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The Ball and Beam System: a Case Study of Virtual and Remote Lab Enhancement with Moodle

Luis de la Torre, Maria Guinaldo, Ruben Heradio, and Sebastian Dormido

***Abstract*—Web-based labs are key tools for distance education that help to illustrate scientific phenomena which require costly or difficult-to-assemble equipment. Easy Java Simulations (EJS) is an authoring tool that speeds up the creation of that kind of labs. An excellent proof of the EJS potential is the Open Source Physics (OSP) repository, which hosts hundreds of free EJS labs. Learning management systems, such as Moodle, provide social contexts where students interact with each other. The work described in this paper looks for the synergy of both tools, EJS and Moodle, by supporting the deployment of EJS labs into Moodle and thus enriching them with social features (e.g., chat, forums, videoconference, etc.). To test this approach, the authors have created the *ball and beam* lab, which helps students of automatic control engineering to train different advanced techniques (robust, fuzzy and reset control), and compare their performance in relation to a conventional proportional-integral-derivative control.**

***Index Terms*—Virtual laboratory, Remote Laboratory, Learning Management System, Web-based Experimentation, Control Engineering Education.**

I. Introduction

It is commonly accepted that digital media (such as simulations, videos, interactive screen experiments or web labs) can positively impact student knowledge, skills and attitudes [1], [2]. Consequently, Learning Management Systems (LMSs) and online experimentation have become widespread in distance education.

LMSs support the administration, documentation, tracking, and reporting of training programs, classroom and online events [3].

Online experimentation is a broad concept that encompasses not only virtual and remote experimentation, but also other online tools based in virtual reality, augmented reality, sensorial devices, live videos, interactive videos and serious games which promote user immersion in virtual environments recreating the real experience [4], [5]. In particular, this paper is focused on the so called virtual and remote labs (following the terminology proposed in [6]), which make possible to illustrate scientific phenomena that require costly or difficult-to-assemble equipment [7]:

- Virtual Labs are computer based simulations which offer similar views and ways of work to traditional hands-on laboratories [8]. Nowadays, virtual labs have evolved into interactive graphical user interfaces where students can manipulate the experiment parameters and explore its evolution.
- Remote Labs use real plants and physical devices which can be used at distance [9], [10], [11], [12], [13], either by teleoperating and receiving measurements from them or by modifying some input parameters and allowing simple visual observation. Remote experimentation through the Internet has been available from nearly two decades [14], [15] and its interest has not diminished over the years [16], [17].

Virtual and/or Remote Labs (VRLs) are complementary tools that can be brought together as hybrid labs [18]. An important concern about VRLs is that developing them from scratch requires a huge effort. Easy Java Simulations[1] (EJS) [19] helps to overcome this problem. It is an authoring tool that speeds up and facilitates the creation of discrete computer simulations. An excellent proof of the EJS potential is the Open Source Physics (OSP) repository[2] [20], which offers hundreds of EJS simulations that can be freely downloaded and modified to create new simulations. During the last few years, EJS has grown for helping to create web-accessible laboratories in control engineering education. With this objective in mind, recent releases of EJS support connections with external applications, such as LabView[3] and Matlab/Simulink[4]. Hence, EJS not only is useful to create virtual labs, but also the Graphical User Interfaces (GUIs) of their remote counterparts [21].

Although there is evidence of the positive effects that collaborative student interaction has over VRL activities [22], [23], [24], most of the online labs developed to date suffer from a lack of providing social contexts which support collaborative group work [25], [26]. A possible approach to enrich VRLs with collaborative features is deploying them into LMSs. Thus, VRLs take advantage of the LMS capacity to support the virtual interaction among participants.

Two different types of collaborative environments may be considered according to the moment when the student-student (or student-teacher) interaction takes place: asynchronous and synchronous [27]. The first ones allow data exchange in flexible timetables and remote access to web-based course

Luis de la Torre, Maria Guinaldo, and Sebastian Dormido are with Departamento de Informatica y Automatica, Universidad Nacional de Educacion a Distancia, Madrid, Spain e-mail: {ldelatorre, mguinaldo, sdormido}@dia.uned.es

Ruben Heradio is with Departamento de Ingenieria de Software y Sistemas Informaticos, Universidad Nacional de Educacion a Distancia, Madrid, Spain e-mail: rheradio@issi.uned.es

[1] http://fem.um.es/Ejs/
[2] http://www.compadre.org/osp/
[3] http://www.ni.com/labview/esa/
[4] http://www.mathworks.com/products/simulink/

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materials to carry out activities in an asynchronous way. They use collaborative tools such as e-mail or forums for on-line communication. This is the typical approach offered by most classic LMSs. However, students may likely feel less engaged with the course if the instructor relies primarily on the use of asynchronous communication [28]. Furthermore, students do not receive instant feedback from their questions and cannot talk in real-time about results obtained in the learning activities. These limitations can been overcome by applying synchronous technologies where students interact with each other in real time.

This paper presents several Moodle and EJS extensions created to support:

1) Deploying EJS VRLs into Moodle.
2) Adding synchronous collaborative support to any VRL developed with EJS.
3) Accessing directly the OSP repository from Moodle.

As a case of study of the aforementioned extensions, this paper describes a VRL that supports students of automatic control engineering to train different advanced techniques, such as robust, fuzzy and reset control, and compare their performance in relation to a conventional Proportional-Integral-Derivative (PID) control. The experimental plant considered for that purpose is the well-known *ball and beam system*, which facilitates the study of real control problems, such as the horizontal stabilization of an airplane [29]. In addition to the two working modes (simulated and real experimentation) provided by the VRL, the remote laboratory presented in this work offers an augmented reality option that superimposes a graphical representation of the virtual system's behavior over the image provided by the webcam. This allows a visual comparison of the theoretical response of the plant with the real response.

Finally, this paper reports an observational study where students were encouraged to carry out several voluntary lab assignments using the VRL (an example of assignment was analyzing the differences between the experimental outcomes obtained by teleoperating the remote lab and the theoretical results computed with the virtual lab). The study provides empirical evidence of positive correlations (i) between using virtual labs and the final exam grades students get, and (ii) between the number of lab assignments that students finish and using VRLs deployed into Moodle.

The remainder of this paper is structured as follows. Section II summarizes related work. Section III describes the authors' approach, i.e., the Moodle and EJS extensions, and the Ball and Beam VRL. Section IV sums up the experimental evaluation of this approach. Finally, Section V shows some conclusions regarding this work.

