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Building Small Prototypes in a PBL Intervention for Learning Automatic Control Systems*

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This paper introduces a Project-Based Learning (PBL) intervention for the learning of automatic control systems. This intervention explores the building of local platforms for experimentation as a learning trigger; an educational experience that covers two issues: (i) to encourage students to develop both engineering skills and transversal skills in an exemplary learning scenario, trying to face several challenges of control education, and (ii) to make an affordable experimental set-up for laboratory practices. The proposed PBL intervention, defined into a curricular alignment model, appears as an integrating solution that involves teaching, learning and evaluation activities, learning outcomes, learning spaces and staff in the building of small control plant prototypes, whose elaboration must meet design requirements, recreating a professional task. The results obtained from the students' feedback and teachers' observations show advantages including the application of previous knowledge and concepts from other areas, especially signals and electronics, practical experimentation, strengthening transversal skills, working with others, and the design of a plant prototype from a constructionist view. Nevertheless, participants commented that their workload increased considerably, and the tutoring results in a more demanding environment than in teacher-centred models.

Keywords: project-based learning; control education; learning by doing; engineering education

1. Introduction

Currently, control systems are a transversal area for many knowledge fields. To understand the impact of this subject on different fields and research areas, it is sufficient to see the Control Systems Society report about control technology [1], which shows how control engineering applications demand work from different disciplines and how real control problems need engineers who cross the boundaries of their engineering fields to understand new challenges, engineers who test not only their theoretical and technical skills but also their transversal skills, such as teamwork, decision making, problem-solving and communication abilities. In other words, practitioners who propose integral solutions to problems in real applications, where both the technical issues of the proposed solutions and their impact on the environment and society are important.

Usually, in engineering undergraduate programs, control education encompasses foundation courses dealing with the classical and modern control theories and elective advanced control courses, such as robust control, optimal control, nonlinear control and intelligent control, among others. In the paper [2] – considered as a seminal paper in control education – the authors stress the importance of knowing four basic concepts: (i) system dynamics, (ii) stability, (iii) feedback, and (iv) compensation, independent of the level or type of control course. According to [2], control education should "provide the basis for lifetime learning" to achieve high standards, keeping a balance between the theory and training.

Regarding this balance, the theory demands rigorous mathematical analysis, challenging some students, and the technical skill development demands the use of resources (hardware and software) to put theory into practice, challenging institutions in the acquisition of suitable laboratory equipment. Furthermore, the real context work also defines new requirements and constraints to professional training; here, transversal skills have become crucial, especially the cooperation with others. Therefore, finding a way to educate in control, beyond mathematical thinking and technical skills, is important for facilitating learning, improving academic performance and designing relevant solutions for the context problems.

Reference [3] presents a summary of challenges in control education, which is mainly devoted to seven issues: (i) balance between theory and practice [2]; (ii) satisfying industry needs [2, 4]; (iii) encouraging transversal skill development [5]; (iv) including web-based resources [6]; (v) the application to other engineering fields [7]; (vi) solving problems in an interdisciplinary way [7]; and (vii) perceiving K-12 education as a stage to encourage the control study [8]. The analysis of these issues keeps a

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research question open for control educators: how to face all control education challenges in control courses?

Facing most of these challenges in educational scenarios implies, first of all, the need to create exemplary learning experiences that encourage students to construct concepts and develop engineering and transversal skills, which could be seen as the first big challenge that summarizes other challenges, and secondly, to design resources to support these new learning scenarios, a second big challenge. An alternative to these two big challenges is to design or apply approaches centred on students since, in the student-centred approaches, "the construction of knowledge is shared, and learning is achieved through students' engagement with activities in which they are invested" [9]. This means that these kinds of approaches offer an exemplary and engaging scenario, in which students can learn with others managing their autonomy.

One of the student-centred approaches with remarkable results in engineering is Project-Based Learning (PBL). PBL emphasizes learning environments that simulate actual professional challenges, considering that professional engineering performance relies on developing projects for solving problems; PBL is an exemplary approach. Furthermore, PBL encourages active learning and stimulates students' self-motivation and self-confidence, among other aspects, which demonstrates its effectiveness [10].

Currently, there is extensive evidence of diverse nature and scope that demonstrates the advantages of PBL in education; some approaches are devoted to curricular models for a whole University, for example, those developed in the Republic Polytechnic (www.rp.edu.sg) in Singapore and Aalborg University https://www.en.aau.dk/ in Denmark. Others are oriented to a particular subject, such as signal processing [11], computation [12], industrial electronics and electrical power [13, 14], FPGA [15, 16], industrial informatics and robotics [17], aerospace engineering [18] or design of machinery [19]; or to specific purposes in engineering education, for example, approaches that combine other educational initiatives, such as CDIO with PBL [20], or approaches that focus on exploring cognitive aspects, as in the case presented in [21].

1.1 PBL in Control Education

In control education, there are also important experiences of using PBL as an educational approach, many of which match partially or totally with the 'PBL alignment of elements in the curriculum,' proposed in reference [22]. This alignment considers seven elements: (1) objectives and knowledge; (2) types of problems, projects and lectures; (3) progression, size and duration; (4) student learning; (5) academic staff and facilitation; (6) spaces and organization; and (7) evaluation and organization. This alignment model is seen as a holistic understanding; therefore, a change in one element can affect the others. Table 1 shows a preliminary classification of PBL contributions in control education. These contributions reveal that the use of projects in control is growing; the interest to adopt PBL as an approach is increasing, and its application or adoption is usually defined to create in-depth learning activities. Nevertheless, the discussion about how to create an exemplary scenario, from an aligned curricular perspective, remains open.

