An Interactive Control Engineering Course

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Abstract— In many engineering disciplines, feedback control systems is the general undergraduate control course. The control course is considered difficult, too theoretical, and even peripheral by the majority of undergraduate students. Since the control field does not have a specific focus area, it is not well-understood by students, engineers, and even academicians today. As a result control courses are in decline in some engineering departments and many small universities do not even include control engineering courses. However, control technology has advanced many engineering fields and offers sophisticated solutions for present scientific and technological systems. Therefore, this paper proposes an improvement of the general control engineering course syllabus to deal with current needs and to emphasize the crucial role of control in engineering education. The course develops the integration of lectures with labs and projects with an updated course syllabus, interactive design tools, project-based learning, and reverse engineering studies so that the general control engineering course can help students to develop useful skills with practical implementations.

Index Terms— control, course design, education, engineering education, laboratory design, project design, interactivity.

1 Introduction

The requirements for a successful career are in constant flux while the content of most of control engineering courses have stayed the same. To be successful in the 21st century, educators have to prepare students for careers and challenges of the advances in technological contexts and contemporary global problems by equipping them with suitable problem-identifying and solving skills. Many sophisticated software packages makes analysis and design faster and easier, which reduces the need for learning of classical tools. Automatic machines have also reduced the need for unskilled workers and raised demand for applied engineering skills. These new demands require a systematic approach to enhancing the effectiveness of control engineering education.

Feedback control has significantly enhanced and affected broad engineering areas, like electrical, mechanical, aerospace, and manufacturing, in over five decades [1]. Control engineering methods, algorithms, and tools are crucial in the design of high performance systems in these diverse branches of engineering. While the mathematical foundations of control systems are significant in engineering and have been funded over four decades, the recent research in the control field is moving towards application to challenges [1]–[4]. Well-prepared control engineers are in demand in the highly competitive global markets to tackle the challenges of continuous progress in technology, marketplace pressures, and increased system complexities. However, the majority of undergraduate students often consider control courses difficult, too theoretical, and even peripheral to their majors [5], [6]. Another problem is that industrial managers comment that many recent graduates do not have sufficient skills on problem definition, team work, and system engineering. The main reasons for these issues include: (a) Control systems courses' theoretical base and laboratories remain unchanged for 20-30 years, creating a disconnect between teachings and real-world demands [7]. (b) The industry aspects of control systems have been ignored in many universities due to the focus on theoretical foundations of control design. (c) Today the contributions of control theory are not fully appreciated outside of the control discipline because of the great diversity of control applications (i.e., there is no one working domain to be appreciated) [1], [8]. (d) The mathematical theory of control systems is important, but the control systems with complex dynamics and measurement uncertainties are not well-understood today [5], [9], [10]. (e) The accreditation sets, e.g. ABET and EUR-ACE label, reduce the number of major courses in the undergraduate degree programs, which results in only one introductory control course specifically in electrical engineering departments.

This paper proposes an improvement to the control engineering course syllabus to catch up with the current needs of global issues and to place control engineering courses into a crucial role in engineering education. This paper discusses the revitalization of the control engineering course for adapting to the fast changing needs of the society. A framework of integrated lectures with labs and projects with a new modern course context is provided. Some specific changes that we propose to improve control education can be listed as follows: (a) the required changes emphasize application rather than theory; (b) the engineering design cycle is incorporated into the control education with practical applications; (c) the multidisciplinary aspect of modeling and identification of the processes are included in the syllabus; (d) research trends are integrated into the undergraduate control course and lab; (e) the supervisory control concept is taught by using programmable logic controllers; (f) the easy-to-use, open-source and low-cost microcontroller based applications are included in the course through projects; and (g) the theoretical and practical contents are balanced with lecture, lab, and project triangle.