II. RELATED WORK

VRLs have been recognized as key distance learning tools for teaching a wide range of topics, such as *Control Engineering* [30], *Physics* [31], *Chemistry* [32], etc. Although there is empirical evidence of the positive effects that collaborative student interaction has over lab activities [33], [34], [22], [23], most of the online labs developed to date suffer from a lack of providing social contexts which support collaborative group work [25], [35]. To overcome such limitation, the following complementary approaches have been proposed:

1) *Deploying VRLs into LMSs*. Thus, VRLs take advantage of the LMS capacity to support the virtual interaction among participants (students and teachers) by means of both synchronous (e. g., chat, videoconference...) and asynchronous (e. g., whiteboards, forums, mailing list...) collaboration tools. For instance, [36], [37], [38], [39], [40] integrate VRLs into Moodle, [41] into LADIRE, and [42] proposes a more general solution in which VRLs can be integrated into many LMSs.
2) *Embedding VRLs into virtual worlds*. Some researchers suggest that both entertainment and highly immersive environments promote effective learning. To do so, VRLs are embedded into virtual worlds that provide multiple communication channels between users and improve presence and awareness in the learning process. For instance, [43], [44] integrate VRLs into Second Life, [45], [46] into the Sun Project Wonderland, and [47] into the game Half-Life 2.
3) *Supporting VRLs to be handled by multiple participants at the same time*. Under a simplistic approach, collaboration is limited to the use of communication tools such as chat or video-conference applications. Other approaches go beyond by supporting the simultaneous interaction of several participants with the same lab [23], [37], [48], [49], [50], [51], [52], [53]. This way, the proper VRL acts as the main communication medium among participants.

The work presented in this paper encompasses many of the former proposals. It deploys VRLs into LMSs and it makes possible VRLs to be handled simultaneously by multiple participants. The integration described in this paper of EJS VRLs into Moodle has an enormous potential. For instance, the OSP offers hundreds of EJS simulations that may be automatically integrated into Moodle by using the add-ons described in Section III-B.

A stable release of the authors' open source code (i) has been checked, approved and published by Moodle[5], (ii) has been included in the last official EJS release 4.3.7, and (iii) is being used in the UNILabs web portal[6], which currently hosts 15 VRLs for 10 university courses.

III. INTEGRATING VIRTUAL AND REMOTE LABS INTO MOODLE

A. Preliminaries

The client-server architecture for remote laboratories deployed using Moodle is shown in Figure 1. Plants located at the university labs are manipulated by the remote user through the Internet. A server computer acts as a middleware layer for each of these remote labs. They are in charge of the translation of incoming commands from the client and sending back measurements or other required information, as

[5] the authors' add-ons are freely available at: https://moodle.org/plugins/browse.php?list=set&id=27
[6] http://unilabs.dia.uned.es/

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well as the acquisition and control loop tasks. A webcam pointing to the plant is often used to provide real-time image feedback at every moment. Another server computer is used to hold the webportal supported by Moodle. This computer serves both the virtual labs applications and the remote labs user interfaces to the clients. The booking system, needed for managing and arranging the connections of students to the remote laboratories, is also established in the Moodle server. This booking system has been developed by the authors and it is freely available on the URL given in Footnote 5.

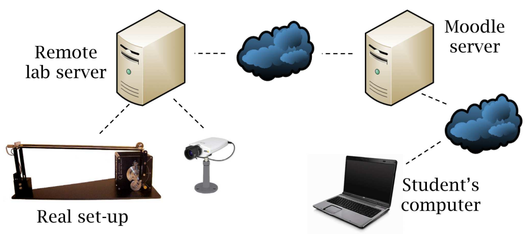

Fig. 1. Architecture of a remote lab deployed into Moodle

1) EJS: EJS is a freeware, open-source tool developed in Java, specially designed for the creation of discrete computer simulations. The architecture of EJS derives from the Model-View-Control (MVC) paradigm, whose philosophy is that interactive simulations must be composed of three parts:

- The model describes the process under study in terms of: (i) variables, which hold the different possible states of the process, and (ii) relationships between these variables, expressed by computer algorithms.
- The view provides a graphical representation (either realistic or schematic) of the process states; i.e., the GUI of the simulation.
- The control defines certain actions that a user can perform on the simulation.

EJS makes things even simpler eliminating the “control” element of the MVC paradigm and embedding one part in the view and the other one in the model.

As an indicator of the widespread use of EJS, many VRLs created or replicated with EJS, such as [54], [55], [56], [57], [58], can be found in the literature.

2) OSP: The OSP project won the Science SPORE Prize in November 2011. Among many other resources for teaching and learning, this collection offers more than four hundred EJS simulations, such as those described in [59], [54], [55], [56], [57], [58].

3) Moodle: Moodle is a widespread LMS that provides a social context for students’ collaboration. Moodle enriches VRLs by facilitating and promoting the tools for students discuss the experiments between them and teachers, exchange their lab reports, etc. In addition, Moodle helps to distribute all the convenient resources for a complete online experiment. For instance, attached to the VRL, Moodle may include a description of the phenomena under study, the task protocol that students must follow to achieve the goals of the VRL activities, etc.

B. Extending Moodle with VRLs

The “M” in Moodle stands for modular. The easiest and most maintainable way to add new functionalities to Moodle is by creating an add-on. Since all the tools and resources in which this work is based on are free (EJS, OSP and Moodle), it was important for the authors to offer the solution that joins all these things together also for free. Therefore, Moodle add-ons are the perfect way to achieve this objective.

1) The EJSApp add-on: To support the one-click deployment of VRLs into Moodle, the EJSApp add-on has been developed. The EJSApp module supports:

- *Deploying VRLs written in EJS*. EJSApp uses the new Moodle 2 feature File Picker, enabling EJS applications (either they are a simulation or virtual lab, or a remote lab user interface) to be uploaded not only from the user computer but also from a variety of repositories such as Dropbox, Alfresco, etc.
- *Controlling user access to the deployed labs*. EJSApp includes a booking system which supports setting the start and end dates when a VRL will be accessible to the students, the minimum grade students need to get in other activities as a previous condition before having access to the lab, etc.
- *Backup and restore*. EJSApp provides maintenance facilities, packaging VRLs into Moodle standard course backups.
- *Supervision and statistics*. Access from Moodle users to VRLs are recorded and can be used for performing statistics and supervising the time students spend working in each lab.

