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Challenges for Control Engineering Curricula: Motivating 800 Students via Current Trends in Industry and Research

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Abstract: This paper presents new teaching curricula developments for Control engineering based on current challenges in industry and research. A major change has been proposed for the core module on *Control Theory* taught at CentraleSupélec for 800 students. The new syllabus is based on the state-space representation of multivariable systems, thus including state-feedback control based on pole placement, Linear Quadratic (LQ) control, together with observers (i.e. Luenberger observer, Kalman filter). Performance and robustness analysis tools are proposed both for monovariable and multivariable systems. A balance between theoretical and practical training, together with the current issues and open problems in Control are the main key points of this new Control course. Feedback and lessons learned are provided in this paper.

Keywords: Control education, Challenges for control engineering curricula, Teaching curricula developments for control and other engineers, Balance issues of theoretical-versus-practical training, Control education using laboratory equipment.

1. INTRODUCTION

Following the discussions during the IFAC Technical Committee 9.4 meetings in the last years (EDCOM (2022), Panel Session "The control curriculum for the 21st century" (2018)), one major concern of the Control Education community is what should be the syllabus of a first Control course (Rossiter et al. (2019), Vásquez et al. (2019)). Great efforts have been invested in this direction: several surveys (EDCOM (2022)), repositories for useful Control resources (Serbezov et al. (2022), Douglas (2022)), overview and future trends analysis (Muñoz de la Peña et al. (2022)), etc. Adapting the pedagogy, using practical experiments (*onsite platforms*, e.g. Bucher et al. (2022), Turnwald et al. (2017), Fehér et al. (2020), Siguerdidjane and Sordi (2020), Stoica Maniu et al. (2019b) and *virtual & remote platforms*, e.g. Peregudin et al. (2022), Fabregas et al. (2017)), following the new trends in Control, using popularizing methods (Douglas (2018)) are some of the tools used to motivate students to better learn Control (Rossiter (2017)).

Ensuing the 2019 survey (Rossiter et al. (2020, 2019)), 74% of the participants agree that a first Control course should focus on transfer function approaches. The opinions are mitigated with respect to using the state-space (or first principles modelling) framework and avoiding to reference

to the frequency domain. Indeed, 45% of the participants agree, 30% disagree and 25% are neutral with respect to a first Control course focused on state-space representations (Rossiter et al. (2020)). In addition, 25% of the participants agree and 50% disagree that first Control course should be devoted to time-domain and avoid referencing to frequency domain. An in-depth analysis of these opinions with respect to the different factors (Shanghai ranking of the universities, country/region of responders, heterogeneity and origin of the students, number of students following a first Control course, etc.) is an interesting point to be considered in the future.

In this context, CentraleSupélec¹ proposed from 2019 to 2021 a core teaching module on *Automatic Control* for the 800 second-year students. This course was mainly based on the transfer function framework and the frequency approach for monovariable systems, mainly focus-

¹ CentraleSupélec is one of the most distinguished French graduate engineering schools, called "Grandes Ecoles". It was created in 2015, by strategically merging two prestigious French "Grandes Ecoles": École Centrale Paris and Supélec. CentraleSupélec has a three-year curriculum (Jankovic et al. (2019)), preceded by two intensive years of higher education in the so-called "Classes préparatoires". Until 2018, the curricula of the two founding schools co-existed, and from 2018-2019 the new curriculum of CentraleSupélec was introduced progressively.

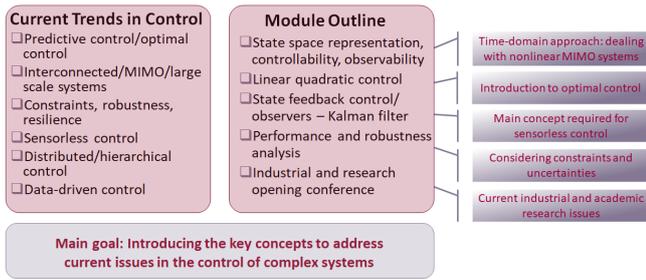


Fig. 1. Current trends and outline of the teaching module

ing on proportional, PI and PID, phase-lead and feedforward controllers. Even if this teaching module was well appreciated by approximatively 80% of the students, it did not render them enthusiastic about Control and few of them pursued in Control Engineering during their third year specialization. Indeed, there was a certain redundancy with notions (e.g. PID control) learned by a large part of the students before coming at CentraleSupélec.

