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A survey of international views on a first course in systems and control for engineering undergraduates

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Abstract

This paper summarises the results of an international survey of academics and industrialists on what should be prioritised in the first, and often only, control course taken by engineering undergraduates. The results are made up both of quantitative data whereby respondents selected from a number of options, and also of qualitative data where respondents entered free comments. Reflections on the results and summaries of common trends are given to help readers consider how the curriculum in their own institutions might be updated and modified to meet modern requirements. At the time of writing the survey had around 500 respondents covering a good spread of nationalities, employment status and engineering disciplines.

Key words: Engineering education, Automatic control curriculum, Introductory control curriculum

1 Introduction

There have been significant changes in technology over the past few years which have hugely significant impacts on what engineering students should learn and master in their studies. For example, it is increasingly common practice for students to access text books solely via a web interface and have no hard copy. Publishers are leading the way in these moves and indeed for well over ten years now (e.g. [10]) produce partner websites for their books containing large numbers of learning resources such as quizzes, learning pathways, videos and more. University libraries now often buy licenses for soft copy access rather than hard copies.

Within the employment market, what is required of students is also constantly changing. Increasingly [6] employers talk about wanting broad based students rather than specialists and interview procedures focus on transferable skills and aptitude as much as, if not more than, the engineering backgrounds. Accreditation also focuses on very broad based development [1,18,27,44].

In response to these changes and others, Universities need to be undergoing continual change to ensure their programmes are fit for purpose, both recognising the starting point and skills of students as they arrive age 18 and also the skills they need to develop in readiness for employment. An example of such an ongoing reflection is currently

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taking place at the first author's institute and denoted Programme Level Approach (PLA, [43]) and is no doubt replicated everywhere in one form or another. A particular core aspect of these reflections is the move away from a focus on the technical learning outcomes (LO) of a programme and instead much more of a focus on holistic student development and their preparedness for a lifetime as an independent learner with creative problem solving skills.

1.1 A Control Engineering Context

Most of the readers of this article will be researchers who need to stay at the forefront of their fields to make novel and useful contributions; no-one would dream of ignoring recent contributions and continuing regardless. It is somewhat surprising then that the very same staff often teach a module/course which is largely the same as it has been for 20 years or more in terms of both academic content and assessment. Some might argue that the foundations of engineering and mathematics have not changed, and thus the fundamentals needed by the students have also not changed. To some extent this is valid, however it is simplistic and lazy to not consider this further. While the fundamentals have not changed, we have tools available now that were not available 20-30 years ago, and it makes sense to utilise these tools to improve the student learning environment and, where logical, to update the curriculum and its delivery [2,17,32].

Simple examples of this are topics such as Nichol's charts and Routh array which were very useful in an age where computers were not generally accessible so computations had to be done on pen and paper. However, such tools are now largely redundant. In a similar way, mathematicians will use computer algebra programmes such as Mathematica or Maple to perform cumbersome/tedious algebraic manipulations where humans are likely to make mistakes and be slow. In parallel there is an increasing recognition that control and feedback are relevant to multiple audiences outside of traditional engineering such as biology, medicine, economics and sociology and thus a future introductory control course may need to consider a broad range of student backgrounds and requirements.

Similar statements can be made about laboratories. Whereas historically access to laboratories was very expensive and thus quite restricted in most universities, recently there has been a huge amount of work on for example remote access laboratories [13,22], take home laboratories [21,33,42], virtual laboratories [8,12,20,30] and thus significant opportunities to improve the student learning experience.

1.2 Contribution of this paper

The Technical Committees for Control Education of both IFAC [15] and the IEEE [24] felt that it was timely to reflect on the syllabus of a typical control engineering course taken by engineering undergraduates across a range of specialities (electrical, mechanical, chemical, etc.). In many programmes students will have just one core control module and thus it is important that we, as a community, make the most of this module and give students the learning that will serve them best. Typically the syllabus will have been created in the 1970s and perhaps undergone very little modification since then so a question worth asking is: *what is a suitable control syllabus for 2020?* It is worth noting that this question is separate from: *how should we teach [28,32,45] and what resources should we use?* More consideration of these latter questions would logically follow once there is consensus on what we teach.

The prime motivation was that by collecting and collating the views of the international community, this would give strong evidence for staff who needed support to instigate change in their own institutions. It would also give confidence to some in driving forward changes that conservative staff may be nervous about.

It is worth noting that several persons have gone this route before [3,4,11,25,29,36], but aside from now being somewhat dated, moreover some have restricted their context to particular countries or contexts [26]. For example, some surveys [22,30–32] have focussed more on good teaching practices and good resources and less on content. Others have restricted their surveys to particular regions [5,9,14,19,36,41] and some have focussed on particular disciplines [7,16,40] such as chemical engineering. One important set of results has looked specifically at industrial requirements [6,27,23,38,39] and how industry might support undergraduate education

The main difference of this survey, apart from being more recent, is the attempt to engage a world wide community across both academia and industry and also across all engineering disciplines. Moreover, there is a very specific focus on the so-called *First course in control* in recognition of the fact that many students will do no more than this and thus that forms a priority for university curriculum design. To some extent keeping the focus on a first course also simplifies the questions that need to be asked which enables clearer conclusions. Most academics realise that what topics students select in higher years could be viewed as somewhat arbitrary; these are primarily tools for developing the deep learning skills and self confidence that provide the foundation for a lifetime of learning.

By way of background, some pilot evaluations [35,37] were carried out on small numbers of respondents through 2018-2019 to gain some input into the questionnaire design and how this could be delivered globally. The final survey was released as a web questionnaire in June of 2019 and responses were collected up to February 2020. The questionnaire was widely publicised, for example through flyers at core international conferences, through eletter, through national member organisation email lists, and so on. The aim was to gain a good spectrum of respondents representing global views and also, differences between engineering disciplines and employment. We are pleased to have about 500 respondents which thus gives any statistics good validity. Readers can view some of the results directly at the website: http://iolab.sk/ifac/results.php. This paper seeks to summarise the findings in a palatable and reflective form which we hope readers will find useful and is a significant extension of the concise summary presented at the world congress [35].

Section 2 gives an overview of the questions asked, section 3 looks at the profiles of respondents and trends in views expressed correlated to these and summarises the quantitative data collected. Section 4 summarises the qualitative data and the paper then finishes with concluding remarks.

2 Questionnaire design

The two committees decided to take their time before releasing the final questionnaire and thus substantive background work was undertaken first.

2.1 Initial pilot

A dedicated panel session and fairly simplistic hard copy questionnaire was distributed at the IFAC Conference on Advances in PID Control in Ghent in 2018 [34]. These gave some useful insights into what questions could be asked as well as noting some fundamental points below which are more linked to implementation than the curriculum itself.

- Motivation is essential. The introductory aspects need to convince students that the topics are important and interesting before we dive into mathematical analysis.
- The availability of significant computing capacity, even on mobile devices, means that we need to update our teaching of classical control to exploit this technology, both to modernise student understanding and design methods and also to improve understanding and assessment.
- We should provide some benchmark problems to the community. Hence this is part of a special session at the world congress 2020.
- PID analysis and tuning is essential for all students.
- If possible questionnaire data should be interrogated by nationality as priorities may differ across the globe.
- An introductory course should focus on concepts, applications, limitations, benefits, uncertainty and so forth rather than an in depth view of just a few techniques which can lead students to link control topics solely with mathematics.
- If not covered previously in the curriculum, a thorough background in modelling and dynamics is essential.
- Authentic activities such as hardware with real challenges should be included.

2.2 Second pilot

Using the insights from the first pilot, a more professional questionnaire was prepared including a much wider range of questions and with more nuance; moreover this was delivered via web tools to improve accessibility and data capture. A limited number of persons were used to gain feedback on this questionnaire and also gain interim comments on the topic itself, that is, what should be in a first course on control? These findings were reported at the IFAC Symposium on Advances in Control Education in 2019 [37]. A panel session was also held to encourage qualitative comments. Unsurprisingly the panel replicated some of the earlier comments and added some other aspects, for example:

- There needs to be a balance of theory, implementation and integration. Integration is perhaps not done enough.
- Essential we excite students first so they decide to study more, for example advanced courses.

- While heuristics are useful and an easy way in, we must encourage students to learn the value of systematic and rigorous analysis which is more generalisable.
- Signals and systems background is essential.
- Modern students will expect us to exploit and recognise technology in what we teach and how we teach.

In terms of the data itself [37], it was clear that a far greater participation rate is needed to allow meaningful analysis, even though the pragmatist amongst us recognises that the data will inevitably be limited. Some aspects such as an evaluation of the differences between industrial and academic preferences, or indeed national preferences or engineering disciplines, need enough data for any corresponding insights to be justified. Both pilots indicated that respondents felt a first course should put a higher focus on concepts and application rather than purely mathematics, so this needs to be incorporated into the questions. There was also a strong suggestion that the curriculum in general needs modernisation. It was encouraging that the differences in the views of industrialists and academics largely reduced to lower priority issues rather than the core decisions. It was evident that respondent understanding of the *size* of a course was unclear and thus the questionnaire should be as explicit as possible. Finally, the questionnaire needed to be simpler, rather than more complicated, if it was to deliver meaningful results that can be evaluated and give clear conclusions. Given the focus was solely a first course in control, this was possible.

2.3 Final questionnaire design

The questionnaire is separated into thematic areas, although there is overlap in the delivery of this. The actual questions will be given in the results section to save duplication, so here we summarise the general ethos. Many questions use a 5 point Likert scale as it was felt that was discriminatory enough in terms of gaining respondent views.

(1) The first section seeks to profile the respondent by means of age, role, discipline, nationality.
(2) The second section focuses on conceptual issues. How does the respondent view a first course in terms of the core philosophies underpinning the design.
(3) The third section looks at technical topics in detail and considers views on what should or should not be included. This is done in two ways.
    - A request to identify the 5 most important topics, while accepting an actual course will include more topics.
    - A request to consider the importance of a large number of topics that could be in an introductory course and to indicate how much emphasis should be placed on these. It is implicit that low priority ones for an introductory course may be higher priority to be covered in later courses, but the survey did not attempt to consider that question in detail.
    - For convenience the topics were split into 6 groups: Signal Processing (4), Identification and Modelling (11), System Analysis (12), Control Design (24), Industrial Implementations (6), Tools (6).

All three sections comprise important findings as the actual technical content that can be included will be effected by local constraints such as prior learning and number of lectures. Inevitably staff will need to select a subset of desirable topics to create a viable course, but we hope the views expressed by their international colleagues will improve consistency and consensus in those decisions.

3 Results

This section presents a breakdown of data with a specific focus on the correlation to respondent background. This allows readers to consider whether there are distinctly different or only mildly different views across nationality, engineering and employment sectors.

3.1 Responder Background

This subsection includes tabulated data on the profile of respondents. In summary, the overall profile matches what one would expect and is sufficiently diverse to imply that the results represent a good and balanced spectrum of interested parties. There are more inputs from some sectors/groups, but in general terms that matches the expected population/university balance so would not be considered an unhelpful bias.

A total of 495 unique responses from 47 countries are included in this paper. The number of responders with academic affiliation was 417 (84 %). Industrial affiliation was 16% (78 responses). Table 1 lists the countries with 5 or more responders. USA and Italy had the highest industrial participation. Half of the responders were between 31 and 50 years of age (Table 2). Half of the responders have recently taught an introductory control course, (Table 3). Most industrialist respondents have had regular interactions with recent university graduates, (Table 3). The application domains were evenly distributed, (Table 4).

Country	Number of Responses		
	Academia	Industry	Total
China	96	7	103
Brazil	61	8	69
USA	35	19	54
Italy	32	12	44
Spain	28	1	29
Belgium	18	1	19
France	15	1	16
UK	13	3	16
Netherlands	11	3	14
Japan	10	1	11
Germany	8	2	10
Sweden	8	1	9
South Africa	3	6	9
Romania	8	0	8
Canada	5	2	7
Argentina	6	0	6
Chile	5	1	6
Switzerland	4	2	6
Portugal	5	0	5
Australia	5	0	5
Czech Republic	2	3	5
Other (less than 5 responses)	39	5	44
Total	417	78	495

Table 1
Countries with 5 or more responses.

< 30	(31-40)	(41-50)	(51-60)	> 60
18%	26%	25%	20%	10%

Table 2
Responders age distribution.