EJSApp is listed in the Moodle official site as one of the more than 600 approved add-ons for Moodle. It received the *Moodle Hat Award* on December 2012, just a few days after it was first released. This award is given by the Moodle staff and only 18 add-ons have received it by November 2013. Considering the number of existing add-ons up to this date, this means that only a 3% of these add-ons get to receive this award. Another indicator of the high quality and/or utility of this tool is that it has been downloaded more than 1300 times in less than one year.

2) The EJSApp Collab Session add-on: Moodle includes a good number of tools that provide asynchronous collaborative support (e. g., forums, the messaging system,...). The authors’ proposal takes advantage of such features by deploying VRLs into Moodle. Moreover, the approach presented in this paper enriches Moodle collaborative support by providing a new feature: the synchronous collaboration among the VRLs included into a Moodle course.

Figure 2 shows an experimental session using the following features of the VRL described in Section III-C: virtual experimentation, synchronous collaborative interaction and skype communication between users. For each participant in a collaborative session, there is a running instance of the shared VRL. The state of all the instances is synchronized, i. e., whenever a participant acts over its VRL instance, the changes produced on the VRL state are propagated to the remainder of the participants’ VRL instances. Thus, although there are

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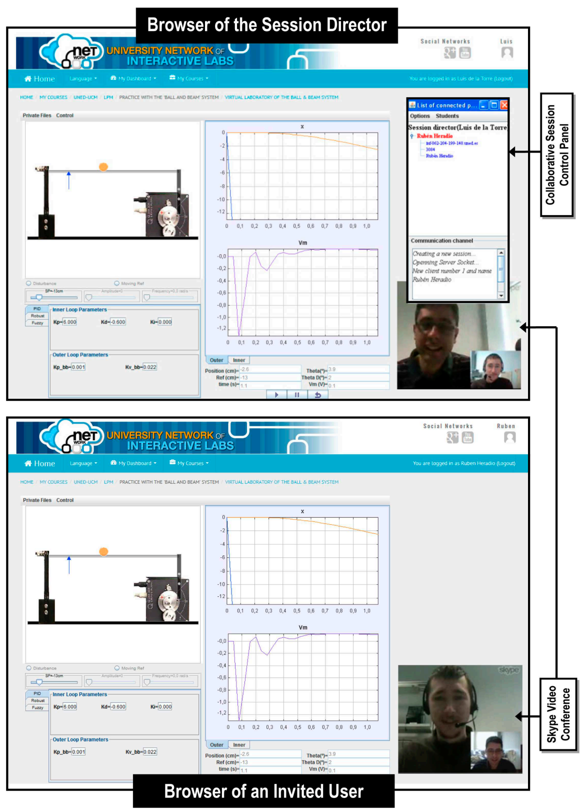

Fig. 2. Example of two users participating in a collaborative experimental session

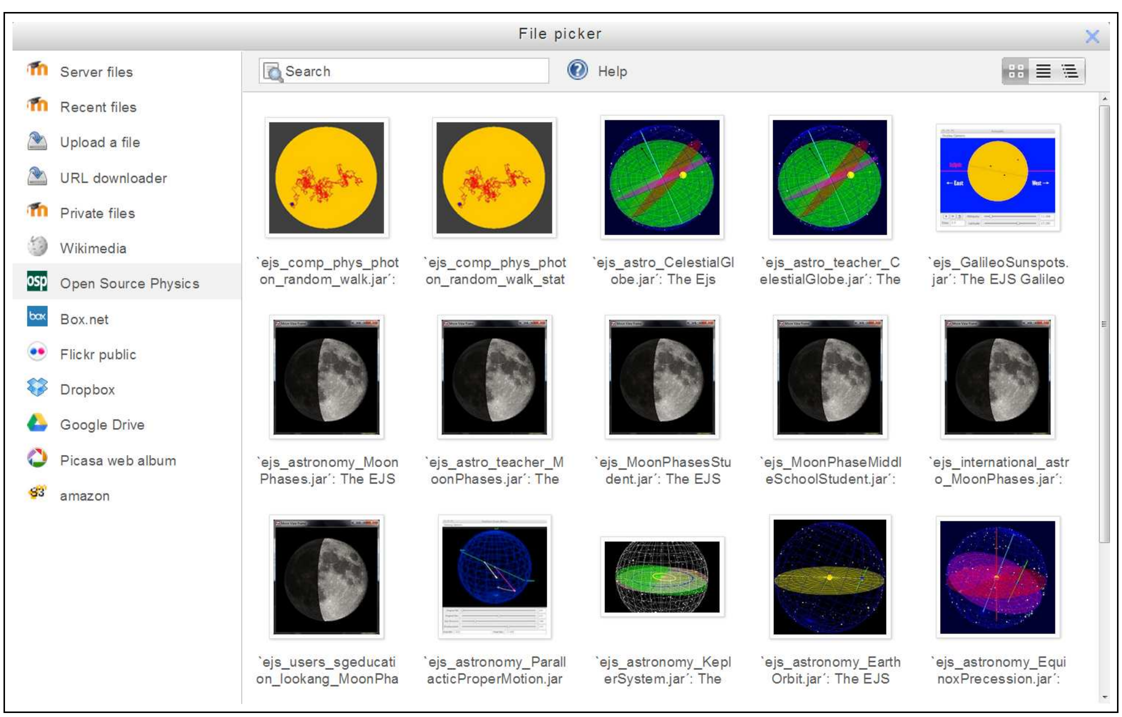

Fig. 3. OSP add-on for Moodle

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running several instances of the VRL, the participants have the feeling of being working on the same VRL.

In addition, one of the participants plays the *session director* role, being responsible for starting, monitoring and closing a collaborative session. The session director's applet manages in realtime the virtual class and synchronizes all the invited user's applets. She has a list of invited users connected to the virtual session and can disconnect any invited user's at any moment. In order to have a suitable floor control, connected invited user's applets are locked and they cannot interact with the shared VRL in a first moment. They are only allowed to see in real time what the session director is doing in the shared application. This way, the collaborative session avoids collisions of events which can cause unwanted and incoherent results. This problem could appear when the real equipment, controlled by the remote lab application, becomes uncontrollable due to unsuitable user interactions. This could happen, for example, if one of the users in the collaborative session is commanding a motor to rotate clockwise while a second user is ordering the same motor to rotate anticlockwise at the same time.