In 2022, the pedagogical team proposed a new core course called *Control Theory* in order to better highlight the advantages of Control of complex systems and, thus, to motivate students to pursuit within Control Engineering. First, the content was adapted to current trends in Control in order to provide them the tools necessary to control and analyse complex systems (see Fig. 1). The state-space framework was used to deal with non linear systems linearized around an equilibrium point, to analyze the open-loop stability and performance and then to design state-feedback control laws (pole placement, LQ control) in a multivariable context. Observers (i.e. Luenberger observer, Kalman filter) were also studied. Performance and robustness analysis tools were proposed both for monovariable (SISO - Single Input Single Output) and multivariable (MIMO - Multiple Input Multiple Output) systems. Second, a good balance between theory and practice was settled, and each student experienced 6h laboratory practice. Applications (in healthcare, transportation, energy, sustainable development, etc.) were chosen in line with the interest² of the students. One novelty of this new course taught for 800 students is the illustration of theoretical concepts via current industrial issues, practical applications and open problems in Control, within an interactive module. An industrial and research opening conference was proposed to the students and the discussed topics were graphically live illustrated by a professional press cartoonist.

The remaining of this paper is organized as follows. A description of the syllabus, together with the topics presented during the teaching activities are detailed in Section 2. Then, Section 3 focuses on the organizing procedures, while Section 4 describes the assessment process. Some feedback and lessons learned are commented in Section 5, while concluding remarks are given in Section 6.

² The students expressed their interest via a survey (see Stoica Maniu et al. (2022)) at the end of the first-year course on *Model Representations and Analysis*.

2. SCIENTIFIC FOCUS

The general objective of the *Control Theory* course is to design control laws for complex dynamical systems to meet the required specifications and to analyze the performance and robustness. To achieve this goal, in a first step, the students have to be able to develop a model (or a set of models), highlighting the inputs influencing the state of this model and the outputs. Then, in a second step, and from the analysis of the inputs (control signals, disturbances), the students have to design a control law in order to ensure the expected specifications. The last step of this course concerns the performance and robustness analysis of the proposed control laws. An overview of the *Control Theory* course is proposed below.

2.1 Lectures

All the first-year students of CentraleSupélec follow the core module on *Model Representations and Analysis* (Stoica Maniu et al. (2022, 2020, 2019a)), thus acquiring the main notions on system modeling (no control strategies are presented in the first year course). Indeed, the 1st year course on *Model Representations and Analysis* offers the prerequisites for the 2nd year core module on *Control Theory*, i.e. 1. State-space representations for nonlinear systems, linearization around an equilibrium point, stability analysis; 2. Transfer function framework (introducing basic concepts on Laplace and z transforms), stability analysis, frequency analysis (Bode diagram), time-domain analysis (impulse response, step response, pole/zero map), identifiability analysis, identification techniques. However, there are international students arriving at CentraleSupélec directly in the second year and some of them do not have the required prerequisites in system modeling. As a consequence, the *Control Theory* course recalls some notions of systems modeling with additional mathematical proofs (provided in the handout) for stability analysis.

The syllabus of this new Control core course presented during the 10 lectures of 1.5h each is the following:

- (1) **Introduction.** The course starts with current trends, open problems and applications in Control illustrating the interest of the closed-loop, the importance of controlling complex systems, the key notions of Control, the trade-off between stability, rapidity and accuracy. Several examples are proposed, e.g. autonomous intersection management, renewable energy sources, water management, robotics applications.
- (2) **State-space representation.** This chapter recalls the main notions of systems modeling in the state-space framework and focuses on the controllability and the observability properties. The examples in this chapter are related to water resources management.
- (3) **State feedback control law design.** First, state-feedback control by pole placement with reference tracking and disturbance rejection is taught. Second, Linear Quadratic (LQ) control laws are proposed, including the case of LQ control with integral action. Several examples such that control of magnetic levitation systems, airplane lateral control, Segway control are proposed to the students.

