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Learning Control Concepts in a Fun Way*

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This paper proposes Hands-On sessions as a didactic strategy for lectures in theoretical courses, where students can construct and understand control concepts when they play a game designed by the teacher. The teacher uses a game to introduce the topic in order to motivate the students to learn in a fun way and improve their knowledge retention. Students develop activities in groups of three to five members; they follow instructions from a guideline describing the game. Hands-On sessions offer an alternative to learning control theory from concrete experiences so students can grasp knowledge and relate the concepts to simple events. The game can be seen as a road to achieving concepts; it has key issues that allow students to construct knowledge. This approach proposes employing Hands-On sessions using simple materials instead of high-technology complex elements, software, or a specialized space. This work describes a model to design and develop Hands-On sessions. It also introduces activities designed for students to learn topics such as: describing a typical control loop, analysis in the time domain, stability, root locus analysis, and frequency analysis, for control courses in an engineering program. Finally, the paper describes feedback and comments from the students.

Keywords: Hands-On sessions; control education

1. Introduction

Control system education usually uses mathematical illustrations to explain concepts. Mathematical analyses such as differential equations, difference equations, Laplace transform, z-transform, state space, and block algebra, among others, are used to explain and deal with control topics; however, the mathematical approach appears somewhat difficult for some students. To improve the academic performance of these students and to prevent drop-out, it is important to include other approaches that facilitate control learning in ways that are different from the mathematical approach.

There are different models defining learning styles, notable among these is the David Kolb model. Kolb developed 'The learning style inventory' [1] to measure differences in learning styles in two basic dimensions: abstract–concrete and active–reflective [2]. This inventory is proposed from the Experiential Learning Theory (ELT) popularized by David Kolb from works developed by John Dewey and Jean Piaget, among others [3]. Kolb identified four kinds of learning styles for students, namely: converger, diverger, assimilator, and accommodator. According to [2], the converger's dominant learner abilities are in abstract conceptualization and active experimentation; whereas, the diverger learns best with concrete experiences and reflective observations. The assimilator's dominant learning abilities are in abstract conceptualization and reflective observation and accommodators work best with real experiences and active experimentation.

On the other hand, Howard Gardner proposes seven kinds of intelligence: linguistic, logical–mathematical, spatial, kinesthetic, musical, intrapersonal, and interpersonal [4]. In [5], these intelligences are defined as: linguistic intelligence involving sensitivity to spoken and written language, the ability to learn languages, and the capacity to use language to accomplish certain goals; logical–mathematical intelligence consists of the capacity to logically analyze problems, carry out mathematical operations, and investigate issues scientifically; musical intelligence involves skill in the performance, composition, and appreciation of musical patterns; kinesthetic intelligence entails the potential to use one's whole body or parts of one's body to solve problems; spatial intelligence involves the potential to recognize and use the patterns of open space and more confined areas; interpersonal intelligence is concerned with the capacity to understand the intentions, motivations and desires of other people; and intrapersonal intelligence entails the capacity to understand oneself and to appreciate one's feelings, fears, and motivations.

Other works like [6] and [7] discuss the relationship between learning styles and multiple intelligences. In [6], the authors state: 'Multiple

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intelligences address what is taught and learning styles address how it is taught, and what the context is'. In [7], the authors define 'Multiple Intelligence as concerned with the difference in the process of learning; whereas, the theory of learning styles centers on the content and products of learning'.

Thus, if there are different approaches to learning and intelligences, and there is a relationship between them, then learning and teaching practices should stimulate learning from different perspectives in order to satisfy the particular needs of students.

In control courses, it is common to teach and to learn subjects using mathematical thinking; this is beneficial for students with logical intelligence and abstract conceptualization, but what happens to students who have other kinds of predominant intelligence or dominant learning abilities? This work suggests a novel way of understanding control concepts in a stage before the mathematical analysis of the topics. This work does not seek to deal with all kinds of intelligences or learning styles, but aims to offer an alternative for students who learn better from concrete experiences. In this proposal, the qualitative aspect is more important than the quantitative aspect. This paper is devoted to the use of Hands-On sessions to motivate students to learn concepts in a fun way and to improve knowledge retention—the term 'Hands-On' has been used because students develop a concrete activity (game) to construct a concept. Hands-On sessions offer new environments, advantages, and resources to learn through 'play' experiences.

In learning about control, Hands-On sessions are often used in laboratory practices to develop technical skills to put knowledge into practice. These sessions seek to facilitate the learning of concepts through experimental practices that include the implementation of plants and design and the testing of control strategies. For example, in [8] and [9] the authors describe the Hands-On design integrating a control process breadboard where freshman, junior, and senior students develop different lab experiences according to their academic levels. Likewise, in [10], the authors present the use of a training simulator in a process of control education to provide students with the significant Hands-On practice that is critical to learning the subject. In paper [11], the authors explain the use of Hands-On experience for fundamental theories in machine science to provide underpinnings to automation and robotics. And in [12], the authors review active learning experiences for the Automatic Control course, among which are using Hands-On laboratories as practice sessions: in the lab course, students work with a thermal system that they have built, which is made up of simple elements.

In addition, this paper proposes Hands-On sessions as didactic strategies for lectures in theoretical courses, where students can construct and understand concepts while playing games designed by the teacher in the classroom.

Other works, like [13] and [14], also propose the use of games to improve student learning in control education. The authors reviewed a series of games for teaching and present a game called Find-T (to find the value of a variable T) to learn frequency response methods and cover topics such as Bode, Nyquist, gain and phase margins, and lead/lag design.

Several papers [15–18] emphasize the use of games and play activities in learning engineering topics. Most of these focus on the analysis of the effects and advantages of computer-supported games on learning. In [15], the authors present experiences on the use of games from three different contexts. Reference [16] reports on a control experiment to compare the learning effectiveness of games played with traditional paper exercises, as well as with textbook reading. Reference [17] presents an on-line, game-based learning model to design a constructivist learning environment and gives an example to illustrate this. Finally, in [18], the authors develop a system where the computer recognizes the states of the user-manipulated objects in real time and gives users advice on executing learning tasks; this system supports Hands-On sessions. The last work presents interesting examples on the use of games and play in learning or resources to support Hands-On sessions, which are computer-supported. In contrast, the approach presented here proposes the use of games to facilitate an understanding of the concepts without employing elements or software of high technological complexity. The approach is being evaluated in control courses for an undergraduate engineering program.

The paper is organized as follows: Section 2 describes how a Hands-On session is planned and developed. Section 3 shows Hands-On sessions designed to introduce control topics such as a description of a typical control loop, time response analysis, stability, root locus analysis, frequency response analysis, and control structures. Section 4 presents student feedback and the survey used to evaluate the use of Hands-On sessions in control education. Finally, Section 5 gives some concluding remarks.