To support the automated conversion of any existing EJS VRL into a collaborative lab, the authors also have extended EJS. In particular, the official EJS release 4.3.7 already includes the authors' collaborative extension.

3) The OSP add-on: The OSP add-on allows Moodle users to connect their *File Picker* to the OSP digital library. Without this add-on, users cannot directly search for EJS simulations in the OSP digital library from Moodle and adding them to the online course. Instead, they first have to go to the OSP webpage, download the simulation or virtual lab to their own computer, then go to their Moodle course and upload the simulation from their hard disk.

Thanks to the OSP add-on, (i) users never need to leave the Moodle environment when adding/reorganizing the simulation activities in their online courses, and (ii) they do not need to download the simulation file from OSP to their computer and then upload it to their Moodle server; instead, the file passes directly from OSP to the Moodle server. Therefore, this tool provides teachers with a very fast and easy way to search, select and deploy virtual labs already created by the EJS community and available at the OSP repository. Figure 3 shows a screen shot of the OSP add-on for Moodle when the keyword "sun" is used to make a search for related simulations.

C. A case study of VRL: the Ball and Beam System

To put into practice the authors' approach and illustrate its usefulness, a case study with a VRL is presented in this section. The ball and beam system is one of the most common setups that can be found in control laboratories. The reason for its popularity is twofold: (i) it has applications to aerospace and automotive fields as well as to robotic industries, and (ii) some challenging control problems can be studied with this relatively setup, e.g., open loop instability or the effect of strong non-linearities. Thus, the aim of this section is to describe briefly how these issues can be tackled from the control engineering point of view, and how they are illustrated in an interactive way by using the framework proposed in this work.

The virtual lab is completely implemented with EJS. As a result, it is a stand-alone Java applet that may be run on a client browser. Figure 4 depicts the client-server architecture of the remote lab. In this case, the EJS applet acts as a simple interface that interacts with a LabVIEW program on the server side, which controls the real setup. The communication EJS-LabVIEW is supported by the JiL Server[7]

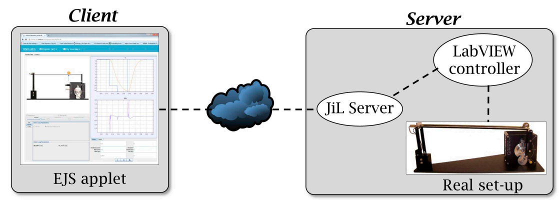

Fig. 4. Client-server architecture of the ball and beam remote lab

Figure 5 sketches the main variables in the virtual lab model, based on the real setup. The experimental plant presents two degrees of freedom: the movement of the ball over the beam, and the movement of the motor that makes the beam angle α to change. In addition, two forces act on the ball: a translational force due to the gravity and a rotational force caused by the rotational acceleration of the ball. The dynamical model of the ball rolling over the beam can be easily derived. As a result, the Equation 1 is obtained.

$$\ddot{x}(t) = \frac{5}{7} g \sin\alpha(t) \tag{1}$$

For this equipment, the variations of α are related to the variations in the servo-motor angle θ by Equation 2, where r is the level arm offset and L is the length of the beam.

$$\theta r = L\alpha \tag{2}$$

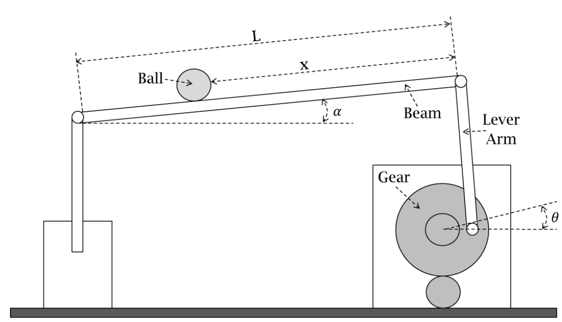

Fig. 5. Sketch for the ball and beam system

Finally, the servo-motor dynamics is modeled as a first order system with an integrator represented by the following transfer function:

$$\frac{\theta(s)}{V(s)} = \frac{-64.12}{s^2 + 36.43s}. \tag{3}$$

[7]JiL Server is freely available at https://github.com/UNEDLabs/jil-server [60], which connects EJS variables to LabVIEW variables via TCP/IP. Thanks to this approach, the student uses the same interface to perform both the virtual and the remote experiments.

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This VRL supports three control strategies: Robust control, Fuzzy control, and Reset control. Students have to tune a number of parameters for the different controllers and to draw conclusions about the advantages and issues of each one.

To tackle the two degrees of freedom (i.e., the angle of the beam and the position of the ball), a cascade structure is used. It helps to reject disturbances and improves the dynamics of the control loop. For the outer loop, the controlled variable is x. The output of this controller gives a set point for the variable controlled by the inner loop, the θ angle (see Figure 5).

Taking a look back to the process dynamics (see Equations 1 and 3), the simplest control strategy is, for both the inner and the outer loop, the Proportional-Derivative (PD) controller described by Equation 4. Thus, four gains have to be tuned, a couple for each control loop. In general, the control law $u(t)$ is given by

$$u(t) = K_p(y_{\mathrm{SP}} - y(t)) - K_v \frac{dy(t)}{dt} \tag{4}$$

where y is the output of the control loop, y_{SP} is the set point, and K_p and K_v are the PD gains.

If conventional tuning methods want to be used for this system (e.g., pole placement [61]), Equation 1 has to be linearized. Nevertheless, the approximation $\sin\alpha \approx \alpha$ is only valid for small values of α. Hence, the control performance gets worse if the position of the ball moves away from the equilibrium or the system is affected by disturbances. Thus, advanced control techniques should be used.

Sections III-C1, III-C2 and III-C3 summarize the control strategies this VRL supports. Later, Sections III-C4 and III-C5 sum up the kind of activities students may perform with the virtual and remote views of this lab.

1) Robust control: The purpose of the robust control techniques is to take uncertainties into account systematically when analyzing a control system or when designing a controller [62].

One of the most popular robust controller design methods is the McFarlane-Glover technique.

The design of a robust controller $C_R(s)$ is based on the weighted plant WP, where $W(s)$ is denominated pre-compensator and P is the plant. The choice of $W(s)$ depends on the given specifications. Figure 6 illustrates the previous idea for the inner control loop, where the output is θ, i.e., the angle of the motor, and θ_{SP} and e_θ represent the set-point and the error for this variable, respectively.

