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Digital Control Education, Engaging and Skill-Oriented ⋆

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Abstract: This paper presents the latest results of a methodology applied in 2023 to a group of Control Systems students. This course is included in the Bachelor's Degree in Electrical Engineering. The methodology was initiated with a group of graduate students enrolled in the Discrete Time Systems course in 2019. The methodology includes new learning methods, resources, and new student and educator roles. With emphasis on the academic approach and practical skills, hybrid learning and the creation of spaces for exchange and interaction between lecturer and students. It proposes activities such as virtual laboratory, assignments through mobile applications, self-managed lessons in Moodle and design of a digital controller that exposes students to real processes. The results showed that the methodology helped to integrate basic concepts of control systems and provided opportunities for students to improve their professional profiles.

Keywords: Control Engineering Education, Hybrid Learning, Competencies, Developing Countries.

1. INTRODUCTION

Teaching control engineering requires leading the students' learning process through a large amount of technical, scientific and technological content. But also providing opportunities to face interesting problems in which they must use their analytical thinking, research and communication skills to solve them. According to (Ye et al., 2009) the theoretical coverage of control systems is broad, but practical experience, implementation of control applications, and interesting real-world engineering lessons can be explored. Control engineering lessons unchanged for decades do not deliver what society needs. Control systems are critical to future technology in medical devices, renewable energy, transportation and much more (Muñoz de la Peña et al., 2022).

Students are expected to improve decision-making processes and accelerate the creation of new technologies. The education sector and pedagogy are also changing. Today, the role of the educator has shifted to that of mentor, collaborator and reference, while the role of the student is active, highly independent, and trained in soft and hard skills (Miranda et al., 2021). Therefore, engineering education should focus on developing students' innovative thinking and their ability to solve engineering problems through creative course design (Wu and Wu, 2020).

On one hand, the new generation has grown up using mainly online information sources, videos and social networks. An integrative approach to engineering education should emphasize the academic approach, foster practical skills and combine hybrid, face-to-face and virtual, but highly interactive learning. According to Statista Research Department, in a 2020 survey of Latin American higher education students, 42% of respondents indicated that they were satisfied with the online tools and resources available to them at the time. In addition, 38% of students said they were very satisfied with the tools available to them, while 16% said they were dissatisfied with them.

On the other hand, according to (Gomez-del Rio and Rodriguez, 2022) the most popular learning theory in educational technology is constructivism. Project-based learning is familiar in engineering education and has been used almost universally in laboratory courses (Gormaz-Lobos et al., 2020). The project-based learning method assigns students various problems to solve in teams. As stated by the psychology of knowledge, the model that integrates project-based learning processes considers students not as passive receivers but as builders of their own knowledge from previous experiences, available through active participation (de los Ríos et al., 2010).

The teaching of control systems during the pandemic and the rapid development of Generative Artificial Intelligence (AI) tools such as ChatGPT led to new innovative experiences and teaching tools. The authors of (Nikolic et al., 2023) evaluated the effect of AI tools on engineering education and recommended encouraging greater use of project-based learning experiences where solutions are unique and require specialized knowledge to explain.

This article takes the opportunity to present the latest results of a methodology applied in the second semester of 2023 in a group of the Control Systems course included in the Bachelor's Degree in Electrical Engineering. It seeks to motivate the teaching of continuous and discrete control systems for the study of concepts using software and

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industrial scale experiments, with a strong vision of the need to enhance the skills of young engineers.

The methodology of project-based learning is presented in two approaches: continuous and discrete time, and also in two different years of the career: bachelor (undergraduate) and licentiate (postgraduate). The methodology was nurtured by the use of mobile applications, interactive lessons, interesting projects needed to engage students in the learning process and an industry-driven approach to address the skill mismatches between industry and education.

2. METHODOLOGY

The first implementation of this methodology took place in 2013 with a group of the Discrete Time Systems graduate students. So far it is still being implemented with improvements and great feedback every semester. The results obtained in the Discrete Time Systems course are briefly discussed first, and then the results of the Control Systems 2023 course, which is the focus of this study.