- (4) **Estimated state feedback control.** This chapter focuses on observer design by pole placement, as well as the Kalman filter, together with the Linear Quadratic Gaussian (LQG) control. Applications on magnetic levitation systems and on marine population are presented, together with open problems in state-estimation of complex systems (communication systems, navigation systems, sensor fusion, etc.).
- (5) **Performance and robustness analysis of a control law.** Firstly, this part proposes some tools and basic concepts (link between linear state-space representation and transfer function/matrix framework, open-loop/closed-loop notions, norms, gains). Secondly, robustness analysis tools are presented: MIMO stability margins (special case of SISO stability margins based on the Nyquist stability criterion), robustness analysis via the small gain theorem. The robustness of LQ and LQG controllers is also analyzed. An application on the inverted pendulum is proposed.

During the lectures, several interactive quizzes using Wooclap (Lebbe and Alzetta (2015)) were proposed to the students. Several videos from Douglas (2022), Rossiter (2020), together with the *Map of Control* Douglas (2018) were indicated to the students in order to deepen their understanding. The main Matlab functions allowing to implement the theoretical notions were also suggested during lectures in order to facilitate the implementations during tutorials and lab work.

2.2 Tutorials

Four tutorials were proposed to the students:

- (1) **Workclass 1** (1.5h) on closed-loop brain stimulation. The goal of this tutorial is to design a state feedback law for a closed-loop deep brain stimulation, based on a simplified model of the involved neuronal dynamics.
- (2) **Workclass 2** (3h) on active control of a flexible mechanical system. The goal of this tutorial is to design LQ and LQI controllers for a mass-spring system and an anti-seismic system.
- (3) **Workclass 3** (3h) on MIMO control of a variable speed wind turbine. The aim of this tutorial is to design a state observer and a Kalman estimator for variable-speed wind turbines control.
- (4) **Workclass 4** (3h) on performance and robustness analysis of a hybrid automotive powertrain. This tutorial proposes an in-depth performance and robustness analysis of a control law of a hybrid powertrain, with a focus on multivariable margins analysis.

Matlab³ was also used during tutorials in order to better illustrate the results and to allow a better comprehension of the concepts. Indeed, basic Matlab functions for Control (e.g. `place`, `lqr`) are used.

2.3 Laboratory Practice

Two sessions of lab work of 3h each by randomly created groups of three students were carried out. Each group studied one topic among the following:

- (1) Control of a rotational inverted pendulum (Fig. 2);
- (2) Modelling and control of an overhead crane;
- (3) Helicopter tilt control (Fig. 2);
- (4) Position servoing;
- (5) Velocity control of an electromechanical chain.

All the subjects of the laboratory works involve implementation using Matlab on an experimental platform. For the sake of consistency of the teaching activities, all the laboratory works are built upon the same structure, i.e. system modeling, parameters identification, state feedback control via pole placement, LQ/LQI control depending on the experimental platform, additional observer design for the proposed LQ/LQI control, robustness analysis of the proposed control structure (with a specific focus on gain margin, phase margin for SISO systems). A detailed written report must be provided by each group of students after the second session of 3h of lab work.

2.4 Industrial and Research Opening Conference

As part of the *Control Theory* course, a 1.5h conference (panel session format) has been organized for the students. The panel was composed of three experts in Control (two industrial researchers and one academic researcher) and a press cartoonist who drew live and displayed his cartoons (e.g. Fig. 3-4) during the conference. The experts presented (in 20min each) their background and their vision on open and current issues in Control. The presentations were followed by a panel discussion. The students were enthusiastic about the conference and they asked numerous questions about Control versus Artificial Intelligence (AI), control of non-linear systems, links between Mathematics and Control Theory, future academic research possibilities (inline with a PhD thesis perspective) in Control, etc.

3. ORGANIZING PROCEDURES

There are 36 on-site hours for the *Control Theory* course: 15h of lectures, 10.5h of tutorials, 1.5h of conference, 6h of laboratory practice (i.e. 2 sessions of lab work of 3h each, involving measurements and implementations on experimental platforms), and 3h of written exam for an estimated total student workload of 60h.



Fig. 2. Example of experimental platforms: Quanser QUBE™-Servo 2 (left) and Quanser Aero 2 (right)

³ During the first year *Model Representations and Analysis* course, all the students completed the Matlab Onramp training.

