frontiers | Frontiers in Education

TYPE Original Research
PUBLISHED 09 January 2023
DOI 10.3389/feduc.2022.1022888

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Higher Education, a section of the journal Frontiers in Education

RECEIVED 19 August 2022
ACCEPTED 06 December 2022
PUBLISHED 09 January 2023

CITATION
Navarro-Durán D, Félix-Herrán LC, Membrillo-Hernández J, Craig KC, Ramírez-Cadena MJ and Ramírez-Mendoza RA (2023) Active learning to develop disciplinary competencies related to automatic control in engineering curricula using low cost do-it-yourself didactic stations. *Front. Educ.* 7:1022888. doi: 10.3389/feduc.2022.1022888

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Active learning to develop disciplinary competencies related to automatic control in engineering curricula using low cost do-it-yourself didactic stations

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Introduction: In general, in automatic control courses, the process of designing and testing a control system includes applying physical laws to model the system, working with virtual models, building one or various prototypes, and testing the control algorithms. However, in the industry, the approach must be more pragmatic because the design and implementation time must be shorter, and the success of the solution must be ensured.

Methods: Challenged with this problem, a black-box model from which data are generated turns into a convenient starting point to design and implement the automation, and this approach is addressed in this research. The herein proposal is the design and implementation of didactic stations and their application in undergraduate automatic control courses. In the context of active learning, by using the stations to identify the model's dynamics, and subsequently, design and implement an automatic system, students reinforce the theory and receive another stimulus for the development of competencies in automatic control.

Results: The didactic stations emulate those cases in the industry where the hardware is already working, and it is necessary to automate or improve some process following a practical approach. During the first phase, students, guided by professors, designed and implemented four electromechanical prototypes. The second phase was using the prototypes in the curricular courses Control Engineering and Computerized Control to implement and evaluate controllers. The research included a control group and an experimental group. The group using the stations had a higher final course average grade than the control group.

Discussion: The findings encourage the application of this type of approach to complement the teaching of automatic control, which could positively impact the professional performance of future control engineers.

KEYWORDS

educational innovation, active learning, problem based learning, competencies, automatic control systems

1. Introduction

In the industrial domain, it is common for a control engineer to improve the performance of a process or a system. In general, engineers have a working solution and it is needed to reduce the production time and/or improve the quality of what is produced through automation, partial or total, of the production system. As a restriction, moving from the current situation to the new version must be done in a short time to impact the production process as little as possible. What is the engineer going to do when challenged with this problem?

Unlike the academy, there is not enough time in the industry to follow the same approach regarding the design and implementation stages reviewed in automatic control courses. Although in the academy, a methodology is followed that includes modeling based on physical laws; simulation, possibly by the use of virtual prototypes; and the construction of a representative scale system to model, analyze, and test the control, in the industry, it is necessary to be pragmatic and agile. The hardware is already in place and available for work, so the challenge is to quickly apply the theory of control to automate the solution or achieve the requested performance. In this context, using teaching stations with ready-to-use hardware for solving a specific problem could help to develop a pragmatic approach relevant to professional life, while it motivates the 'know-how' in engineering students.

In educational institutions, active learning has proven its relevance because it focuses on developing analysis, synthesis, and evaluation skills through the effective participation of students. This learning strategy is based on scholars "doing/participating" instead of just "seeing and/or hearing," and it demands an atmosphere that keeps students engaged, self-motivated, and eager to learn. Moreover, it requires one or more didactic techniques to implement the learning activities and achieve strategic outcomes (Bonwell and Eison, 1991). It is known that many didactic techniques can be deployed inside an active learning context, such as problem-based learning (PBL), project-oriented learning (POL), flipped classroom (FC), and collaborative learning (CL). Due to the cooperative use of workstations where there is a problem to be solved, the educational proposal presented herein takes the advantage of CL (Pardjono, 2016) and PBL (Mora et al., 2017) within the framework of active learning.

Collaborative learning (CL) is a didactic technique centered on learning through small groups. In CL, teams of students carry out learning sequences to acquire knowledge and develop competencies on certain content. This technique was conceived as a team of persons collaborating to learn a topic (Bonwell and Eison, 1991). Current CL strategies also include new ingredients such as the development of competencies, participants' roles, evaluation proposals, and remote collaborative environments. In all cases, the basic idea is teamwork, where each member contributes and cooperates to achieve the learning outcomes, and team members are responsible for their learning (Pardjono, 2016). CL also considers that students share and discuss their findings as part of the process to develop the competencies (Aldrin Menezes et al., 2021; Estriegana et al., 2021; Rafique et al., 2021).

Problem-based learning (PBL) is a didactic technique where small teams of students work on real problems and are guided by an instructor. The problem itself is the way to address the theoretical and procedural aspects. Some reported advantages of PBL are the acquisition of knowledge, the development of skills to solve real problems, being self-taught, and the identification of problems (Mora et al., 2017). In a PBL environment, students must have an active role during the entire learning process, from identifying and understanding the problem to proposing and evaluating potential solutions. Moreover, PBL is a didactic technique highly oriented to collaborative work (Mabley et al., 2019), to the development of competencies (Webster, 2022), and with a focus on scenarios related to real problems (Jaeger et al., 2021); thus, it has very relevant elements for the research work that is developed herein.

Experiments have been reported where active learning has been applied to improve skills in STEM, and the advantages and disadvantages have been also detected. For computational sciences, the development of Practical Active Learning Stations (PALS) has been reported to reduce the costs involved in active learning, which generally requires the use of equipment or workstations (Eickholt et al., 2017). Another reported experiment with classrooms equipped with low-cost PALs refers to having improved programming skills in introductory courses with performance measures of the course grades (Eickholt et al., 2021). Moreover, ways of equipping active learning with new tools have also been developed; for example, artificial intelligence (AI) algorithms guide the experiments carried out by students and trigger self-reflection and feedback (Yannier et al., 2020). These are some applications and improvements of this didactic approach that have been in use for decades (Renkl et al., 2002), and applying adequate didactic techniques with teaching stations could improve various aspects of the teaching–learning process (Hakimzadeh et al., 2011).