2.1 Discrete Time Systems Course

Discrete Time systems course was in the first semester of the 1st year of the Electrical Engineering Licentiate degree at the University of Costa Rica. The course is equivalent to 192-hour per semester. With theoretical lessons of 64-hour and 12-hour of practical classes. The course started every semester with a group of 30 students and one lecturer. The total project experience included three lab sessions.

The main learning outcomes of this course are to experimentally apply the fundamentals of discrete time systems, the ability to apply engineering knowledge, and the ability to produce correct oral communication. Therefore, the main competencies are Problem analysis, Design and development of solutions, Research, Use of modern engineering tools, and Individual and team work.

Teaching by solving complex mathematical problems applied to simulated processes is very common. The control design assignment in the Discrete Time Systems course consisted of a simulation of discrete controllers such as Dahlin, Kalman filter, Deedbeat, digital Proportional-Integral-Derivative (PID), pole placements using Matlab. However, students generally perceived this subject as difficult and not generating the desired industrial skills. Students are becoming less and less interested in mathematically elegant approaches (Rossiter et al., 2023). To increase student's enthusiasm and boost their programming skills, a control design project was proposed. Experimental practice is vital for proper engineering education. Unfortunately, the acquisition of equipment entails an important economic cost (Lerma et al., 2019).

Project Lab of Digital Control The project of Digital control was divided into two activities: a controller design using Matlab and a real-time implementation.

The laboratory project presented was developed as a project-based learning activity, and involved collaborative work and interaction between team members. Therefore, it was based on the pedagogical theory of constructivism (hands-on and experiential learning in teams with other students and the educator) (Gomez-del Rio and Rodriguez, 2022).

The instructor required threes theoretical lessons: 1. Design of controllers and demonstrations of how to perform validations in Matlab. 2. The programming of the control algorithm in a microcontroller board. Arduino is a low-cost option and its programming is simple, which saves time explaining it in class. 3. An explanation of the operation of each part needed for the actual implementation. For instance, the interface between the plant and the microcontroller, the analog/digital and digital/analog converters, how to read the controller signal, the setpoint and the controlled signal. Moreover, an active filter was built to obtain the DC signal from the PWM output of the Arduino. All material was available in a virtual site called EIEVirtual. The instructor was responsible of choosing and identifying the model of a first or second order plant.

The recommended team size is three students. Each team designed the controllers using the model and tested it in Matlab. They met with the lecturer in class to validate the results; and proceed to improve the controllers. Then, the students created a program in C++ using the discrete time approximations for the controllers. Finally, they attend to test the design in two lab sessions with the instructor, who was in charge of setting up the equipment and downloading the student's program.

Experimental Procedure The project consisted in the design, implementation, tuning and testing of a digital PID controller using an Arduino. The following level control system was presented: "PID Process Control Trainer model 610" equipment (See Fig. 1). The process had the following FOPDT transfer function:

$$P(s) = \frac{9.22e^{-3.17s}}{34.31s + 1} \tag{1}$$

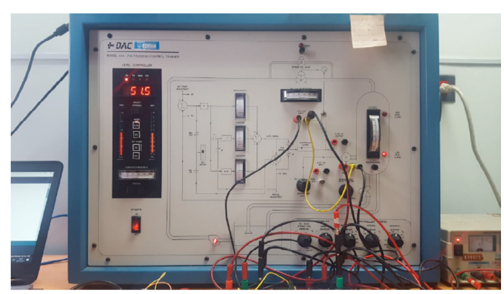

Fig. 1. Plant for level control

The project stages were:

(1) Controller Design
   (a) Students were required to investigate, implement and explain the methodology used to tune the PID controller, taking into account both the robustness and performance.
   (b) Analyze the result with simulations and the theory studied throughout the course (stability, Bode diagram, Maximum sensitivity (Ms), performance measures error (IAE), control effort variation or maximum value, among others)
(2) Programming
   (a) Program a PID algorithm and choose a sampling time. Produce the equation of the controller using

the velocity or incremental difference equation and solve for $\Delta u = u_k - u_{k-1}$.
   (b) The controller and plant inputs and outputs were to be connected according to the schematic provided.
   (c) The program was to have a manual and automatic mode operation.
   (d) An anti-wind up stage was to be implemented to limit the controller output signal.
(3) Plant Test
   The system was tested over two sessions with each team's tuning. They had the opportunity to repeat the plant test up to two times in each session, so they were be able to make changes. Also the instructor evaluated participation, the ability to explain the procedure and mastery of the topic, and provided feedback to the students. In the third and final lab session, each team presented their proof of concept.
(4) Communicating the Results
   The lab assessed oral and writing communications skills. Students had to write a comprehensive report explaining the research, design, testing, implementation, results and analysis, conclusions, references, and appendices. In the final session, a presentation of the work was compulsory, to be made by all team members, and each member was evaluated separately according to his o her performance.

2.2 Control Systems Course

The Control Systems course is located in the 4th year of the Bachelor's Degree in Electrical Engineering at the University of Costa Rica, that is, one year earlier in the curriculum, compared to the Discrete Time Systems course. Three groups of 30 students each were opened each semester, and a summer group of 30 students. Each group had a lecturer. The course was restructured in 2020 according to the needs of the country and a review of the topics suggested by the IFAC Education Committee, academia and industry.

The learning objective of this subject is that the student can analyze the fundamentals of feedback control systems, using techniques in the time and frequency domain and based on models to design feedback control systems, with the support of computational tools. The main competencies are Applying scientific, technological and instrumental concepts, Design and development of solutions, Research and Use of modern engineering tools.

The course had a final project and consisted in simulating feedback control loops using process models in Matlab. The students worked in teams virtually and created a video. However, it was difficult to interact with students in fully simulated classes where no physical equipment could be displayed.

Although the analytical thinking of graduates continues to be highly regarded, employers increasingly pointed out some shortcomings. Lack of proficiency in laboratory practices, as well as lack of communication and teamwork skills. These factors enhanced the process of transforming the typical theoretical course into a practical one.

The challenge was taken up and it proved difficult to run the labs, as the equipment would have to withstand the testing of 70 teams per year. However, the final methodology could always be used and successfully applied to courses with large groups.

The methodology consists of several stages: Interactive lecture, virtual experiment, assignment in mobile application, all individual and the final team project. The first two are laboratory activities in which virtual lessons are used and the lecturer supports the students' learning. This is the key factor of student engagement and enthusiasm (Rossiter et al., 2023). The pandemic has led us with a plethora of modalities and resources to enhance the learning experience. All the course material was available on the Moddle virtual site, common to all three groups.

Interactive Lesson First, the introduction of the PID controller was done through a self-managed class in Moodle, in which the concepts are introduced, and short videos with explanations and resolution of exercises are embedded. The lesson contained 10 pages where the students had to complete an evaluation before moving to next section. The lesson indicated the controller's function and structures and examples of micro and industrial controllers. Modes, control action and effort, anti-wind up, degrees of freedom and discrete time approximations were explained. The last part of the lesson introduced the microcontroller through a short video. It presents the Arduino platform, its programming and basic concepts. The topics of DA/C and AD/C and quantization error were also reviewed. Fig. 2 presents a page of the lesson.