In an attempt to contribute to the generation of exemplary educational scenarios (first big challenge discussed above), this paper describes a PBL intervention for a control course immersed in a PBL approach (the UPTC-PBL approach) published in [3], that follows the PBL alignment model [22]. This approach corresponds to an Add-On strategy or mode 1 of PBL [29]. Starting from the research question, how does a prototype plant's construction serve as a learning trigger for linear control education? In the proposed PBL intervention, the authors explore "the design and building of a local platform for experimentation" – which can be seen, at the same time, as a problem, opportunity or need. The 'design and building of a local platform for experimentation' is defined as an 'exemplary learning experience' that encourages students to develop both engineering and transversal skills, focusing mainly on self-directed learning, team working and problem-solving. Moreover, in seeking to keep the exemplarity in its components, the authors highlight the importance of two alignment elements: (5) academic staff and facilitation, forming a team of teachers instead of assigning a single teacher per course, and (6) spaces and organization, using new learning spaces (#learningspacesuptc), in which laboratory practices and lectures can coexist in a unique scenario.

1.2 Learning Support Resources for Control Education

The learning resources in control education usually involve software or physical prototypes, commercially available by different companies as didactic equipment. These prototypes allow students to develop technical skills while putting theory into practice and enable students to work in a laboratory environment with industrial variables, such as velocity, pressure, position, liquid level, flow, etc., where students can directly observe the variables' behaviour by using instrumentation and define different setups to evaluate new control targets,

Table 1. Preliminary classification of PBL contributions in control education

PBL alignment's elements	
(1) objectives and knowledge	Reference [23] defines dimensions, information, abilities and attitudes, and categories: disciplinary, interdisciplinary, and personal; in [24], the authors use ABET criteria; and the work [5] considers transversal competencies as objectives.
(2) types of problems, projects and lectures	Reference [25] specifies problems; in [23], the authors propose to use structured units around a problem or a project; the contribution [24] bases on problems; reference [26] bases on projects; the work [5] centres on contextual problems and projects; and finally, in [27], the authors use projects.
(3) progression, size and duration	In [25], the authors show an experience that defines seven or eight problems per semester; in [24], the authors consider 48 hours per semester for project tasks; the contribution [26] proposes less lecture and more laboratories; and the work [5] establishes two semesters and rotation among student teams. Most of the contributions plan activities by using phases, stages or units, in which the time management and course schedule results are crucial.
(4) student learning	The work [26] includes transversal competencies (ethics, sustainability, etc.); the contribution [5] devotes to team working, problem-solving, self-learning and communication abilities; and in [27], the authors focus on autonomy and teamwork.
(5) academic staff and facilitation	In [25], the authors show the use of a website; the work [23] considers the use of a campus virtual (WebCT), prototypes, concept album and forum; in [24], the authors also includes a campus virtual and training stations, and this approach considers a teacher for laboratory; the contribution [28] presents a complete platform of different resources, like analysis tool, simulator and remote experimentation tools, and a repository for content; and in [5], the authors propose the use of didactic prototype plants, simulation, emulation and remote experimentation, and the approach considers a teacher for theory and another for the laboratory.
(6) spaces and organization	Most of the consulted works use traditional education spaces for the control education, which includes classrooms and laboratories.
(7) evaluation and organization	Reference [25] presents the application of peer-assessment and self-assessment (Rubric); in [23], the authors involve peer-assessment and self-assessment (a ranking and conceptual maps, among others); the work [26] considers portfolios, final reports, oral presentations and self-assessment; and the contribution [5] proposes peer-assessment and self-assessment.

and where manipulating and handling the equipment is essential. Although commercial platforms are suitable for control education, many teachers and researchers, concerned about the affordability and availability of laboratory resources, have proposed contributions to support learning in this area; most have emerged seeking to facilitate access to experimentation tools.

Some contributions centre on the design of physical experimentation platforms [30] or on virtual laboratories designed using Matlab [31], Matlab linked to Easy Java [32], Java [33] or Java scripts [34]. Other works use virtual instrumentation software, such as LabVIEW, to create user interfaces that command local physical platforms or remote platforms [35, 36]. Virtual laboratories based on emulation are also available; for example, in [37], authors present a learning resource that imposes limitations or constraints to real systems. Likewise, other proposals are devoted to reproducing industrial control characteristics, for example, by using PLC banks [38].

The design of educational resources for control seems to tend toward the development of platforms for remote experimentation on real plants, along with the promotion of sharing resources available in different places and the development of resources by collaboration networks [39], although other contributions focus on the development of low-cost prototypes [40], the use of well-known tools like Excel to analyse systems [41], technological tools such as FPGA [42], embedded control systems [43], or affordable platforms, like Arduino or Raspberry Pi, to implement controllers [44–46]

Moreover, there are contributions that stress on a special need for education, such as distance education [47] or STEM education [48]. This last contribution presents a TRIK tool that shows special features such as the versatility for tackling complex projects. The growth in use of embedded systems, specialized kits and low-cost electronic prototyping platforms shows that affordable laboratory resources for everybody are a trend in control education.

Regarding the second challenge related to the design of learning support resources for exemplar experiences, this paper proposes an integrated solution from the constructionist theory, which promotes technology to consolidate learning through constructing artefacts or real objects [49]. Thus, the proposed solution, centred on "the design and building of a local platform for experimentation", becomes an alternative for strengthening student learning and supporting resources for laboratory practices. Moreover, this proposal is focused to (i) improve the "handling" of actual equipment, (ii) make affordable an experimental setup for students, and (iii) define an exemplary experience into a PBL intervention considering different constraints. Likewise, the design requirements encourage students to build small and portable prototypes by using low-cost platforms and emerging technologies, like 3D printing and laser cutting, which, in turn, become new learning tools.

This PBL intervention is being applied in the system modelling (SM) courses that belong to the control area of the electronics engineering program at Universidad Pedagógica y Tecnológica de Colombia (UPTC), Sogamoso, Colombia.

The remainder of this paper is organized as follows: Section 2 describes the designed PBL intervention. Section 3 illustrates how the PBL intervention was applied, describing the learning activities and showing examples of students' prototypes. Section 4 is devoted to showing the results of the impact evaluation of PBL intervention upon a control course, the applied questionnaire, and a recompilation of the participants' impressions and observations made during the PBL experiences. Finally, the authors discuss some concluding remarks.