3.2 General questions on a first course in control

This section focuses on the overall design of a first course rather than the fine detail and thus asks for strategic decisions on the content and delivery rather than fine detail.

Most of the responders, from both academia and industry, selected 40 to 50 lecture hours for the time expectations of the course (Fig. 1). This is consistent with a university schedule of 13-15 week at 3 contact hours per week.

The responses for course prerequisites are summarized in Fig. 2. Responders were allowed to select any combination of the four prerequisites, listed in the legend. The majority of the responders, from both industry and academia, agreed that the three competencies listed below should be included as course prerequisites:

Responders' Roles	Count	% of Total
Academic (taught introductory control recently)	250	51%
Academic Researcher	115	23%
Academic (have not taught introductory control recently)	52	11%
Industrialist (regularly interacts with recent university graduates)	47	9%
Industrialist (does not interact regularly with recent university graduates)	17	3%
Researcher (non-academic)	14	3%

Table 3
Responders counts by role.

Electrical	Systems	Mechatronics	Electronic	Automotive	Computing	Chemical/Process
15%	11%	11%	10%	9%	9%	9%
Aerospace	Mechanical	Manufacturing	Bioengineering	Civil	Materials	Other
6%	6%	5%	4%	1%	1%	4%

Table 4
Application domains of responders. Application Domain % of Total

- Derivatives and integrals;
- Solution of differential equations;
- Working with matrices.

The desired pre-requisites are mostly relatively standard material from a mathematics course so unlikely to be a problem.

The choice of breadth and depth is essential in planning the first control course. A course could cover a broad selection of topics with lesser details, or alternatively, focus on a narrower scope of material and require deeper knowledge and mastery. The survey included several general questions related to this matter. The responses are shown in Fig. 3a-3c. The majority of the responders agreed that the course should:

- put more emphasis on students understanding core concepts rather than on being able to perform detailed mathematical operations/algorithms. [Indeed use software tools to support tedious computation.]
- be structured around classical tools, such as closed-loop transfer functions and Laplace.

Opinions differed on whether to set the course in a first principles or state space modelling framework, Fig. 4; industry and academia were evenly split. Approximately half of the academic and industry responders agreed, while a quarter disagreed. Aerospace and Automotive favoured this approach, while Chemical/Process disagreed. Other disciplines were evenly split.

Opinions also differed on whether to avoid digital systems, Fig. 5. Approximately half of the academic and industry responders agreed, while a quarter disagreed. Industry and academia were evenly split. In the application domains, Automotive showed a clear disagreement, while other areas were evenly split.

There is a definite disagreement of whether to set the course exclusively in the time domain and exclude frequency domain, Fig. 6. Automotive and Chemical/Process are in favour, while Electrical, Electronic and Mechatronics are against.

3.3 Analysis of the importance of individual topics

This section looks in fine detail at which topics respondents feel should be included and also, in what level of depth. It is inevitable that there will be much more spread of opinion here as fine detail will reflect local curriculum structures, disciplines, year group and so forth. However, the results are still useful as there is a nevertheless a clear trend in terms of which topics are routinely high on the list and those which are not.

The responses for the level and depth of coverage of course topics are summarized by industry and academia in, Fig. 7 to Fig. 15. The ranking is based on a weighted sum calculated for each topic that is later normalised against the top scoring item (feedback loop concepts). The response interpretations and the weight factors associated with them are listed in Table 5. Summary interpretations are given in the following subsections for each thematic area covered in the questionnaire.

Response	Interpretation	Weight Factor
Fine Detail	Use precise mathematical analysis	+5
Good Detail	Use some mathematical analysis	+4
Minimal Detail	Use little or no mathematical analysis	+3
Awareness Only	No detail or analysis	+1
Lab Only	Cover primarily through a lab activity	+2
Do Not Cover		-4
Second Course	Cover in a second / advanced course	-2

Table 5
Interpretation and weight factors for responses in Fig.7 to Fig. 15.

3.3.1 Signal Processing

The results for signal processing topics are presented in Fig. 7. Delays and Deadtime received top ranking by academia but last by industry. Low Pass Filters was ranked the highest by industry and second by academia. It is notable that all 4 topics received substantial support for inclusion and were rated more important by industry.

3.3.2 Identification and Modelling

The results for modelling frameworks are presented in Fig. 8. Both academia and industry agreed on the top 5 topics. These topics, in order, are:

- Modelling of simple, 1st and 2nd order systems
- Block diagrams
- Laplace and transfer functions
- Models with integrating response
- State space models

While there is reasonable consensus for most topics, there is a discernible disagreement between academia and industry in the ranking score for Nonlinear Models and Linearization with the academic score almost twice that of industry. The detailed responses for this topic are shown in Fig. 9. The two options with the largest differences between academia and industry are Good Detail, favoured by academia, and Do Not Cover, favoured by industry. To further explore the differences, Fig. 9 shows the distribution in the Good Detail and Do Not Cover responses by areas of application. Aerospace, Automotive, and Chemical/Process show definite preference to cover this topic, while Electronic, Mechanical, and Mechatronics do not. Thus, we attribute the difference in the ranking score to differences in the application domain, rather than on academic/industrial affiliation.

3.3.3 System Analysis

The results for systems analysis tools are presented in Fig. 10. Both academia and industry agreed on the top 6 topics, which are:

- Stability
- Frequency response
- Bode diagrams
- Bode diagrams, gain/phase margins
- Nyquist diagrams
- Nyquist stability criteria

It is interesting to note that frequency domain skills are implicit here which somewhat contradicts the results in Fig. 6, unless one reads this as: *if frequency domain is covered, this is the priority list.*

The most obvious disagreement (Fig. 11) between academia and industry in the ranking score for Routh Array / Criteria with the academic score almost twice that of industry, albeit this was relatively low on the academic priority list for both. To further explore the differences, we investigated the detailed responses from academia by age distribution. It was interesting to discover that younger population (less than 40 years of age) favoured Fine Detail, while older population (more than 60 years of age) favoured Do Not Cover. One could speculate that the new academic generation in their 30s are more influenced by the curriculum they were exposed to, whereas the older generation are becoming more reflective on what is really needed.

3.3.4 Control Design

The results for control design methods are presented in Fig. 12 (top 12 topics) and Fig. 13 (bottom 12 topics). Compared to the top 12 topics, the bottom 12 group received much lower ranking scores. Given this survey focuses on a first course, it is inevitable anyway that the topics in Fig. 13 would be highly unlikely to fit into the curriculum, and indeed it would even be difficult to include all of those in Fig. 12.

Both academia and industry agreed on the top 6 topics. These topics are:

- Feedback loop concepts, definitions, and hardware components
- PID
- Control loop requirements
- Control performance
- Disturbances
- Design with frequency response

Several topics received significantly higher scores by industry than by academia. These topics are:

- Feedforward
- Lead and lag
- Measurement noise
- Wind-up and anti-windup
- On-off control.

3.3.5 Industrial Implementations

The results for industrial aspects are presented in Fig. 14. Both academia and industry agreed on the top 3 topics. These topics are:

- Control implementations
- Hardware laboratories
- Industrial case studies

Several topics received significantly higher scores by industry than by academia, although still relatively low compared to many other items. These topics are:

- PLC
- Industrial control software
- Alarm management

3.3.6 Tools

The results for tools are presented in Fig. 15. Compared to other groups, the topics in this group received very low rankings with the exception of the first one: Matlab/Simuink

Both, academia and industry were in agreement on the importance of Matlab/Simulink, although it is likely this also reflects the ready availability of MATLAB within Universities, so it is also a choice of convenience.

3.3.7 *Top Five Most Important Topics*

Of particular interest, respondents were asked to select their 5 highest priority areas (Figures 16-19). Some thought this number too small, but the results are still helpful as they give a strong guide in terms of what **must** be included, notwithstanding local requirements.

The time constraints of a typical course will not allow all 63 topics listed in the survey to be included so inevitably, students will have a knowledge gap somewhere. But the first course in control is just a stepping stone on the long road to mastering the subject matter. Thus, the goal of the first course should be to equip students with the most essential skills and awareness that will enable them to jump over any knowledge gaps on their own as required. Consequently, responders were asked to list the top 5 most important topics in the curriculum. An aggregate score was assigned to each of the selected topics by computing a weighted sum in which 5 points were given for first choice, 4 points for second, and so on.

The topics that received similar ranking by academia and industry are presented in Table 6 (upper tier) and Table 7 (lower tier). There is a very good agreement between academia and industry for the most and least important topics in a first control course.

Topic	Rank (Aggregate Score)		
	Academic	Industrialist	(A-I)
Modelling of simple systems	1 (1125)	1 (193)	0
Laplace and transfer functions	2 (812)	2 (99)	0
Stability	3 (651)	7 (71)	-4
Feedback (concept, hardware)	4 (463)	5 (74)	-1
PID	5 (392)	3 (95)	2
Block diagrams	6 (335)	4 (78)	2
State space models	7 (333)	8 (51)	-1
Signal processing and impact of measurement	8 (229)	6 (72)	2
Frequency response	9 (204)	11 (25)	-2
Bode diagrams	10 (116)	13 (19)	-3
Delays and dead-time	12 (89)	9 (34)	3
Modelling from real data	13 (85)	10 (30)	3
Matlab/Simuink	14 (69)	14 (19)	0

Table 6
Topics from Top Five selection with similar ranks between academia (A) and industry (I) upper tier.

Topic	Rank (Aggregate Score)		
	Academic	Industrialist	(A-I)
Digitalization (model and controller)	21 (49)	22 (10)	-1
Signal flow graphs	33 (24)	31 (7)	2
Optimal control	38 (15)	40 (3)	-2
Free/open simulation software	43 (10)	46 (1)	-3
Luenberger observer	44 (7)	44 (2)	0
Constraint handling	48 (3)	47 (1)	1
Nonmodelled dynamics	49 (3)	51 (0)	-2
Labview	53 (1)	54 (0)	-1
Analogue implementations	46 (4)	42 (3)	4

Table 7
Topics from Top Five selection with similar ranks between academia and industry lower tier.

3.4 Regional Differences

The top four most represented countries in the survey are China (103), Brazil (69), USA (54), and Italy (44). These countries represent distinct regions: Asia, South America, North America, and Europe. In this section we analyse responses from these four countries in an attempt to identify regional differences in opinions for the content of the first control course. Fig. 20 shows the distribution of responders by field of application. The individual fields are not equally represented. For example, China is dominated by Automotive, USA by Chemical/Process, Brazil by Electrical/Electronic/Mechatronic, and Italy by Computing/Electrical/Mechatronics/Systems. Thus, observed regional differences may in fact be due to disproportionate field of application representation. On the general question about first principles modelling, Fig. 21, China and Italy have higher Agree/Strongly Agree percentages, while USA has higher Disagree/Strongly Disagree. However, comparison with Fig. 4 shows that Automotive background has a higher percentage of agreement, while Chemical/Process background has a higher percentage of disagreement. Since China is dominated by Automotive and USA by Chemical/Process, the regional differences that appear in Fig.21 may be attributed to application domain differences.

Regional responses for the question of avoiding digital systems are shown in Fig. 22. At first glance, there are no obvious regional differences. However, it was shown in Fig. 5 that Automotive background has a higher percentage of disagreement. Since Chinas responders are dominated by Automotive, it was expected that China would have a higher Disagree/Strongly Disagree percentage compared to the other three countries. Since this is not the case, it can be concluded that Automotive other than China has the most disagreement with the statement.

Regional responses for the question of avoiding frequency domain analysis are shown in Fig. 23. What stands out is the disproportionate percentage of Disagree/Strongly Disagree answers from Italy. However, comparison with Fig. 6 shows that Electrical/Electronic/Mechatronics application domains have the highest percentage of disagreement, and since Italy is dominated by these fields, the observed regional difference is most likely caused by disproportionate representation of application domains.

4 Overview of qualitative results

After a group of questions with tick the box replies, respondents were invited to enter free text comments. We have listed a large number because we feel it is useful to the readers to see the large range of views expressed. Nevertheless we cannot list all the comments here, especially as many of them express similar views. Hence, where possible we have grouped the comments and expressed the sentiments in an equivalent summary. Apologies that clearly these are much abbreviated, combined and paraphrased and words such as *my opinion* removed as implicit, but the original comments in full are available on the website: http://iolab.sk/ifac/results.php

We should add that there could be some accusation of bias in how we have curated this summary and we can only state that we have done our best to represent all the views expressed and then, in the summary of section 4.3, emphasised more those which multiple people expressed.