2 Planning the Control Course

Control engineering tools are needed in many areas from technology to economics, and control has played a crucial role in the development of technologies such as communications, power, manufacturing, and transportation [4]. The control field is seen as an interdisciplinary, mathematics-based, and information technology-based field [1], [6]. This means that there is no specific focus area of control, and thus control engineering is not well understood by many students and engineers today. As a result, control courses in electrical engineering departments are in low demand, and even many small universities do not include control engineering courses in their

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curriculum in recent years. The reduction of control courses is partially because of the accreditation systems, e.g. EUR-ACE label, which determine the number of major courses in the undergraduate engineering education. To renew the relevance of control engineering and make it understandable and attractive, there is a strong need for changes in control course planning.

The main changes in control education must be in the direction of increased practical applications with research projects. By considering current syllabus and textbooks, control systems education currently has a very narrow approach with a strong focus on mathematics of the controller synthesis [8]. The contexts of the textbooks are mainly composed of classical analysis and design methods. However, researchers rarely use such classical methods (e.g. root locus and Bode plot based control designs). While more than 90% of the process control systems in industry utilize PID controllers, it is given insufficient attention in textbooks and control syllabi. To improve control education, we have to emphasize the PID control design and tuning methods together with modern control tools in lectures. It is also necessary to have all the design cycle of a control system integrated with the engineering design process. Another significant topic is related to modeling and identification of processes to be controlled for accomplishing a satisfactory design of control systems [11]. As pointed out in [12], the common learning objectives for control laboratories must contain designing controllers, modeling systems, and connecting theory to practice. Hence, a comprehensive education in control systems must include effective laboratory experiments and must balance the theoretical and practical contents.

The proposed control systems course syllabus is provided in Table 1. The proposed syllabus offers practical solutions for making necessary changes in research methods and pedagogy that are cost effective and easier. This syllabus takes into account the improvement of the control engineering course to meet current global needs and to enhance the value of control engineering course in electrical engineering education. Topics addressed include the role of mathematics; the philosophy of engineering; the use of computer-based tools; the role of the industrial process control tools; practical aspects; project management; and intelligent control design. Modern data acquisition systems, lab equipment, and microcontrollers are incorporated into control engineering course. It is aimed to highlight the technological dimension of control, clarify control objectives, explain the physics behind the control law, analyze everyday control problem, and balance the theory and practice in the control education. One main goal is to improve the structure and content of the control course, and to recruit more students to study control engineering. The other main goal is to revitalize the control engineering course and adapt to the fast changing needs of society.

Model based design is gaining importance in industry [10], [11]. All major robotics, automotive, aerospace, and high-precision machinery companies are working on advanced engineering by applying model-based designs. As a result engineers equipped with sophisticated methods to deal with increasingly complex engineering problems are in high demand. Mathematical modeling and analysis now precede the development of actual systems and tests with the advent of powerful simulation tools, e.g. industry standard tools Matlab/Simulink, Labview, and others. For these reasons, the modeling lectures are strengthened with lab studies, i.e. HIL tests. The hands-on laboratory is designed to close the gap between industry and university education. Plenty of affordable off-the-shelf components, including Arduino and Lego, are easily accessible to implement (replicate) control studies in (from) the real world. We can extend teaching beyond the lab with project assignments to design many activities including open-ended problem solving and multi-disciplinary exercises.

Table 1: An integrated control course syllabus.

Topic	Lecture Description	Lab	Project
Intro (3 hours)	*Course description *Control examples *Future of control *Feedback definition *Control system classifications *Types of processes	**Basics of Engineering Design Process* **Class demos* -Arduino based modeling & control using Simulink	** Arduino designs* -Robot control -Home automation -Motor control -Dc-dc converter control -Vehicle control -System identification -etc. ** FPGA projects in Simulink / Labview* -Vehicle control -Robot control ** Small PLC applications* -Motor control -Temperature control -Level control -Conveyor control -etc.
Modeling (9 hours)	*Transfer functions *Block diagrams *State modeling -Electrical modeling -Mechanical modeling -Electromechanical modeling *Discretization	**Lab: DC motor* (2 hours) -Modeling -Data acquisition -Model validation	
Analysis (9 hours)	*Time response *Frequency response *Linearization *Stability analysis	**Lab: Rotary inverted pendulum* (2 hours) -Nonlinear modeling -Linearization -Stability analysis	
Design (18 hours)	*Design specifications *Control architectures *PID controller *State-feedback control *Optimal control basics *Fuzzy logic controller *Digital control basics *PLC basics *Implementation issues	**Lab: DC motor* (2 hours) -PI, PD, PID control **Lab: Rotary inverted pendulum* (2 hours) -State-feedback -LQR design **Lab: PLC* (2 hours) -PLC ladder programming -Discrete-event control	