2. Project-Based Learning Intervention Design

The SM course is in the 7th semester and covers topics like transfer function, experimental models (step test) and state-space models, as well as some control design foundations, specifically PID tuning and state-space feedback. This course is characterized by using mathematical analyses and abstract conceptualization, which some students have difficulty with, many of whom have to take the course at least twice. Moreover, when students attempt to apply the concepts, they have many problems understanding how to use the knowledge in an actual problem; in particular, how to convert the mathematical model into an algorithm that can be implemented in a digital device (DPS, microcontroller, FPGA or microprocessor). In this semester, students discretise a model; however, they have many difficulties and doubts about the implementation of digital controllers. This is an important issue, considering that electronics engineers design, reconfigure or synthesize hardware based on models for solving problems, usually using digital technology.

2.1 Goals and Learning Outcomes

The main teaching goals for this PBL intervention are (i) to change the teaching practice, seeking more autonomy for students in their learning process and (ii) to design learning activities that engage students to understand more easily the concepts taught.

In addition, the goals related to learning are:

GOAL 1: To strengthen students' knowledge and skills of the SM course for implementing digital PID controllers.

GOAL 2: To promote transversal skills, especially problem-solving, collaborative and cooperative work among students, in order to facilitate the learning process and promote team working and communication abilities, especially for performing oral presentations and writing technical reports.

Teachers defined the following learning objective: "At the end of the course, students should be able to apply the theoretical knowledge in a practical exercise related to the design and implementation of a digital PID controller".

According to the course content and the expected skills, teachers defined the following learning outcomes (LO): at the end of the designed PBL intervention, students of the SM course should be able to:

LO1: Obtain a linear model using a step test, recognizing the difference between a first-order, second-order and FOTPD system.

LO2: Identify the difference between an analogue model and a digital model and the implications of their synthesis (actual electronics circuit).

LO3: Recognize constraints and potentialities of different models in the design and implementation of a control system.

LO4: Discretize a PID algorithm for its implementation in a digital device.

LO5: Present the results of the controller design process by using technical vocabulary.

The learning outcomes LO1 to LO4 are related to GOAL 1, and LO5 relates to GOAL 2.

2.2 General Outline for the Design of the Courses' Master Plan

For a PBL intervention, it is recommended that an outline for the course is defined beforehand, in terms of how, when and where the academic activities will occur. Fig. 1 shows the general framework for the PBL application in the SM course, which is a summary of the "Master Plan" that specifies teachers' and students' roles, stages and project progression, as well as teaching and learning activities.

2.3 Group Formation

Following the master plan, teachers define criteria for the group formation. Taking into account that students invest some money in the platform building, and that they have worked in groups previously (and, therefore, already have a partner), teachers defined that students choose another classmate for the grouping criterion of this specific PBL intervention; thus, forming teams of two students. Another important issue is the "teacher team", i.e., that

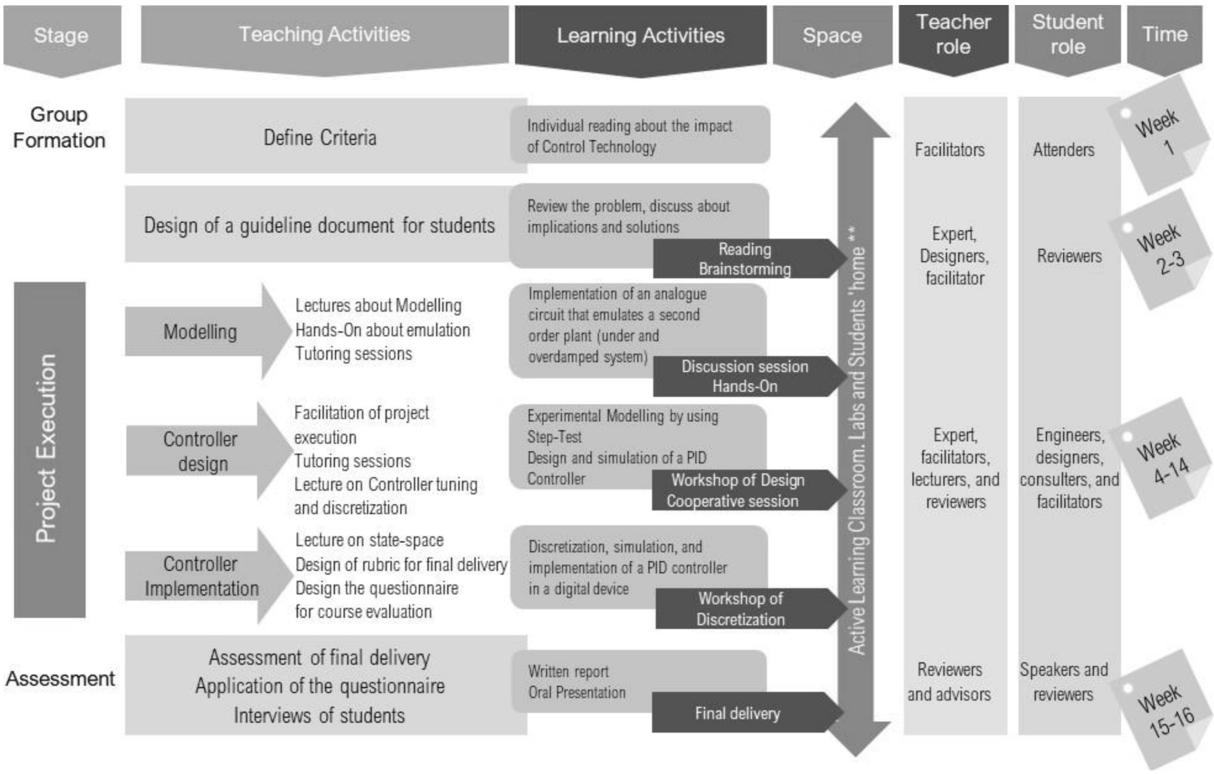


Fig. 1. Master plan for the SM course.

teachers work in a team; this is a crucial aspect in a PBL intervention to meet the "exemplarity" principle, to carefully design academic activities to stimulate the development of transversal competencies.