Automated control courses in undergraduate curricula are usually considered difficult and full of theory and complex classes. Moreover, it has been observed that the development of disciplinary competencies related to the analysis and design of automatic control systems is troublesome due to the extensive list of topics in the course. Besides, either most control theory courses do not consider practical work or the activities are limited to simulation assignments, so it is not possible to employ theory in real applications. In this context, the objective of laboratory activities is the implementation of control systems where theoretical tools are applied and verified.

To bring theory closer to practice, didactic stations have been used to implement active learning in automatic control courses. This could have arisen as a need to have practical experiences that favor the development of professional skills appreciated in the industrial field (Morales-Menendez and Chávez, 2006). Based on this idea, research results have been reported, such as low-cost stations where the airflow is controlled by means of PID and fuzzy controllers (Pilatasig et al., 2019) or others for the development of automatic flight systems in aerospace systems (Castaldi and Mimmo, 2019). Stations are typically built with industrial components, such as controllers, and allow various control strategies to be tested for academic, research, or professional training purposes (Vásquez et al., 2019). The resources applied in these research efforts have been acquired functional and are ready to use, some of them are available at a considerable economic cost, and it is in this situation that an opportunity is observed to apply a different approach when using didactic stations.

This research proposes the use of didactic stations in automatic control courses to emulate automation situations where the focus is to obtain a functional solution in a short time. In addition, the research includes a previous stage where students and teachers work as a team to design, build, and test the teaching stations. Then, the academic systems are employed in automatic control courses as a complement to theory and for the future implementation of industrial control systems. The investigation endeavor includes the application of a research methodology to give structure, support, and theoretical support to this work.

2. Materials and methods

2.1. Research methodology

This section develops the applied educational research methodology. The study considered the following guiding hypothesis: the implementation of different controllers on didactic stations within automated control courses (stimulus) contributes to reinforcing the developed competencies established for the course (response). Besides, the investigation included the following items: research methodology, data collection instruments, population selection, and research procedure. Furthermore, a mixed and sequential research methodology was considered (Gay et al., 2006). The flow of the research, from its conceptualization to the writing of the article, is presented in Figure 1. The flowchart depicts the actions carried out, in chronological order, throughout the entire research endeavor. Each milestone of the process will be explained in the following paragraphs.

As part of the methodology, it is important to define the objective pursued by the MR2004 Control Engineering and MR2007 Computerized Control courses. As established in the official curricula of the engineering bachelor Mechatronics Engineering, version 2011, at Tecnológico de Monterrey, after the completion of MR2004, students should be able to analyze, model, design, and evaluate closed-loop continuous control systems for analog processes, which achieve the desired performance according to specifications for regulatory control applications for products and processes (Tecnológico de Monterrey, 2022a); moreover, after the completion of MR2007, students should be able to analyze, implement, and evaluate the computerized product and process control systems with a focus on practical application (Tecnológico de Monterrey, 2022b). These guidelines provide an accurate idea of what they are supposed to learn.

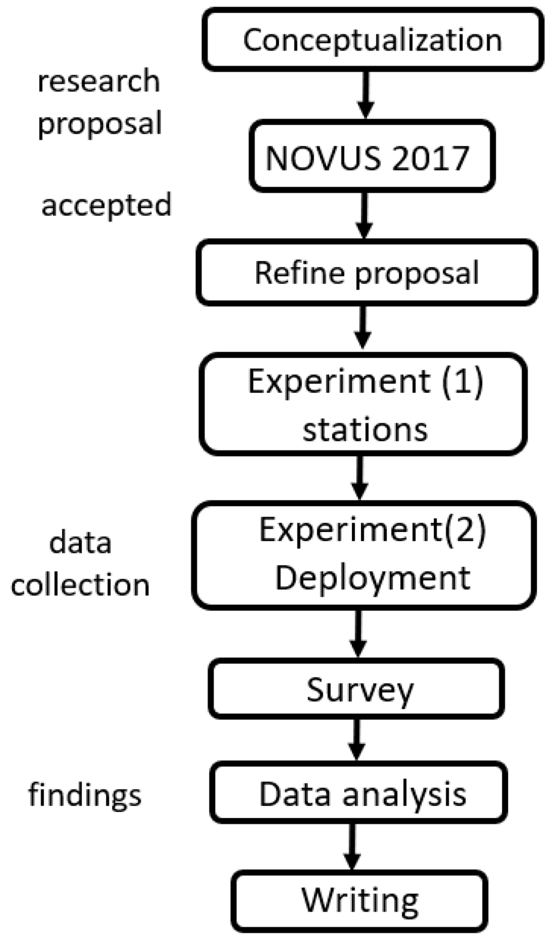

FIGURE 1
Research flowchart.

The first actions were conceptualization and focus on gathering financial resources. The problem statement, the guiding hypothesis, and an outline of the mixed-method research methodology that would be applied were clarified. As the research was going to require financial resources, an opportunity arose to participate in the 2017 NOVUS Educational Innovation Fund of the Tecnológico de Monterrey (NOVUS, 2022). NOVUS is an initiative to encourage educational innovation by professors within the Tecnologico de Monterrey.

There was a record that the program NOVUS had supported active learning projects and educational stations, so a proposal was generated with the requirements of the initiative and submitted. Previously supported proposals with didactic stations during automatic control are electromechanical equipment adapted to carry out practical activities in an undergraduate control course (Aguayo and Navarro, 2014), and the design and build of robotic manipulators as part of a challenge in which students developed disciplinary and transversal skills. These manipulators, along with the manuals to build them, were used as a reference for students of other courses to develop them during the semester (Gutiérrez et al., 2014). The difference between these proposals is that now the students will be the ones who completely build the didactic stations from the prototypes, also generated by students during the August–December 2017 semester. The learning of the experimental groups includes the manufacture of the stations.

In the summer of 2017, the proposal was accepted by NOVUS, and feedback was received to improve the research. The next step was the design of the didactic stations, and this enterprise required the participation of students during part of 2017 and 2018. The participation of some students was a part of the course's activities, whereas others did it as an external activity not linked to educational credits. The equipment was purchased and stations were assembled and tested in open-loop and closed-loop; all this was part of the first stage of the experiment. The second part was carried out between 2018 and 2020, which consisted of using the stations in automatic control courses as part of the activities with weight in the grade of each course. This deployment of the experiment allowed the collection of data for quantitative analysis.