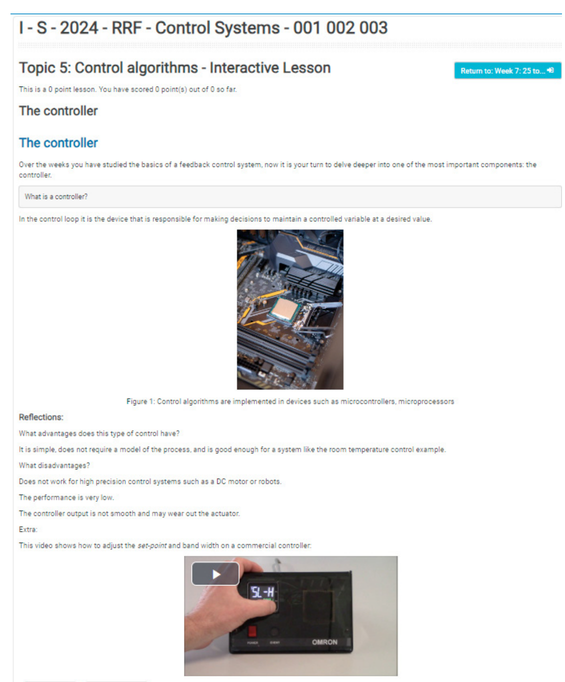

Fig. 2. Lesson in Moodle

The student was comfortable working directly online. It was a linear and graduated learning experience. The lesson had a path in which the learner could progress but also allowed to jump back to any page to review concepts. At the end, the student was evaluated in the knowledge learned. Examples of evaluation activities were a matching exercise of expected time responses according to the effect of varying controller modes, a multiple choice of controller action. There were also interesting exercises on prototype control systems for medical devices, where tuning was needed to meet performance requirements.

More importantly, the main concepts were briefly reviewed in the next class with the lecturer through a presentation.

Virtual Control Experiment The next stage was a virtual class to perform a experiment guided by the lecturer where each student had to solve a second-order RC circuit simulated in the Tinkercad online platform.

The student had to work a theoretical and practical part. First, they recognized the analytical equations of the electrical circuit. It simulated the behavior of a critically damped plant. The student obtained a model from the analytical equations. For the practical part, the student had to assemble the RC circuit in Tinkercad. They connected, in the virtual environment, the circuit on the breadboard as well as the oscilloscope to measure the output voltage of the capacitor. The student tested the circuit in a open loop and compared the response in the oscilloscope with the expected behavior.

Moving to the control system, the student connected the plant to an Arduino, and a signal generator to simulate the system's setpoint. Specifically a time-varying setpoint (a square signal) was applied to the input of the circuit and the Arduino. The experiment is shown in 3.

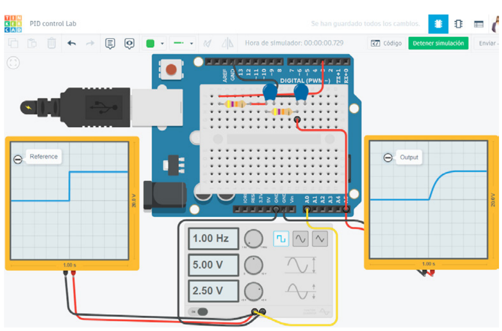

Fig. 3. RC circuit implementation

Next, the lecturer shared the program that implemented a feedback control loop with the digital PID controller. Explained the general structure of the code, linked the theory of the interactive lesson to the implementation of the resulting difference equation, analog/ digital conversion, lines of code to generate anti-wind up, etc. The student uploaded the program and changed the parameters in the controller using a standard PID algorithm and studied the responses.

Finally, there was a final review of the lesson on what they had learned and how they could apply it in an industrial scale.

Assignment in a Mobile App The widespread use of mobile devices has stimulated the creation of applications (Visioli, 2023). Students were tasked with performing PID tuning using Quanser's Aero aerospace experiment. The platform is illustrated in Fig. 4. Here to increase excitement and interest an aviation problem was exploited. Again, the Moodle platform was used to present the statement and questions. The task assessed the applications of basic PID control to the aerospace experiment. The student was required to perform tests on the mobile application and include screenshots of the results.

They practiced pitch angle control with a two-motor system, studied the effect of increasing or decreasing gain, integral time, derivative, steady state error, checked the stability of the system, studied the difference in the maximum values of the controller signal (voltage applied to motors) and the actual limits of the equipment.

The solution of the task was performed in a similar manner to the presentation of a quiz or exam where several multiple choice questions were presented. There were also essay questions in which they had to explain their reasoning and include pictures. The analysis had to be done by the person, and not with AI tools, so they were notified that tools would be used to detect plagiarism.

