistic but possibly unrealistic framework.

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Appendix A. TOPIC RANKINGS

Table 3. Topics Ranking in Order of Industrial Selection I (industrial rank), A (academic rank), Δ=I-A

Topic	I	A	Δ
State space models	1	2	-1
State feedback (optimal control)	2	15	-13
Convergence, divergence and stability	3	3	0
1st principles modelling of simple systems	4	6	-2
Laplace and transfer functions	5	5	0
Optimal control	6	41	-35
Modelling from real data	7	31	-24
Concepts of state feedback	8	32	-24
Optimal control state feedback design	9	38	-29
Definition of PID compensator	10	9	1
Dealing with parameter uncertainty	11	22	-11
Kalman filter	12	25	-13
Z-transforms	13	50	-37
Definitions of regulation and tracking scenarios	14	11	3
Eigenvalue/vector decompositions within the context of state space behaviours	15	40	-25
Impact of disturbances on behaviour	16	20	-4
MIMO systems	17	24	-7
Nonlinear models and linearization	18	17	1
State feedback (pole placement)	19	14	5
Mathematical/theoretical assessment	20	13	7
Software laboratories	21	1	20
Simulations and implementations too authentic scenarios	22	54	-32
System behaviours (e.g. 1st and 2nd order)	23	4	19
Continuous design with discrete implementation	24	33	-9
Hardware laboratories	25	10	15
Assessment focused on concepts	26	48	-22
Frequency response	27	7	20
First principles derivation of state space models	28	18	10
Industrial case studies	29	34	-5
Controllability	30	35	-5
Observability	31	36	-5
Integral action with a state feedback control law	32	67	-35
Sensitivity	33	28	5
C2d operations	34	51	-17
Control loop requirements	35	43	-8
Integral action	36	23	13
Delays and dead-time	37	44	-7
Constraint handling	38	45	-7
Bode diagrams	39	8	31
Block diagrams (multi input)	40	37	3
State trajectories and phase plane	41	53	-12

Topic	I	A	Δ
Pole placement state feedback design	42	39	3
Luenberger observer	43	55	-12
Aliasing	44	68	-24
Implementation issues	45	59	-14
PID	46	21	25
Fourier transform	47	66	-19
Block diagrams (simple case only)	48	19	29
Feed forward	49	64	-15
Time series models	50	73	-23
Effect of measurement noise	51	47	4
Non-minimum phase processes (and RHP poles)	52	52	0
Industrial control diagrams and notation	53	77	-24
Feedback loop concepts and definitions (closed-loop vs open-loop)	54	12	42
Wind-up and anti-windup	55	65	-10
Nyquist stability criteria	56	29	27
Design with Bode diagrams (and/or frequency response methods)	57	16	41
Offsets to steps	58	46	12
Nyquist diagrams	59	26	33
Signal processing and impact of measurement	60	27	33
Hierarchies in practical control implementations	61	63	-2
Analysis with Root-loci	62	49	13
Low pass filters	63	60	3
DFT	64	74	-10
RHP/LHP	65	30	35
Unit circle	66	70	-4
Use of or exposure to global benchmark systems	67	81	-14
Alarm management	68	82	-14
PLCs (introduction)	69	75	-6
Industrial control software (e.g. DCS systems,)	70	76	-6
Offsets to ramps	71	69	2
Models with integrating response	72	56	16
On-off control	73	78	-5
PI	74	42	32
Lead and lag	75	58	17
Band pass filters	76	71	5
Signal flow graphs	77	79	-2
Proportional	78	61	17
Design with Root-loci	79	57	22
PLC programming	80	72	8
Routh array/criteria	81	62	19
Analogue implementations	82	80	2

Table 4. Topics Ranking in Order of Academic Selection I (industrial rank), A (academic rank), Δ=I-A

Topic	I	A	Δ
Software laboratories	21	1	20
State space models	1	2	-1
Convergence, divergence and stability	3	3	0
System behaviours (e.g. 1st and 2nd order)	23	4	19
Laplace and transfer functions	5	5	0
1st principles modelling of simple systems	4	6	-2
Frequency response	27	7	20
Bode diagrams	39	8	31
Definition of PID compensator	10	9	1
Hardware laboratories	25	10	15
Definitions of regulation and tracking scenarios	14	11	3
Feedback loop concepts and definitions (closed-loop vs open-loop)	54	12	42
Mathematical/theoretical assessment	20	13	7
State feedback (pole placement)	19	14	5
State feedback (optimal control)	2	15	-13
Design with Bode diagrams (and/or frequency response methods)	57	16	41
Nonlinear models and linearization	18	17	1
First principles derivation of state space models	28	18	10
Block diagrams (simple case only)	48	19	29
Impact of disturbances on behaviour	16	20	-4
PID	46	21	25
Dealing with parameter uncertainty	11	22	-11
Integral action	36	23	13
MIMO systems	17	24	-7
Kalman filter	12	25	-13
Nyquist diagrams	59	26	33
Signal processing and impact of measurement	60	27	33
Sensitivity	33	28	5
Nyquist stability criteria	56	29	27
RHP/LHP	65	30	35
Modelling from real data	7	31	-24
Concepts of state feedback	8	32	-24
Continuous design with discrete implementation	24	33	-9
Industrial case studies	29	34	-5
Controllability	30	35	-5
Observability	31	36	-5
Block diagrams (multi-input)	40	37	3
Optimal control state feedback design	9	38	-29
Pole placement state feedback design	42	39	3
Eigenvalue/vector decompositions within the context of state space behaviours	15	40	-25
Optimal control	6	41	-35
PI	74	42	32