One of the main focus areas of the course is the design of control systems. The course is taught in the fifth semester of Electrical and Mechanical Engineering departments. We offer significant content changes in favor of modern control approaches. The length of the classical control methods, including root loci and Bode diagrams based control designs are significantly reduced. The PID control, state feedback control, fuzzy control, optimal control, digital control and discrete-event control systems are emphasized in the lectures. Various

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process control architectures are also taught. To point out the industrial applications, a brief lecture on programmable logic controllers (PLCs) is given. The lab studies are provided for practical implementation of the control methods by dc motor control, rotary inverted pendulum control and PLC applications. The free-selective projects are designed by the student under instructor guidance to deal with different design implementations of control systems.

The other important instructional methods used in control course include online learning, class discussions, homework studies, web-based tutorials, quizzes and textbooks. There is a class discussion session every week to engage students and connect the control lectures with the real-world. To stimulate practice and deepen learning, homework problems include practical control designs from problem definition to simulation and evaluations. Homework is far more useful when students receive immediate feedback on their answers [13]. Students are encouraged to benefit from textbooks but no specific one is assigned because the control engineering textbooks mostly focus on classical control approaches with an extensive mathematical background. In addition, innovations in teaching such as the flipped classroom and service-learning [14] are integrated into the lectures and labs to improve the effectiveness of education. Students can learn basic concepts in the classroom or other digital sources and then apply their learning to the real world in the lab or project studies. This allows them to gain experiences based on team-based problem solving, deep case studies, and interactive hands-on lab activities.

The world is currently facing many challenges in energy, security, health, and environment that require practical engineering solutions for the short and long terms. Today's engineers must have knowledge that goes beyond theory to produce successful engineering solutions. Thus, laboratory directed education, research, and development are becoming more important to advance engineering training fit for real life demands [15]–[17]. The labs and projects are realized at Matlab/Simulink and LabView platforms, programmed with C/C++, VHDL and ladder programming languages.

2.1 Lab Development

The fundamental objectives of a control engineering laboratory should expose students to three knowledge domains: cognitive, psychomotor, and behavioral domains [16]. The cognition domain includes instrumentation, modeling, data acquisition, data verification and design. The psychomotor domain is related to the ability to manipulate an apparatus for selecting and operating suitable engineering devices (e.g., sensor and actuator selections). Lastly, the behavioral domain is related to students' teamwork abilities, learning from failure, communication, work ethics, safety, and creativity. All these objectives may not be necessary to generate efficient engineers who can understand and gain insight of the real world, but in general these are required for control engineers who have to work in a multidisciplinary environment.

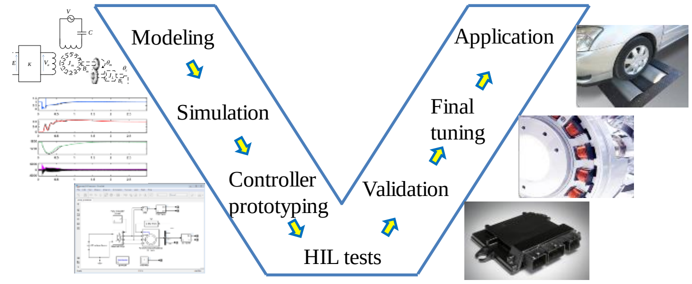

Fig 1. The V diagram representation of model-based designs.