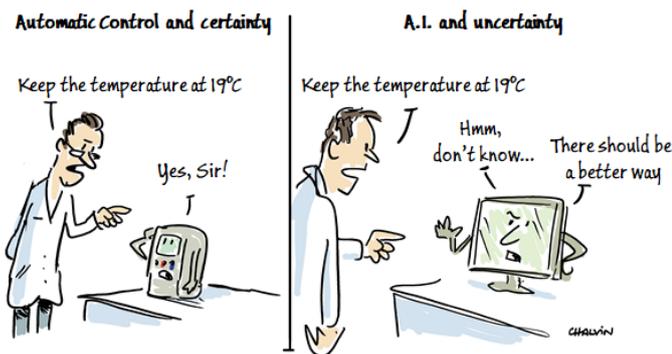


Fig. 3. *Automatic Control versus AI* by Marc Chalvin



Fig. 4. *Non-linear systems illustration* by Marc Chalvin

The approx. 800 second-year students from the Saclay campus of CentraleSupélec are regrouped in seven pathways⁴ (six French pathways and one English pathway) for 2 half-classes. There are about 35 students per tutorial group and 14 persons teaching the tutorials. Regarding the laboratory work, there are mainly 4 (occasionally 5) groups of three students in one class, with a total of 281 groups of students implementing control laws on lab platforms using Matlab & Simulink (MATLAB (2018)). There are 12 persons supervising the lab work and 8 rooms equipped with the experimental platforms, with 35 lab groups working at the same time.

It is important that the students are aware of the advantages of this curriculum change and of the efforts made by the pedagogical team to set up this new course in a very short time. Therefore, at the beginning of the first lecture, the teachers explained the reasons of the major change of the syllabus, presented the learning outcomes, the requirements (e.g. mandatory presence during the lab works), the module structure, the available resources, the assessment process, etc.

⁴ Usually, a core course at CentraleSupélec is taught for eight pathways. This year, exceptionally seven pathways were constituted.

Taken into account pedagogical recommendations⁵, as well as timetable constraints⁶, this module has been sequenced as follows: 3 lectures (1.5h each), first tutorial, 2 lectures, second tutorial, 2 lectures, third tutorial, 3 lectures, conference and fourth tutorial. The first part of the lab work sessions started after the first tutorial, while the second part of the lab work sessions started after the third tutorial.

The resources (slides in French and English, French hand-out⁷, Control theory glossary French-English and English-French, several training exercises with correction, links to resources available on free access, Matlab document with the main functions for Control, etc.) were shared with the students on the Edunao platform (Edunao (2014)).

4. ASSESSMENT

An alignment between the learning outcomes, the teaching activities and the assessment process is implemented for this module.

After completion of this course, the students are able to:

- (1) Understand and analyze the interest of a closed-loop control structure.
- (2) Model the behavior of a dynamic system: 1. design a state-space representation or possibly a transfer function/matrix for a given system; 2. choose a model (or a set of models) suitable to the control and/or the analysis objective (linearization, model reduction, etc.); 3. validate the relevance of the (set of) model(s).
- (3) Design control laws in a state-space framework (if necessary, by the synthesis of an observer): 1. analyze the characteristics of the initial system and compare them to the required specifications; 2. choose and design the appropriate control law; 3. determine an observer allowing to estimate the unmeasured state variables; 4. validate (in simulation and experimentally) the control law; 5. analyze the performance and robustness of control law.
- (4) Use simulation software to implement theoretical developments and validate control laws (particularly through experimental work).
- (5) Master scientific and technical communication (via the report of lab work).

Both knowledge and skills assessment are accomplished for this core module. The knowledge assessment involves lab work (25%) and written exam (75%). The lab works (which are mandatory activities) are evaluated by group (not individually) via a report submitted after the completion of the 6h laboratory practice. The written exam is individual, with calculator and all documents authorized.

Between the nine skills⁸ evaluated in the entire curriculum of CentraleSupélec, two skills are assessed during the

⁵ Pedagogical training sessions are often proposed in Université Paris-Saclay and CentraleSupélec.

⁶ The theoretical notions have to be taught during lectures and tutorials, before applying them during the lab work.

⁷ An English version of the handout will be provided to the students in the future.

⁸ Details on the nine skills are provided at <https://www.centralesupelec.fr/en/engineering-curriculum>.