At the end of each course where the didactic stations were used, an anonymous survey was conducted on students to know their learning experience, their perception of using the stations, and the skills acquired, always considering the link between theory and practice. The data collected from these surveys were used for qualitative analysis, and together with the quantitative ones, they would lead to the research findings. The last step was the writing of the article to share the research effort and its results.

The participants are all the students and professors who were involved in the experiment. In the first part, students of the course MR2023 Automatic Control Laboratory designed and implemented the didactic stations, although, on another campus, the student's participation was not linked to any course of the curricula. In this phase, the professors served as guides during the design, implementation, and testing process.

There were two groups of populations for the deployment of the experiment: the reference group that worked with the traditional scheme and the experimental one that was impacted by educational innovation. The data were collected in two ways: quantitative (individual final exams) and qualitative (surveys). Moreover, the participants were the students of MR2004 Control Engineering and MR2007 Computerized Control at Tecnologico de Monterrey in Mexico City (CCM) and Hermosillo (CSN) campuses. The activities were implemented between 2018 and 2020. Furthermore, in CCM, individual final grades were used to generate a quantitative comparison between the base and experimental groups. The evaluations were of the same type and with a similar degree of difficulty, besides, the same teacher taught both groups (base and experimental).

The budget and human resources to build the stations impacted the development of the experiment. These elements have to be considered in the pedagogical context of the research methodology. The initial idea was to have more teaching stations for more students, but the expected number of stations could not be built. In a certain way, this eventuality influenced the deployment of the experiment.

In education, it is very important to keep the educational programs updated and aligned with current society and industry requirements. For instance, Tecnológico de Monterrey is undergoing a change in the implementation of a new educational model, and comparative analysis of students with different didactic approaches is a relevant matter of study. The circumstances of the implementation of a new educational model allow this type of study that could be of great value for those researchers interested in educational strategies.

The next subsection explains how the research was divided into two stages: the design and construction of the prototypes and the application of the stations in the courses to collect the data. After gathering the data, statistical analyses were accomplished to obtain findings and to discuss their impact on the teaching–learning process.

2.2. Stage 1: Stations design and construction

The main objective is to develop didactic stations to enhance students' outcomes on the automatic control, and for this reason, the stations selected are a pneumatic levitator, a ball and beam, an inverted pendulum, and a propeller–arm system. According to the research, the stations were selected because of the low-cost materials to be built and the ease of implementing a control algorithm.

The design and construction of the first prototypes took place from January to May 2018 (JM-2018) semester. The professors involved in the project developed the first prototypes based on a Computer Assisted Design (CAD) model. A brief description of the function and control objective for each prototype is given in the next paragraph.

The pneumatic levitator of a tube is coupled to a blower fan, and in the center, there is a ball that can be raised due to the force of the air. The main control objective is to keep the ball in the position that the user indicates. The ball and beam consist of a beam that can modify its inclination and a sphere moves over it. Depending on the inclination, the control objective of this experiment is to maintain the sphere in the desired position only by moving the inclination of the bar. Furthermore, the inverted pendulum is an experiment with a pendulum that must be kept at the top, and this is achieved by placing a motor with a mechanism that allows it to swing the pendulum and reach the top position. In addition, the propeller–arm system consists of a propeller placed in a rotatory arm, and by increasing the speed of the motor; the propeller generates a force that can move the arm. The control objective of this experiment is to maintain the arm at a specified angle set by the user.

After developing the design models, a proper search of components was performed to build the first prototype of stations.

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As shown in Figure 2, the result of the prototypes is presented. The ball and beam and the pneumatic levitator were developed in CCM, and the inverted pendulum and the propeller-arm system were developed in CSN. The prototypes were tested before implementation to validate the viability of course implementation, and the four prototypes were ready to perform tests on groups in the semester of August–December 2018 (AD-2018). So, in the next section, the deployment to apply the didactic stations in the courses on AD-2018 will be explained.

2.3. Stage 2: Stations implementation on courses

The stations were implemented on two campuses, Hermosillo and Mexico City, on the courses MR2004 Control engineering and MR2007 Computerized control. The didactic stations were assigned to teams with a maximum of three students to allow them to collaborate and use the stations. The experiment took place as follows: in the August–December 2018 (AD-2018) semester, there were two groups of MR2004 control engineering and one group of MR2007 computerized control, and all of them were imparted on CCM. In the semester of January–May 2019 (JM-2019), there were two groups of MR2004 and one group of MR2007 imparted on CCM, and in CSN, there was a group of MR2004. In the semester of August–December 2019 (AD-2019), there were two groups of MR2004 and one group of MR2007 imparted on CCM, and in CSN, there was a group of MR2007. Finally, in the intensive period of winter 2020 (W2020), which took place in January 2020, there was a group of MR2004 on CCM.

The way the experiment was deployed on the semesters and groups previously mentioned is as follows: the stations that were built on each campus could accommodate properly just one group at a time, and that is the reason there was one experimental group and one control group. For this study, it is of particular interest that the groups of MR2004 on CCM were imparted by the same teacher, and this means that the only difference was the stimulus of the didactic stations. In the case of the MR2007, there were alternating control groups on CCM and CSN, but the main difference was that different professors were teaching the course. The general working plan implemented in the experimental groups is presented in Figure 3. Notice that the didactic stations were submitted into a continuous improvement process, and that is the reason why there are three versions of the pneumatic levitation system in Figure 2C.

As it was mentioned on CCM that the course MR2004 was imparted by the same teacher, the only difference in those groups was the didactic stations. In the experiment, there were four periods in which the stations were implemented as is shown in Table 1. The total number of students in the experiment was 191, considering that 86 participated in the control group and 105 in the experimental group. Teamwork is essential in developing the didactic station applications, and for this reason, teams with a maximum of three students were assigned to work in each station. In some cases, the students prefer to work in couples, or, in some rare cases, the students work with the stations individually.