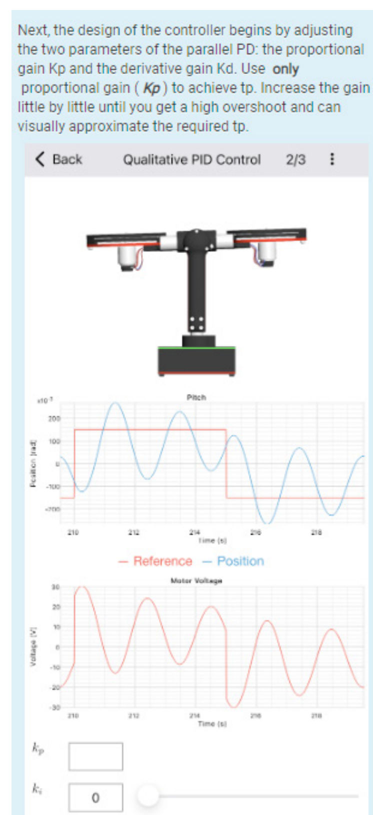

Fig. 4. Test for pitch control using the app

Lab Project The final project of the course is introduced as a digital control design lab. It consisted of two activities: a system identification and a controller design. Each was designed using Matlab and tested using the actual process. To do this, the instructor had to perform a test of the process, collect the experimental data and provide it to the students, create the electronics and interfaces needed to obtain real-time signals from the control loop.

The lab project involved teamwork. Teams of three students were selected. Each team developed the identification of a process model with the experimental data.

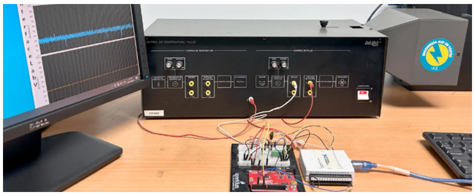

Fig. 5. Flow control process

They used identification methods as well as the Matlab Identification toolbox, which was studied in class. Each team was assigned a specific operating point, so the teams generated different results.

Students had to identify the best possible model and use it in the design of the feedback control system. The teams and the instructor met in class to validate the model. Then the students proceeded to design and evaluate the controller in Matlab. In addition, they selected the best one to be tested in the real-world plant. They attended to test the control design in two lab sessions with the professor in charge of assembling the equipment. The lab only required each team to indicate the control parameters of a standard PID controller. In each session the instructor asked the team members to explain their results, evaluating communications skills, understanding of the concepts and provided feedback to the students.

Experimental Procedure The process for the project corresponded to a Labvolt airflow control shown on the Fig. 5. The project stages were:

(1) Choose the type of operation servo or regulatory control.
(2) Check performance requirements.
(3) Find the best model.
(4) Investigate a tuning rule according to the requirements.
(5) Choose if derivative action is required, include filter.
(6) Tune the parameters of the PID control. Matlab Sisotool could be used as taught in class.
(7) Implementation the control loop using the PID's block. The PID autotuning tool could be used as long as the student explained the optimization behind it.
(8) Test in the lab and include the results, performance metrics and analysis.

Experimental results from a Control systems 2023 course team are showed in Fig. 6. An acquisition system was also implemented with a National Instruments card and graphical interface in LabVIEW to observe the signal response in real time. A serial plotter was also available in the Arduino. The controlled airflow is the output and the voltage applied to the fan motor is the input. Two changes were made in the slot on the duct where air was allowed to escape, and the effect of the disturbance could be seen in the chart.

The final proof of concept for each team was presented in the last session along with a final presentation performed by all team members. To assess communications skills, each member was evaluated separately based on their performance. The duration of the presentation was 10 minutes per team. The lecturer evaluated that: 1. The dynamics and characteristics of the controlled process were carefully analyzed. 2. All considerations or assumptions were clearly justified. 3. Additionally, the validity and benefits of the proposal were discussed.