2. Planning and developing a hands-on session

During the first semester of 2008, the system control staff of the Electronics Engineering Program at the Universidad del Valle in Cali, Colombia decided to use Project-Based Learning (PBL) as an educational approach [19] and proposed changing traditional lectures for activities that, like PBL, promote active learning. Thus, the staff suggested the use of Hands-On sessions in lectures to encourage the learning of control concepts [20] and improve knowledge retention.

The object of Hands-On sessions is to motivate students to learn while having fun so that they have a ‘feel’ for the knowledge and relate concepts to simple events without using mathematical explanations, complex equations, or technological resources. Though Hands-On sessions are carried out within a PBL approach, the proposal presented here can be used in other approaches such as traditional education. This paper proposes four stages for planning and developing a Hands-On session for learning control concepts, these are: design, development, brainstorming, and mini-lectures (Fig. 1). These stages are described below.

2.1 Designing a Hands-On session

When a new topic is presented through a Hands-On session, the teacher designs a motivational game, carefully planned from the concept, taking into account constraints such as materials, number of students, and time. The teacher uses inexpensive and portable material such as Styrofoam plane boards and rollers, strings, plastic cups, Plasticine, etc. The designing of the game is the first stage of the Hands-On session and it is the sole stage developed by the teacher outside the classroom (Fig. 1).

The game is the main element of the activity aimed at bridging the gap between knowledge and learning because it addresses the understanding of a concept. The game seeks to illustrate a fundamental concept by the use of play. Because Hands-On sessions are focused more on the construction of concepts than on the development of technical skills, the game must be clear and concise, and the information it gives must help students to walk towards the concept. The game does not explicitly have the concept; it only has key-actions to construct it.

The success of the Hands-On session strongly depends on the motivation of the students who are conducting the activity. This motivation is encouraged by the game. The design of the game demands a great deal of creativity from the teacher and becomes the most important challenge in the design of a Hands-On session. Once the game is designed, it is presented to teachers in the control system area to get their suggestions and comments, and later it is tested and adjusted. Finally, the teacher writes the guideline that will guide the students during the development of the Hands-On session.

The guideline has four elements: execution time, materials, instructions, and queries. Instructions itemize the directions in which to develop the activity and the query section has questions or requests that students must answer during the game (Fig. 2). The questions focus on the concept encouraged by

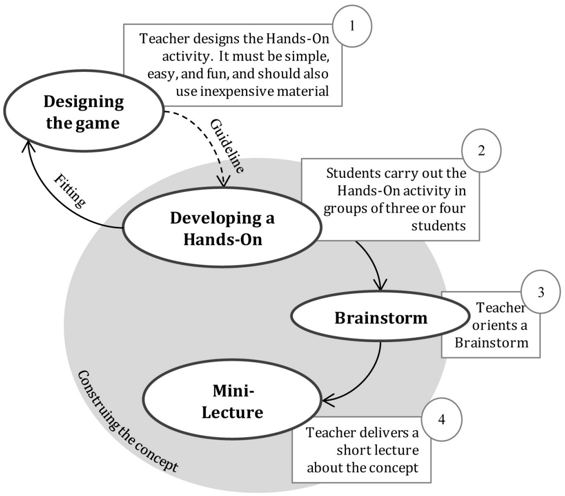
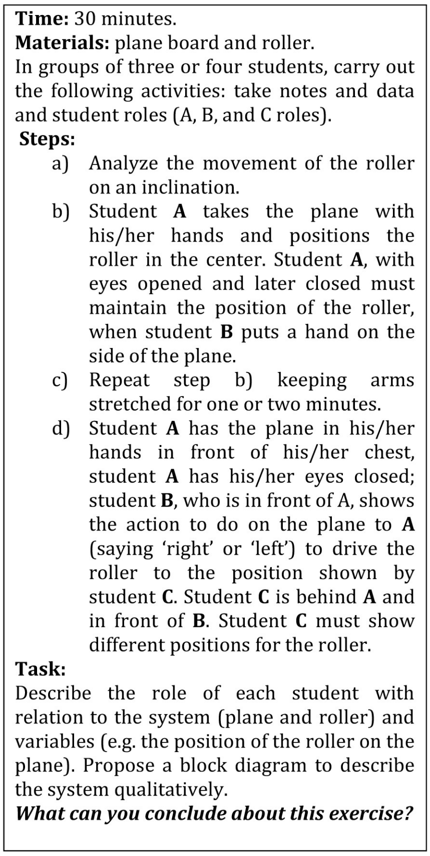


Fig. 1. Proposed model for planning and developing a Hands-On session devoted to learning control concepts.


Time: 30 minutes.
Materials: plane board and roller.
In groups of three or four students, carry out the following activities: take notes and data and student roles (A, B, and C roles).

Steps:

a) Analyze the movement of the roller on an inclination.
b) Student **A** takes the plane with his/her hands and positions the roller in the center. Student **A**, with eyes opened and later closed must maintain the position of the roller, when student **B** puts a hand on the side of the plane.
c) Repeat step b) keeping arms stretched for one or two minutes.
d) Student **A** has the plane in his/her hands in front of his/her chest, student **A** has his/her eyes closed; student **B**, who is in front of A, shows the action to do on the plane to **A** (saying ‘right’ or ‘left’) to drive the roller to the position shown by student **C**. Student **C** is behind **A** and in front of **B**. Student **C** must show different positions for the roller.

Task:
Describe the role of each student with relation to the system (plane and roller) and variables (e.g. the position of the roller on the plane). Propose a block diagram to describe the system qualitatively.
What can you conclude about this exercise?

Fig. 2. Example of a guideline used in Hands-On sessions.

the Hands-On session. The guideline is not labeled, so students have no other information than that obtained from the activity and previous readings.

Feedback from the students about the activity is very important to improving the Hands-On session; therefore, after students have carried out the Hands-On task, the teacher assesses the feedback in order to redesign and adjust the game.

2.2 Developing a Hands-On session

Students receive the guideline at the beginning of the lecture sessions; they carry out the activity in groups of three to five members: the students are free to choose their group members. Each group receives the necessary materials; this material is easily available. Some Hands-On sessions can be developed without materials.

During the session, students read the guidelines and develop the activity according to their interpretations. There is a specific time allocated to develop the activity; students must manage their time in order to develop all the steps described in the guideline. The teacher indicates when the game time is finished, so students must answer the questions.

In short, students learn the concept by play. Teachers have observed that students enjoy carrying out the Hands-On session because it is unusual to find this in a theoretical course in a technical education topic and these activities awaken a curiosity for the topic. Teachers and students consider that this is a good way to cultivate expectations for knowledge.