4.1 Comments on the size and conceptual design of a first course

(1) The first course covers classical PID Control; PID control is quite effective even when models are poor or not even available. In the second course we cover state space methods and root locus design. The first course should enable the students to understand the philosophy of control, concepts of analysis, design, feedback limitations and uncertainty. Additionally they should be able tune a PID controller and understand the required equipment (sensors, actuators, hardware, PLCs).
(2) A first course should include the basic mathematical foundations and focus on linear continuous time systems, system behaviours, classical tools like transfer functions, concepts of feedback and why feedback is important, basic control loops and loop requirements, first principles modelling and state space based control. Some mathematical rigour is helpful for student deep understanding.
(3) I believe that philosophy and deep understanding behind of what actually "control theory" is much important than showing a bunch of differential equations. With too much focus on mathematics students memorize how to solve control theory problems without understanding what control actually is and get stuck when facing a new control problem.
(4) How I was taught controls was mathematically heavy, ...it took several courses before things actually "clicked". This influences my approach in connecting the material to real world systems more quickly to help students gain a deeper understanding.

(5) My experience is that including digital systems results in too much material for a first course, at the cost of less exposition of core concepts.
(6) Simulation alone does not prepare you to deal with real world physical control problems. A first course should include industrial instruments and components if possible.
(7) Time domain is more broadly accessible and extends to nonlinear. This is particularly the case for Chemical Engineering where time domain models link easily to the context.
(8) Within a typical first course, it is difficult to find space for frequency domain design methods which, while a tool allowing good insight, is less intuitive than in time domain.
(9) It is most important to focus on motivation/reasons for control, control philosophy and principles, as well as on physical means of concepts, continuous as well as Discrete Event Systems and PLCs should be addressed; experiments are more important than software. Use good case studies to motivate before moving to mathematics.
(10) It would be ideal if some basic machinery such as differential equations, linear algebra, modelling, Laplace transforms, etc. could be outsourced to pre-requisite courses. The first course would then be late in 2nd or 3rd year.
(11) The focus of a first course should be SISO systems.
(12) State space formulations and concepts can be introduced in the last few weeks from a conceptual and computational standpoint keeping the rigorous mathematics light. Grasping transfer functions in the Laplace domain seems to be easier for beginners than state space.
(13) A brief overview of more advanced methods should be provided, to whet the students appetite and allow them to see what the possibilities are.
(14) Having the appropriate background is a key part when undertaking the first control module. I'm not very keen on watering down the content to make it accessible even to a first year undergrad. Education needs to cause a bit of discomfort.
(15) Discrete Time Systems are essential and more relevant. The days of continuous control finished with the analogue era. All the core concepts can equally be presented using difference equations. Laplace is no longer a strong competitor as the majority of Modern Control Systems are based on State Space representations.
(16) Classic feedback control acting on the output error is more intuitive to understand than state feedback control. Also, given the prevalence of PID in industry it seems sensible to focus on that. Digital should be covered because that is how controllers are now generally implemented but possibly just as an introduction.
(17) Frequency domain vs. time domain is a false trade-off. A good first course should cover both. Also, concepts and motivation-based reasons vs. mathematics is also a false trade off. A good course (and instructor) should be able to provide motivation and philosophy (the why) in addition to teaching methods grounded in mathematics. Bode had it right. We must be careful to avoid "hacking" in education.
(18) Modeling in state space from the start is easier to understand, easy to shift to transfer function domain and more advanced concepts.
(19) Numerical methods are essential since integration and differentiation is done digitally and simulators are essential for testing control.
(20) The process context is essential. Students need to be able to figure out what could be the input, output, disturbances, how do process coefficients change in time, performance criteria, hardware selection and so forth.
(21) Regarding state-space models, in 40 teaching hours it is a little bit of a stretch to introduce also state-space models. Students typically have poor knowledge of matrix calculus. The concepts of equilibrium point and of linearization however are important and provide a strong justification for the extensive focus on linear systems.
(22) I take the approach of teaching them with a hands-on lab and practical simulation scenarios so that students have concrete examples before delving into the mathematical principles.
(23) You only get one chance usually to grasp the fundamentals -don't skip any.
(24) I would favor breadth-first rather than depth-first in a first course. First principles based modeling, representation in Laplace and state space and relationships, pole-zero diagrams, stability, concepts of P, PI, and PID and feedforward, concept of Zero order hold for discretization.
(25) 90% of industry uses classical tools so these should take priority in what may be the only control class.
(26) Digital systems are what most students will end up working with in industry so should be included.
(27) For some disciplines such as Chemical Engineering, the industrial context may be more important to embed.
(28) Many tools such as Routh-Hurwitz, Root loci etc. are simply replaced by computers and can be removed.
(29) Students should have a lumped parameter systems modeling course before or within the control module.
(30) Exposure to practical and non-trivial hardware is very important.
(31) Recent graduates with only one 40 lecture course are unlikely to be undertaking detailed control design so excessive mathematical rigour is secondary. They need to appreciate what control delivers to products, safety and performance.
(32) Some theoretical understanding is essential at all levels of university studies.
(33) Establishment of some mathematical background is necessary to deliver relevant knowledge for dealing with

practical control engineering problems; otherwise the course may become too superficial.
(34) It should delineate what Controls is NOT - i.e. software engineering or iterating in Matlab/Simulink until it works.
(35) State space methods, discrete time systems, advanced methods and theoretical rigour are important but should be reserved for later modules.
(36) Frequency domain techniques were never used during my years as control engineer with Imperial Oil in Canada.
(37) What you can include depends on what pre-requisites are covered earlier and this will vary hugely by discipline and institution.
(38) Concepts can hardly be presented without a glimpse on the theory to justify them.
(39) State-space/time domain and frequency domain are both relevant as some aspects are easier approached in one domain or the other.
(40) The complexity of the mathematics involved should increase gradually over the course as mathematics are essential to control theory and as the motivation for them becomes clearer.
(41) It seems beneficial to start from within the time domain as it is much more intuitive.
(42) Exposure to process simulation tools is useful.
(43) A first course must connect the students with the subject.
(44) Delays are critical and should be included somewhere; this is not easy in state space.
(45) It is not possible to cover in a single course everything we would like but we need to argue for enough lectures to cover the most important material.
(46) The experimental part of the course is vitally important.
(47) The most important subject is simply the concept of feedback.

4.2 Miscellaneous comments

(1) It is helpful if tools such as MATLAB are covered elsewhere.
(2) Work with physical models that are covered elsewhere in the same curriculum, so that students can immediately focus on the modelling/simulation aspects.
(3) Automatic control is not only feed-back control!
(4) It is good if a first course motivates students to take later courses and develop the mathematics skills that may be needed for research.
(5) More attention should be devoted in basic control courses to the actuation and ensuring the controllers are implementable.
(6) Use software tools only after the student has been taught to solve and understand the solution to an ODE.
(7) I think a first course could contain concepts from robust control.
(8) This list is too short. There is little in this list about the real issues faced in practice.
(9) Less is more when it comes to teaching certain topics like controls. That is, it's better to know the fundamentals well than everything superficially.
(10) Control is applicable only when system/plant behavior is well-understood.
(11) What is most important varies by context, but students should come out of a first course with a solid understanding of the fundamentals and capable of learning what they "missed" as needed.
(12) It's important not to overload students with information.
(13) Completely missing from the topics is the understanding of dynamics - static gain, time constant, ...
(14) The goal of a single course should be to have engineers that have enough awareness and understanding of feedback principles, tools, and implementation so that if they needed to work on a real control problem, they are functional.
(15) Give sufficient focus to practical issues such as: i) what can be measured and how?; ii) typical control hardware; iii) actuators; iv) filtering.
(16) There are useful software tools for visualisation out there that we can share better.
(17) I think it is important to cover overdamped, integrating, and unstable systems and show the characteristics and differences.
(18) For students in aerospace and mechanics the state-space approach is essential. For students in energy, a frequency-domain approach with Bode analysis gives more insight.
(19) In 30 years in industry I have never once used a Bode plot or Nyquist diagram.
(20) Choosing 5 topics is not sufficient!

4.3 Summary of textual comments

Clearly there are diverse views and a recognition that there must be differences in a first course based upon what topics the students have taken previously and also, the discipline. Here we attempt to capture the major points which have a general consensus.

Must include: If not covered in earlier courses, first principles modelling, solution of ODEs and dynamics/behaviours, Laplace transforms/signals and simulation software should be covered to some extent. Moreover, the importance of PID was emphasised by the majority. Simulation tools should be used wisely.

Concepts: The general consensus is to focus on concepts, the critical role of feedback (and requirements) and motivation first and to make students enthusiastic. Then gently introduce some mathematical tools and rigour to ensure students have good competence and understanding of the basics.

Breadth: The first course should be broad enough to capture as much core content as possible so students can engage effectively in their careers. Worry less about the degree of technical depth to avoid overloading students and they can learn this later as required.

Differences: A notable difference is between those who are in the process engineering sector and those from the aerospace/mechanical sector with the former favouring much more real world context, hardware and time domain/Laplace methods and the latter wanting more focus on state space.

Laboratories: Unsurprisingly, the core role of laboratories was stated by many, with several emphasising the need to make these non-trivial and include realistic practical attributes.

Do not include: Very few argued for frequency response methods to be included in a first course. Similarly there was an acceptance that advanced methods such as Kalman filtering, LQR design, z-transform theory, predictive control and so forth must be in a 2nd or 3rd course.

Digital: Many would like a brief introduction to digital control to be in a first course.

State space: There is a split view on state space, with many wanting this to be centre stage and others suggesting it may be included only briefly but should largely be in a 2nd course.

5 Conclusions

The paper has presented data from an international questionnaire on what should be in a first course in control. It is pleasing that the views presented represent a wide diversity of engineering disciplines, nationalities and roles and thus, with around 500 responses is a good insight into an collective community viewpoint. It is also pleasing that there is broad consensus with regard to many of the most important aspects, even though there is inevitably some differences with respect to the lower priority decisions.

5.1 General conclusions

The one area where there was overwhelming consensus is that a first course should begin with concepts, case studies, motivation, context and so forth. We should attempt to get students to understand the power and relevance of feedback loops before pushing them towards the mathematical tools that will enable them to contribute to this in their careers. It was felt a first course should introduce students to some mathematical depth/rigour, but as means to an end rather than an end in itself.

Secondly, while there is still widely varying views on whether state space should or should not be in a first course, it was clear that first principles modelling, dynamics, quantification of behaviours and the ability to analyse these through appropriate mathematical tools was agreed by all. In general terms, most felt Laplace should be included regardless of whether state space was or not.

The importance of engaging with hardware and the issues that appear on on real applications was raised by many and thus such aspects must be in the course to some extent. There was a trend that these aspects were more important to process engineers who therefore wanted practical application/software/issues to make up a larger proportion of the curriculum.

Unsurprisingly, given its universality, pretty much every respondent emphasised the importance of students being confident with PID tuning. Most staff seem to support the use of simulation software to support analysis and control design in these courses, but students must be made aware of the limitations and pitfalls of being over-reliant on simulation.

An interesting observation, that is probably counter to many existing courses, is the number of respondents who felt an introduction to digital control and the corresponding issues, needs to be in a first course.

There is a general feeling that more advanced topics, especially those involving more challenging mathematics, do not belong in an introductory course and we should feel relaxed about having these in 2nd and 3rd courses. We should aim to pique the interest of students so that they choose to study these later optional courses.

5.2 Future work

There is enough data to perform an indicative evaluation of differences between disciplines and nationalities in terms of their quantitative responses. Only a few aspects of this have been included in the current paper for fear of blurring the core messages and also making the paper too long. However, the data is available and so such a data interrogation will take place in the future.

Another core issue which was not central to this paper is control education resources. Now we have a tentative list of priorities, it will be possible to set out focused calls for teaching resource contributions that can be shared with the community, especially in some areas of increasing need due to modernisation, where staff would appreciate any good guidance to upgrade their knowledge and skills.

References

[1] ABET. Accreditation in the USA. `https://www.abet.org/`. Accessed: 2020-01-14.

[2] P. Albertos. MOOC in dynamics and control. `http://personales.upv.es/~palberto/`. Accessed: 2020-01-17.