Today, inexpensive off-the-shelf electronics and robotics components, e.g. Arduino and Lego based designs, are available for practical implementations. However, hobby electronics and robotics are not enough to tackle complex real-world problems because they are mostly designed based on trial-and-error. This problem can be solved with hardware in-the-loop (HIL) testing. A common expression of the V diagram of the model-based design process is shown in Fig. 1. It is composed of modeling, simulation, prototyping, HIL tests, model/control validation, final parameter tuning/optimization and real application studies [18]. The left side of the diagram represents mathematical theory and the right side of the diagram represents the outcome of theoretical works. HIL tests provide a systematic evaluation of subsystems such that the performance of models and actual hardware is evaluated with realistic configurations [19].

The objectives of control engineering instructional lab are exhaustive. To make the course successful and attractive, the lab objectives are matched with the course syllabus with appropriate experimental sets in our control course. The lab experiments are constructed from cost-effective and portable experimental sets. The lab systems are modeled, analyzed, and designed during the course so that students gain sufficient knowledge from experiments and their theoretical aspects before actually doing their lab studies. The specific dimension of the lab context includes realistic experimental test beds with integrated modeling and simulation studies. By considering the three knowledge domains, the objectives of lab correspond as follows:

- Understand the main elements of a control system, e.g., data acquisition, feedback and control algorithm synthesis;
- Understand and apply modeling, analysis and design concepts of the control theory;
- Connect controllers to sensors and actuators;
- Design basic PLC-based automation applications;
- Understand and apply engineering design process;
- Gain team-based problem solving.

The lab experiments that can be performed using training sets allow us to illustrate practical control concepts while providing extensive experience with control concepts, the effect of plant variations, and delays and nonlinearities by using interactive, open-source, and visual tools. Interactivity and graphical visualization of the lab studies makes the control course more attractive and accelerates the control engineering learning process for students. In lab experiments students also

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utilize the reverse engineering concept defined by the process of extracting information from the product itself [20]. Reverse engineering of hardware and software facilitates the learning of practical aspects of complex systems with less effort for students. To get enough knowledge to apply reverse engineering, the needed theoretical knowledge on the related experimental sets is first taught, followed by the experiments. All the lab hand-outs are made available through an online learning management system, i.e. Canvas, to facilitate teaching and learning. Each team is consisted of a team of two or three students to do the prelab assignments and experiments. The aim of having a small group is to allow each student to be able to have some hands-on experience with hardware and open-source software.

2.2 Project Development

Students must be equipped with systematic problem solving skills through engineering design process [21]. As described in Fig. 2, it guides engineering teams for solving problems systematically. It is clear that teamwork and design are key themes of the engineering design process. We have to teach and encourage students to follow the steps of the design process in order to improve their understanding of open-ended design and highlight creativity and practicality.

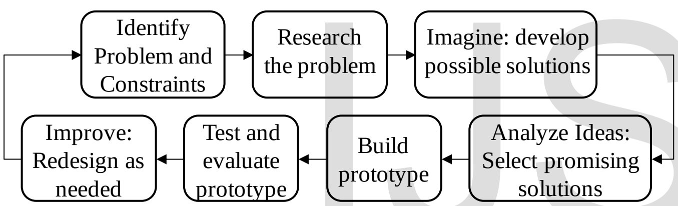

Fig. 2. The cyclic view of the engineering design process.

While the selected laboratory sets are suitable for project-based learning [22] and open-ended problem solving, it is important for students to have opportunities to get professional skills such as project management, research, and technical communication by designing their own projects. In the project design, the uses of feedback and control algorithm are the main requirements. The students are allowed to develop many different projects, mostly mobile robots, using microcontroller and FPGA based systems.

3 Experimental Results and Discussion

The lab and project has served as a learning tool to point out practical aspects of control systems. Some results that are obtained during lab practices are summarized below.