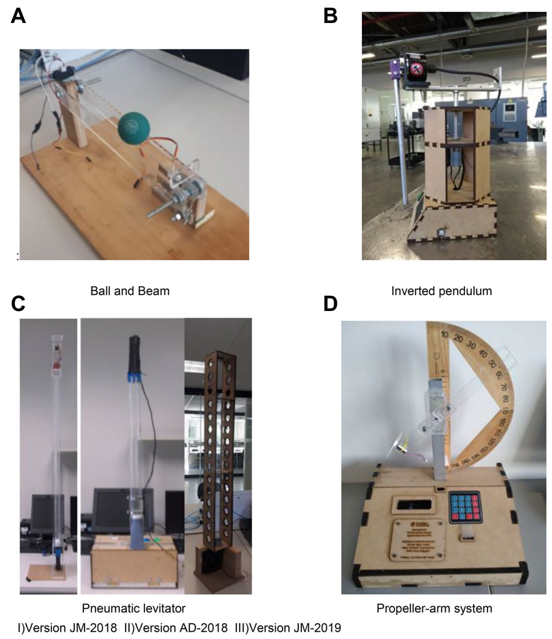

FIGURE 2
Functional didactic stations. Figures: **2A**, **2B**, **2C**, and **2D** depict the 4 types of stations that were designed and implemented.

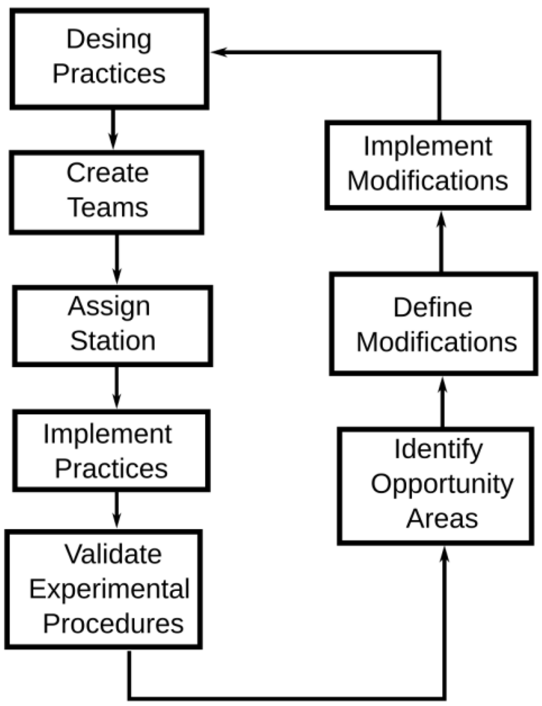

FIGURE 3
Implementation diagram.

TABLE 1 Students in MR2004 courses.

Period	Control group	Experimental group
AD-2018	29	29
EM-2019	26	26
AD-2019	31	28
W2020	0	22

To implement the didactic stations, a planning process was developed in which the first step was to find the key concepts and topics to be implemented in the stations. After discussing with some colleagues who imparted automatic control systems, the common concepts to be implemented in the stations were as follows: (1) transient response, (2) open and close loop, (3) system identification, and (4) PID controller design and implementation. Based on these topics, there was a process to prepare the practices with the stations and relate the theoretical concepts.

In both courses, the methodology and the teaching process were the same. The only difference was that in the control group, there were only mathematical demonstrations and simulation analyses that were commonly developed on Matlab® and Simulink®; meanwhile, in the experimental group, the only difference was that it added the stimulus of the didactic stations as practices to reinforce the knowledge from the mathematical demonstrations and the simulation analysis. The practical activities that could be performed with the different stations and the matching of the topics are presented in Table 2. In all the courses, the topic was explained in the course and then it was reinforced by the activity using simulation stimuli such as Matlab® and Simulink®, and for the experimental group, it was added to the application of the didactic station. The learning process implemented in each group is presented in Figure 4. It is important to mention that at the end of each topic, the student received feedback for the simulation or validation of the concepts in the didactic stations.

Some of the topics cannot be applied directly to many stations, for example, transient response, system identification, and Ziegler–Nichol's method are not appropriate for the ball and beam, propeller and arm, and inverted pendulum. As an example, the implementation of the different topics can be achieved in a single station that is the pneumatic levitation system. A system identification using a frequency response can be performed using different sinusoidal inputs to obtain a linear behavior of the system according to the restrictions mentioned by Escano et al. (2005). As is presented in Escano et al. (2005), the pneumatic levitation system is a complex model, but with proper considerations, a linear system can be set to several equilibrium points. Using the results presented in Escano et al. (2005), it is possible to simplify the dynamics of the system and use the fourth-order linear system, which gives a pair of dominant complex conjugate zeros that cause some oscillations. Also using this kind of identification, a Ziegler-Nichol's using the transfer function that simplifies the model and with the transfer function, it is possible to develop some controllers that allow control of the pneumatic levitation system, considering the restrictions imposed by linearizing the system.

In the case of the other stations, it is possible to implement different methodologies to develop a controller but it depends on the characteristics of the system. The main idea is that with the whole set of stations; the student can get a practical approach to designing and implementing different controllers in the system.

Following the explanation of the methodology in Table 2 and Figure 4, experimental data were gathered from each semester and stored in files for further analysis and using the data collected, statistical analysis was performed to convert the data into valuable information for this research. The findings and the data provided will be discussed in more detail in the next section and the discussion.

3. Results

In this section, the results obtained from the implementation of the didactic stations on the courses MR2004 control engineering and MR2007 computerized control are presented. The period considered in the study is three semesters AD-2018, JM-2019, and AD-2019. In each course, there was an experimental group that used the didactic stations and a control group that was taught in a traditional classroom.

It should be noted that a traditional Control Engineering or Computerized Control course is usually 100% theoretical. Due to the large number of topics to be studied, these courses focus on reviewing the theory and the procedures to follow to solve examples and exercises on paper or, in the best of cases, with the support of simulators. The practical work as a means to reinforce the theory is applied until the laboratory course MR3029 Integral Automatic Control Laboratory (Tecnológico de Monterrey, 2022c).

