A Remote Laboratory as an Innovative Educational Tool for Practicing Control Engineering Concepts

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Abstract—**This paper presents the development, structure, implementation, and some applications of a remote laboratory for teaching automatic control concepts to engineering students. There are two applications: formation control of mobile robots and a ball-plate system. In teaching control engineering, there are two main approaches to control design: model-based control and non-model-based control. Students are given insight into: 1) for model-based control: identification of real processes (i.e., dealing with noise, choosing the sampling time, observing nonlinear effects at startup, pairing input–output variables); and 2) for non-model-based control: the advantages and disadvantages of auto-tuning techniques. The paper concludes by presenting an evaluation of these remote labs and discussing the advantages of using them as complementary tools for teaching control engineering at the Bachelor's and Master's level.**

Index Terms—**Auto-tuners, ball and plate, control engineering, education, identification, mobile robots, proportional-integral-derivative (PID) control, remote laboratory.**

I. Introduction

THE PREFACE of a 1996 special issue on the "Application of information technologies to engineering and science education" begins: "The World Wide Web (WWW) was not yet a household word." [1]. That special issue marked the dawn of the use of the Internet as a tool for educational purposes; its articles provide a picture of the first generation of user interfaces for classroom exercises via the Internet. Virtual laboratories have become available for teaching electronics [2], [3], power systems [4], manufacturing [5], and control engineering [6].

Experience has shown that students are more motivated to learn new concepts if they are confronted with real-life applications and they feel they are *engineers*. This implies that they are given practical tasks and that teamwork plays an important role during project assignments, i.e., active learning [7], [8]. However, the ever-increasing number of students in engineering makes this a rather difficult problem since the capacity of laboratories is limited, and large groups of students must then be divided into smaller groups for direct guidance, which significantly increases the workload of the academic staff. The solution to this was the creation of virtual laboratories and, where applicable, remote laboratories. Nowadays, virtual and/or remote laboratories have become the "must-have" in the modern, global, and successful teaching environment [9]. A remote lab has an advantage over the virtual lab: It gives real-life feedback to the student and offers a more realistic and dynamic perspective.

This paper presents the development, structure, implementation, and applications of a remote laboratory for teaching control engineering to Bachelor's and Master's students. In particular, attention has been focused on two applications: 1) mobile robot formation control, and 2) a ball-and-plate system.

In the case of the ball-and-plate system, many pilot plants have been developed in many universities, e.g., [10] and [11]. This system is widely used to teach control engineering because it allows many control concepts to be demonstrated. Most of these pilot platforms are designed to be locally controlled, with fewer platforms having been developed for remote use. In the case of the mobile multirobots systems, current research is in areas such as cooperative mapping exploration [12], event-based communication [13], formation control [14], and motion coordination [15]. However, only a few of these areas have been introduced in engineering education, mainly due to the cost and the complexity of the system communication infrastructure needed to guarantee proper behavior. Few such platforms have been developed to be remotely controlled for educational purposes.

This paper is organized as follows. Section II provides the educational context of the remote laboratory. Section III describes the remote laboratory environment, structure, and data flow. Section IV presents the two applications: 1) mobile robots, and 2) the ball-and-plate system. Section V gives an overview of the test-case applications within the remote laboratory: identification, auto-tuning techniques, and model-based proportional-integral-derivative (PID) control design. Section VI presents an evaluation, as well as the advantages, of such a remote lab and its impact on the results of the cognitive process. A final section summarizes the main outcome of this work.

II. Educational Context

There has been a continuing boom in the number of students enrolling in higher degree studies across Europe. The theoretical concepts of mechanical, electrical, and control engineering need to be experienced in practice for better understanding. Since a basic control engineering course is compulsory in all these disciplines, providing face-to-face laboratories is difficult due to the following:

- the high enrollment, which is increasing year after year;
- inadequate financial resources to provide the increasing amounts of laboratory equipment needed for the higher numbers of students;

Manuscript received August 21, 2012; revised December 30, 2012; accepted February 11, 2013. Date of publication March 21, 2013; date of current version October 28, 2013.

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Digital Object Identifier 10.1109/TE.2013.2249516

- the amount of time (often overtime) that teachers must spend to prepare and teach labs; this eats into their research time, a crucial component of academic life.