2.4 Problem Definition

Teachers define the "project", which aims "to design a digital PID controller for a home-made local platform and visualize the variables" behaviour by using a mobile device'. The modelling must consider both physical and experimental analysis. This problem considers the design of a digital PID controller because it is a usual task for electronics engineers in industrial automation. Moreover, the platform constraints are also important; therefore, teachers define the following platform requirements: (i) maximum size of the platform base: nine inches; (ii) type of variable: position and velocity; (iii) control strategy: PID controller; (iv) controller implementation: digital; and (v) visualization of variables on a mobile device (smartphone or tablet).

2.5 Size

This requirement is related to the use of the Active Learning Environments (ALE, #learningspace-suptc) so that students can work in a longer session than the usual two-hour teaching session; the session for the SM course considers four hours of work, which means that students can face major challenges compared to a traditional lecture. Likewise, the main idea is that students can have all the necessary resources in one place, so they do not need to move to the laboratory. Taking into account the learning furniture available in the ALE, and other devices needed to control the plant, teachers defined the size of the prototype base as nine inches (9″). As a result, the size of plant defines a portable small prototype.

2.5.1 Type of Variable

Regarding the didactic use of the local platform in the learning process, teachers considered the following to be important aspects: (i) using industrial variables and (ii) observing the variable performance in an easy way (to observe the variables' behaviour). Teachers then defined the use of plants that have rotational or translational movements, defining position and velocity as controlled variables because these variables are easier to measure, and sensors (potentiometers and encoders) and actuators (small motors) are affordable by students compared to other equipment.

2.5.2 PID Controller

Teachers chose the PID control strategy because it is the most used in industrial environments. Moreover, it is the most documented and studied strategy, both in terms of conceptual design and practical implementation.

2.5.3 Digital Implementation

This requirement responds to the tendency of the practical implementation of the actual controllers. Although the continuous analysis of controllers is still usual in control contents and could be suitable for understanding the design and synthesis of controllers, the new available platforms and devices force the use of digital technology.

2.5.4 User Interface

This requirement relates to the use of smartphones or tablets to visualize the behaviour of the variables, because most of the students had a device or the student team, at least, had a mobile device available. Moreover, the use of this kind of device is very motivating for the students, strengthening other engineering skills related to programming and computation.

2.6 Project Execution

The project considers three stages: (i) modelling, (ii) controller design, and (iii) controller implementation. In the electronics engineering program at UPTC, the SM course is developed over 16 weeks, two sections per week (labelled as S1 and S2 in the master plan), with each section being two hours long; as mentioned above, currently, both sessions are successive, resulting in a longer session in the ALE. This means that students can work directly with the teachers for 64 hours in a semester, via 12 lectures and advising meetings, 3 advance project deliveries and 1 final project delivery or academic fair.

2.7 Student Assessment and Course Evaluation

To assess student learning, teachers defined the assessment activities presented in Table 2. These include written reports and rubrics to assess the academic performance in terms of content and technical skills, as well as interviews, photos and participating observations to evaluate the course and assess transversal skills, which would mainly be cooperative work and communication abilities.

3. Developing The PBL Intervention

The implementation of the course was developed according to the master plan. Considering that the proposed PBL intervention was designed as an aligned activity, the activities of the project are related directly to the evaluation and student learning. Therefore, teachers define three kinds of learning activities: (i) hands-on and workshops and (ii) discussion and cooperative sessions and, as the last activity, (iii) the "final delivery", which is held at the end of the semester through an academic fair, in which students present their results to classmates and teachers.

3.1 Hands-on and Workshops

The first hands-on relates to the implementation of an analogue circuit that emulates a second-order plant as an underdamped system and an overdamped system. This hands-on was oriented from a guide, whose main objective was to enhance the comprehension of how to recreate a mathematical model from a physics implementation (in this instance, the circuit) and, vice versa, to understand that a mathematical model can describe physical behaviour. Later, students carried out the second activity (workshop 1), associated with experimentally modelling the plant using a step test, and designing and simulating a PID controller for the plant. Once the circuit was implemented, students analysed the system behaviour in the laboratory using simulation and tested the actual circuit. Likewise, students designed a controller for the implemented circuit and tested it in a simulation; the result obtained in this workshop was mandatory for the next one. The third activity was devoted to the

Table 2. Assessment activities for SM course

Assessment activity	What	When	How	Instruments	Focused on
Hands-on Workshops	Theoretical knowledge and technical skills	At the end of each workshop	Checking deliveries at the end of each workshop during project execution.	Written report	LO1 LO2
Final delivery	Fulfilment of requirements of the product Communication abilities	At the end of the project	Reviewing of controller design process	Rubric	LO3 LO4
			Student performance in oral presentations	Rubric	
Discussion and Cooperative sessions	Communication abilities and cooperative work	During the workshops	Observing the performance of students during the sessions	Photos, interviews teacher' observations	LO5

discretization, simulation and implementation of a PID controller in a digital device (workshop 2). Students obtained the discrete PID controller and programmed it in specialized software. They then implemented it on a digital device (Arduino or Microcontroller).

3.2 Discussion and Cooperative Sessions

In the discussion sessions, the SM course students participated with students from the control (CS) course. The main goal of this activity was for students from the CS course to support the SM course students' learning, allowing SM students to share doubts, expectations and possible solutions to problems with their peers. Teachers developed three discussion sections. The first was among students who developed the project, to discuss the issues and alternatives for the circuit implementation related to the hands-on activities. The second was among students of both courses, where the CS course students could ask about the project; this section sought to improve CS students' oral communication abilities, particularly as they must explain and argue to expert interlocutors. Finally, the last session was devoted to strengthening the cooperative work; thus, the CS course students shared their findings with SM course students through a common activity for both courses, in which the CS course students worked together with the SM course students in groups that were different from the project teams. This academic activity also allowed senior students to give feedback to the junior students about the process that they were carrying out in the project, based on their experience.