[3] P. Ansaklis, T. Basar, R. DeCarlo, N. Harris, M. Spong, and S. Turkovich. Report on the nsf/css workshop on new directions in control engineering education. *IEEE Control Systems Magazine*, 19(5):35 – 58, 1999.

[4] D. P. Atherton. Some thoughts on the first course in control engineering. *IFAC Proceedings Volumes*, 39(6):229 – 234, 2006. 7th IFAC Symposium on Advances in Control Education.

[5] S. Bajpai, S. Khare, and R. Yadav. Control education in india : Present & future. *IFAC-PapersOnLine*, 49(1):813 – 818, 2016. 4th IFAC Conference on Advances in Control and Optimization of Dynamical Systems ACODS 2016.

[6] M. Bauer, K. S. Brooks, and C. Sandrock. Industry expectations and academic practice in control engineering education a south african survey. *IFAC Proceedings Volumes*, 47(3):12226 – 12231, 2014. 19th IFAC World Congress.

[7] B. W. Bequette. Process control practice and education: Past, present and future. *Computers & Chemical Engineering*, 128:538 – 556, 2019.

[8] I. Cameron. Pedagogy and immersive environments in the curriculum. In *Blended Learning conference*, pages 290–294, 2009.

[9] J. A. Cook and T. Samad. Controls curriculum survey. Technical report, Control Systems Society, 2009. (Outreach Task Force Report).

[10] T. Croft and R. Davison. *Mathematics for Engineers Companion Website, 4/E.* Pearson Higher Education, 4 edition, 4 2015.

[11] S. Dormido. Control learning: Present and future. *Annual Reviews in Control*, 28:115 – 136, 2004.

[12] S. Dormido, J. Snchez-Moreno, H. Vargas, L. de la Torre, and R. Heradio. UNED labs: a network of virtual and remote laboratories. In Javier Garca Zuba and Gustavo R. Alves, editors, *Using Remote Labs in Education: Two Little Ducks in Remote Experimentation*, pages 253–270. University of Deusto, Bilbao, 2011.

[13] S. Dormido, H. Vargas, and J. Snchez. AutomatL@bs consortium: A spanish network of web-based labs for control engineering education. In Abul K.M. Azad, Michael E. Auer, and V. Judson Harward, editors, *Internet Accessible Remote Laboratories: Scalable E-Learning Tools for Engineering and Science Disciplines*, pages 206–225. IGI Global, 2012.

[14] A. Dourado, A. Cardoso, J. Henriques, and C. Teixeira. Systems and control for biomedical engineering students. *IFAC Proceedings Volumes*, 45(11):413 – 417, 2012. 9th IFAC Symposium Advances in Control Education.

[15] EDCOM. Website of EDCOM committee including minutes of meetings. `https://tc.ifac-control.org/9/4/wellcome`, 2018. Accessed: 2020-01-14.

[16] T. F. Edgar, B. A. Ogunnaike, J. J. Downs, K. R. Muske, and B. W. Bequette. Renovating the undergraduate process control course. *Computers & Chemical Engineering*, 30(10):1749 – 1762, 2006. Papers form Chemical Process Control VII.

[17] M. Egerstedt. MOOC on control of mobile robots. `https://www.coursera.org/course/conrob`, 2016. Accessed: 2020-01-14.

[18] ENAEE. European network for accreditation of engineering education. `http://www.enaee.eu`. Accessed: 2020-01-17.

[19] C. Falsetti, S. Ramazzotti, and T. Leo. First degree control systems curricula in Italy: A survey. *IFAC Proceedings Volumes*, 39(6):327 – 331, 2006. 7th IFAC Symposium on Advances in Control Education.

[20] G. C. Goodwin, A. M. Medioli, W. Sher, L. B. Vlacic, and J. S. Welsh. Emulation-based virtual laboratories: A low-cost alternative to physical experiments in control engineering education. *IEEE Transactions on Education*, 54(1):48–55, Feb 2011.

[21] J. D. Hedengren. Temperature control lab kit. `http://apmonitor.com/heat.htm`, 2019. Accessed: 2020-01-17.

[22] R. Heradio, L. de la Torre, and S. Dormido. Virtual and remote labs in control education: A survey. *Annual Reviews in Control*, 42:1 – 10, 2016.

[23] M. Hoernicke, A. Horch, and M. Bauer. Industry contribution to control engineering education: An experience of teaching of undergraduate and postgraduate courses. *IFAC-PapersOnLine*, 50(2):133 – 138, 2017. Control Conference Africa CCA 2017.

[24] IEEE TC. Website of IEEE TC on control education including minutes of meetings. `http://control-education.ieeecss.org/control-home`, 2018. Accessed: 2020-01-14.

[25] N.A. Kheir, K.J. Astrom, D. Auslander, K.C. Cheok, G.F. Franklin, and M. Masten. Control system engineering education. *Automatica*, 22:147 – 166, 1996.

[26] A. Leva. PID control education for computer engineering students: A step to bridge a cultural gap. *IFAC Journal of Systems and Control*, 8:100051, 2019.

[27] Y. Luo, P. R. Westmoreland, D. Alkaya, R. V. Alves da Cruz, I. E. Grossmann, W. D. Provine, D. L. Silverstein, R. J. Steininger II, J. B. Talbot, A. Varma, T. McCreight, K. Chin, and D. Schuster. Chemical engineering academia-industry alignment:expectations about new graduates an NSF-sponsored study led by the american institute of chemical engineers. Technical report, American Institute of Chemical Engineers, November 1 2015.

[28] A. Middleton. Digital voices. `https://melsig.shu.ac.uk/melsig/publications/digital-voices/`, 2013. Accessed: 2020-01-17.

[29] R.M. Murray, K.J. Astrom, S.P. Boyd, R.W. Brockett, and G. Stein. Future directions in control in an information-rich world. *IEEE Control Systems Magazine,*, 23:20 – 33, 2003.

[30] J. A. Rossiter. Using interactive tools to create an enthusiasm for control in aerospace and chemical engineers. *IFAC-PapersOnLine*, 50(1):9120 – 9125, 2017. 20th IFAC World Congress.

[31] J. A. Rossiter, S. Dormido, L. Vlacic, B. Ll. Jones, and R.M. Murray. Opportunities and good practice in control education: a survey. *IFAC Proceedings Volumes*, 47(3):10568 – 10573, 2014. 19th IFAC World Congress.

[32] J. A. Rossiter, B. Pasik-Duncan, S. Dormido, L. Vlacic, B. Jones, and R. Murray. A survey of good practice in control education. *European Journal of Engineering Education*, 43(6):801–823, 2018.

[33] J. A. Rossiter, S. A. Pope, B. Ll. Jones, and J. D. Hedengren. Evaluation and demonstration of take home laboratory kit. *IFAC-PapersOnLine*, 52(9):56 – 61, 2019. 12th IFAC Symposium on Advances in Control Education (ACE2019).

[34] J. A. Rossiter, K. Zakova, M. Huba, A. Serbezov, and A. Visioli. A first course in feedback, dynamics and control: Preliminary findings of a survey for the ifac community. In *18th European Control Conference (ECC)*, pages 3065–3069, June 2019.

[35] J. A. Rossiter, K. Zakova, M. Huba, A. Serbezov, and A. Visioli. A first course in feedback, dynamics and control: findings from 2019 online survey of the international control community. In *21st IFAC World Congres*, June 2020. (to be accepted).

[36] J.A. Rossiter, D. Giaouris, R.J. Mitchell, and P. McKenna. Typical control curricula and using software for teaching/assessment: a uk perspective. *IFAC Proceedings Volumes*, 41(2):10331 – 10336, 2008. 17th IFAC World Congress.

[37] J.A. Rossiter, K. Zakova, M. Huba, A. Serbezov, and A. Visioli. A first course in feedback, dynamics and control: findings from an online pilot survey for the ifac community. *IFAC-PapersOnLine*, 52(9):298 – 305, 2019. 12th IFAC Symposium on Advances in Control Education ACE 2019.

[38] A. Serbezov and D. Cummings. University-industry co-operation to promote industrial relevance in the field instrumentation component of control education. *IFAC-PapersOnLine*, 49(6):309 – 313, 2016. 11th IFAC Symposium on Advances in Control Education ACE 2016.

[39] A. Serbezov and R. Rice. Imparting industrially relevant process control skills in chemical engineering students with loop-pro trainer. *IFAC-PapersOnLine*, 52(9):27 – 32, 2019. 12th IFAC Symposium on Advances in Control Education ACE 2019.

[40] Francis G. Shinskey. Process control: As taught vs as practiced. *Industrial & Engineering Chemistry Research*, 41(16):3745–3750, 2002.

[41] D. L. Silverstein, M. A. Vigeant, and M. Staehle. How we teach process control: 2015 survey results. In *ASEE Annual Conference & Exposition*, New Orleans, Louisiana, June 2016. ASEE Conferences.

[42] B. Taylor, P. Eastwood, and B.Ll. Jones. Development of a low-cost, portable hardware platform for teaching control and systems theory. *IFAC Proceedings Volumes*, 46(17):208 – 213, 2013. 10th IFAC Symposium Advances in Control Education.

[43] The University of Sheffield. Programme level approach. `https://www.sheffield.ac.uk/staff/learning-teaching/our-approach/programme-level`. Accessed: 2020-01-14.

[44] UK-SPEC. Engineering council. `http://www.engc.org.uk/ukspec.aspx`. Accessed: 2020-01-14.

[45] D.I. Wilson and P. Maclaren. From chalk talk to tablet talk: Pedagogies for control engineering. *IFAC Proceedings Volumes*, 46(17):144 – 149, 2013. 10th IFAC Symposium Advances in Control Education.

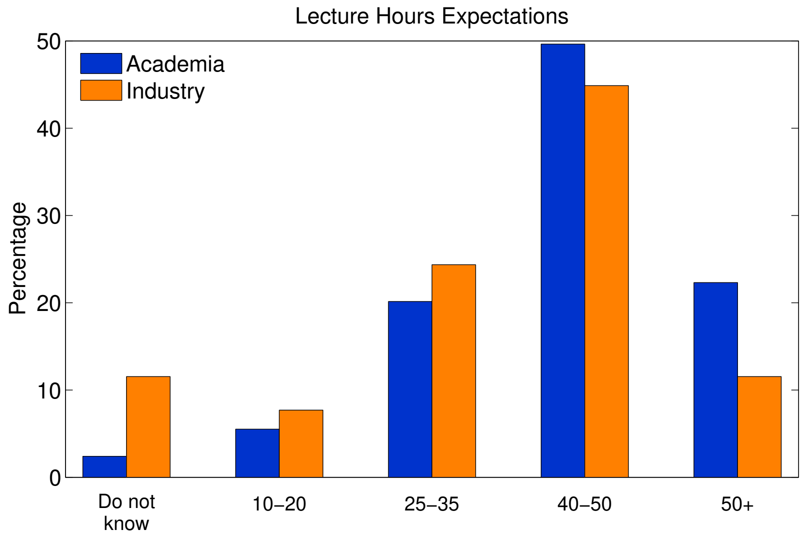


Fig. 1. Lecture hours expectations for a first control course.