The results are divided into quantitative results involving the performance of the student measured with the final score, qualitative results measured by a survey the students answered, and finally, the results from an external institution called Centro Nacional de Evaluación para la Educación Superior (CENEVAL in Spanish) are presented to support the results on the study.

3.1. Quantitative results: Course grades

The final score of the course was used as the instrument to measure the impact of the application of the didactic stations. It was considered that the final score was a consequence of using the stations to develop the disciplinary competencies of the students. The most significant scenario is presented in the course MR2004 control engineering in CCM, in which the same professor was teaching both groups, the experimental and the control group. This means that the only difference was the implementation of the didactic stations as a stimulus for the student's performance.

This study involved seven groups in which 191 students participated, 105 students were impacted by the implementation

TABLE 2 Activities comparison.

Topic	Control group activity	Experimental group activity
Transient response	Simulation of first and second order systems	Obtain the transient response from the didactic stations
Open and close loop	Simulate open and closed loop systems and compare performance.	Implement an open loop response and compare it to the close loop with proportional gain on the didactic stations
System identification	Obtain the model of a Blackbox model from a Simulink® simulation	Measure input and output from the didactic station and perform system identification with the data.
PID controller design	Design of a PID controller by Ziegler-Nichol's method and root locus design on simulation	Design a PID controller using Ziegler-Nichol's method and root locus to be applied to the didactic stations
PID controller implementation	Implement on simulation a PID controller to evaluate the system performance.	Implement on the didactic stations a PID controller to evaluate the system performance.

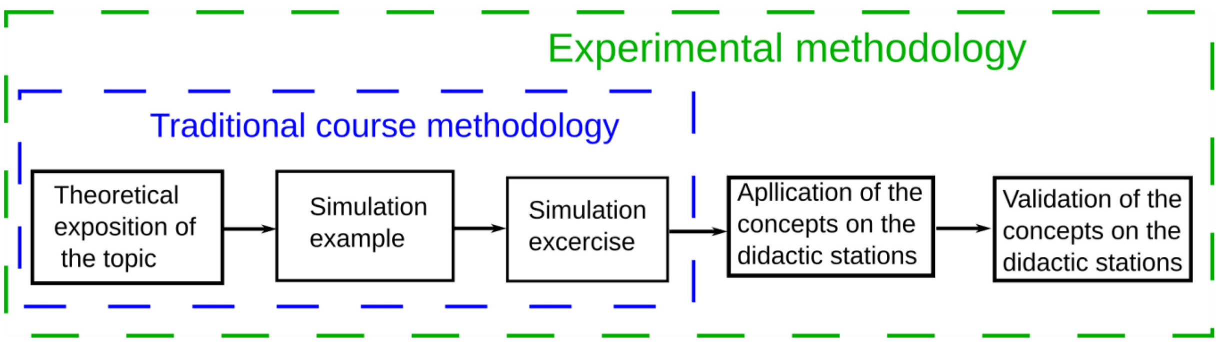

FIGURE 4
Course methodology to implement each topic.

of the didactic stations in the experimental group, and 86 students participated in the traditional learning experience in the control group. The experiment took place in the semesters AD-2018, EM-2019, and AD-2019 in which there were two groups, one group was the control group and the other an experimental group, with the same professor. A winter course in 2020 (W-2020) implemented the didactic stations, but in such a period, there was no control group for comparison.

In Figure 5, the average of the final score obtained by each group is presented. Notice that the results from the semesters AD-2018 and JM-2019 obtained better scores in the groups with the stimulus of the stations. Moreover, in the case of the semester AD-2019, the result is almost the same with or without the stations. In the winter course 2020, there was only the experimental group, and it can be observed in Figure 5 that the average obtained by the group increased significantly up to a score of 85. From the overall perspective, the results mainly presented that the students developed and implemented control systems more efficiently with the didactic stations.

In Figure 6, the grading is presented on the different ranges obtained by the students at the end of the courses. As can be seen, the students with better performances in the course are the ones in whom the didactic stations were implemented. On one hand, the highest frequency with didactic stations is in the range from 90 to 80, with 42.74% of students, on the other hand, without

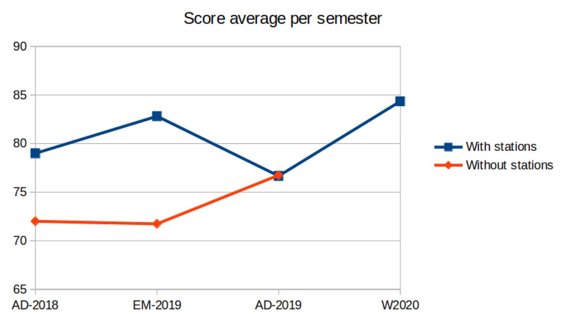

FIGURE 5
Average scores per semester.

didactic stations, the highest frequency is presented in the grading range from 80 to 70 representing the 53.49% of the students.

Also, from Figure 6, it can be noticed that the students with the stimulus of the didactic stations fail the course with better notes, almost ranging from 70 to 60. But that is not the case without stations in which there are students that obtained grades lower than 50. It is important to point out that the failing percentage without the didactic stations is 18.6%. The stations helped the students develop disciplinary competencies, and as a result, the failing percentage is reduced significantly to 6.45%. This

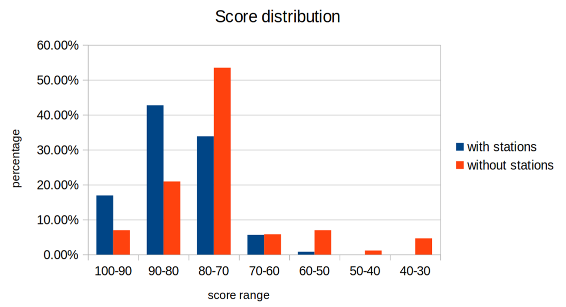

FIGURE 6
Course gradings.