3.3 Final Delivery

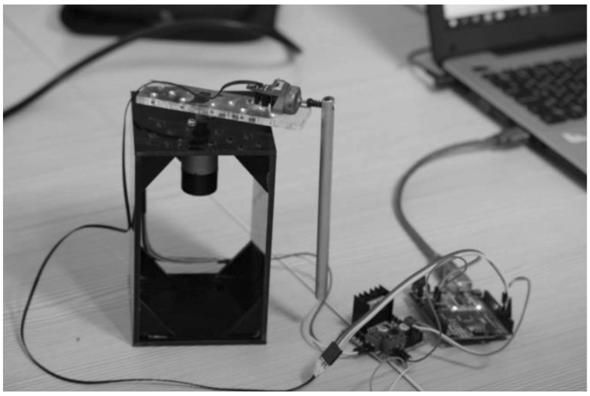
The final delivery is an academic fair, which is mainly focused on oral presentations. Students present their project results to their classmates, reviewers and other students who are interested in the exposed topic. Both SM and CS students participate in this delivery. Thus, presenter students have a real scenario in which to interact with others about their project execution. Students deliver their written reports prior to the fair so that reviewers can opportunely give their feedback. Below, the authors present examples of the final small prototypes that work as local experimentation platforms, evaluated at the academic fair of Semester II-2018.

3.4 Examples of Prototypes

During eight years of the UPTC-PBL approach, students have built more than 50 prototypes under the advice of their control teachers. Some of these correspond to prototypes inspired by regional challenges, such as a heater to counteract the effects of frost [50] and a mining ventilation prototype [51]. Others correspond to well-known case studies; students have built cranes [52], magnetic levitators, wind followers, pendulums, air levitators [53], tank systems, helicopters, incubators, ball and plates [54], and ball and beams, among others. These prototypes show several issues, variables, actuators and sensors. Each prototype results from the resourcefulness and creativity of students and teachers, who transform, adapt and change appliances and devices, and design new pieces and circuits to achieve the project goal. Herein, the authors describe some examples of prototypes resulting from the application of PBL intervention.

The ball and plate prototype, Fig. 2a, uses a piezo-resistive plate as a sensor; its structure consist of an axial terminal that facilitates the movement of the plate, and two servo motors to control the movement in x and y, respectively [54]. The second prototype (Fig. 2b) corresponds to a ball and wheel structure; for its design, students used laser cutting in acrylic and 3D printing for its structure, a DC motor as an actuator, and a radio-

Fig. 2. (a) Small prototype of ball and plate comprised by a piezo-resistive flat and two servomotors, its structure was made in acrylic (left), (b) Small prototype of ball and wheel, its structure was made by using 3D printing (right).



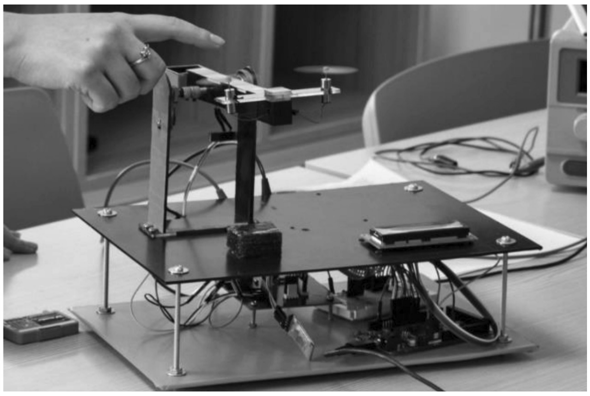


Fig. 3. (a) Small prototype of Furuta's pendulum, its structure was made in acrylic, and it uses a potentiometer as a sensor and a servomotor as an actuator, its pendulum is an aluminum bar (left), (b) Small prototype of a helicopter that uses two micromotors to action two mini propellers, it has a little box to put coins as disturbances (right).

frequency sensor for measuring the position of the ball [55].

For the prototype structure of Furuta's pendulum (Fig. 3a), students used laser cutting to shape acrylic pieces and a linear potentiometer as a sensor to measure the pendulum's position [56]. The helicopter prototype, shown in Fig. 3b, aims to control the vertical position of a beam using the thrust produced by two propellers, operating a one-degree-of-freedom system since the two propellers are commanded with the same control signal [57]. The model has a little box for coins, which works as a disturbance for the system, as the coin weight applies a load torque in the opposite direction to the propellers' thrust.

Finally, in the first didactical 2DOF helicopter model (see Fig. 4a, left), users can monitor the variable behaviour and define different set points using a didactic app. This helicopter model uses two propellers, placed at 90° from one another, to control yaw and pitch position [58]. For the second 2DOF helicopter prototype (see Fig. 4b, right), students used 3D printing. The shape of this helicopter makes it visually striking, especially for STEM education oriented to kids or outreach programs, and it uses two servo motors to control the yaw and pitch position [59].

All models used Arduino as a platform to synthesize the controller and have an app to monitor the behaviour of the variables; some prototypes additionally used data acquisition system (DAQ) of National Instruments. For oral presentations, students designed posters, slides and written reports; videos and photographic records also were shown. For Semester II-2018, five teachers visited the fair as reviewers, to understand and assess the students' learning performance. Control teachers revised the final reports taking into account the learning outcomes proposed for the course. Likewise, at the end of the assessment activities, teachers asked open questions relating to the PBL intervention, as an evaluation activity. These questions related to the students' impressions of the project execution, in terms of (i) advantages, (ii) disadvantages, (iii) self-

Fig. 4. Small prototypes of 2DOF helicopters comprised of two mini propellers, main and tail rotor, respectively; a) it is an ingenious model commanded by an App developed in Android (left) facilitating the interaction with the user, b) it corresponds to a prototype designed with striking shape for STEM education in K-12 courses (right).