The objective of the work described here is to provide a remote laboratory with several applications, to be used by multiple groups of engineering students as a complementary activity to their on-site exercises and/or laboratory work [16]. After working at home with the system, students can attend face-to-face labs, discuss their results, and ask questions. Usually, students who carry out this individual (home)work have superior skills to those whose work was done in groups of significant size. Moreover, these students can solve the task at hand at their own pace, leading to a better cognitive assimilation.

The syllabus of the undergraduate-level control engineering course at Ghent University, Gent, Belgium, covers the basic concepts of system modeling, system dynamics, stability, closed-loop response, and time-domain and frequency-domain analysis; it then deals with the use of basic control structures such as PIDs, either by model-based computer-aided design techniques (i.e., the frequency response toolbox [17], root locus toolbox [18]), or via auto-tuning algorithms [19]–[21]. In addition to theoretical classes, students also have problem classes, in which they apply analytical methods to analyze, control, and evaluate the performance of the system in the time or frequency domain. However, this learning experience is a rather abstract formulation of concepts that are ubiquitous in engineering practice. It is therefore helpful to show students easy yet efficient applications to illustrate abstract control engineering concepts.

Since all big universities face the problem of a high number of students and limited staff availability (i.e., teaching assistants), remote laboratories offer an elegant and promising solution to a number of pedagogical issues. For high student enrollment, multiple assistants are necessary to supervise students' work, answer their questions, and provide guidance in real time during a class of limited duration. Students' various levels of intellectual capacity and their different interests may also make the classroom experience less effective. With the remote lab, each student can tackle the course exercises at his or her own pace and according to his or her level of interest, without being forced to wait for their colleagues to catch up. This improves student motivation. Moreover, the remote lab is not limited to conveying basic control engineering concepts in the undergraduate course, but can also be used in the Master's-level course to teach system identification and adaptive, predictive, and internal model control concepts. There are fewer students in the automation Master's program, which allows a different teaching strategy to be used. These students are expected to be mature and able to study autonomously, so teaching is not performed on a regular schedule. The usual graduate-level pedagogic techniques at Ghent University consist of providing materials for self-study, followed by holding roundtable discussions.

The two applications presented here were evaluated by all involved groups of users Bachelor's, Master's, and Ph.D. students at Ghent University. After working at home with the platforms, their general opinion was positive, with feedback indicating that the remote lab had a user-friendly interface and offered significant control engineering insights. These two applications are to be included in a repository called UNEDLabs [22]. This project is an interuniversity collaborative network consisting of a battery of 45 different laboratory setups. These laboratories have been widely used with very good results in undergraduate courses of the National University for Distance Education (UNED), Madrid, Spain. The labs are also part of the curriculum of the "Systems and Control Engineering Master of Science," an interuniversity program offered by the UNED and the Complutense University of Madrid (UCM) in Spain.

Two possible undergraduate-level tasks in the remote lab are the following.

- *For model-based control (PID, Internal Model control, etc.):*
  1) study the systems dynamics (step, impulse or chirp signal identification, obtain parameters, obtain model);
  2) design a control algorithm using computer-aided design tools (frequency response tool, root locus tool, etc.);
  3) obtain the controller parameters;
  4) test and evaluate for setpoint trajectory and disturbance rejection;
  5) investigate improving noise filtering by adding feedback filters on the measured signals;
  6) investigate anti-reset windup schemes if saturation is active;
  7) investigate having filters on the reference for bumpless transfer, etc.
- *For non-model-based techniques:*
  1) perform relay experiment(s);
  2) tune controllers;
  3) follow the same steps as for model-based control.

For Master's students, these tasks can be enhanced by discussing adaptation, recursive identification techniques, multivariable control, constraints, and so on.

An important pedagogical aspect is how the assignment has to be carried out by the students. At Ghent University, a lot of emphasis is put on teamwork and student–student interaction. Experience has already shown that students working in small groups (i.e., of four to five persons) learn to share tasks, have useful interactions, and in general are better motivated to perform the required tasks. This interaction leads to brainstorming, where students discuss their ideas and opinions, which stimulates "thinking" rather than just "performing simulations and producing figures." In general, teamwork is a good environment to increase student maturity and to introduce them to the real-life context, given that engineering is team-based in industry. At the undergraduate level, the remote lab applications can be done either individually or in a team, but in either case, the results are discussed in groups of four to five students. This is already a standard approach at Ghent University at the Master's level.