2.3 Brainstorm and mini-lecture

At the end of the Hands-On session, the teacher guides a brainstorming activity and the students present and debate their responses to questions from the guideline. Moreover, students have the opportunity to discuss opinions and ask additional questions about the topic. These new questions can be answered by the teacher or by other students. The brainstorming session aims to encourage students to present arguments about their observations and to share different points of view, perspectives, and interpretations on the assignments given in the guideline. Once the brainstorming is over, the teacher delivers a short lecture on the topic. The goal of this lecture is to offer a reference with which to compare the knowledge constructed from the game and the brainstorming session. At this stage, students can get more from the lecture because they have previous knowledge of the topic; furthermore, the game allows them 'to grasp' knowledge differently. The teacher uses experiences obtained from the Hands-On session as examples to explain the topics.

3. Learning control concepts through Hands-On sessions

Teachers have designed Hands-On sessions to introduce topics such as a typical automatic control loop, response time, Shannon theorem and sampling, feedback characteristics, stability, root location, frequency response, and PID control structures. These topics correspond to the control courses in the Fundamentals of Linear Control Systems and Analysis and Compensation of Linear Systems courses. The following subsections describe the most outstanding Hands-On sessions.

3.1 Identifying elements and signals of a typical control loop

This is the first topic in the control courses. The goal of this Hands-On session is to help students to identify the components of a typical control loop, namely the actuator, sensor, controller, and plant. Students also learn about the interaction between input and output signals.

At the end of the game, students can identify the function of each component and the differences between an open-loop system and a closed-loop system. This is an example of a Hands-On session that does not use additional material; here, the students all have different roles. The content of the guideline is as follows:

> Organize into groups of three. Group members stand in line (Fig. 3); the member standing in the middle closes his/her eyes. The first group member should move in different directions (forward, or to the right or left). The student who has his/her eyes closed must follow the indications from the third student who is behind him/her to track the first student who is moving. Repeat the exercise, but now both the second and third students have their eyes closed.
>
> 1. What is the function of the second student?
> 2. What operations should the third student carry out so that her/his instructions are consistent to allow the second student to track the first student? Is there direct or indirect observation? Is there a time delay in the response from the student whose eyes are closed?
> 3. What is the role of the third student's eyes? Is this student guiding the student whose eyes are closed?
> 4. What is the role of the first student who is moving in different directions?
> 5. What can you conclude about the exercise carried out? Compare the roles of students with a typical control loop.

In this instance, the third student acts as the controller and this student's instructions are the control signal. The second student whose eyes are closed is the plant and her/his legs and arms are actuators. Finally, the first student establishes the reference. The control target is for the second student to track the position of the first student. The sensors are the

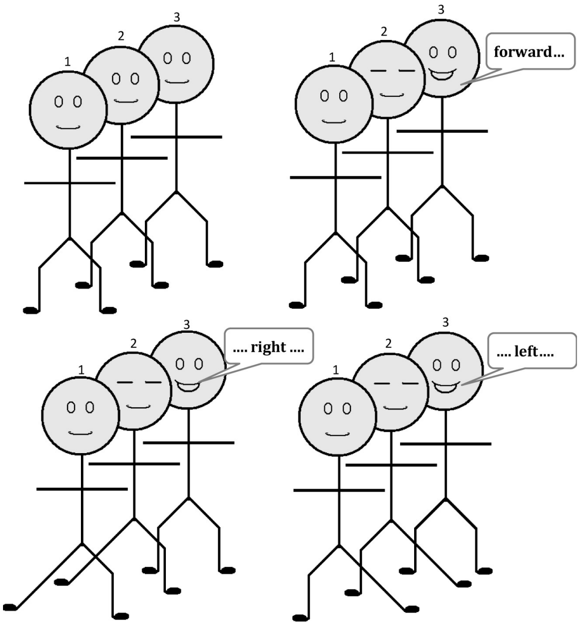


Fig. 3. Students' roles in the Hands-On session for identifying elements and signals of a typical control loop.

eyes of the third student. Once the Hands-On session is finished, students share responses to queries with other students. They discuss the roles and actions executed, and the relationship between their roles and the components of a typical control loop (Fig. 4). In addition, in order to identify the components of a typical loop, students become aware of issues such as the quality of the control signal and the delay time of the actuator. For the quality of the control signal, if the instructions are not good enough to enable tracking then the error increases, i.e., the second student's position in relation to the first student's position is different. For the actuator delay time, if the time required by the second student to interpret instructions is rather long, then the third student will give more instructions than the second student is able to interpret and, therefore, the error will increase. The challenge of this Hands-On session is not only to introduce the topic, but also to present the control subject and the didactic strategy used in the lecture sessions.

3.2 Sampling

This Hands-On session stresses the sampler work and the relationship between the sampling frequency and the reconstruction of a signal from samples. In addition, students can observe the effects of sampling processes on the performance of a control system. For this Hands-On session, each student group uses a Styrofoam flat surface and roller. Instructions for this activity are:

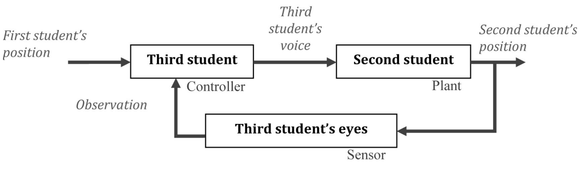


Fig. 4. Students' roles vs. components of a typical control loop.

Step 1: The members of each group stand in line. The third student moves his/her arm at a constant rate, the second student rhythmically interrupts the first student's view (field of vision) of the third student, by using an object (e.g. a notebook), taking as a reference the position of the arm and allowing for the view to occur in the same position. The first student must observe and register the arm position (Fig. 5(a)).

Step 2: The second student allows the first student to see the third student. Here, the second student uses two objects, taking one in each hand. By moving his/her left hand, the second student allows the first student to view the third student's arm near the lowest position and by moving his/her right hand allows them to see the highest position of the third student's arm. The first student must observe and log the positions of the arm (Fig. 5(b)).

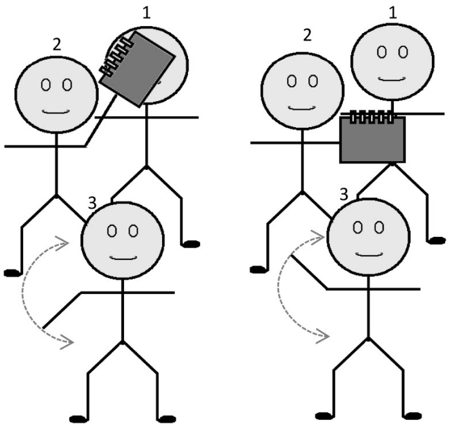
Step 3: A student holds the Styrofoam flat surface in a horizontal position, and drives the roller (which is on the Styrofoam) from one side to the center. Then, the experiment is repeated, but now the second student interrupts the first student's view (field of vision) of the flat surface, allowing a glimpse of it for just a short time. The third member of the group must register the performance achieved in the positioning of the roller in both instances (with and without interruption) by observing the speed and accuracy with which the positioning of the roller is achieved (Fig. 5(c)).