Table 3. Questionnaire applied to UPTC students

TRANSVERSAL COMPETENCES *		LEARNING
Teamwork and cooperative work	QT1: The activity helps me to acquire skills for working in a team. QT2: The teacher orients my team in the solution of conflicts, problems and difficulties in a timely manner. QT3: I participated actively in team meetings. QT4: I lead and orient the activities developed by my team. QT5: I carried out the tasks assigned by my team. QT6: I helped to identify and to solve work difficulties in my team.	QL1: We achieved the learning objectives proposed for the project task. QL2: I can obtain the model of a system by using a step test. QL3: I can analyse the different interrelations of the time response of continuous and discrete systems. QL4: I can analyse the effect on the time response of the digital control system, due to sampling, rounding and computing delay. QL5: I can define the desired specifications for the time response of a system. QL6: I can identify the control actions by observing the behaviour of a system. QL7: I can design a PID controller by using experimental methods. QL8: I can obtain a discrete transfer function of a designed PID controller. QL9: I can obtain the control signal in the difference equation. QL10: I can implement the obtained difference equation on a digital platform. device (e.g., microcontroller, microprocessor, Arduino, FPGA or any other).
	QCP7: I advised other student teams.	
Self-learning	QS8: The course helps me to improve my self-learning. QS9: The teachers oriented students about how to search for information by themselves and how to use the learning resources. QS10: I consulted documents and additional references.	
Communication abilities	The developed activity – project task – helps me to acquire: QC11: Capability to communicate effectively with others. QC12: Capability to communicate with experts from other disciplines. QC13: Capability to write reports and respect the copyright. QC14: Capability to follow standards and templates. QC15: Capability to manage references and follow academic styles for citation. QC16: Capability to perform in an oral presentation. QC17: Capability to solve engineering problems.	

* T: Teamwork, CP: Cooperative, S: Self-learning and C: Communication abilities.

confidence to use the knowledge in other contexts (for example, in a company), and (iv) the solution of problems that involve the discretization of different controllers to those used in the project.

4. Discussion of Results and Student Feedback

To evaluate the impact of PBL intervention upon a control course, teachers designed a questionnaire. Table 3 shows the questions used in the questionnaire, which was applied to students at the end of the intervention. To analyse the results, queries were grouped into two aspects: the first, labelled "Transversal competences", relates to the development of self-learning, collaborative and cooperative work – the stage prior to teamwork – , and communication abilities, which are connected to LO5; the second aspect, labelled "Learning", relates to learning outcomes LO1–LO4. The statistics results correspond to the responses of students of semester I-2018.

4.1 Results for Transversal Competences (LO5)

In Fig. 5, the authors present the average obtained from scores given to queries by students, which are related to teamwork (QT1–QT6), cooperative work (QCP7), self-learning (QS8–QS10), and communication abilities (QC11–QC17). Likewise, Fig. 6 shows the results grouped according to students' scores, where a scale ranging from 1 to 5 was used. The score corresponds to 1: strongly disagree, 2: disagree, 3: neither agree nor disagree, 4: agree, and 5: strongly agree. In the questionnaire, teachers defined queries as statements.

Fifteen students responded to the questionnaire. The results show that students accepted the designed PBL intervention and considered that it

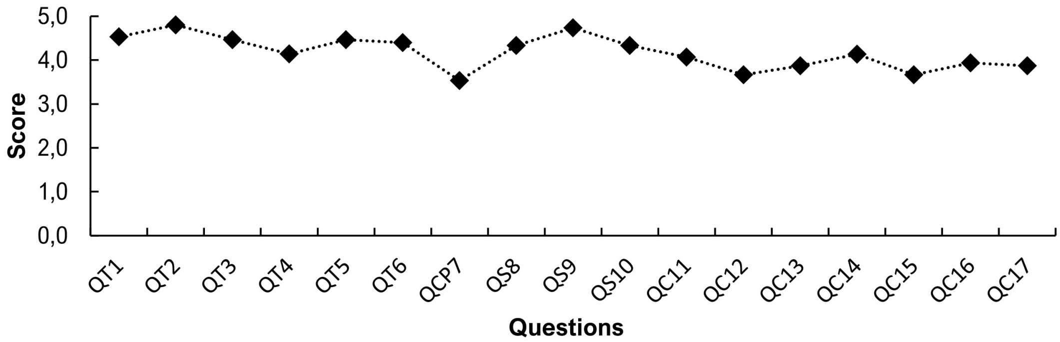


Fig. 5. Results of questionnaire applied to UPTC students (transversal competences),