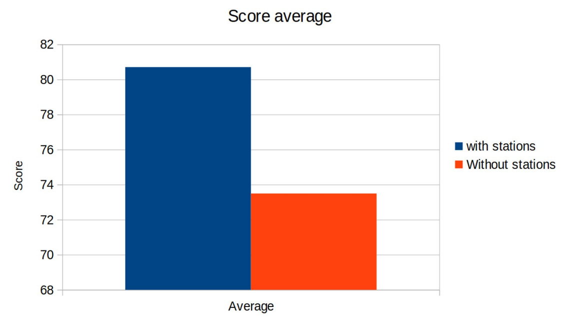

FIGURE 7
Overall average.

is another effect of the practical implementation of control systems, and it is presented that if the competencies of a course are developed, the result on academic performance will be improved, as the previous results demonstrate.

Figure 7 presents the overall average of the courses, considering the AD-2018, EM-2019, AD-2019, and W2020 courses. Notice that the average using the didactic stations is 80.707 and without the stations, it is 73.495, this means that a difference of 7.212 points is present, and consequently, it is possible to conclude that the application of the theoretical concepts to a practical application improves the knowledge and development of the skills the students will require.

Over the different results obtained by the application of the stations in the group, it was noticed that the standard deviation was higher in the control group than in the experimental group. It can be noticed in Table 3 that the standard deviation of the experimental groups is lower than 9, but on the other hand, the standard deviation of the control group is higher than 10. It is important to note that the grades are not only higher with the didactic stations, but the standard deviation is also another parameter that allows measuring the performances of the student, showing that the differences are lower in students with the use of didactic stations than in the students without the use of the didactic stations.

3.2. Qualitative results: Student survey

The qualitative results were obtained with a survey answered by the students that used the didactic stations. The survey included the following questions "The use of didactic stations helped to relate theory to practice," "A control system with moving parts reinforces the understanding of the following concepts: reference, process variable, error and manipulation," "In alignment with the intention of the course described in the syllabus, it is preferable to work with ready-to-use didactic stations, instead of building them in the classroom," and "The didactic stations cover everything necessary for the proposed practices and practically do not have areas of opportunity." The survey included seven items, and this inquiry gathered information from the four closed questions to be responded to on the Likert scale.

The survey was intended to obtain information about the student perception of the stations and the benefits obtained by using them in the course. In this study, 77 students from the AD-2019 semester answered the survey, of which 70.1% were from the Mexico City campus and 29.9% were from the Hermosillo campus. A total of 80.5% of students were on the MR2004 control engineering course and 19.5% on the MR2007 course. The result of each one of the questions will be explained according to the corresponding graphic.

Figure 8A presents the result to the question "The use of didactic stations helped to relate theory to practice." As can be observed, 88.4% of the students who participated in the survey agree and completely agree with the fact that the application of the concepts to a practical case of study helps them to understand the practical application of the theoretical concepts. It can be found that 7.8% maintain a neutral posture and 3.9% did not find any relation between theory and practice.

In Figure 8B, the question explored the perception of the students to basic concepts in control engineering such as reference, process variable, error, and manipulation. From Figure 8B, it can be noticed that 89.7% of the students agree that the didactic stations help them to understand the basic concepts, 6.5% maintain a neutral posture, and 3.9% completely disagree. As it can be observed, a major part of the students perceived they had a better understanding of the basic concepts because of the implementation of the didactic stations.

In Figure 8C, the question measured the perception of the student of using a prebuilt station or developing their own on the course. As can be seen in Figure 8C, 68.9% of the students agree that it is better to work in a ready-to-use didactic station. The other 24.7% presented a neutral attitude and 6.5% disagreed that it is better to use a prebuilt station than to build their own. It can be observed that the majority of the students prefer to work directly in a didactic station and avoid the design process; this helps the student focus on the control engineering concepts instead of the mechanical and electrical concepts required to build the prototype.

TABLE 3 Standard deviation per academic period.

Period	AD-18 Control	AD-18 Experimental	JM-19 control	JM-19 Experimental	AD-19 control	AD-19 Experimental	W-2020
Standard deviation	14.21	8.91	13.85	6.64	10.96	7.54	7.16