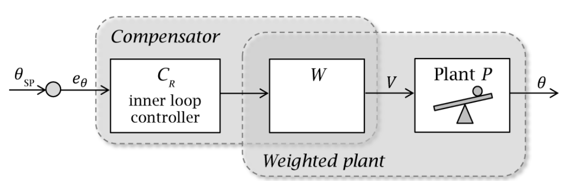

Fig. 6. Block diagram of the robust controller for the inner loop

The simplest choice of $W(s)$ is a constant value. This gives a second order controller for the system. If a higher order pre-compensator is considered, the controller complexity increases. $W(s)$ determines the crossover frequency and the roll-off rate of Bode's diagram. The parameter that measures the good or bad mismatch between the target and the achieved Bode's magnitude is called gamma (γ). The closer γ to the unit, the better.

2) Fuzzy control: Fuzzy control is an alternative for a great variety of problems, as it provides a method to construct nonlinear controllers using heuristic information [63]. The fuzzy controller consists of the following elements: a rule base set, an interference mechanism, a fuzzyfication interface, and a de-fuzzification interface.

For the ball and beam system, fuzzy controllers have been designed for both the inner and the outer loop. They have two inputs: the error and the derivative error.

Following the proposed approach in [64], membership functions have been defined as triangular, with seven linguistic terms (i.e., Big negative, Medium negative, Small negative, Zero, Small positive, Medium positive, and Big positive).

3) Reset control: A reset controller is described by impulsive differential equations as bellow:

$$\begin{cases} \dot{x}_r(t) = A_r x_r(t) + B_r e(t) & \text{when } e(t) \neq 0 \\ \dot{x}_r(t^*) = A_r x_r(t) & \text{when } e(t) = 0 \\ u(t) = C_r x_r(t) & \end{cases} \tag{5}$$

where (A_r, B_r, C_r) is the state space representation of the controller, x_r is the state of the reset controller, $e(t)$ and $u(t)$ are the input and output signals, and t^* is the resetting time.

The motivation for reset control lies on the existence of some classes of linear plants, such as those containing integrators, right half-plane poles or zeros, or time delays, that are very difficult to control with linear controllers and are subject to linearly unsolvable trade-offs between competing design objectives. It has been shown that a nonlinear controller (like a reset controller) can overcome the limitation and outperforms any linear solution [65].

The first results on reset control date back to the late fifties when Clegg [66] showed that a reset integrator (known as Clegg integrator) has a describing function similar to the frequency response of a linear integrator but only with $38.1°$phase lag instead of $90°$.

For the state of the PD controller, a reset control will provide a better phase lag and improve the system response:

$$u(t) = \begin{cases} K_P(y_{\mathrm{SP}} - y) - K_v \frac{dy}{dt} & \text{if } y_{\mathrm{SP}} - y \neq 0 \\ 0 & \text{if } y_{\mathrm{SP}} - y = 0 \end{cases} \tag{6}$$

4) Activities supported by the virtual lab: The simulated mode of the lab (see Figure 7) serves students to get used to handling the experimental environment. Students can select on the top menu which control law want to apply to the modeled system. More than one strategy can be selected at the same time, and so compare the efficiency of each one through the view and the set of graphs at the right side.

Below the view of the simulation, three tabs contain a set of controls to change the different controllers parameters. Users can modify, for example, the gains of the PD cascade controller, choose the pre-compensator for the robust controller,

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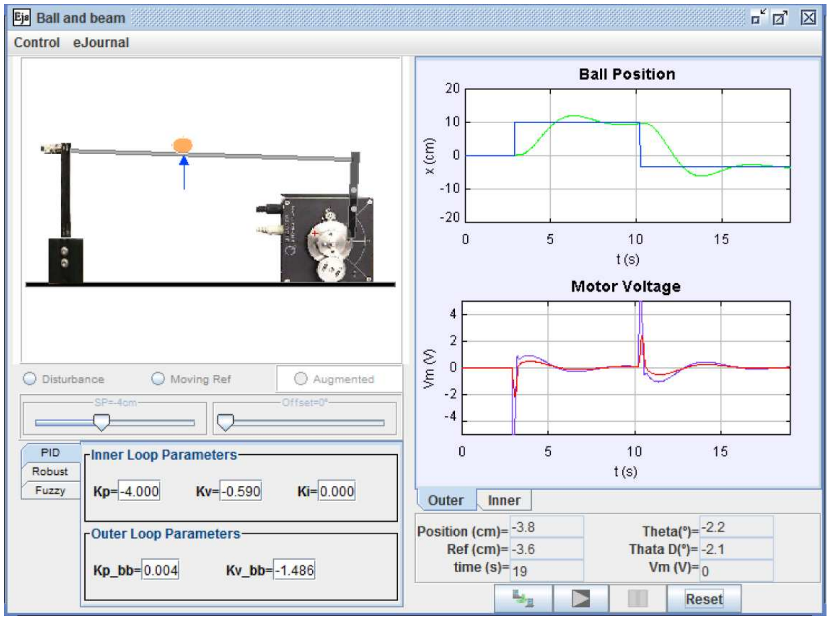

Fig. 7. GUI for the ball and beam system working on the simulation mode

or alter the shape of the membership functions of the fuzzy controller. Any change is performed online and the result can be immediately observed in the view.

Disturbances can be induced by clicking on the ball or pressing a button. Therefore, the robustness of the different controllers when rejecting disturbances can be compared.

The set point can be dragged manually, or students can choose the frequency of its movement described as a sin function. Figures 8 and 9 show the response of the PD, Robust, and Fuzzy controllers for a particular set of parameters when the reference is a sine wave of frequency 0.4 rad/s and 0.6 rad/s, respectively.

One of the most attractive parts of this web lab is the interface designed for the fuzzy controller. The membership functions are displayed in an additional window, where their properties can be modified globally (through sliders in the fuzzy tab) or individually (clicking and dragging). Figure 10 displays an example of the membership functions of the error and derivative error of the outer controller.

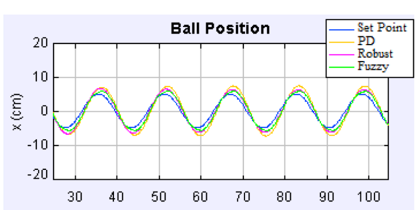

Fig. 8. System response for a sine wave reference of frequency 0.4 rad/s

Thus, the virtual lab activities include tuning the different controllers, a comparative study of the disturbance rejection, and the set-point tracking. All this has to be reported before proceeding to the next step: the remote lab.