3.1 DC Motor Speed Control

Speed tracking error signal is evaluated with the following PI controller;

$$u = k_p(\omega_r - \omega) + k_i \int (\omega_r - \omega)dt \qquad (1)$$

where the reference speed ω_r (rad/s), proportional gain k_p (V·s/rad) and integral gain constant k_i (V/rad) are the controller parameters. To design control parameters of (1), by assuming that the electrical time constant $\tau_e = L_a/R_a$ is much smaller than the mechanical time constant of the system $\tau_m = JR_a/k_e^2$, the reduced-order dynamics can be written as $\omega(s)/u(s) = K/(\tau_m s + 1)$. The parameters of the model is obtained from the bump test as $K = 31$ (rad/V·s) and $\tau_m = 0.15$ (s). The bump (step) test based experimental setup is illustrated in Fig. 3, where students collect measurement data from the real system and then obtain the dc motor parameters for control design. The closed-loop system dynamics under PI controller is

$$\frac{\omega(s)}{\omega_r(s)} = \frac{K(k_p s + k_i)}{\tau_m s^2 + (Kk_p + 1)s + Kk_i} \qquad (2)$$

Now, the controller parameters can be designed from the characteristic equation of (2) via pole placement approach. An experimental result is given in Fig. 4.

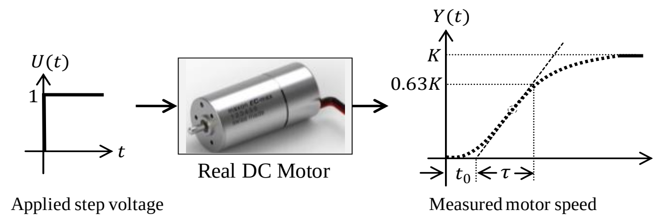

Fig. 3. Bump test to identify dc motor model parameters.

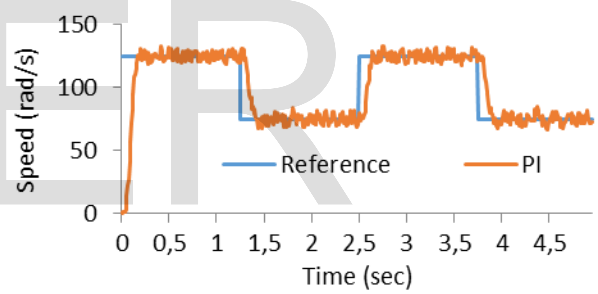

Fig. 4. Time response of the PI speed control.

3.2 DC Motor Position Control

In this lab, students experiment with PID controllers for the purpose of position control of the motor shaft. Position tracking error signal is evaluated with the PID controller;

$$u = k_p(\theta_r - \theta) + k_i \int (\theta_r - \theta)dt + k_d(\dot{\theta}_r - \dot{\theta}) \qquad (3)$$

where θ_r (rad) is the reference position, θ (rad) is the motor's position, k_p (V/rad) is the proportional gain, k_i (V/rad·s) is the integral gain and k_d (V·s/rad) is the derivative gain constant. By using the reduced-order DC motor dynamics for motor's position, the closed-loop system dynamics under PID controller can be written by

$$\frac{\theta(s)}{\theta_r(s)} = \frac{K(k_d s^2 + k_p s + k_i)}{\tau_m s^3 + (Kk_d + 1)s^2 + Kk_p s + Kk_i} \qquad (4)$$

The control parameters can be designed from the characteristic equation of (2) via pole placement approach. The experimental results are shown in Fig. 5.

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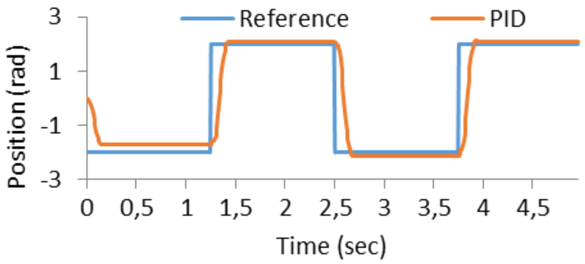

Figure 5: Time response of the PID position control.