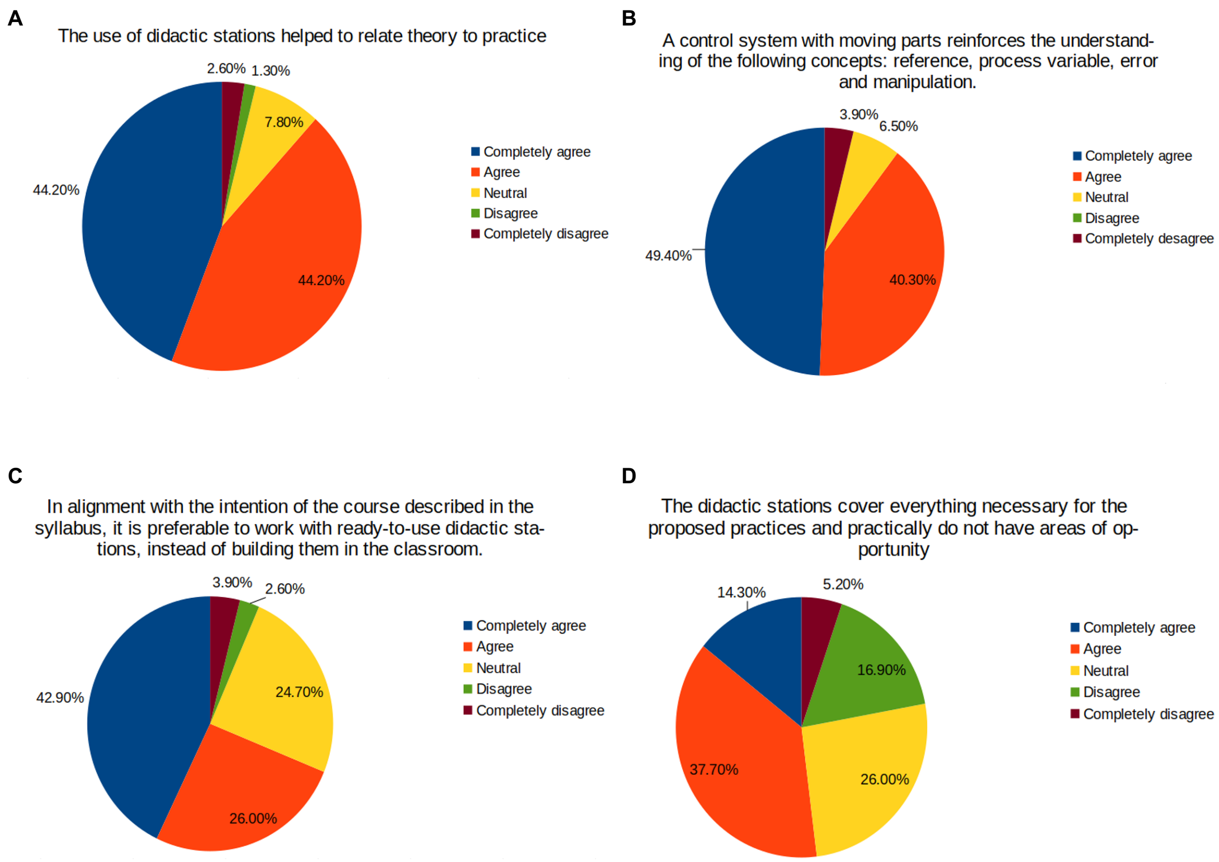

FIGURE 8
Figures **A**, **B**, **C**, and **D** show the graphical results of each question of the survey.

Finally, Figure 8D presents the result of how the students perceived the stations, considering if there are any areas of opportunity. In this case, there was more dispersion in the results than in the previous questions. As can be seen, 52% of the students agree that the stations satisfy the basic needs and are ready for testing; 26% present a neutral position, considering that neither the stations are ready nor do they have opportunity areas; 22.1% disagree that the didactic stations cover the necessary aspects to be implemented in the courses. It is understandable that the stations can be upgraded for better performance and better user experience.

Overall, the quantitative and qualitative results present that the use of the didactic stations had a positive impact on student performance in the course. As can be seen, the implementation of the different concepts and the practical application of controllers to the black-box model prepare the students for the challenges they will be facing in the industry.

3.3. CENEVAL-EGEL exam for mechatronics engineering

The Centro Nacional de Evaluación para la Educación Superior (CENEVAL in Spanish) is a non-profit Mexican association that performs as an Evaluation Center for Higher Education. The CENEVAL does not depend on any educational institution and is focused on designing and applying evaluation instruments in high school and bachelor education (CENEVAL, 2022). The General Examination for Bachelor's Degree (EGEL in Spanish), designed and applied by CENEVAL, is an exit examination that students take in the last semester of their degree and is applied in many universities in Mexico. The purpose of the exam is to measure the student's performance in work–life situations, i.e., measure to some degree if the future graduates have the required competencies to successfully start their professional life. Despite being a paper test, the exam items are focused on making decisions in real scenarios.

The CENEVAL-EGEL exam for Mechatronics Engineering, which is considered in this study, is made up of the following sections and subsections in parentheses: Integration of technologies for mechatronic design (Technologies for the solution of a mechatronic problem and Design of mechatronic models and prototypes), Systems automation (Instrumentation and supervision of systems and Industrial control), and Development and coordination of mechatronic projects (Project research methodology, mechatronics and technological innovation, Coordination of mechatronics projects, and Evaluation of mechatronics projects; EGEL, 2022).

For more than a decade and without interruption, the students of the academic program of Mechatronics Engineering at Tecnológico de Monterrey have taken the CENEVAL-EGEL exam, and for the purpose of this experiment, it was used as an instrument to collect quantitative data. The students who participated in the control or experimental groups for this research took the CENEVAL-EGEL exam in one of the applications between December 2018 and December 2019 and the application in 2021.

Of the 191 students who participated in the experiment, only 39 graduated in the period that the CENEVAL-EGEL exam was presented. The reason is that many of the students graduated in 2020, and due to the restrictions of the pandemic, the CENEVAL-EGEL was suspended. Of the 39 students who presented the exam, there were 27 students in the experimental groups and 12 in the control groups. From the CENEVAl sections, this study considers the section "Systems Automation" in which the automatic control theory is evaluated. The average obtained by those students can be observed in Figure 9. Notice that the average from the experimental group is slightly higher than the control group by 1.87 points.

The EGEL-CENEVAL presents three different performance results: outstanding development (DSS) is obtained by a student with 1,150–1,300 points, satisfactory development (DS) is obtained by a student with a score from 1,000 to 1,149, and not satisfactory yet (ANS) is obtained with a score from 700 to 999 points. In Figure 10, it can be observed that the results from the DSS are higher in the experimental groups than in the control group. But the results in the control groups are higher in DS development. In the ANS performance, the students in the experimental group present three students failing the exam compared to the control group which corresponds to one student.

Figure 11 presents the average score obtained by the students in each period. Notice that in the AD-2018 and FJ-2019, only one student from the control group and two from the experimental group presented the exam, but the student who presented in the experimental group obtained a better score. In the subsequent semesters, both the control and experimental group presented the exam, and it can be noticed that in almost all the periods, the results from the students in the control groups are higher than the ones in the experimental group.

The results presented in this subsection are preliminary because, from the sample of 191 students in the experiment, only 39 presented the exam. It is important to mention that from those 39 students who presented EGEL CENEVAL, 12 students were in the control group and 27 in the experimental group. Of the whole

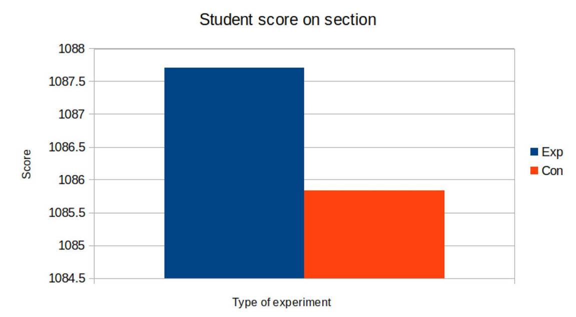

FIGURE 9
Student's average score on the control section.