1. What are the frequencies of the observed signals during the development of steps 1 and 2?
2. Is it possible to know the rotation frequency of the arm, for the cases presented in steps 1 and 2?
3. Is it possible to know the total trajectory of the arm, for the cases presented in steps 1 and step 2?
4. What can you conclude about the performance of the control system of step 3, taking as reference the frequency of interruption of the vision of the first student?

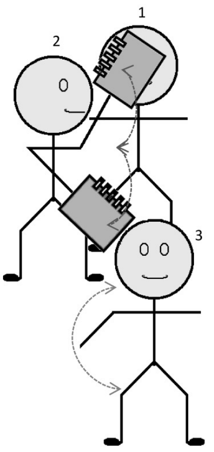
In Step 1, the first student can only see one position (DC signal) of the third student's arm; whereas, in Step 2 the first student can see two positions of the third student's arm: the first position on the top and the second position on the bottom. Thus, in Step 2, the first student has more information about the classmate's arm position. Therefore, in Step 2, the first student can deduce the frequency of the arm movement, but in Step 1 there is not enough information to do so. In other words, the exercise in Step 1 does not satisfy the conditions of the Shannon theorem [21].

The activity in Step 3 focuses on observing the relationship between the sampling and the performance of a control system. In this activity, the second student, with roller and flat surface, acts as a closed control system and controls the position of the roller over the Styrofoam flat surface. When the second student blocks the vision of first student (see Fig. 5(c)), the second student has a worse performance than before. Then, they can observe that more samples are necessary (less interruption) to improve the performance of the control system.

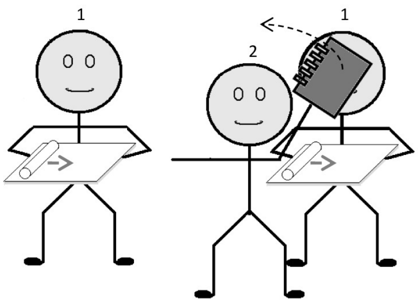
Note that in this Hands-On session students can associate the sampling process with simple events. The Hands-On session introduces the topic; after that, students learn the mathematical analysis of the Nyquist–Shannon theorem.



(a) Step 1



(b) Step 2



(c) Step 3

Fig. 5. Student activities for understanding the Nyquist–Shannon theorem in the Hands-On session.

3.3 Time-response analysis

Teaching topics such as Analysis in Time Domain usually involve the development of exercises using the blackboard or specialized software such as MATLAB® and Scicos. The Laplace transform and Inverse Laplace transform are used to enlarge on the theme. This subsection describes a Hands-On session that helps students to understand Time-Response analysis. This activity centers on the study of first- and second-order systems.

The materials for developing this Hands-On session are a string of inelastic nylon, a mass weight, a pen, and four 12-oz plastic cups (two of which have holes about 4 mm in diameter in the bottom); see Fig. 6. The capacity of the plastic cups is chosen to be greater or equal to 12 oz so that the experiment can be observed. The guideline for Time-Response analysis has two activities: the first is devoted to first-order systems and the second is dedicated to second-order systems. Initially, the guideline describes the materials and the procedure as the groups are organized. The instructions for the first activity are:

> Place a non-perforated cup on a flat and horizontal surface; over it, place the perforated cups, one above another (Fig. 6).
>
> Fill another non-perforated cup with water; then empty it into the first perforated cup, seeking a fixed level for this cup to keep a constant input flow into the second perforated cup. *Suggestion! The student who takes the first perforated cup must hold it firmly to keep the cup from dripping.* Observe the level of the second perforated cup when filling and emptying. Register the change in the level vs. time (*Tip: record the time whenever the level goes through a striation on the cup*); sketch the time evolution. What can you conclude about the evolution of the level while filling and emptying the cup? How long does it take for the cup to achieve a constant value?

In this instance, students observe the behavior of the liquid level in the second perforated cup. Initially, the second cup is being filled and students can register the level vs. time until the level achieves a constant value. The input flow is then almost the same as the output flow and the level is almost constant. The second cup then acts as a first-order level system described by Equation (1); where C is the cup capacitance, R is a constant equivalent to resistance offered by the output hole, $Q_i(s)$ is the Laplace transform of input flow $q_i(t)$, and $H(s)$ is the Laplace level transformer. The large capacity of the cup made its capacitance almost constant.

$$\frac{H(s)}{Qi(s)} = \frac{R}{RCs+1} \tag{1}$$

Once the first cup is empty, the second cup begins the discharge; students again record the level vs.

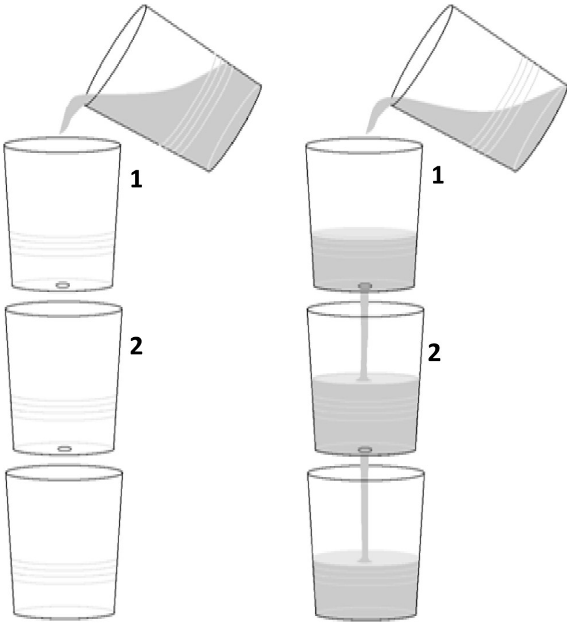


Fig. 6. Positions of plastic cups to develop the Hands-On session devoted to analyzing the time response of a first-order system.

time. The record allows the students to sketch the liquid level behavior in the time domain, so they know the time response from a first-order system during a step input and the discharge from an initial condition.

Instructions for the second activity are:

> Tie a 150-g weight mass at an end of a 1-m inelastic nylon string. Then tie a pencil to the other end of the string. A student holds the pencil and another student lifts the mass weight, keeping the tension in the nylon string, then they drop the mass and observe the behavior of the mass (Fig. 7). Register the number of oscillations and their frequency.
>
> 1. What do you observe about the horizontal displacement (x) of the mass?
> 2. How much does the maximum x decrease with each oscillation?