As a final remark on the educational context, it should be noted that the particular applications chosen in this remote lab are not limited to teaching control engineering concepts. Aspects of other disciplines such as mechatronics, robotics, computer science, and communication could also be incorporated and enhanced.

III. Remote Lab

A. Architecture

The role of the remote laboratory is to ensure communication between students and the experimental setups at the university.

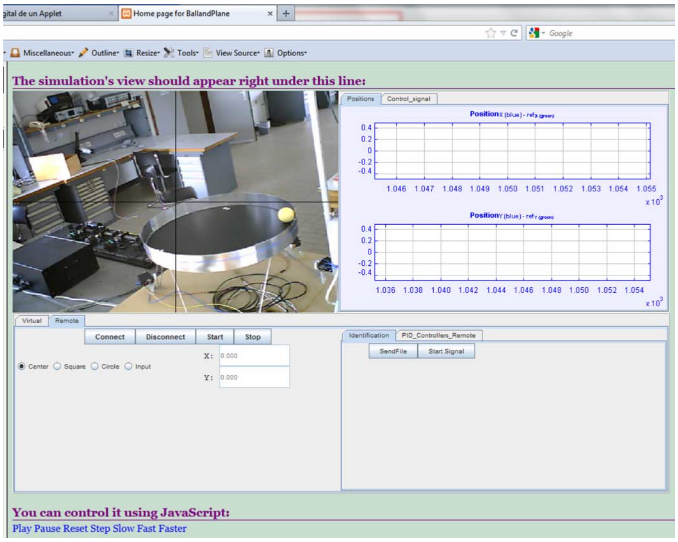

Fig. 1. Screenshot of the GUI used to communicate with the remote laboratory.

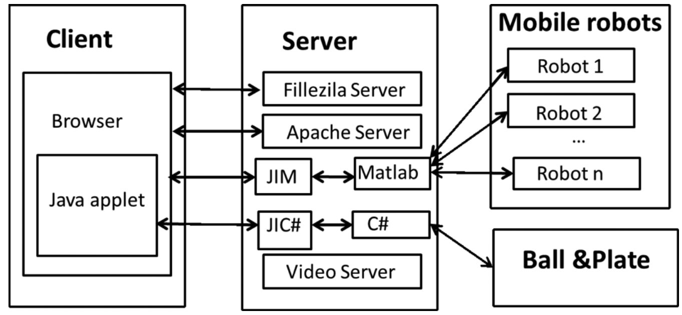

Fig. 2. Schematic overview of the software architecture. This can be easily enlarged to accommodate other applications.

This is achieved by a common client–server architecture [23]–[25].

Irrespective of the type of the application or possible experiments, the remote laboratory consists of four major elements: a client, a server, a network camera, and the plant itself. The communication between the first three elements is made using the common TCP/IP protocol, while the protocol and form of communication with the plant can vary depending on the application. This architecture allows expansion by an easy integration of any other setup.

B. Client

The client—the student—has no limitation on location. The only requirements are a Java runtime environment, a Web browser, and an Internet connection. Once the student connects to the remote laboratory, an applet with the graphical user interface (GUI) will be initiated. This GUI was built using Easy Java Simulations (EJS), a freeware open-source tool for rapid creation of applications in Java with high-level graphical capabilities and with an increased degree of interactivity (http://fem.um.es/Ejs/) [26].

Using this applet, the client is able to send commands, files, and messages to the server. The server will then communicate with the plant and send back the feedback, i.e., the file with the data collected from the experiment. The student is also able to upload his or her own file for testing the system (e.g., a pseudo-random binary signal for system identification). Cameras with independent IPs are mounted above each plant, so the student can see the experiment in real time. This feature makes the remote lab more attractive, realistic, and user-friendly.

C. Graphical User Interface

A screenshot of the client application is given in Fig. 1. The GUI is divided in three separate panels.

In the upper left panel, the user can see the images from the remote IP camera, with various buttons for zooming or positioning the camera at different angles.

On the right of the GUI, plots of the evolution of the data (input–output signals) from the experiment can be seen in real time. This helps the student to predict the output and to stop the experiment if necessary.