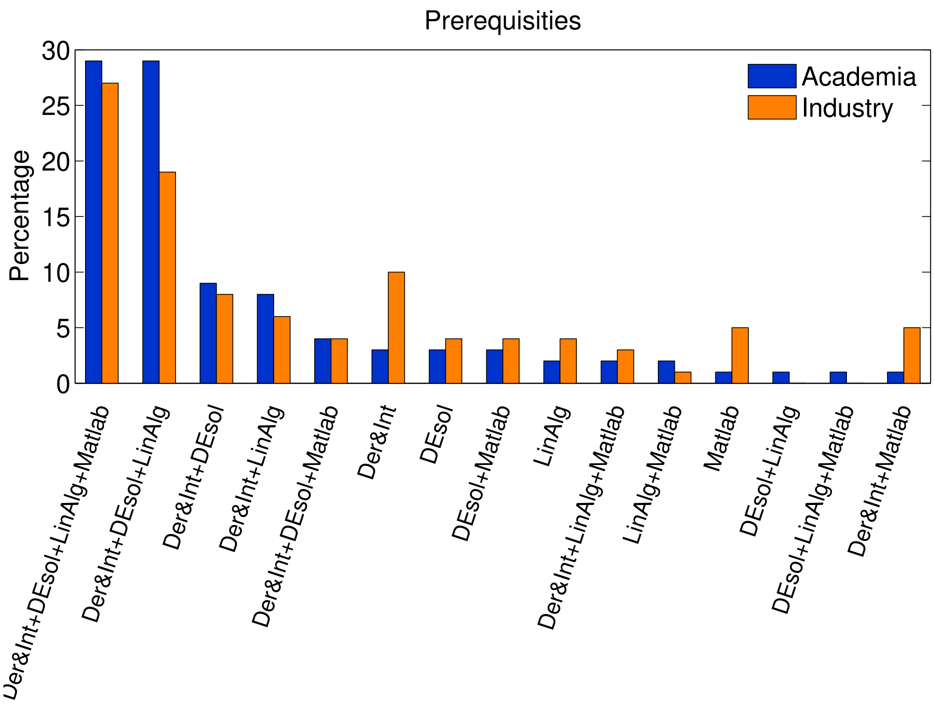
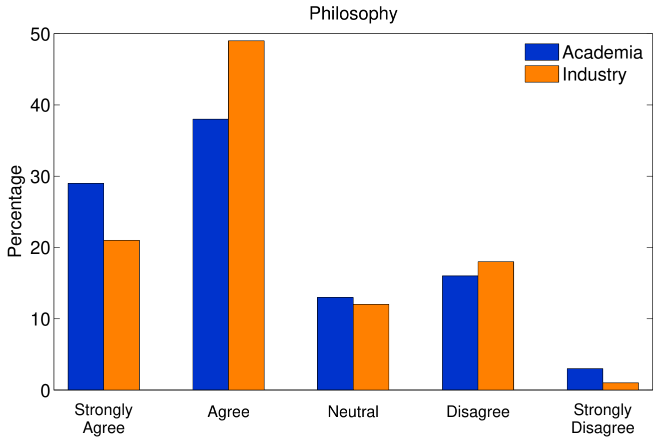
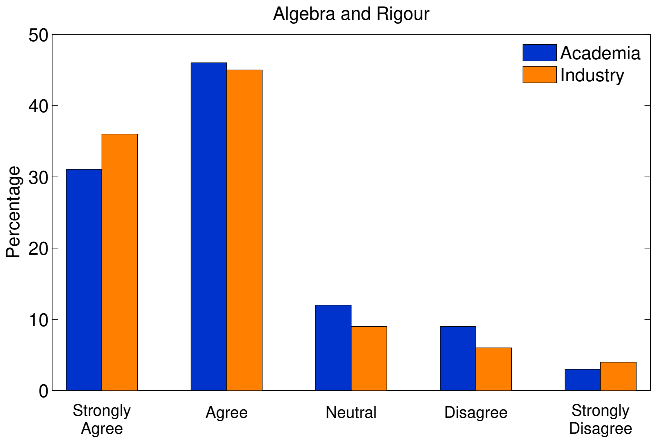


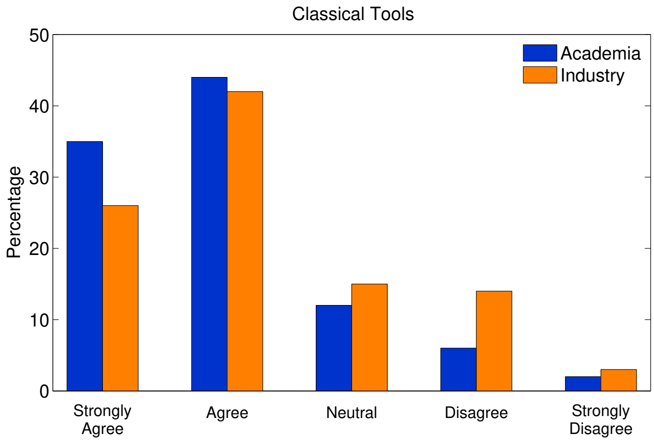
Fig. 2. Control course prerequisites: (i) Der& Int = Derivatives and integrals; (ii) DEsol = Solution of differential equations; (iii) LinAlg = Linear algebra (working with matrices); (iv) Matlab = Relevant knowledge of Matlab



(a) Statement: 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.



(b) Statement: 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.



(c) Statement: A first course should focus on classical tools such as Laplace, closed-loop transferences and lead/lag/PID design.

Fig. 3. Responses to general questions about the breadth and depth of a 1st control course.

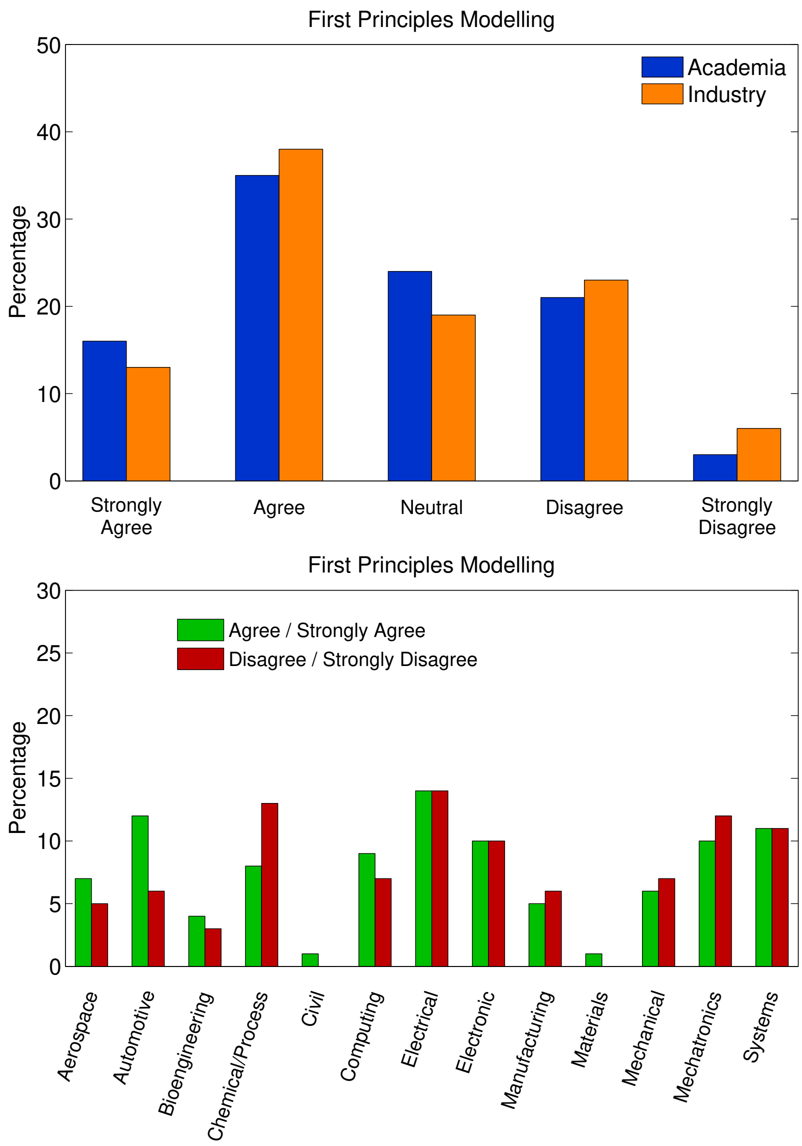


Fig. 4. Responses to the specific question: A first course should be set in a state space (or first principles modelling) framework.

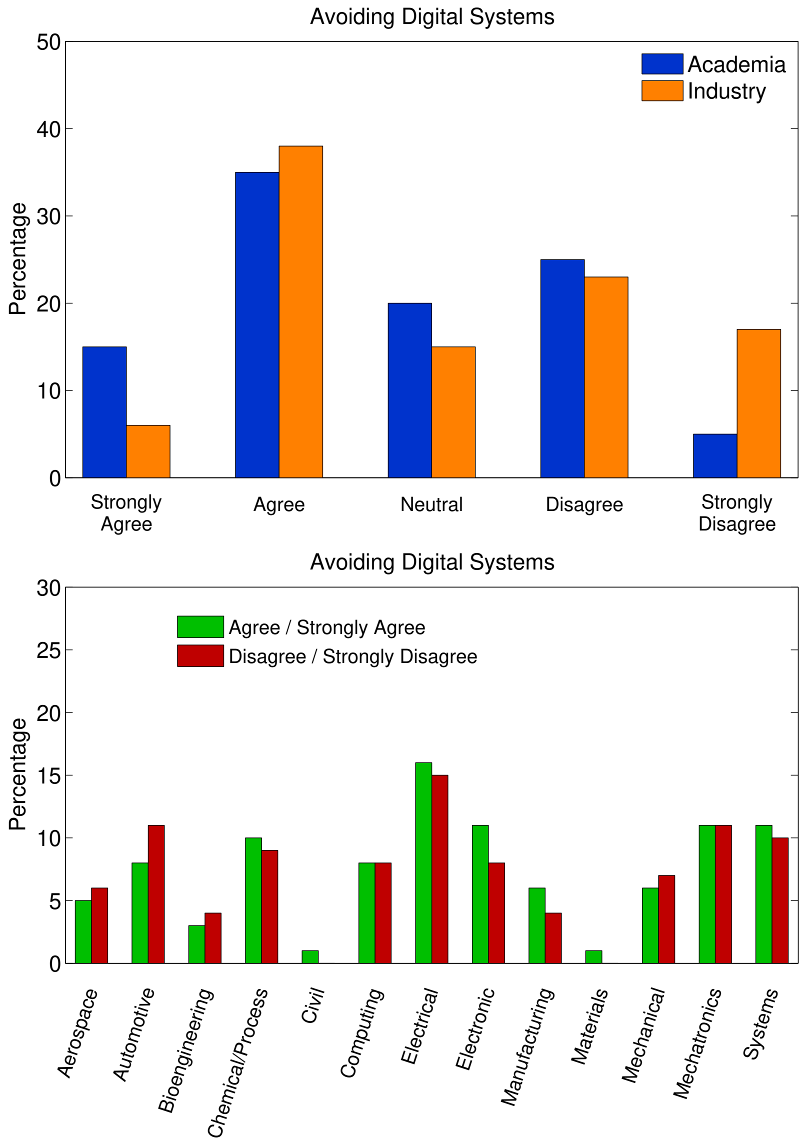


Fig. 5. Responses to the specific question: A first course should cover just linear time continuous systems and avoid digital systems.

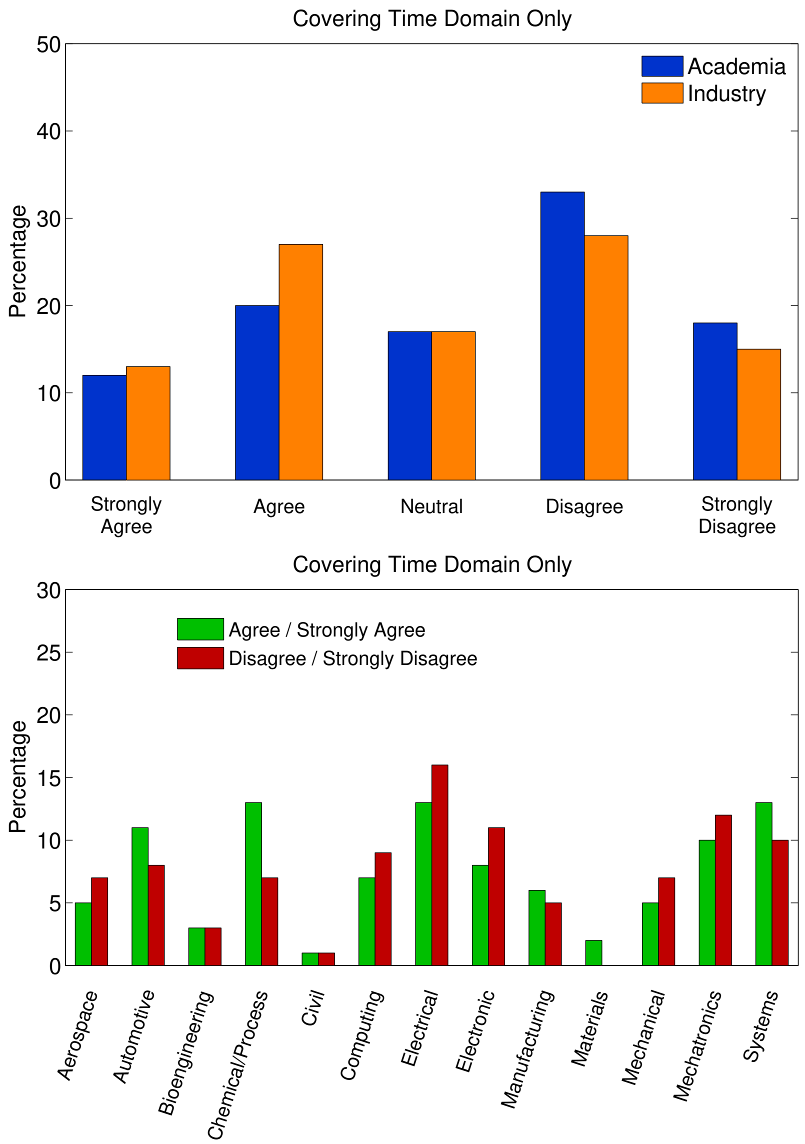


Fig. 6. Responses to the specific question: A first course should be devoted to time domain and avoid reference to the frequency domain.