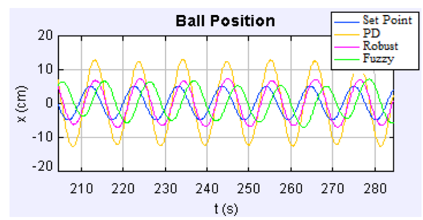

Fig. 9. System response for a sine wave reference of frequency 0.6 rad/s

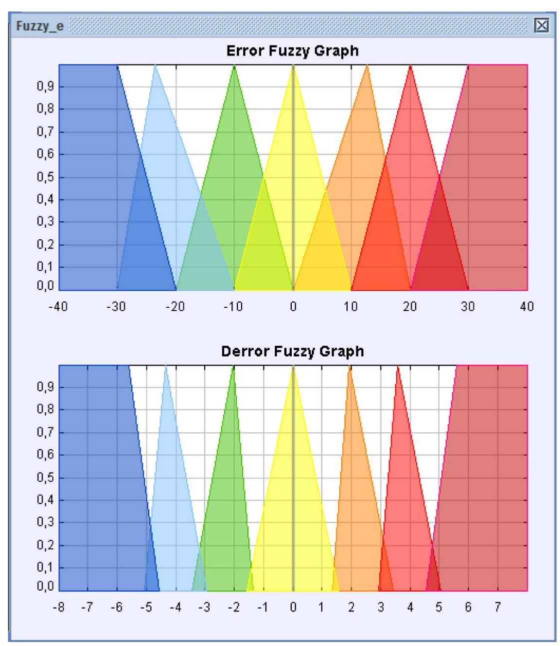

Fig. 10. Membership functions of the fuzzy controller for the outer loop

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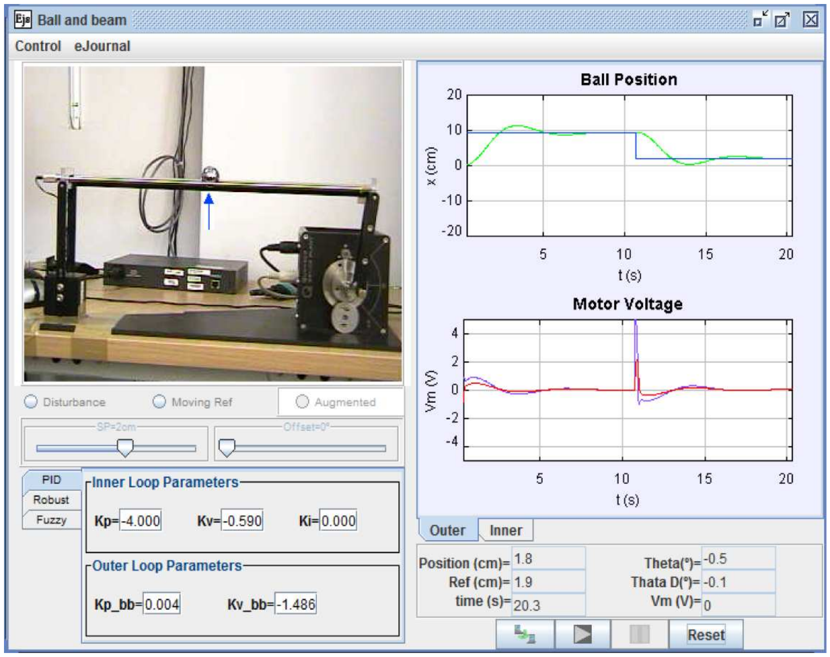

Fig. 11. GUI of the applet in remote mode

5) Activities supported by the remote lab: Once students get familiar with the virtual lab and have reached the goals cited above, they can test their control designs over the real system. Figure 11 depicts the GUI of the EJS applet in this mode. The view of the simulation mode is replaced by a real time image of the real system. Users can select one of the three controllers to check its behaviour with a particular set of parameters. Although the simultaneous comparison of more than one controller is not available for the real plant, there is available a third working mode of *augmented reality* that supports to compare the real system with the theoretical model.

The LabVIEW program running on the server, which implements the three different controllers, includes some security mechanisms, such as control signal saturation and an *emergency stop routine* triggered when the derivative of the control signal exceeds some bounds during a predefined period of time.

IV. Experimental evaluation

In terms of number of students, the Spanish Open University (UNED), with more than 260,000 students, is the biggest university of Spain and the second one in Europe, next to the English Open University. To support their students, UNED is composed of a network of associated learning centers scattered around the world (more than 60 centers distributed across Spain, Europe, America and Africa). Unfortunately, the geographical dispersion of the students makes impossible to provide the scientific courses of UNED with traditional labs at a reasonable cost. To overcome this problem and help students to carry out lab experiments, the authors of this paper have created the *UNILABS* web portal[8], which hosts VRLs for different subjects taught at the UNED *Schools of Computer Engineering* and *Sciences*. In course 2012-13, the aforementioned schools had 4,039 and 4,605 students, respectively. In particular, the VRL described in Section III-C was developed to provide support for the subject *Automatic Control I*, taught in the Faculty of Science, and the *Instrumentation and Control Laboratory Practices and Intelligent Control* subjects of the Systems Engineering and Automatic Control Master of the School of Computer Engineering. This section reports the evaluation of the authors' approach by analyzing the effect that the VRL and its deployment in Moodle had over the students' comprehension of advanced control techniques during courses 2011-12 and 2012-13.

Statistical experiments may be classified into *controlled experiments* and *observational studies*. In a *controlled experiment* the investigators decide who will be in the *treatment group* and who in the *control group* (e.g., in a possible evaluation of the VRL usefulness, the treatment group would consist of those students that have used VRLs, whereas the control group would be those that have not). In contrast, in an *observational study* the investigators do not assign the subjects to treatment or control groups: they just watch what happens. Compared to observational studies, controlled experiments where subjects are randomly assigned to the treatment and control groups have the advantage of supporting drawing *casual links* between the *independent* and the *dependent variables* [67]. Unfortunately, such kind of experiments cannot be performed because they would violate ethical standards: it must be guaranteed that all students have access to any available lab resource (i.e., the access should not be limited to some randomly selected students just to support a statistical study). Thus, this section reports an observational study that draws *correlational links* between independent and dependent variables. In particular, Section IV-B reports positive correla-

[8]http://unilabs.dia.uned.es/

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tion between performing experiments on a virtual lab and the students' final exam grades, and Section IV-C shows a positive correlation between using VRLs deployed into Moodle and the number lab assignments that students finish.