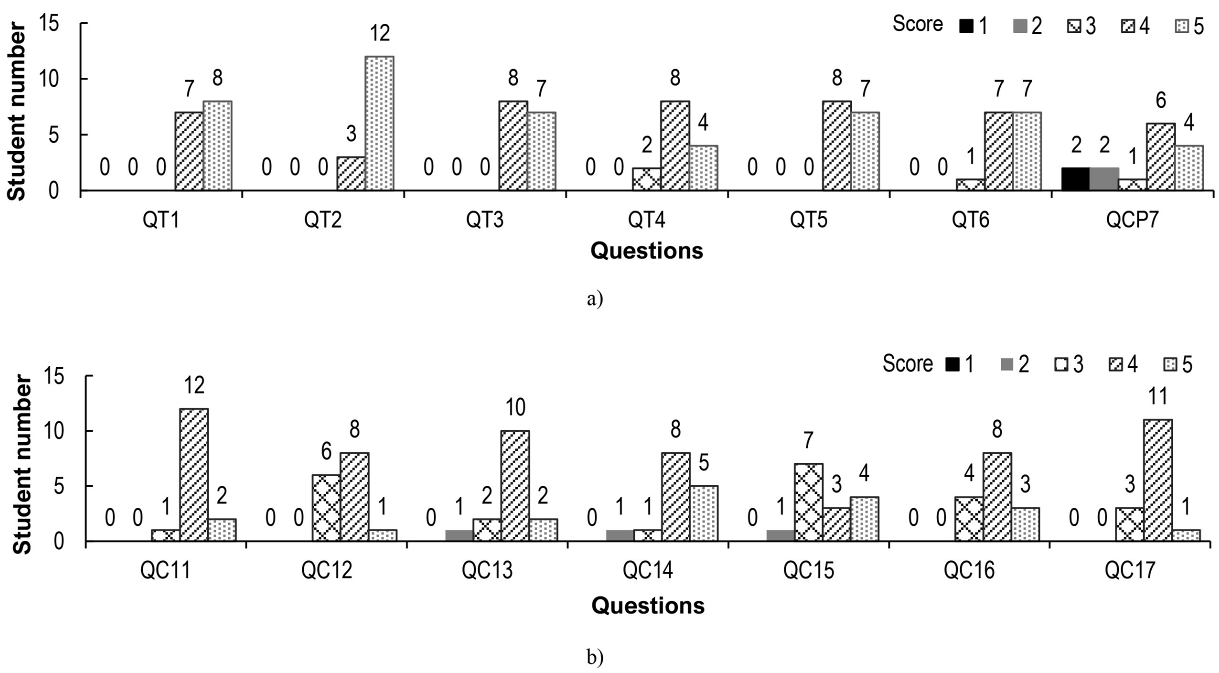


Fig. 6. Results distributed by chosen scores, according to the Likert scale. (a) Teamwork, (b) Communication abilities.

improved their transversal competences. For queries relating to teamwork, all queries were graded over 4.1; for example, the scoring average for QT1 was 4.5. This means that students considered that the PBL intervention enhanced their teamwork; likewise, they recognized the teachers' support in their results, with a grade average for QT2 of 4.8.

Regarding students' participation in meetings, the development of tasks and conflict resolution (QT3, QT5 and QT6), the first two were graded as 4.5 and the last as 4.4. A slight decrease was observed for QT4, regarding leadership, and QCP7, regarding cooperative work; however, most of the students scored these statements with scores of 4 or 5, see Fig. 6a. In short, according to the students' responses to the questionnaire, the designed PBL intervention enhances their teamwork skills.

Most of the students graded the queries related to communication abilities with 4.0 (agree, a yellow bar in Fig. 6b). The query about effective communication with peers (QC11) obtained an average score of 4.1, and QC12 obtained a lower average, which was 3.7. According to the data, students have less self-confidence when interacting with experts. Moreover, the queries associated with the written reports (QC13–QC15) obtained an average of 3.9, 4.1 and 3.7, respectively; this means that students can follow templates (QC14), but they need to improve their skills for citing and following reference styles (QC13 and QC15). In short, students are more self-confidence when they talk with peers than when they speak with teachers or experts, and it is

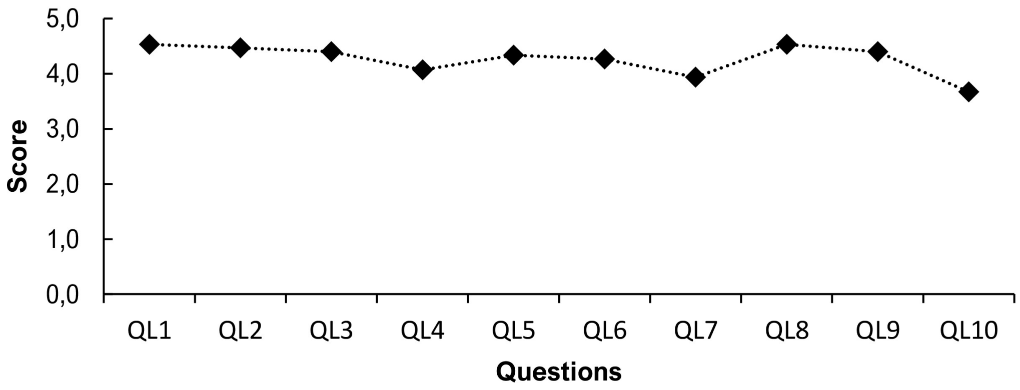


Fig. 7. Results of questionnaire applied to UPTC students (Learning).

necessary to improve the training in scientific writing.

4.2 Results of the Questionnaire for the Learning Aspect (LO1–LO4)

To consider the learning outcomes defined for the SM course, teachers included different queries in the questionnaire. The reliability of the survey for the learning aspect was 0.853 using the Alpha Cronbach Coefficient [60]. The query QL2 is related to LO1 (Obtain a linear model using a step test, recognizing the difference between a first-order, second-order and FOTPD system); this query obtained a scoring average of 4.5. Queries QL3, QL4 and QL5 focused on evaluating LO2 (Identify the difference between an analogue model and a digital model and the implications of their digital synthesis) and obtained 4.4, 4.1 and 4.3, respectively (see Fig. 7).

Moreover, queries QL6 and QL7 focus on LO3 (Recognize constraints and potentialities of different models in the design and implementation of a control system); these obtained a score of 4.3 and 3.9. Finally, queries QL8, QL9 and QL10 relate to LO4 (Discretize a PID algorithm for its implementation in a digital device), and students scored these queries with 4.5, 4.4 and 3.7, respectively.

For the statements of the "Learning" aspect, most students chose the option "5" (strongly agree) or "4" (agree), see Fig. 8. In general, according to the scores, the designed PBL intervention helped students to improve their learning in the design of digital PID controllers. However, the query with the lowest scoring average was QL10, in which three students scored with "1" (strongly disagree), indicating that they had difficulties implementing a real PID on a digital device. Although they correspond to only 20% of the students, it is an important indicator of the need to strengthen the workshop relating to this topic and follow the learning of these students in future activities, in which the facilitation process must cover all students and their needs.

4.2.1 Student Feedback

The blank space of the questionnaire allowed the opportunity to collect some students' impressions of the developed PBL intervention. To understand these responses, the teachers coded the completed questionnaires with the letter "E" plus a number (#); E corresponds to the first letter of the word "student" in Spanish (*Estudiante*).