In this activity, a simple pendulum commonly used in physics allows an understanding of the time response of second-order systems in the control topic. Taking as the output variable the horizontal displacement (x), the pendulum acts as a low-damping system, which allows the observation of the system dynamics described by Equation (2), where K is the DC gain, ω_n is the natural frequency that depends on the length of the string and gravitational field strength (g) and ρ is rate of damping. Students observe the free-response of the system, record data from the experiment and draw the position of the mass. Given that the system has a low-damping rate and is excited by a small signal, the parameter ω_n is nearly equal to the oscillating frequency recorded by the students; moreover, the students can infer the damping rate from the decrease observed in the peak horizontal displacement at each oscillation.

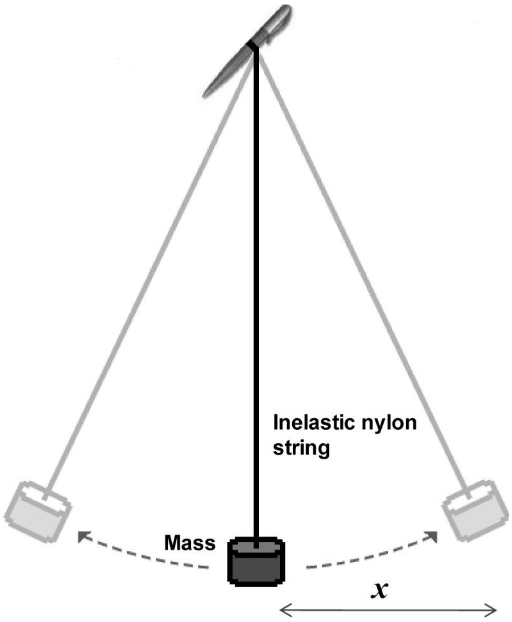


Fig. 7. Element set-up used to analyze the time response of a second-order system.

$$G(s) = \frac{k\omega_n^2}{s^2 + 2\rho\omega_n + \omega_n^2} \tag{2}$$

3.4 *Root locus analysis*

In this topic, students carry out an activity by again using the Styrofoam roller and flat surface. In this Hands-On session, students also organize themselves into groups of three or four. They distribute tasks amongst themselves to achieve a successful activity. The guideline instructions describe an exercise repeated several times under different conditions. The target of the activity is to move the roller from a side of the flat surface to center it. The instructions are as follows:

> Take into account that all experiments must have the same initial conditions: roller position, hand position, velocity, angle of the flat surface, and so on. Develop several tests as training before carrying out the final exercise. Put the flat surface in front of you and lift it by holding it with your thumb on the top as in Fig. 8. Repeat this experiment for the following instances:
>
> a. The plane surface rests on the opposite edge to the hand that holds it (Fig. 9(a)).
> b. The plane surface rests on its center (Fig. 9(b)).
> c. The plane surface rests as close as possible to the hand (Fig. 9(c)).
> d. The plane surface is not rested on anything. Rotate the plane surface from the wrist, keeping the forearm in contact with the body.
> e. Repeat the experiment seeking the quickest possible behavior (without breaking the plane surface), see

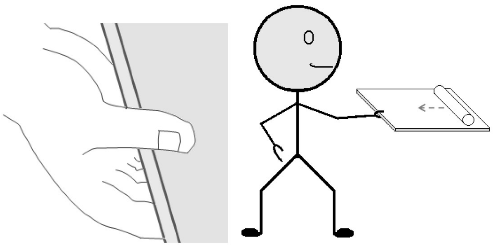


Fig. 8. How to hold the flat surface used in the Hands-On session for the root locus analysis.

Fig. 10(a). Carry out this activity using both a thin flat surface and a thick flat surface.

f. The plane surface is not rested on anything. Move the plane from the elbow joint keeping the arm in contact with body above the elbow (Fig. 10(b)).
g. The plane surface is not rested on anything. Move the plane from the shoulder joint keeping the arm stretched forward (Fig. 10(c)).

Questions:

1. How is the behavior of the controlled system (rested plane surface) with regard to the rest position?
2. What is the relationship between the results from the (a) and (d) instances?
3. What is the behavior of the controlled system for the plane surface resting and not resting on anything?
4. What differences are there between the (d) and (e) instances?
5. What is the behavior of the controlled system, with the plane surface not resting on anything, relative to the joint used to move it ((d), (f), and (g))?
6. What can you conclude about the behavior of the system?
7. Can you sketch a graph to show general information about the system performance for the different situations studied?

In root locus analysis, the different pole locations of the closed-loop system are plotted on the 'S' plane. These locations depend on the change of a parameter, usually the Gain of the open-loop system. The root locus analysis allows a knowledge of the stability of the closed-loop system from the information contained in the plot.

In the Hands-On session designed to understand root locus analysis, students observe how the performance of the system (student, plane surface, and roller), whose target is to position the roller, changes according to the task to be executed. Each task represents a different gain, this means that parameter K of the open-system transfer function varies (Equation (3)), in other words, the gain changes as a function of the flat surface position with regards to the body. Therefore, the dynamics of the closed-system are also different for each task. Step (e) tries to show high-frequency dynamics (the Styrofoam flexibility) excited by a high-speed control. This qualitative means of introducing the root locus analysis was developed by taking into account that the gain is the sole parameter that changes, since the control target and elements making up the system are kept to develop all the tasks.

$$GH(s) = \frac{K}{s(\tau s + 1)} \tag{3}$$

3.5 *Frequency-response analysis*

This Hands-On session is one of the most elaborate; it uses many materials, including two nylon strings (one elastic nylon and the other inelastic nylon), Plasticine, a 3-cm radius ring, weights, 4-cm radius

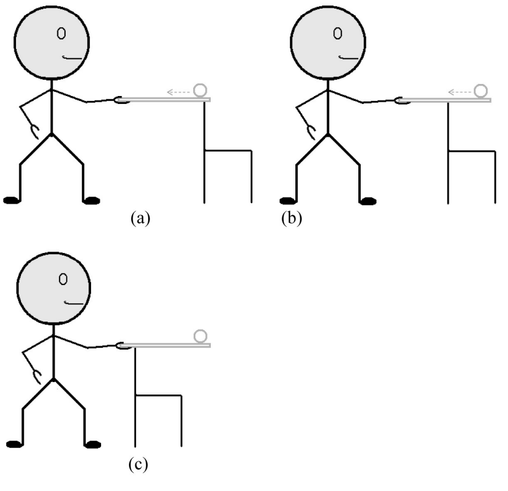


Fig. 9. Cases with the roller rested on something for the Hands-On session focused on the root locus analysis.