A. Participants

Students were encouraged to carry out two voluntary lab assignments:

1) Undertaking the activities described in Section III-C4 by using the virtual mode of the lab, thus tuning different advanced controllers (robust, fuzzy and reset control) and comparing their performance to conventional PID control.
2) Teleoperating the Quanser module BB01 through the remote mode of the lab to test the controllers designed in the simulation phase (i.e. when working with the virtual lab) and compare the experimental results with the theoretical ones (obtained from the virtual lab).

In course 2011-12, the VRL was available as a Java applet embedded in a simple static web page. In contrast, in course 2012-13 the VRL was deployed into Moodle by using the add-ons described in Section III-B. This way, the VRL was enriched not only in the ways described in that section but also with the built-in social features provided by Moodle (forums, messages system, chats...).

Table I and Figure 12 summarize the grades students got for the *Automatic Control* final exam in courses 2011-12 and 2012-13 (note that exam grades are rated on a 10-point scale).

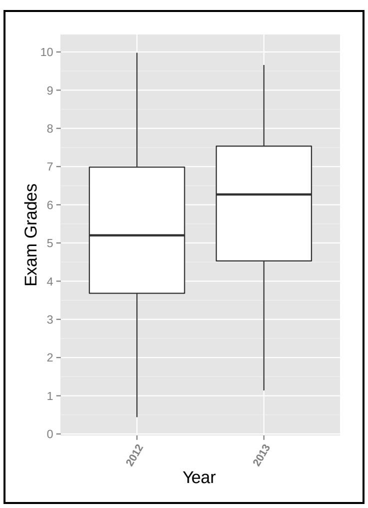

Fig. 12. Box plot of the students' exam grades by course

B. Evaluating the VRL usefulness

Histogram in Figure 13 depicts students' grades according to the kind of lab assignments performed. Note that, in this section, both courses 2011-12 and 2012-13 are considered jointly. It suggests a possible correlation between the type of lab activity and the exam grades: whereas most of the best marked students completed some voluntary lab assignment, most of the worst marked ones did not perform any lab activity at all.

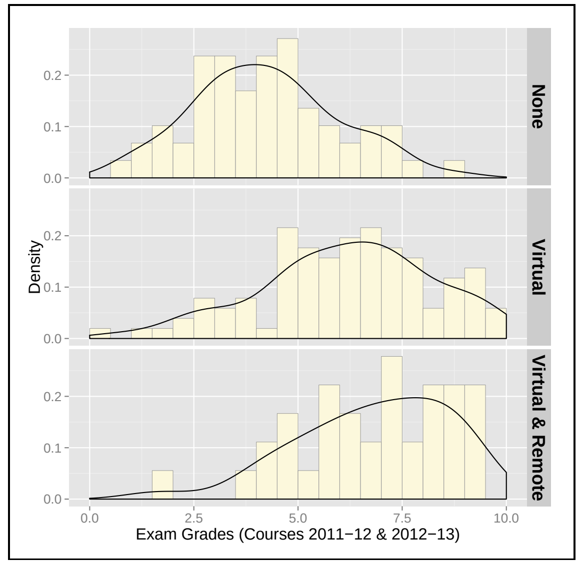

Fig. 13. Histogram of the students' exam grades according to the kind of lab used

To check the statistical significance of the grade difference between the students (i) who did not undertake any lab assignments, (ii) just the virtual one, and (iii) both the virtual and the remote ones, an *ANOVA test* was run. The following assumptions, required to run the test, were satisfied:

1) *Normality of the dependent variable*. In the present case, the dependent and independent variables are *grades* and *kind of lab assignment*, respectively. The shape of the dependent variable histogram (see Figure 14), and its low skew and kurtosis (see the last row in Table I) support the assumption that a normal distribution is approximately followed (as a common rule of thumb, skew > 3 and kurtosis > 10 indicates a non-normal distribution; in this case, skew$= -0.15$ and kurtosis$= -0.69$).
2) *Homogeneity of the variances*. To check the similarity between the variances of the three groups of students (i.e., those who did not carry out any lab assignments, just the virtual one, and both the virtual and the remote ones), a *Levene's test* was run, getting a F-value$= 1.1$ and Pr$(> F) = 0.33$. Due to $0.33 > 0.05$, the test was positively passed.

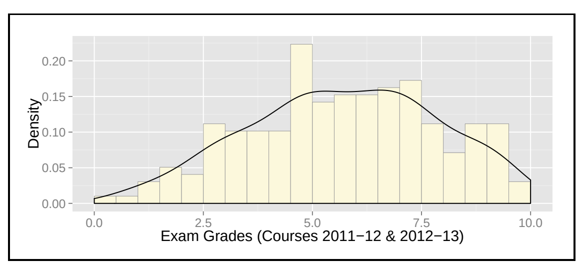

Fig. 14. Histogram of the students' exam grades for both courses 2011-12 and 2012-13

Table II summarizes the results of the ANOVA test. Since the p-value is less than 0.001 (in particular, p-value$= 1.1 \cdot$

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TABLE I
SAMPLE STATISTICS OF THE STUDENTS' EXAM GRADES BY COURSE

Course	Number of Students	Mean	Standard Deviation	Median	Skew	Kurtosis
2011-12	94	5.38	2.14	5.2	0.07	-0.59
2012-13	103	6	2.15	6.27	-0.36	-0.65
Both courses	197	5.7	2.16	5.77	-0.15	-0.69

TABLE II
ANOVA TEST

	Degrees of freedom	Sum of squares	Mean of squares	F-value	Pr($> F$)
Kind of lab (None, Virtual, Virtual & Remote)	2	193	96.4	25.8	$1.1 \cdot 10^{-10}$
Residuals	194	724	3.7		

10^{-10}), the experimental results are statistically highly significant. Table III summarizes the *power* analysis of the ANOVA test. Given the sample size and the effect size (i.e., the values of η^2 and *Cohen's* f^2), the ANOVA test has high statistical power.