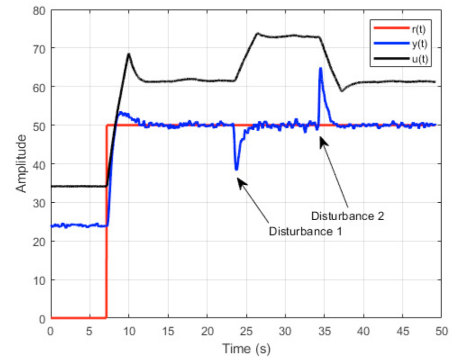

Fig. 6. Plant response to disturbances for flow control

3. ASSESSMENT OF THE PROJECTS OUTCOMES

First a qualitative assessment from the reports, and then the results from surveys sent to the students are presented.

The educator evaluated the advantages of the methodology by comparing previous experiences of teaching the courses. The laboratory work allowed students to handle devices, as well as to work in teams. It offered hands-on experience that could reinforce the concepts learned in the course. The use of videos was a great way for students to study at their own pace, and they liked that. Most important, the participation of the students in meetings with the lecturer achieved a 1:1 dialogue and a change in their participation and motivation. Among the competencies evaluated in the curriculum of the career, four were evaluated during the methodology: communication, problem solving, teamwork, and ability to apply knowledge to real implementations. Specifically, these are knowledge of modeling fundamentals, controller design, hardware and software implementation.

The experience helped to increase creativity, motivation, and intrigue about the real-world operation. Also to integrate important concepts: open loop vs. closed loop operation, setpoint vs. operating point, frequency vs. time analysis, understanding the limits of the real signals such as current and voltage. They learned to use modern Matlab tools such as Sisotool and Identification toolbox. Programming the controller and anti-wind up. This approach teaches students principles of software engineering, which they could apply to their future jobs and subsequent courses (Caeiro-Rodríguez et al., 2021).

3.1 *Discrete Time Systems course*

Engineering graduates of this new era must be able to move from technology to solutions and from solutions to operations (Gürdür Broo et al., 2022). The teams demonstrated their ability to analyze real application problems, such as the effect of sampling time, derivative mode, process nonlinearity and operating point. Students showed interest in tuning and improving performance by thinking about the non-reproducible values of the simulated controller output in Matlab. They benefited from understanding realistic problems in real implementations.

3.2 Control systems course

A comparison between the results before and after implementing the methodology are presented. First, at the end of the first semester of 2021, a survey was developed to evaluate whether the old project's objective had been met. A Likert scale from 1 to 5 was used. 18 responses were obtained from 30 students. 77% stated that the level of complexity of the project was difficult (4) or very difficult (5). The responses about the feasibility of working in teams virtually were very close. 55.56% agreed or strongly agreed and the rest disagreed.

At the end of the first semester of 2023, in the fourth iteration after implementing the new proposed methodology, another survey was sent to contemplate further improvements. 12 of the 30 students answered. 91.67% responded that the quality and feasibility of the project was very good or excellent.

After the completion of the courses in 2021 and 2023 an official survey from the University's evaluation office was also sent to the students. A Likert scale of 0-10 was used. All evaluation items improved from 2021 to 2023, for example the items: *Lecturer encouraged student participation in course activities* increased from 9.10 to 9.73. *Introduced activities that allow students to think critically, diversely and innovatively* from 8.84 to 9.59. *Lecturer used examples related to the future profession* from 9.15 to 9.95. *Proposed activities involving research* from 9.15 to 9.58.

4. CONCLUSIONS AND FUTURE WORK

The results showed that the methodology provided opportunities for undergraduate and graduate students to enhance their professional profiles through the practice of new skills in communication, problem solving and programming. The methodology explored and tested with great results a comprehensive learning experience using resources such as virtual lab, assignments using mobile applications, self-managed lessons in Moodle, and design of a digital controller exposing students to real processes. The methodology helped to integrate basic control system concepts. There were challenges in terms of the number of students, with 30 students per group it was required much organization and collaboration for the implementation of the laboratories, and the consistent follow-up to each person. Since the number of students who responded the surveys was low, it was suggested to schedule a space during class to complete the survey. Future work will be done to provide students with more industrial and professional synergy, and a final project using a micro-scale industrial process is underway.

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