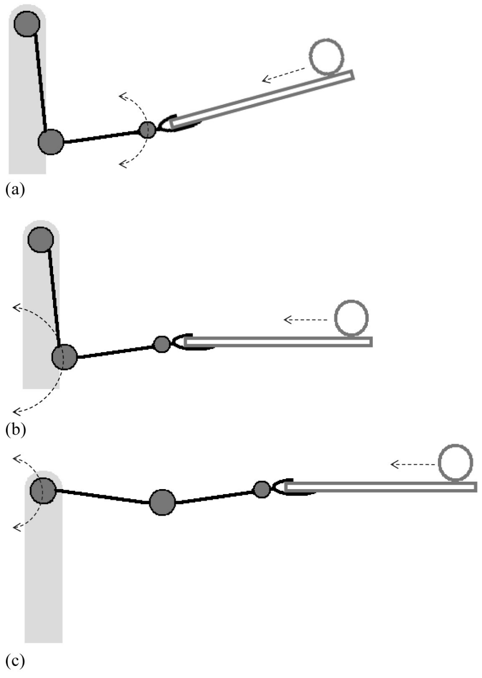


Fig. 10. Cases when the plane surface does not rest on anything for the Hands-On session focused on the root locus analysis.

cup lids, a watch, pencils, and sheets of plotting paper. The development of this Hands-On session requires about 90 minutes, unlike previous Hands-On sessions that were scheduled for 30 minutes. Moreover, this Hands-On session is carried out by five students each developing different tasks. Each task is labeled with letters, thus: register of notes, RD; data measurer, MD; ring holder, PA; sinusoid generator-controller, GS; master clock, *W*, and rest for the process, AP.

Once the tasks are distributed among group members, they follow instructions from the guideline, which has three activities as described below:

Activity 1:

a. Tie one end of the elastic nylon string to the mass weight and the other end to the inelastic nylon string. Mark the union of the two strings using Plasticine; this mark serves to enable the students to observe the displacement (*R*) of the inelastic nylon string (Fig. 11).
b. Pass the free end of the inelastic string through the ring and then tie it to a pen (Fig. 11).
c. **GS** moves the pen circularly over the cup lid to generate a horizontal displacement.
d. The ring turns the horizontal displacement into vertical displacement.
e. **GS** follows the rhythm defined by **W**, as required by the experiment.
f. The rhythmic pattern is generated from the clock (*i.e.* **GS** turns the pen, with a period of five seconds).

NOTE: Ensure that the knots tying the elements are tight, to prevent accidents.

Activity 2:

GS is stopped. Move the mass weight up so that can oscillate freely.

The number of oscillations and their frequency (F_n) will be registered by RD and MD.

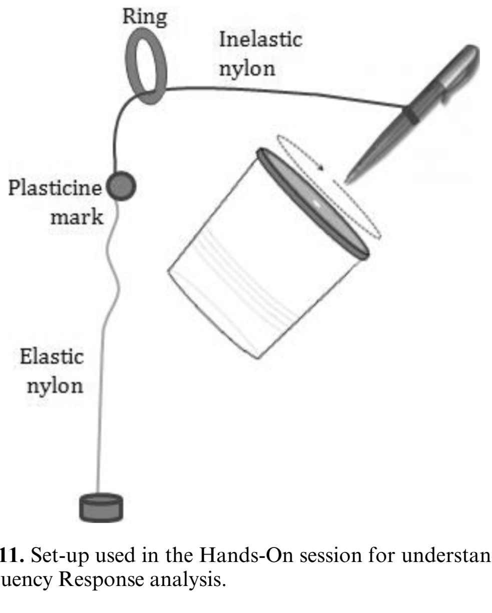


Fig. 11. Set-up used in the Hands-On session for understanding Frequency Response analysis.

Activity 3:

Observe the peak-to-peak deviation of the mass weight (*M*) and its position (*F*), taking as a reference a value of *R* (for example, the top or bottom). Record the data only after achieving a uniform periodic movement. Record *W*, *M,* and *F* in a table. Repeat these instructions for the following situations:

a. At the slowest rhythm, ensuring a uniform velocity of the pen.
b. A little faster than in the previous step so that *M* increases.
c. At the rhythm where the maximum, *M,* is observed.
d. At the rhythm where the phase of *M* is opposed to the phase of *R*.
e. Faster than in the previous step to achieve similar displacements for *R* and *M*.
f. Faster than the last case so that *M* is 70% of *R*.
g. As fast as possible, ensuring a uniform velocity of the pen.

Questions:

1. What are the approximate dynamics of the spring–mass system?
2. What is the ratio between the magnitudes *M* and *R* (*M*/*R*) and the phase difference between the sinusoids shown by the inelastic nylon and mass weight, at low and high rhythms?
3. What is the maximum ratio of the magnitudes *M* and *R* (*max M*/*R*)? At what frequency are these values obtained?
4. What is the ratio between *M* and *R* in step *d*? If it were 1, would it be easier or harder to control the system?
5. What phase difference was observed in step *e*? If it were 180°, would it be easier or harder to control the system?
6. What can you conclude about the behavior of the system?
7. Can you outline some graphs that furnish general information about the system performance for the different cases studied?

The mass weight and the elastic nylon string act like a mass–spring system. The system position changes according to the movement of the pen over the cup lid. In other words, the output signal behavior depends on the input signal represented by the movement of the pen (rhythm pattern). Given the periodic movement of the pen, which sketches a circle over the cup lid, the input signal is sinusoidal and its frequency depends on the movement velocity. The frequency response is obtained by observing the system performance for different frequencies, which ranges from zero to a large value (ideally infinity). The variations in frequency are approximate. The clock is used as a reference to generate the input signal and observe the system.

The inelastic nylon string transmits the movement to the spring–mass system and the Plasticine mark allows visualization.

The ratio between *M* and *R* is the system gain (*M*/*R*). Questions 4 and 5 stress the system stability; in these questions, students are asked for the phase and gain margins. Note that, in these questions, students must obtain the phase when the gain is unitary and also, the system gain when the phase is 180º and discuss the performance of the system.

In the guideline instructions for the Hands-On session, students are encouraged to obtain the frequency response at key values so that they can outline the system gain in the frequency domain, for example, instructions c and f ask for the maximum gain and 70% of the gain, respectively. It is worth noting that this Hands-On session seeks to introduce the study of frequency response by using simple and inexpensive items, and defining several tasks where each student has a different role.

3.6 Other Hands-On sessions

The Industrial Control Research Group (GICI) at the Universidad del Valle has developed other Hands-On sessions for topics such as: Feedback Characteristics and Stability, PID Controllers, and Control Structures. Figure 2 shows the guideline used for understanding Feedback Characteristics. In this Hands-On session, students can observe the advantage of Feedback through comparing the behaviors of an unstable system and a stable system. In activity a, students observe an unstable system in open loop. In activity b, the closed-system response is compared with the open-system response, when there is a perturbation. Activity c repeats the previous comparison and a change of parameters (due to fatigue) is additionally introduced. Finally, activity d shows an unstable controlled system. The activities presented in the guideline for Feedback Characteristics can also be used to learn about Stability.