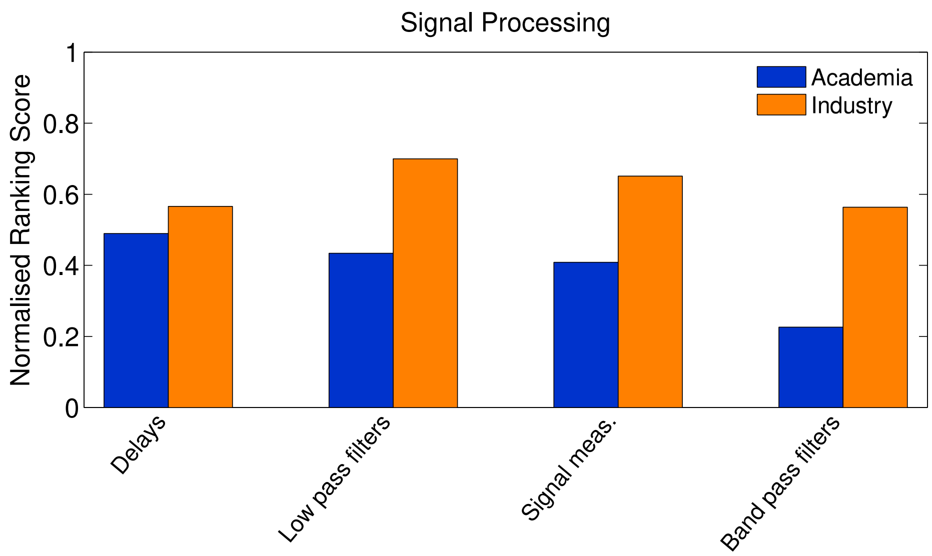


Fig. 7. Ranking of Signal Processing topics.

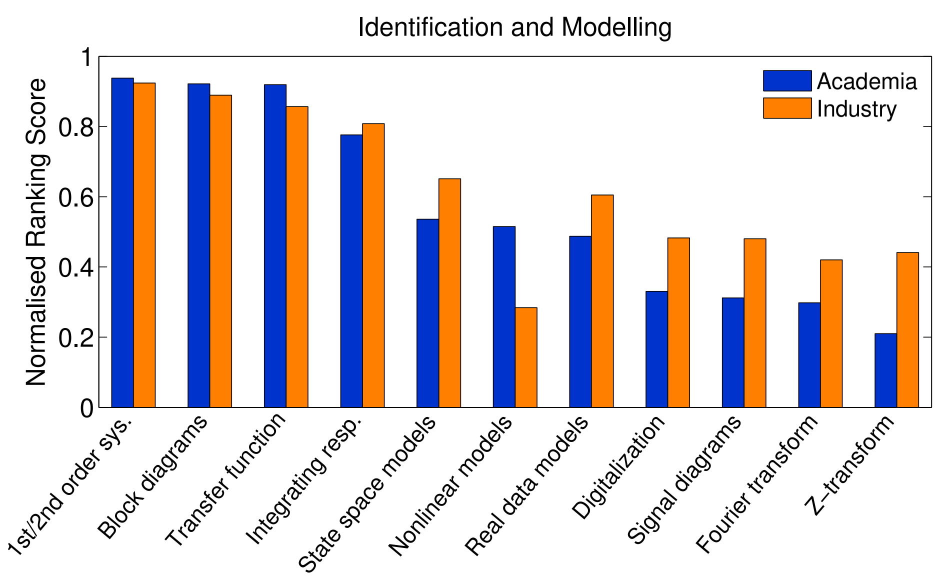


Fig. 8. Ranking of Identification and Modelling topics.

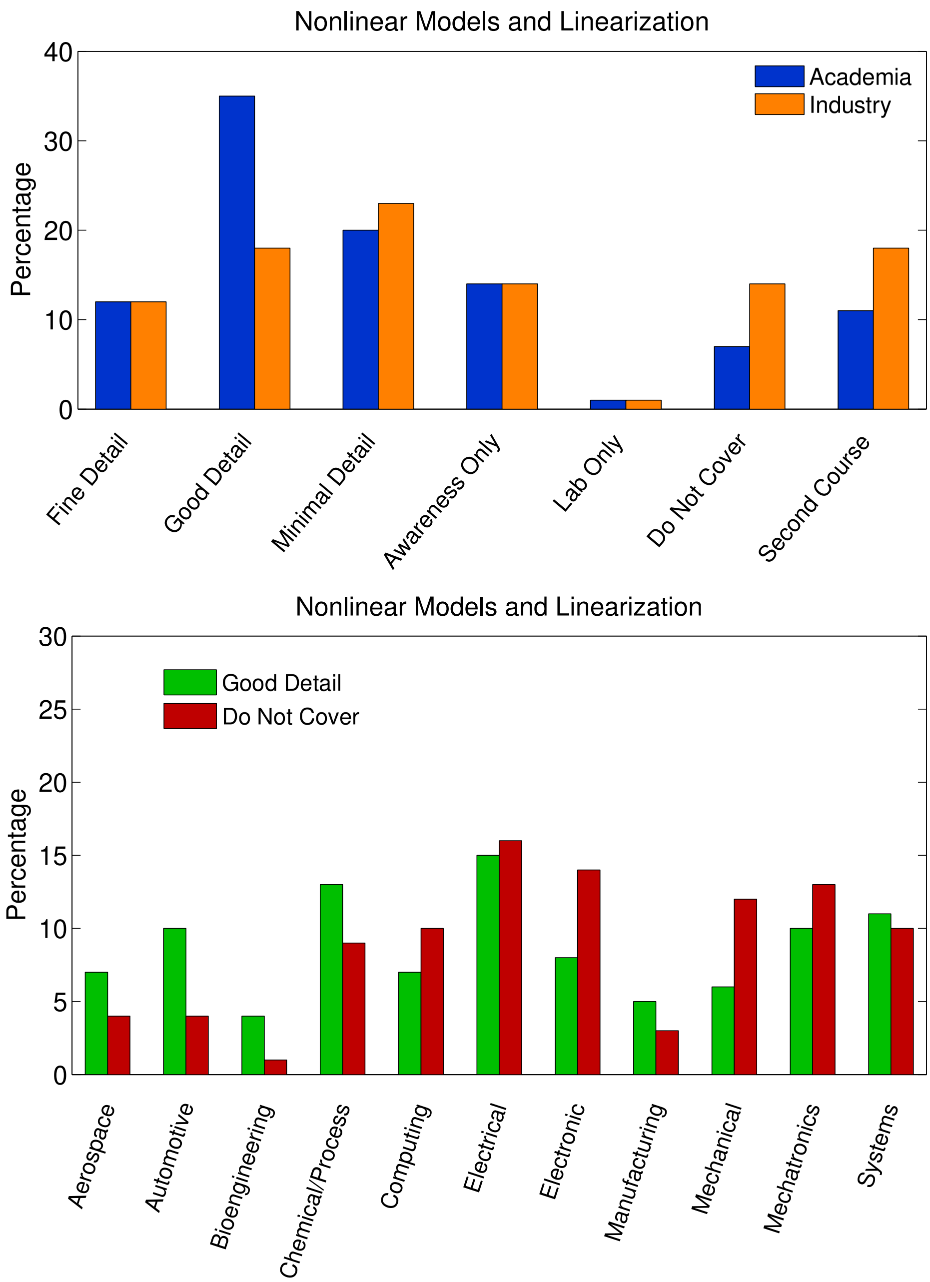


Fig. 9. Detailed responses for the topic of Nonlinear Models and Linearization.

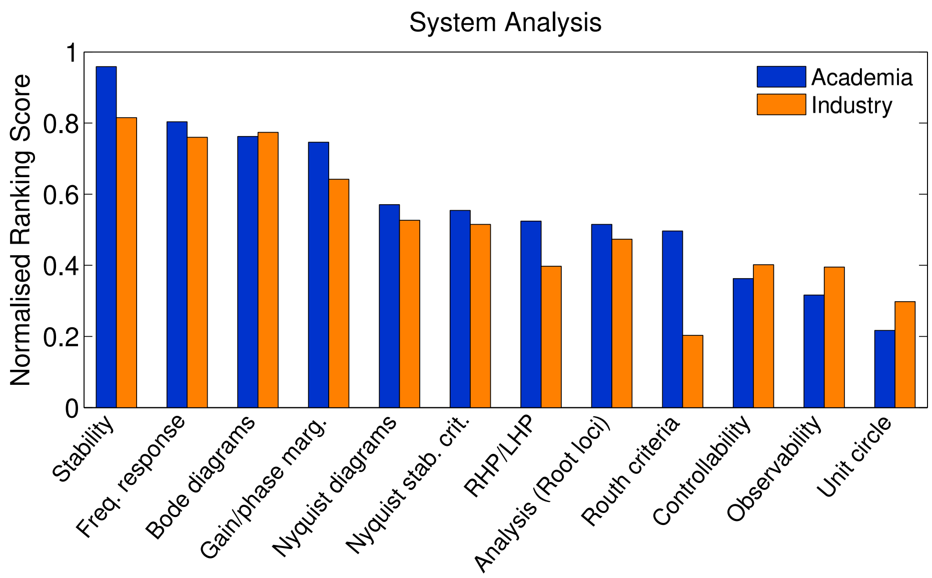


Fig. 10. Ranking of System Analysis topics.

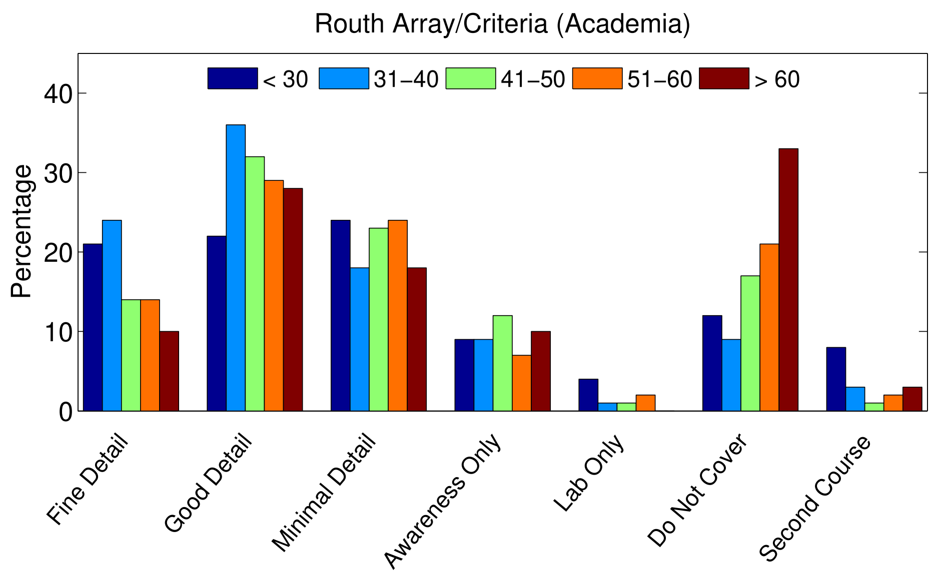


Fig. 11. Detailed responses for the topic of Routh Array Criteria from academia by age distribution.