Control Theory course by means of the lab work and final exam:

- (1) Skill C1 “Analyze, design and build complex systems with scientific, technological, human and economic components”, with the sub-skills:
 - C1.1 “Study a problem as a whole and an overall situation. Identify, formulate and analyze a problem in its scientific, economic and human dimensions”;
 - C1.2 “Use and develop appropriate models, choose the right modelling scale and the relevant simplifying assumptions to deal with a problem”;
 - C1.3 “Solve a problem by means of approximation, simulation and experiments”;
 - C1.4 “Specify, design, implement and validate all or part of a complex system”;
- (2) Skill C2 “Develop in-depth skills in an engineering field and in a family of professions”, with:
 - C2.2 “Importing knowledge from other fields or disciplines”;
 - C2.3 “Identify and independently acquire the required new knowledge and skills”;
 - C2.4 “Produce data and develop knowledge according to a scientific approach”.

All the tasks for validating these two competencies were explained by the teaching staff at the beginning of the first lecture. Skills C1 and C2 are evaluated (Pass/Failed format) in two different situations:

- The two lab work sessions enable evaluating the learning outcomes, the students having a real process to model, analyse and control. In particular, this pedagogical method allows students to experience experimental training and validation of the modelling and design approach.
- The written exam also confront students with a real problem of a process that should be modelled, analyzed and controlled. The emphasis is less on experimental aspects than on the ability to solve a Control problem through its specifications.

The Viatique platform (EXATECH (2017)) is used by the pedagogical team to assess the exam of the 800 students.

5. ANALYSIS

This section illustrates some insights of the implementation of this new Control course at CentraleSupélec, together with some feedback from students and colleagues.

5.1 Students Feedback

The students appreciated this new course and the efforts of the pedagogical team. Using the state-space framework allowed us to smooth the students’ heterogeneity. Students who learned control notions in a transfer function framework (e.g. P, PI, phase-lead control) during the so-called “Classes préparatoires” appreciated to study new Control notions based on the state-space representation, with an additional mathematical perspective. Students with a different background who did not study control before managed to understand the concepts using the state-space framework (the robustness analysis seemed more difficult to them).

After the completion of the course, a survey was sent to the students in order to collect their feedback about this course and an official meeting between the students’ representatives and the pedagogical team was organized. The results of this survey are summarized here: module global appreciation (78%), module goals understanding (85%), clarity of assessment process (93%), module management (81%), proposed teaching resources (86%), alignment assessment & content (90%), appropriate rhythm during lectures (78%), correlation between the scientific level of the course and the initial background of the students (78%), and appropriate number of tutorials/lab work (81%). Some comments of the students are further provided: “Very good course, well constructed, well calibrated, well explained”, “A real engineering course! In the continuity of the *Model Representation* course, with clear objectives and means”, “High quality provided resources”, “The teaching team is committed, motivated, dynamical and pedagogical”.

5.2 Lessons Learned

Most of the students of CentraleSupélec have an excellent background in Mathematics and the first year curricula offers reinforced mathematical concepts. Therefore, the new course on *Control Theory* proposes more in-depth theoretical notions in Control with respect to the previous course on *Automatic Control*. Analyzing the assessment results, this was not a difficulty for the students. In addition, despite the fact that the new syllabus could seem ambitious, the students of CentraleSupélec are used to assimilate a multitude of concepts.

The pedagogical team decided during the Spring of 2022 to propose in September 2022 a new core course, by considerably changing the syllabus of the previous course in control. The main constraints were related to the short time period. However, with a strong motivation and a considerable effort of the entire pedagogical team, this major change was made possible. A new handout (approx. 200 pages) was proposed to the students, each chapter being written by one or two persons. The tutorials, laboratory works and slides were also dispatched to several binomials in order to deal with the time constraints. However, difficulties were encountered with notations which were mainly uniform along each individual chapter and considerable efforts were necessary to standardize the notations in the entire course. The pedagogical team have appreciated the existing free resources in the open literature (e.g. Rossiter (2020), Douglas (2022), Douglas (2018)).

6. CONCLUSION

This paper reported the implementation of a new core course in Control (based on the state-space framework) for 800 students in the second year at CentraleSupélec. Current trends in industrial and academic research, together with a balanced syllabus between theory and applications are the key elements of this major change. An important element is the set-up of 6h laboratory work for 281 groups of 3 (and occasionally 2) students with implementation of control laws on an experimental platform.

Future work will mainly focus on analyzing the impact of this major Control curriculum change on the interest in Control Engineering of the students from CentraleSupélec.

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