Thirteen students filled out the blank space; most students highlighted the importance of this kind of intervention and its relevance to developing a better understanding of the design of discrete controllers. Regarding this, one student says, *"The activity is very good, we understand the function and design of a controller, we grasp many things. . ."* (E12); another student stated, *"The development of the activity was very relevant for learning the techniques of control, methods and their implementation. . ."* (E9).

Other students emphasized the importance of the designed PBL intervention as a connector to other subjects. For example, one student wrote, *"I think that the activity was good for strengthening the concepts studied in subjects like signals processing, modelling, DSP and the fields related to programming . . ."* (E6). Another student said, *"The activity resulted in interesting . . . because we used topics learned in previous subjects . . ."* (E11). Students also talked about the need to carry out more activities like it, and the limitations that they found.

Finally, regarding transversal competencies, one student stated, *". . . moreover, being able to teach the obtained knowledge to other students of other courses allowed us to improve our abilities for oral presentations, better every time . . ."* (E1).

4.2.2 Students' Comments and Teachers' Observations

In Table 4, there are some comments and opinions of the students in the interviews conducted by reviewers at the final delivery. The main purpose of these interviews was to establish the students' impressions of the project execution, concerning aspects such as (i) advantages of the PBL intervention, (ii) disadvantages of the PBL intervention, (iii) self-confidence to use the knowledge in other contexts (for example, in a company), and (iv) the solution of problems that involve the discretization of different controllers to those used in the project.

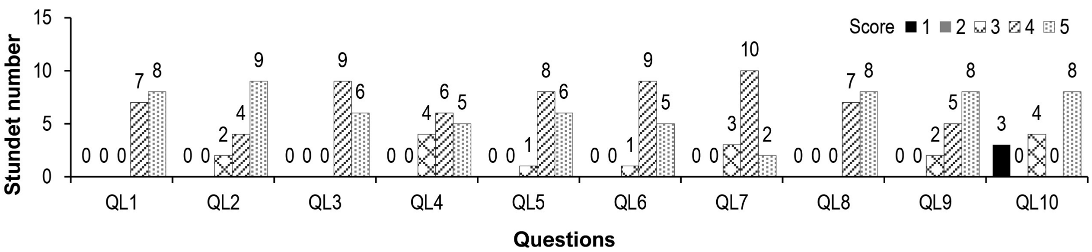


Fig. 8. Results for learning aspect distributed by chosen scores according to the Likert scale.

Table 4. Summary of comments from participating students*

Team	Advantages	Disadvantages
1	Putting together knowledge from different subjects. Learning by doing. The use of knowledge of previous subjects.	Teacher tutoring is not enough.
2	Application of simulation and theoretical results in a practical implementation. Strengthening and verification of theoretical knowledge.	Adjustments were needed in some elements at the time of implementation, because they did not meet the requirements of the design.
3	Application of subjects such as analogue electronics, digital and signal processing. Remembering the topics of the different subjects. Better understanding; in the classroom, the topics were only dealt with theoretically – referring to previous experiences –. Application of knowledge in practical exercises.	The teacher tutoring is not enough (he/she was too busy).
4	Incorporation of different topics. Autonomous learning of things, which is not possible in a lecture. Strengthening knowledge of previous subjects. Sharing experience with others, which allowed. complementing knowledge among students, and learning more, in this way.	
5	Retaking, strengthening and applying concepts from previous subjects.	Failures in the digital processing of signals that we had. The previous courses lack a practical application of the knowledge that is being seen, which would contextualize the student.
6	For understanding the concepts better, a practical activity is necessary and not only theoretical. Increasing in teacher advising.	The activities demanded more time. Topics of some subjects were necessary – referring to other courses –.
7	Application of studied whole theory. Advising by the teacher.	

* The original responses are in Spanish, the content of this table corresponds to translations made by the authors.

Students highlighted the advantages of using previous knowledge of other subjects, reinforcing concepts and strengthening the learning and theoretical knowledge, and improving their abilities to apply theory into practice, as well as self-learning, sharing knowledge with other students and taking advantage of their peers' experience. Although they highlighted an increase in advice from teachers, they also considered this to be one of the more significant limitations, along with an increase in the workload. This situation indicates that PBL intervention in single courses can be unstable, showing the need for a holistic PBL design that considers all subjects of a semester or whole curriculum.

5. Conclusion

The proposed PBL intervention offers an outstanding experience that is devoted to dealing with two big challenges of control education: the design exemplary scenarios in which both engineering skills and transversal skills are encouraged by the proposed learning activities and the design of resources for control education. The PBL intervention offers an integrated solution from a constructionist view, through the creation of small prototypes, which meet three goals: (i) to have an artefact that serves as a local experimentation platform, (ii) to integrate previous knowledge and concepts from other areas, like signals and electronics, and (iii) to define a practical challenge that organizes and nurtures the learning process.

In the questionnaire analysis, most responders graded the queries associated with learning outcomes with a 4 or 5. The responses to queries related to transversal skills had a similar evaluation, showing that the project offers scaffolding in a socio-constructivist scenario that facilitates the learning and emphasizes the strengthening of transversal competencies, such as self-learning, cooperative work, and communication abilities.

The results obtained from students' feedback and observations made by teachers show different advantages, including (i) the use of previous knowledge, (ii) the practical application through learning by doing, especially that motivated by project execution and workshops, (iii) the knowledge construction by collaborative work, and (iv) building a prototype as a learning support resource. However, teachers and students' workloads increased considerably, resulting in a more challenging environment than in teacher-centred models due to the new capabilities demanded by the adoption of PBL. Therefore, it is necessary to carry out an analysis that allows incorporating PBL as an approach for a semester or as a holistic design model for the whole curriculum. For example, courses that are usually taken sequentially in different semesters are put together, to offer a longer and more in-depth PBL scenario for control education.

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