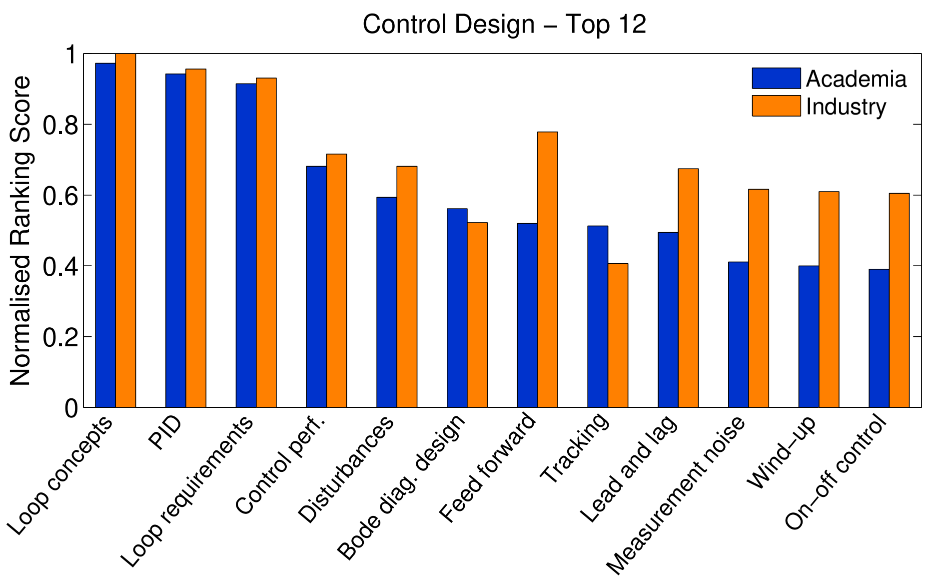


Fig. 12. Ranking of Control Design topics, 1st to 12th.

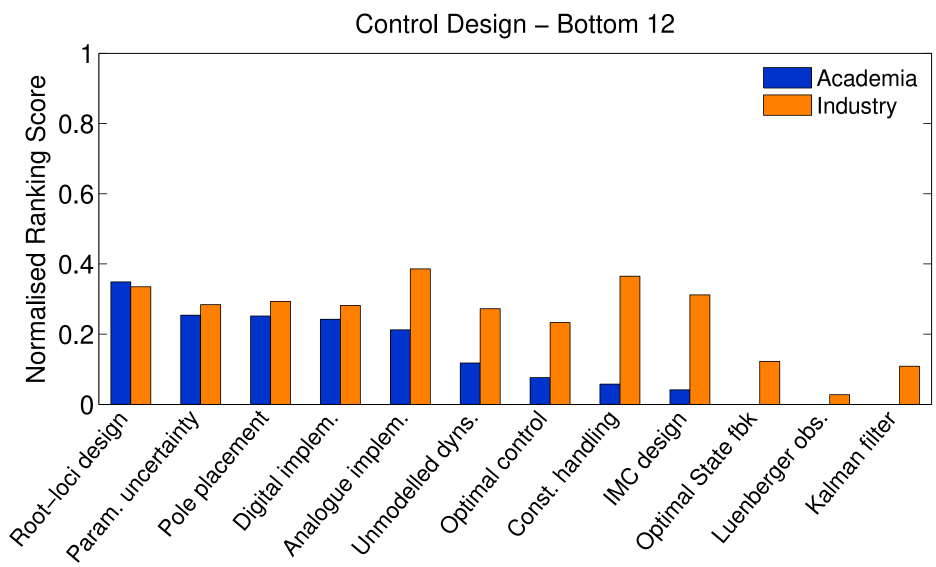


Fig. 13. Ranking of Control Design topics, bottom 12.

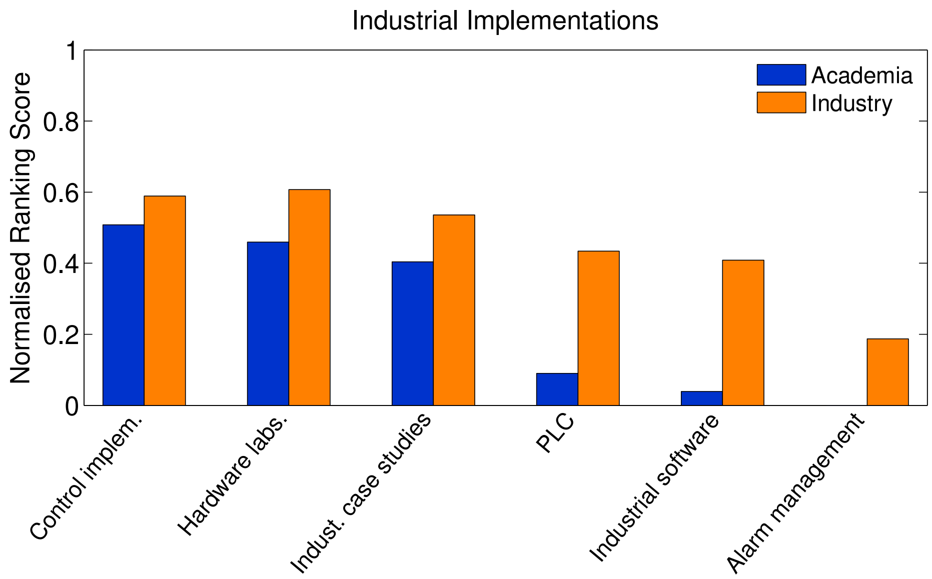


Fig. 14. Ranking of Industrial Implementations topics.

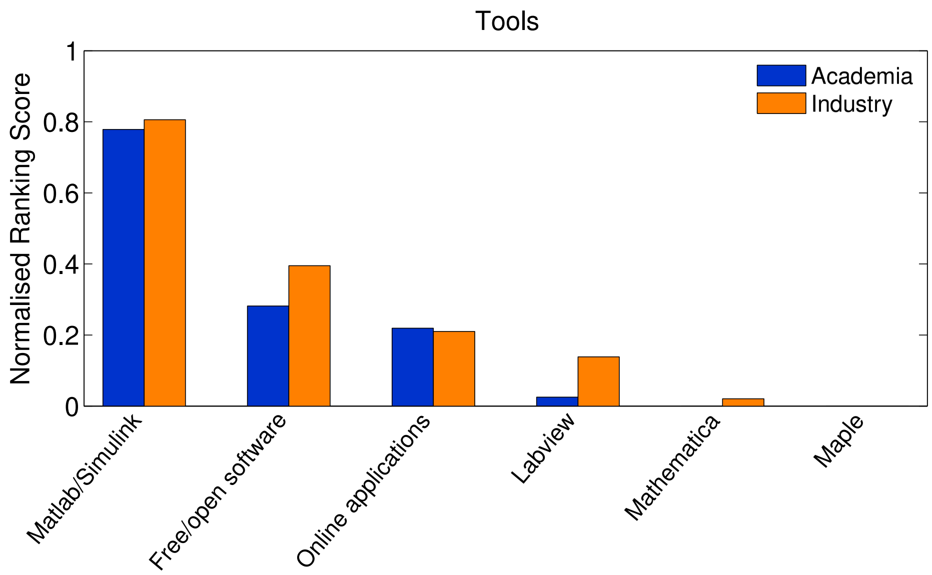
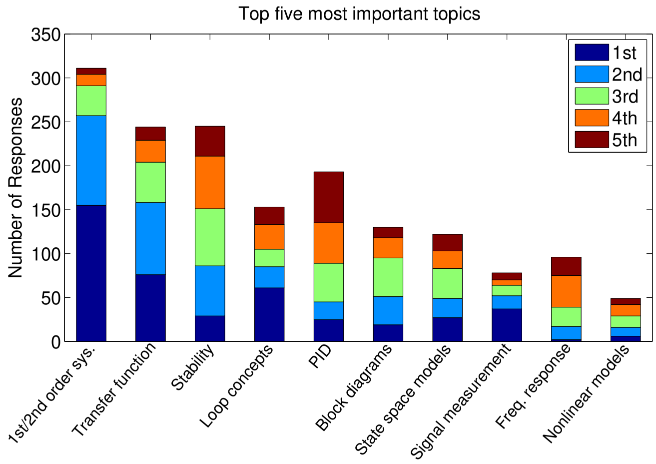
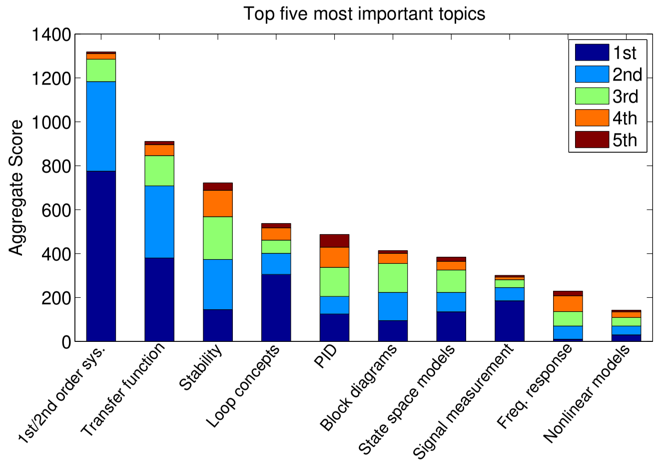


Fig. 15. Ranking of Tools topics.



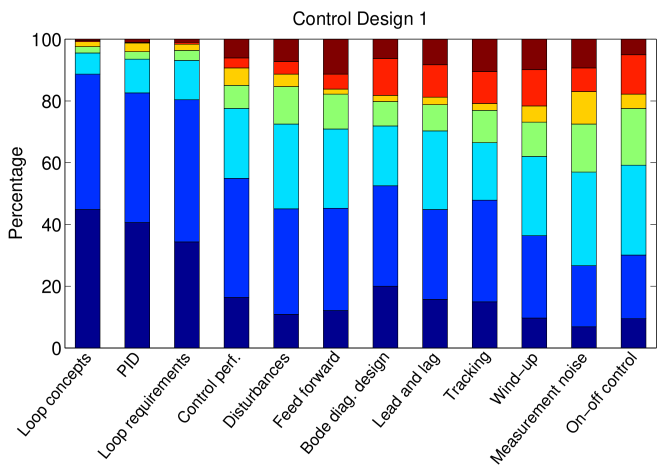
(a) Listed by number of responses.



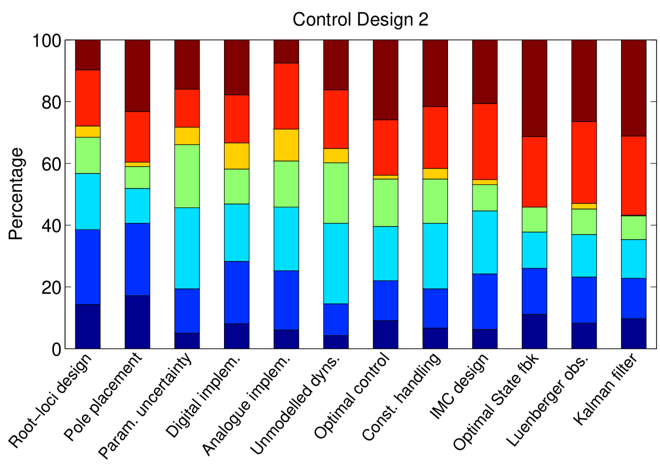
(b) Listed by aggregate score.

Fig. 16. Relative ranking of topics rated as being the top 5 most important.

Fig. 17. Legend used in Figs. 18 - 19.

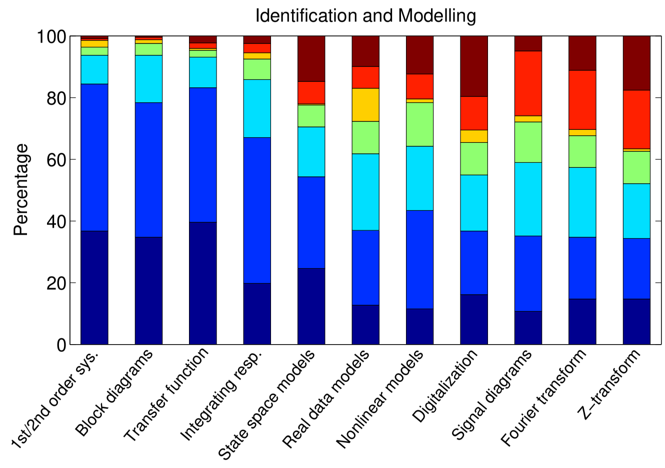


(a) Most popular control design methods.