3.3 Balance Control of the Rotary Inverted Pendulum

The goal is to design a stabilizing controller that balances the rotary inverted pendulum in the up-right position (Fig. 6).

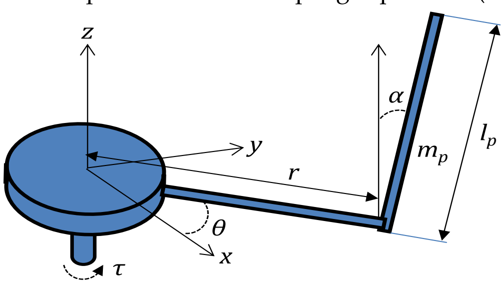

Fig. 6. Modeling the rotary inverted pendulum system.

The system dynamics by applying Lagrange-Euler equations can be obtained as

$$
\begin{aligned}
&J_{eq}\ddot{\theta} + m_p r^2 \ddot{\theta} - m_p L r \cos(\alpha)\ddot{\alpha} - m_p L r \sin(\alpha)\dot{\alpha} = \tau \\
&J_p \ddot{\alpha} + m_p L^2 \ddot{\alpha} - m_p L r \sin(\alpha)\dot{\theta} - m_p L r \cos(\alpha)\ddot{\theta} \\
&\qquad - m_p L r \sin(\alpha)\dot{\theta}\dot{\alpha} - m_p g L \sin(\alpha) = 0
\end{aligned} \quad (5)
$$

By linearizing the system around $\alpha = 0$, for the states $x = [\theta\ \alpha\ \dot{\theta}\ \dot{\alpha}]^t$, an unstable behavior is observed. Then, a state feedback control law is designed by $u = K(x_r - x)$ where the control gain is defined by K and the reference is taken as x_r. The control gain can be computed by using the LQR algorithm via the cost function

$$J = \int_0^{\infty} \left[(x_r - x)^T Q (x_r - x) + u^T R u \right] dt \quad (6)$$

For $Q = diag\{5,1,0,0\}$ and $R = 1$, the LQR algorithm finds the control gain as $K = [-2, 30, -2, -2.5]^T$.

First the pendulum manually brought close neighborhood of the linearization point and the effect of the linear controller was observed (Fig. 7). Then, initially a swing-up controller is implemented:

$$
\begin{cases}
u = \text{sat}\left(\mu(E_r - E)\text{sgn}(\dot{\alpha}\cos(\alpha))\right) \\
E = \frac{1}{2} J_p^* \dot{\alpha}^2 + m_p g L \cos(\alpha)
\end{cases} \quad (7)
$$

where μ is a control coefficient, E_r is the reference energy, J_p^* is the moment of inertia about the pendulums center of mass and E is the total energy of the pendulum. The application of swing-up controller allows students to get experience about nonlinear control and hybrid control concepts.

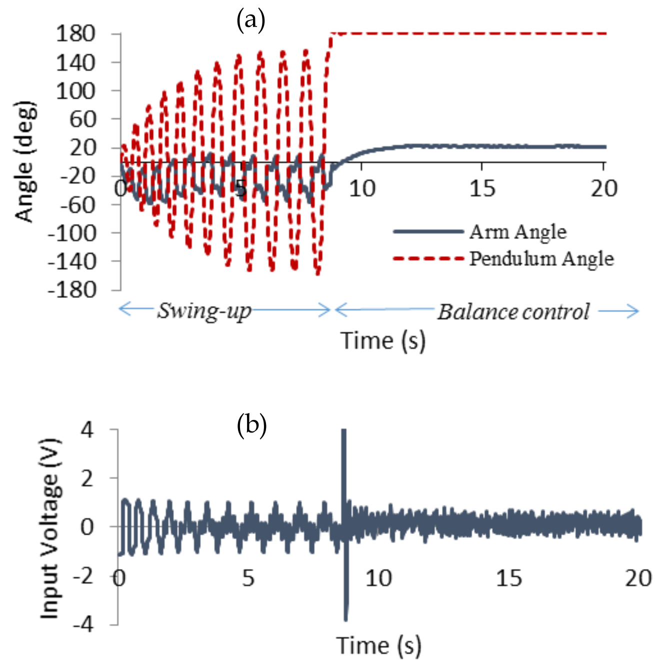

Fig. 7. Time responses of (a) balance control and (b) control voltage.