All Hands-On sessions designed so far can be consulted in the GICI web site http://gici.univalle.edu.co, including activities centered on PID and control structures. These activities will be presented in a future paper focusing on understanding different control strategies through Hands-On experiences.

Hands-On sessions have been used in control courses since the autumn semester of 2008. Professors and students on control courses have helped to adjust the activities. Currently, GICI is developing new Hands-On sessions for other control systems topics. GICI hopes that teachers from different places around the world will use the activities shown in this paper and propose new Hands-On sessions that will enhance control learning in the same way.

4. Student feedback

Table 1. Survey to evaluate the Hands-On Sessions

Q1:	Hands-On sessions facilitate learning of the concept
Q2:	Hands-On sessions motivate interest in the topics
Q3:	Hands-On sessions help me to construct knowledge
Q4:	Hands-On sessions stimulate cooperative work
Q5:	Hands-On sessions were developed by using suitable resources
Q6:	Hands-On sessions have clear and well-defined guidelines
Q7:	Hands-On sessions help me to understand the concept in a fun way
Q8:	I participated actively in Hands-On sessions
Q9:	I felt comfortable with Hands-On sessions
Q10:	I remember easy concepts learned by using Hands-On sessions

A survey was designed to evaluate the impact of Hands-On sessions in the theoretical courses. In the survey, questions are presented as statements. Students evaluate the level of compliance of each statement. The scale ranges from 1 to 5: 1 = no compliance and 5 = excellent level of compliance. The reliability of the survey was evaluated using the Cronbach Alpha Coefficient [22]. The survey was applied in the courses Fundamentals of Linear Control Systems (Control I) and Analysis and Compensation of Linear Systems (Control II). In the first course, 12 students filled out the survey and 33 students did so in the second course. The statements in the survey are presented in Table 1.

In both courses, all statements obtained a score average greater or equal to 4 (Fig. 12). Most students scored the statements with levels of compliance of 4 or 5. The total score average was 4.6 for the first course and 4.3 for the second course.

For the survey results analysis, the queries were grouped according to three aspects: Contribution to Learning, Resources, and Motivation. There are four questions about the Contribution to Learning, Q1 asks if the Hands-On sessions facilitate learning the concept, Q3 asks about knowledge construction, Q7 emphasizes understanding the concept in a fun way, and Q10 focuses on remembering the concept when Hands-On sessions are used. In the first course, the score averages for the response to these queries are 4.6, 4.5, 4.5, and 4.4, respectively; and in the second course these score averages were

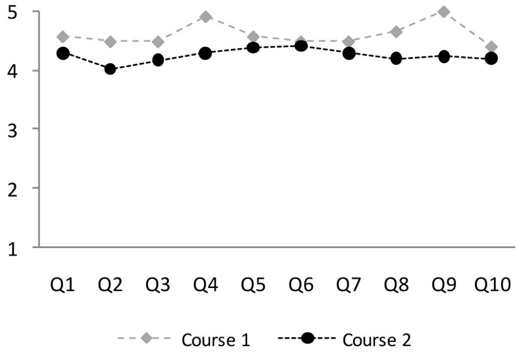


Fig. 12. Results of the Survey to evaluate the use of Hands-On Sessions in control courses.

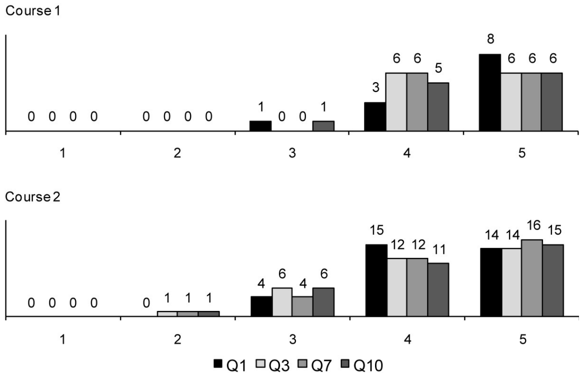


Fig. 13. Survey results for the Contribution to learning aspect. Queries Q1, Q3, Q7, and Q10. The horizontal axis corresponds to query scores; the scale used is from 1 to 5, 1 = no compliance and 5 = excellent level of compliance with the statement. The standard deviations of responses to queries about learning are 0.67, 0.52, 0.52, and 0.67, respectively, for the first course and 0.68, 0.85, 0.81, and 0.86, respectively, for the second course.

4.3, 4.2, 4.3, and 4.2. The Survey results for the learning aspect are shown in Fig. 13.

Student scores are concentrated on scores 4 and 5 of the range. The scores of responses to queries to the *Contribution to Learning* aspect show that Hands-On sessions are useful to support control learning and help students to understand the topic in a different way from the traditional lecture.

Two queries focus on evaluating the resources of the Hands-On sessions; Q5 specifies the pertinence of the resources used in a Hands-On session, and Q6 seeks to find student opinions on the design and content of the guidelines. In the first course, the average score for query Q5 is 4.6 and 4.5 for Q6; in the second course, the average score is 4.4 for both queries. Figure 14 presents the results for queries about *Resources*. Results of the survey about the resource aspect indicate that students agreed on the material chosen for the Hands-On session and that the content of the guideline is enough to carry out the experiment.

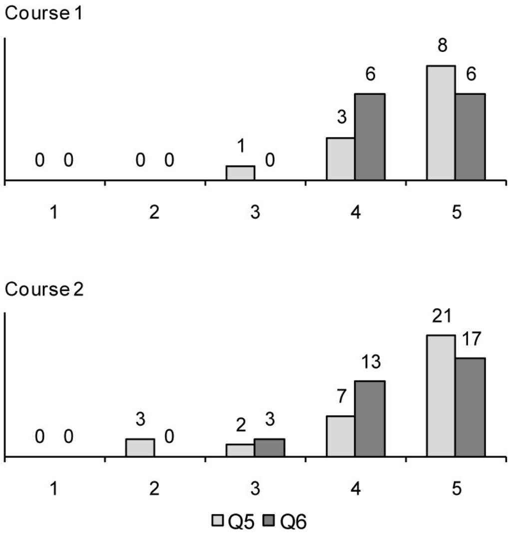


Fig. 14. Survey results for the Resource aspect, queries Q5 and Q6. The horizontal axis corresponds to query scores; the scale used is from 1 to 5, 1 = no compliance and 5 = excellent level of compliance with the statement. The standard deviations of responses to queries about Resources are 0.67 and 0.52, respectively, for the first course and 0.97 and 0.66, respectively, for the second course.

Queries Q2, Q4, Q8, and Q9 stress the motivation of students to learn and participate in Hands-On sessions: Q2 asks about interest on the topics, and Q4 asks about cooperative work; the score averages for responses to these queries are 4.5 and 4.9 for Course 1 and 4.0 and 4.3 for Course 2.