TABLE III
POWER ANALYSIS

Effect size		Power
Eta squared η^2	**Cohen's f^2**	
0.21	0.27	≈ 1

According to the ANOVA test, there is an overall difference between the three groups of students. Nevertheless, ANOVA cannot identify where the differences are occurring between the groups. Since some authors have reported that students perceive that virtual labs are less effective than remote labs because simulations do not feel as realistic [68], [69], the authors decided to check if there was a significant difference between the grades of the students who just used the virtual mode of the lab and those that used both the virtual and remote modes. To do so, ANOVA was complemented with a *post-hoc* test. In particular, Table IV summarizes the outcomes of the *Tukey Honest Significant Differences (HSD)* which was run. According to HSD results, the following conclusions may be drawn:

1) The difference between the grades of (i) those students that did not perform any lab assignment and (ii) those that just used the virtual mode of the lab is statistically highly significant.
2) The difference between the grades of (i) those students that did not perform any lab assignment and (ii) those that used both the virtual and remote modes of the lab is statistically highly significant.
3) The difference between the grades of (i) those students who just used the virtual mode of the lab and (ii) those that used both the virtual and remote modes is not statistically significant. Remember that the remote assignment was repeating the experiment previously performed in virtual mode by teleoperating the Quanser module BB01. The goal of such repetition was mainly to help students to notice the differences between the real outcomes and the theoretical ones. According to Table IV, this is not enough to influence the final course grades.

TABLE IV
TUKEY HSD TEST

	Difference	95% CI	Adjusted p-value
Virtual *vs* None	1.93	[1.18, 2.67]	≈ 0
Virtual & Remote *vs* None	2.58	[1.61, 3.54]	≈ 0
Virtual & Remote *vs* Virtual	0.65	[-0.24, 1.53]	0.2

To sum up, the evaluation shows a positive correlation between exam grades and performing lab assignments with the ball and beam online lab. However, the remote lab addition to the virtual lab does not seem to pay off on the students's grades.

C. Evaluating the usefulness of deploying VRLs into Moodle

Figure 15 depicts the number of students who completed the labs assignments in courses 2011-12 (dark grey bars) and 2012-13 (light grey bars). The VRL was deployed into Moodle just in course 2012-13. So, Figure 15 suggests a positive correlation between the use of Moodle and the amount of students who performed the lab assignments.

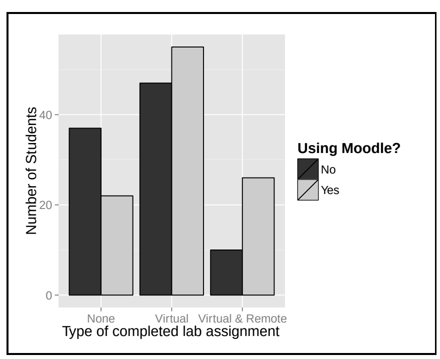

Fig. 15. Number of students who completed each type of lab experience using/and not using Moodle

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To check the aforementioned correlation, a *Chi-square test of independence* was run. The following assumptions, required to run the test, were checked:

1) *Observations independence*. In the present case, observations are independent of each other (i.e., not correlated). For instance, "students who performed the virtual lab assignment were not influenced by students who did not completed any kind of lab activity".
2) *Adequate expected cell counts*. Table V summarizes the expected counts under the null hypothesis (i.e., the hypothesis that the number of students who performed a lab assignment do not depend on the Moodle usage). The data-set satisfies the following common rule of thumb: "expected counts must be ≥ 5 in 80% of the cells and there cannot be cells with zero counts".

TABLE V
EXPECTED COUNTS FOR THE CHI-SQUARE TEST UNDER THE NULL HYPOTHESIS

	Not using Moodle	Using Moodle
No lab assignment	28.16	30.85
Just the virtual lab assignment	48.67	53.33
Both the virtual and the remote labs assignments	17.18	18.82

Table VI summarizes the results of the Chi-square test. As the p-value is less than 0.05 (in particular, p-value$= 0.0037$), the experimental results are statistically significant. Due to the sample size and the effect size (i.e., the Cramer's V), the test has high statistical power.

TABLE VI
CHI-SQUARE TEST

Degrees of freedom	X-squared	p-value	Cramer's V	Power
2	11.16	0.0037	0.24	0.86

V. CONCLUSIONS

Moodle and EJS are two free outstanding software tools for e-learning and VRL development, respectively. This work looks for their synergy by supporting (i) the deployment of EJS VRLs into Moodle, (ii) the addition of synchronous collaborative features to VRLs, and (iii) providing direct access from Moodle to the OSP repository.

To test the presented approach, a VRL has been created to help students to train different advanced control techniques (robust, fuzzy and reset control) and to compare their performance to conventional PID control. An observational study has been performed revealing the positive impact of this VRL and its Moodle deployment over students' learning.

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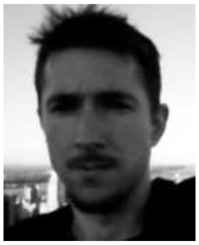

Luis de la Torre received the M.Sc. degree in Physics from the Complutense University of Madrid, Spain, in 2008, and the Ph.D. degree from the Universidad Nacional de Educacion a Distancia (UNED), Spain, in 2013, where he is an assistant professor of the Department of Computer Sciences Automatic and Control. His research interests are in VRLs, distance education, evolutionary algorithms, UAVs and path planning.

Maria Guinaldo received the M.S. degree in Physics and the B.S. degree in Computer Engineer from the University of Salamanca, Spain, in 2008, and the Ph.D. degree from Universidad Nacional de Educacion a Distancia (UNED), Spain, in 2013. Since 2008, she has been with the Department of Computer Science and Automatic Control from UNED. Her research interests include networked control systems, event-based control, control of multi-agent systems, and engineering education.

Ruben Heradio received the M.Sc. degree in Computer Science from the Polytechnic University of Madrid, Spain, in 2000 and the Ph.D. degree from the Universidad Nacional de Educacion a Distancia (UNED), Spain, in 2007. Since 2001 he works as Assistant Professor at the Software Engineering Department of the UNED. His research and teaching interests include Software Engineering, Computational Logic and E-Learning.

Sebastian Dormido received the Ph.D. degree in physics from Complutense University of Madrid, Spain. Currently, he is working as a full professor of automatic control in the Department of Computer Science and Automatic Control at Universidad Nacional de Educacion a Distancia (UNED), Spain. His research interests include automatic control and web-based labs for distance education.