3.4 Discussions and Final Considerations

Student achievement, with respect to completed tasks, are evaluated to support assertions of instructional effectiveness. The learning objectives are assessed through exams, homework, quizzes, lab report, pre-lab questionnaire, project report, project demonstrations and group discussions. A discussion session was completed weekly and students had high interest in completing short quizzes and providing their ideas on course topics and real-world examples. Table 2 provides the mean grades of students who completed the required activities and tasks. These assessment results are positive overall which verifies the instructional effectiveness of the proposed control course. One interesting point is that at the end of some lectures, a question is asked to randomly assigned student groups and the winning team earned bonus points. This lead to high interest and created enjoyable moments for the course.

A student course evaluation survey distributed at the end of the course is used as evidence of teaching effectiveness. The survey and task evaluation results are used as evidence that the students achieved the learning outcomes. Table 3 presents the mean results from the course evaluation survey, which includes measures for different aspects of teaching and course usefulness. Overall 42 students are contributed to the survey. Each survey item is based on a 5-point Likert scale (1-strongly disagree to 5-strongly agree). Overall the students provide strongly affirmative results about the course. Course satisfaction and items regarding learning novel concepts are rated highly, with averages around 4.68.

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Table 2: Task evaluation.

Critical Learning Objectives	Tasks	Evaluation (Mean grades)
Understand and apply modeling, analysis and design concepts of the control theory	Homework, quizzes, exams	79.4%
Understand main elements of a control system, e.g., feedback and algorithm synthesis	Homework, project reports	89%
Connect controllers to sensors and actuators	Lab, project activities	92.6%
Design basic automation system	Lab reports	92.7%
Understand and apply engineering design process	Project report & demonstration	92.5%
Gain team-based problem solving	Project/lab activities, group discussions	93%

Table 3: Results of student survey.

Questions	Mean ratings (max. 5)
Q1. I am satisfied with the concepts covered in the feedback control course.	4.44
Q2. The concepts covered in the course are broad enough.	4.82
Q3. I gained oral and written communication of results from the course studies performed.	4.68
Q4. I found the introduction of the interactive control projects useful.	4.58
Q5. The simulation tools helped me to improve my theoretical knowledge of control problem solutions.	4.66
Q6. The simulation packages are helpful.	4.52
Q7. I think that the virtual control laboratory is user-friendly.	4.78
Q8. The experiment helped me to understand basic concepts of design and implementation of control engineering.	4.74
Q9. The experiment-based teaching helped me to get insight in real-time about hardware control components.	4.86
Q10. I learned how to use new software package.	4.96
Q11. The instructor was effective in helping me to learn course material.	4.84
Q12. The control design techniques covered are helpful for engineering design.	4.22

4 Conclusion

Parallel to research directions, the control education curriculum must have a significant shift from theory to application. This paper proposes an integrated control course syllabus consisting of lecture, lab, and project studies for electrical engineering education. The course is designed to develop skills in students by including lab and project studies, and computer control aspects such as digital techniques, intelligent control, and distributed control approaches. To make control engineering attractive to students and to enhance the role of control in engineering education, interactivity design tools, project-based learning, and reverse engineering studies can enhance control education. Since few engineering students become control engineers, the modeling, analysis and design aspects of feedback control systems are taught with the implication that control is one branch of applied science and engineering. The task evaluation and student survey show that the learning goals are successively achieved and the importance of the control course in engineering design process is well-understood.

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