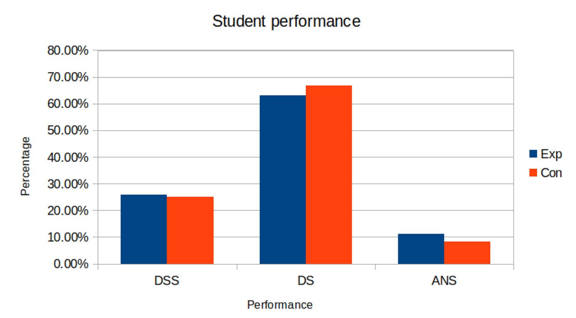

FIGURE 10
Students' performances in the exam.

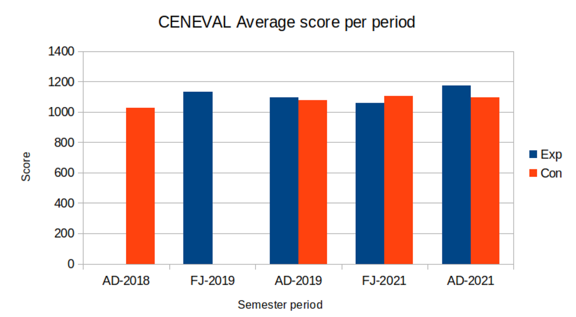

FIGURE 11
Average score per period.

population involved in the experiment, only 20.41% of students presented the EGEL CENEVAL. Considering that 13.95% of the students in the control group presented the CENEVAL exam and 25.71% of the students presented the CENEVAL exam in the experimental group, the first result on the impact of implementing the didactic stations on the course is presented. It presents that the didactic stations help the students to retain knowledge and get a better comprehension of the theoretical content. Moreover, a more balanced sample between control and experimental groups will provide solid results. To complement these results, it is important to continue experimenting according to the methodology previously proposed to get more information on the outcome skills the students get at the end of their bachelor studies.

4. Discussion

In the results section, the quantitative and qualitative results obtained by analyzing the final score and the survey the students answered are presented. It can be concluded that the didactic stations are proper support to teach control engineering subjects, even though the stations have opportunity areas to be improved. In addition, students' perceptions support that the active learning obtained by the implementation of the controllers and concepts on the stations allows them to understand and develop the necessary skills.

As can be observed, the quantitative results support the fact that the didactic stations help the students obtain better grades. This event is a consequence of the active learning experience that supports the practical application of the concepts and the required procedures to implement a controller so that students can have a better understanding of the theory. It can be observed in Figure 5 that all the grades from the experimental groups were moved to a higher grading, and the control groups obtained poor grades at the end of the course. Another important consequence is that the failing percentage with the didactic stations is reduced to one-third compared to that without the didactic stations. Due to the good approach obtained in the final grade by the students, it would be important to evaluate the previous knowledge as an important factor for the success of the course and not only the final grade.

The quantitative results present the perception of the professor on the implementation of the didactic stations, but it is also important to consider the students' viewpoints. The qualitative results obtained from the survey examine the students' opinions, and this makes the research study more valuable. As presented in the result section, the survey consisted of four questions in which it was presented that the students feel more confident about the control concepts because of the practical application in the station. Considering the reinforcement of the basic concepts and the practice and theory relationship, more than 85% of the respondents demonstrate that active learning combined with the PBL presented a positive impact on their learning process.

With the qualitative results, the station's readiness was evaluated. From the perception of the students, it is shown that it is better to use a prebuilt station instead of developing the whole system. It is commonly observed that if the system or station is built on the course alongside the control implementation, not in all cases, the control theory is applied to the prototype. The other aspect that is important to resemble is although the stations are student-based models, they satisfy almost all the requirements needed to implement a controller. In some cases, the stations require some components that students must give to implement the controller and let the stations work properly, such as motor drives or programmable microcontrollers.

The COVID-19 pandemic had a negative impact on the experience. Of the universe of participants, those who graduated in June 2020 and December 2020 did not take the CENEVAL-EGEL exam because the assessment was suspended nationwide in 2020. These data could not be collected, which would have reinforced the results presented in Figures 9–11 when comparing the performance in the CENEVAL-EGEL exam.

It is considered to continue applying the experiment and keep updating the activities deployment. To have more reliable results, it is necessary to continue collecting data and generating comparative grade results for more semesters. This would reinforce the trends of average score per semester, score grading distribution comparative, and overall average presented in Figures 5–7. Furthermore, as part of the continuous improvement process, it is necessary to check that the deployment of activities continues to be adequate for the teaching–learning environment after the COVID-19 pandemic.

In future works, the process of continuous improvement of the didactic stations will be presented. There is an interest in working with the feedback provided by the students and detecting opportunity areas to improve the prototypes. In addition, the findings would be reinforced with those expected to be collected in AD2022 to further identify result behaviors over time. It is likely that a trend will be detected, and the hypothesis reaffirmed or refuted, etc.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study involving human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants in accordance with the national legislation and the institutional requirements.

Author contributions

DN-D and LF-H contributed to the conception and design the didactic stations. LF-H, KC, JM-H, and RR-M participated on the methodology used to implement the experiment. DN-D, MR-C, and RR-M participated in validating the experiment. MR-C and D-ND participated in implementing the experiment and the data collection and data analysis. JM-H and LF-H participated on the research proposal. LF-H, KC, JM-H, and DN-D participated on writing the original draft. MR-C and RR-M reviewed and edited the paper. All authors contributed to the article and approved the submitted version.

Acknowledgments

The authors first thank José de Jesús Barajas Cid for having participated as leader of the NOVUS proposal at the start of the project. They also thank all the students who participated in the design and implementation of the didactic stations. In CCM, the authors are grateful to the Mechatronics students of the MR3029 class of the EM2018 semester and to the students who participated in the improvement of the stations in the AD2018 and EM2019 semesters. In CSN, the authors extend their thanks to the five mechatronic students who carried out their scholarship service in these activities. Thank you all for being part of this educational innovation project. Furthermore, The authors wish to acknowledge the financial and technical support of the Writing Lab, Institute for the Future of Education, Tecnológico de Monterrey, Mexico, in the production of this work. Besides, The authors acknowledge the financial support of Novus Grant with PEP No. PHHT032-17CX00009, TecLabs, Tecnológico de Monterrey, Mexico, in the production of this work.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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