Q8 and Q9 ask about students' feelings during the activities: Q8 asks about participation and Q9 seeks to identify if students are comfortable with the activities. In Course 1, the score averages of the responses to these queries are 4.7 and 5.0, respectively; in Course 2, both queries obtained 4.2 as an average score. Figure 15 shows the distribution of the students according to the scores for each query. Students scored queries related to the *motivation* with high scores; this means that students consider the Hands-On session as a suitable academic activity to encourage learning about control systems.

The survey has a blank space for open comments and suggestions. Comments made by the students included: 'The Hands-On session is an excellent tool to acquire knowledge', 'These activities are useful to suitably know the topics', and 'These activities are good because we learn in a fun way without the conventional lecture'.

The Hands-On sessions allow students to under-

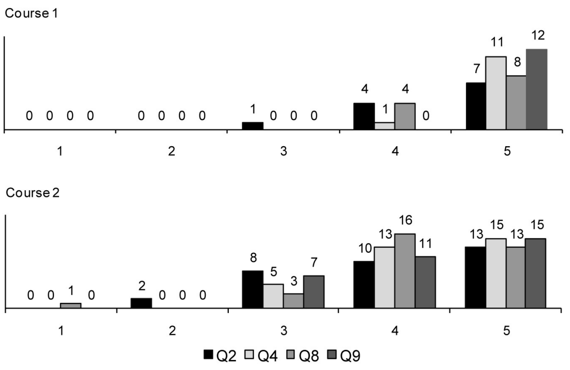


Fig. 15. Survey results for Hands-On activities for the Motivation aspect, queries Q2, Q4, Q8, and Q9. The horizontal axis corresponds to query scores; the scale used is from 1 to 5, 1 = no compliance and 5 = excellent level of compliance with the statement. The standard deviations of responses to queries about learning are 0.67, 0.24, 0.49 and 0.0, respectively, for the first course and 0.95, 0.73, 0.86 and 0.79, respectively, for the second course.

stand the topics in a different way and permit teachers to exploit their creativity and to change their roles. Teachers can now help students to gain knowledge through a different approach. Students are involved in activities that stimulate their observation and interpretation of events; hence, they can find explanations for complex concepts through simple actions.

Student scores also show that the Hands-On sessions help students to improve their learning in the control courses. Though Hands-On activities are part of the changes implemented in the control courses, among these are the use of Project-Based Learning as an educational approach and a new evaluation design. The Hands-On sessions are the main activity for learning concepts in lectures; therefore, the better results obtained by students depend largely on the Hands-On sessions.

Table 2 shows the students' grade point averages for control courses using Hands-On sessions and courses using traditional lectures. In courses with Hands-On sessions (HO), student grade point averages are higher than the averages obtained in courses using classical lectures (CL). Moreover, the percentage of students with poor performance (SPP) decreased in courses with Hands-On sessions; for Control I courses, this percentage ranged between 6% and 15% less than the percentage achieved in courses developed with classical lectures, which ranged from 13% to 22%. For Control II courses, the percentage of students with poor performance was near zero when the Hands-On sessions were used. The variation coefficients (VC), presented in Table 2, indicate a higher concentration of grades in courses using Hands-On sessions, distributed in a higher rating.

Furthermore, when teachers were consulted about the control courses, they highlighted the use of the Hands-On sessions to encourage student learning.

Table 2. Overall results per semester from student scores

	Semester	$\bar{x}$	σ	SN	SPP	*VC*	
CL	Feb-Jun/07	3.3	0.5	32	13%	14.88%	Control I
	Aug-Dec/07	3.1	0.8	32	22%	25.70%	
HO	Feb-Jun/09, G1	3.7	0.4	17	6%	10.765	
	Feb-Jun/09, G2*	3.6	0.5	13	15%	13.36%	
CL	Aug-Dec/07	3.3	0.8	43	28%	24.27%	Control II
	Feb-Jun/08	3.7	0.7	32	3%	17.65%	
HO	Aug-Dec/08*	3.7	0.4	33	3%	10.51%	
	Aug-Dec/09_G1	3,7	0,4	19	0%	9.80%	
	Aug-Dec/09_G2	3,9	0,3	8	0%	6.58%	

$\bar{x}$ = average, σ = standard deviation, VC = Variation Coefficient; SN = Student Number, SPP = Students with Poor Performance. HO = courses using Hands-On sessions, CL = courses using Classical Lectures. * Semesters in which the survey was applied.

5. Concluding remarks

Hands-On sessions are designed by using four stages: design, development, brainstorming, and a mini-lecture. The design involves much creativity from the teachers. It is the only stage carried out outside the classroom. The design of a Hands-On session implies proposing a game whose goal is to motivate and encourage students to learn a concept in a fun way. In the development stage, students are free to interpret the game from the information that they are given in an instructions guideline. The brainstorming allows students to discuss the topics and compare their interpretations. Finally, the mini-lecture orientated by the teacher helps students to identify the core of the concept and relate it to their experience during the development of the Hands-On session.

All Hands-On sessions use inexpensive and easily available materials. The aim is to develop an activity with simple elements that facilitate an understanding of the concept without using software or highly technological and complex elements. Thus, students can get a 'feel' for the knowledge through the game and relate to it with simple events. In this proposed approach for Hands-On sessions in control learning, the qualitative aspect given by the game is more important than the quantitative aspect, which is conventionally achieved by means of software or specialized lab equipment. In addition, the Hands-On sessions do not need special physical spaces for their development.

Hands-On sessions have been designed for students to learn topics such as the description of a typical control loop, analysis in the time domain, stability, root locus analysis, and analysis in the frequency domain. Most Hands-On sessions use materials such as Styrofoam rollers and flat surfaces, nylon strings, mass weights, and cups. Students work collaboratively in groups of three to five members, to develop the activity.

The impact of Hands-On sessions was evaluated by means of a Survey that focused on three aspects: contribution to learning, motivation, and resources. According to query scores graded by students, the Hands-On session is useful in supporting learning about control and in helping students to understand concepts in a way that is different to the traditional lecture. Survey results show that students consider the Hands-On session a suitable academic activity to encourage learning in control systems. Moreover, scores for the resource aspect indicate that students agreed on the materials chosen to conduct the activity; likewise, they gave high scores to the query asking whether the content of the guideline gives enough information to successfully play the game in the Hands-On session.

Teachers of control courses opine that Hands-On sessions are a good didactic strategy to engage students in the control subject and improve information retention. They have observed students to be more motivated and committed to course assignments and noted increased memory retention compared with control courses developed via traditional education. Currently, GICI is designing new Hands-On sessions for other control topics, which include themes of multivariable control and modern control.

Hands-On sessions are a novel way of helping students to improve learning about control because they present the topics in a different way and offer an alternative method of understanding the control topic, using play and having concrete experiences where they can grasp knowledge.

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