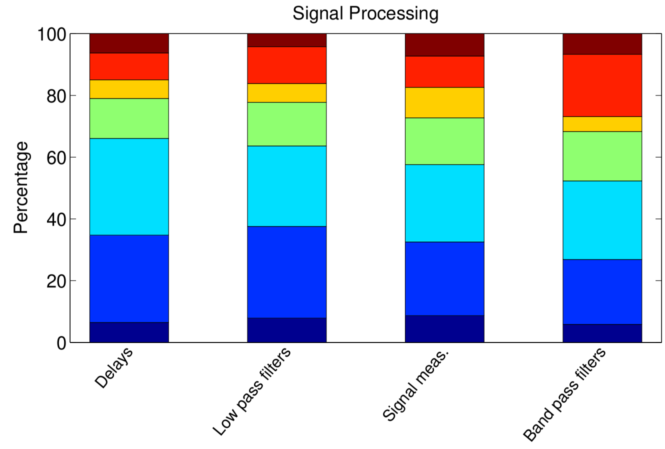


(b) Less popular control design methods.

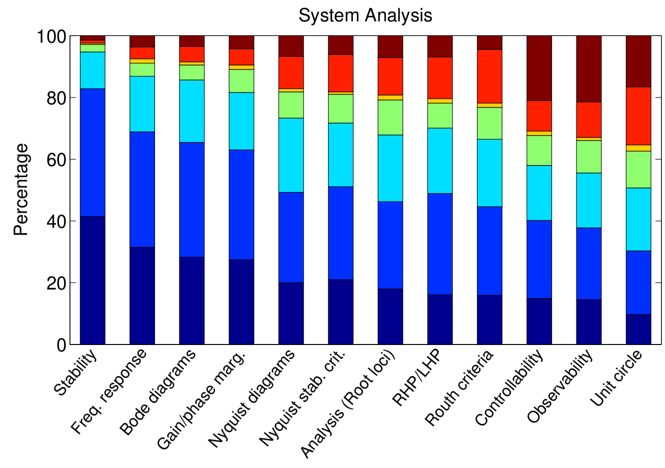
Fig. 18. Relative popularity of design tools in the survey.



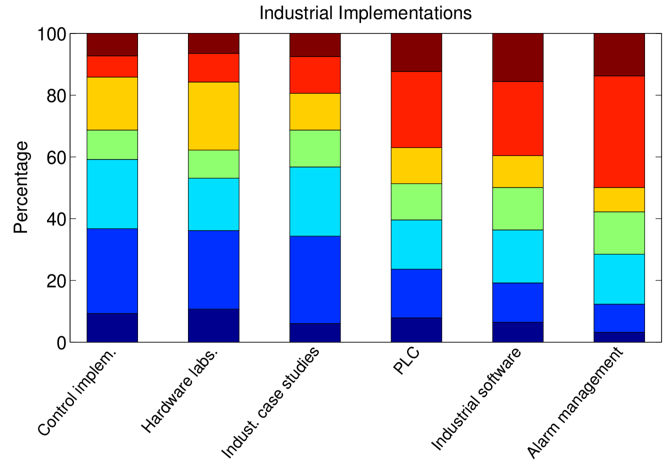
(a) Popularity of topics in modelling theme.



(b) Popularity of topics in signal processing.



(c) Popularity of topics in systems analysis.



(d) Popularity of topics in industrial implementations.

Fig. 19. Relative popularity of different topics by theme for a 1st course in control.

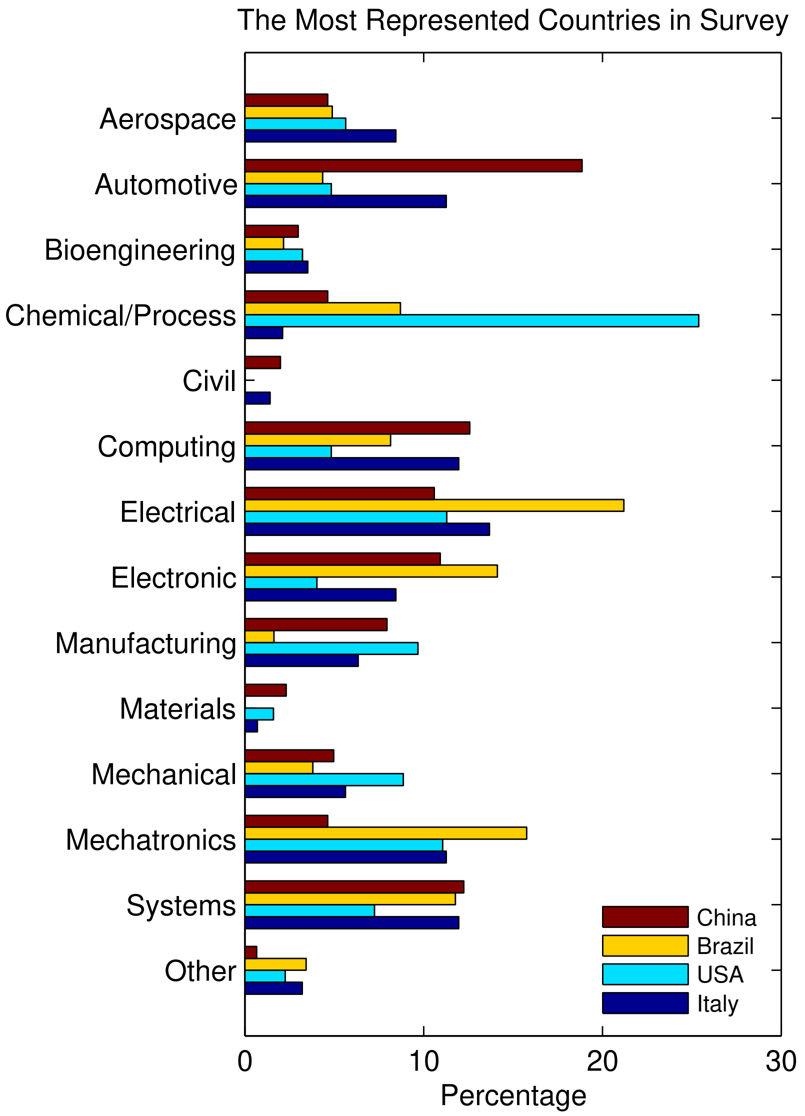


Fig. 20. Fields of application for the responders from the top four most represented countries in the survey.

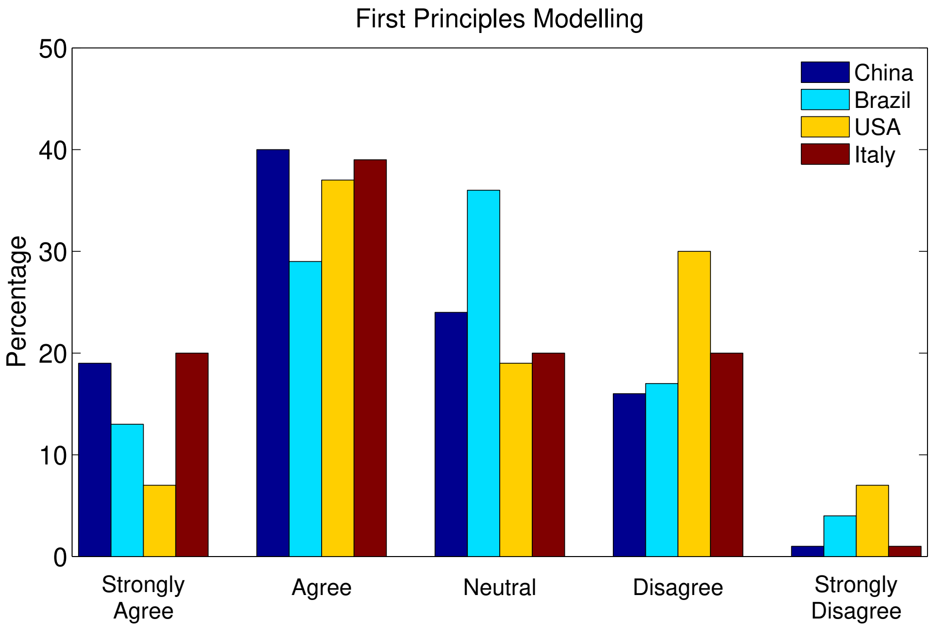


Fig. 21. Responses to the first principles modelling general question by the top four most represented countries.

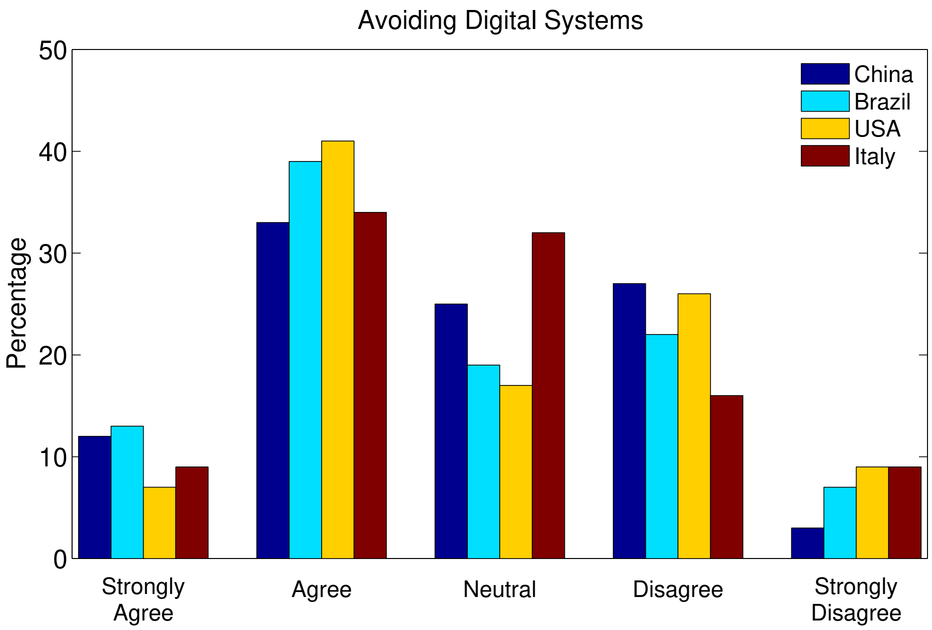


Fig. 22. Responses to the avoiding digital systems question by the top four most represented countries.

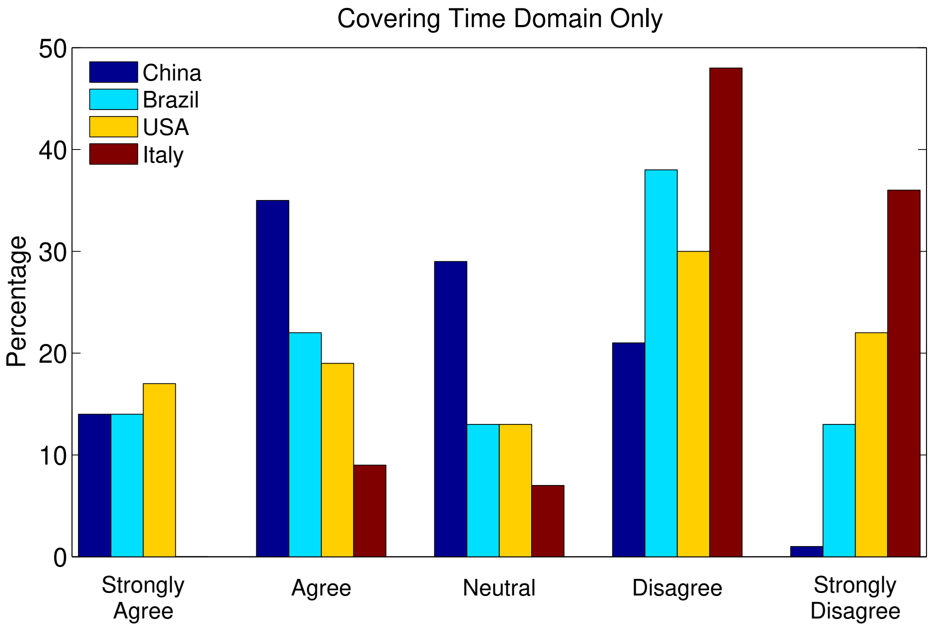


Fig. 23. Responses to the time domain only question by the top four most represented countries.