Topic	I	A	Δ
Control loop requirements	35	43	-8
Delays and dead-time	37	44	-7
Constraint handling	38	45	-7
Offsets to steps	58	46	12
Effect of measurement noise	51	47	4
Assessment focused on concepts	26	48	-22
Analysis with Root-loci	62	49	13
Z-transforms	13	50	-37
C2d operations	34	51	-17
Non-minimum phase processes (and RHP poles)	52	52	0
State trajectories and phase plane	41	53	-12
Simulations and implementations too authentic scenarios	22	54	-32
Luenberger observer	43	55	-12
Models with integrating response	72	56	16
Design with Root-loci	79	57	22
Lead and lag	75	58	17
Implementation issues	45	59	-14
Low pass filters	63	60	3
Proportional	78	61	17
Routh array/criteria	81	62	19
Hierarchies in practical control implementations	61	63	-2
Feed forward	49	64	-15
Wind-up and anti-windup	55	65	-10
Fourier transform	47	66	-19
Integral action with a state feedback control law	32	67	-35
Aliasing	44	68	-24
Offsets to ramps	71	69	2
Unit circle	66	70	-4
Band pass filters	76	71	5
PLC programming	80	72	8
Time series models	50	73	-23
DFT	64	74	-10
PLCs (introduction)	69	75	-6
Industrial control software (e.g. DCS systems)	70	76	-6
Industrial control diagrams and notation	53	77	-24
On-off control	73	78	-5
Signal flow graphs	77	79	-2
Analogue implementations	82	80	2
Use of or exposure to global benchmark systems	67	81	-14
Alarm management	68	82	-14

Table 5. Topics with Similar Ranking between Industry and Academia, [-6≥Δ≥5] I (industrial rank), A (academic rank), Δ=I-A

Topic	I	A	Δ
State space models	1	2	-1
Convergence, divergence and stability	3	3	0
1st principles modelling of simple systems	4	6	-2
Laplace and transfer functions	5	5	0
Definition of PID compensator	10	9	1
Definitions of regulation and tracking scenarios	14	11	3
Impact of disturbances on behaviour	16	20	-4
Nonlinear models and linearization	18	17	1
State feedback (pole placement)	19	14	5
Industrial case studies	29	34	-5
Controllability	30	35	-5
Observability	31	36	-5
Sensitivity	33	28	5
Block diagrams (multi-input)	40	37	3
Pole placement state feedback design	42	39	3
Effect of measurement noise	51	47	4
Non-minimum phase processes (and RHP poles)	52	52	0
Hierarchies in practical control implementations	61	63	-2
Low pass filters	63	60	3
Unit circle	66	70	-4
PLCs (introduction)	69	75	-6
Industrial control software (e.g. DCS systems)	70	76	-6
Offsets to ramps	71	69	2
On-off control	73	78	-5
Band pass filters	76	71	5
Signal flow graphs	77	79	-2
Analogue implementations	82	80	2

Table 6. Topics Ranked Significantly Higher by Industry than by Academia, [Δ<-6] I (industrial rank), A (academic rank), Δ=I-A

Topic	I	A	Δ
State feedback (optimal control)	2	15	-13
Optimal control	6	41	-35
Modelling from real data	7	31	-24
Concepts of state feedback	8	32	-24
Optimal control state feedback design	9	38	-29
Dealing with parameter uncertainty	11	22	-11
Kalman filter	12	25	-13
Z-transforms	13	50	-37
Eigenvalue/vector decompositions within the context of state space behaviours	15	40	-25
MIMO systems	17	24	-7
Simulations and implementations to authentic scenarios	22	54	-32
Continuous design with discrete implementation	24	33	-9
Assessment focused on concepts	26	48	-22
Integral action with a state feedback control law	32	67	-35
C2d operations	34	51	-17
Control loop requirements	35	43	-8
Delays and dead-time	37	44	-7
Constraint handling	38	45	-7
State trajectories and phase plane	41	53	-12
Luenberger observer	43	55	-12
Aliasing	44	68	-24
Implementation issues (practice does not match theory)	45	59	-14
Fourier transform	47	66	-19
Feed forward	49	64	-15
Time series models	50	73	-23
Industrial control diagrams and notation	53	77	-24
Wind-up and anti-windup	55	65	-10
DFT	64	74	-10
Use of or exposure to global benchmark systems	67	81	-14
Alarm management	68	82	-14

Table 7. Topics Ranked Significantly Higher by Academia than by Industry, [Δ>5] I (industrial rank), A (academic rank), Δ=I-A

Topic	I	A	Δ
Software laboratories	21	1	20
System behaviours (e.g. 1st and 2nd order)	23	4	19
Frequency response	27	7	20
Bode diagrams	39	8	31
Hardware laboratories	25	10	15
Feedback loop concepts and definitions (closed-loop vs open-loop)	54	12	42
Mathematical/theoretical assessment	20	13	7
Design with Bode diagrams (and/or frequency response methods)	57	16	41
First principles derivation of state space models	28	18	10
Block diagrams (simple case only)	48	19	29
PID	46	21	25
Integral action	36	23	13
Nyquist diagrams	59	26	33
Signal processing and impact of measurement	60	27	33
Nyquist stability criteria	56	29	27
RHP/LHP	65	30	35
PI	74	42	32
Offsets to steps	58	46	12
Analysis with Root-loci	62	49	13
Models with integrating response	72	56	16
Design with Root-loci	79	57	22
Lead and lag	75	58	17
Proportional	78	61	17
Routh array/criteria	81	62	19
PLC programming	80	72	8