The bottom panel is used to manipulate the remote laboratory in general. Its buttons allow the student to Connect/Disconnect and Play/Stop the running experiments. The Stop button ends the connection to the remote server. When the Play button is pressed, the applet initiates communication with the plant, and all other controls on the interface are activated. For each type of experiment, the student is able to set his own experiment scenario/parameters. There are standard functionalities such as applying system identification techniques, or PID control, but some specific types of experiments can also be performed. After each experiment, the student can connect to the server using Secure File Transfer Protocol (SFTP) and download the input–output data from the plant.

D. Server

The server makes the link between the plant and the student by controlling the plant and allowing bidirectional communication. For the mobile robots application, the link between server and plant is wireless, and a MATLAB software application was implemented to send commands and receive data/messages from robots. For the ball-and-plate application, however, the link between server and plant is made using serial communication, and the communication tool was developed in the C# programming language.

The applet on the client side can connect to the external tools Scilab, Sysquake, MATLAB/Simulink, and LabVIEW [26], [27]. For the mobile robots, a Java Internet MATLAB (JIM) server [28] was used to make the connection between EJS and the MATLAB software. For the ball and plate, a new functionality was added to make the connection between EJS and Visual C# language. Both applications use the TCP/IP for communication.

On the server side, the Apache HTTP Server hosts for the remote laboratory Web site. Filezilla server is needed to perform the file transfer. Fig. 2 shows a schematic overview of the software required on the server, as well as the connections with the client and the process application.

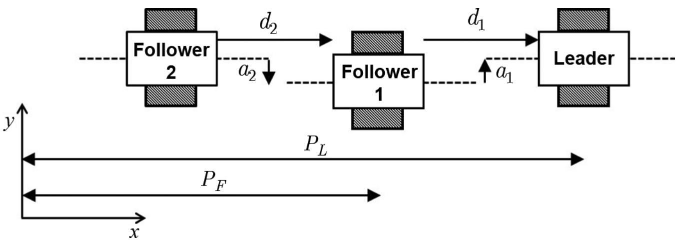

Fig. 3. Relative distance between the follower and its leader.

IV. Test Setups

A. Mobile Robots

The application of mobile robot formation control has generated a lot of interest in the field of control engineering due to its interdisciplinary nature [27]–[30].

In this paper, an *in-line* formation control of mobile robots is implemented by means of speed and position control. This remote laboratory works with Surveryor SRV-1 mobile robots, produced by the Surveyor Corporation. The robots communicate via wireless protocol with the host computer by means of a Lantronix Matchport WiFi, using a safe TCP/IP protocol. Notice that from the formation control point of view, one of the challenges is the lack of communication between robots. The formation is maintained using a camera mounted on the front of each robot and a colored marker on the back. Additional speed sensors (optical encoders) are available, as well as a microcontroller with embedded speed control loops.

The *in-line* leader–follower approach is presented in Fig. 3. In this configuration, each robot is a follower of the previous robot and a leader for the next robot. The lateral offsets a_1 and a_2 are set to 0. The data used for the lateral and longitudinal control, i.e., the distances d_1 and d_2 and the lateral offsets a_1 and a_2 in Fig. 3, are extracted using a camera on each robot. By applying image processing techniques, a feedforward proportional control is combined with a proportional-integrator cascade control to maintain formation [31].

B. Ball and Plate

Unlike the previous application, the ball-and-plate system is an open-loop unstable system. It consists of a platform that can be tilted by servos, with a ball on top of the plate, as shown in Fig. 4(a).

In order to move the ball, the plate is tilted using six servos, resulting in the six degrees of freedom of a freely suspended body. From a control standpoint, the main movements for the ball-and-plate system are the two rotations: pitch and roll. The remaining degrees of freedom can be further exploited to optimize the control strategy and performance, but this falls beyond the scope of this remote laboratory and this paper.

The platform is controlled by a computer via a purpose-built interface, whose designed printed circuit board has an on-board microcontroller that translates the commands given by the computer into pulse-width modulation (PWM) signals controlling the servos. In order to build a controller, feedback on the position of the ball is necessary; here, this is obtained by a simple webcam mounted on top of the platform, as depicted in Fig. 4(b).

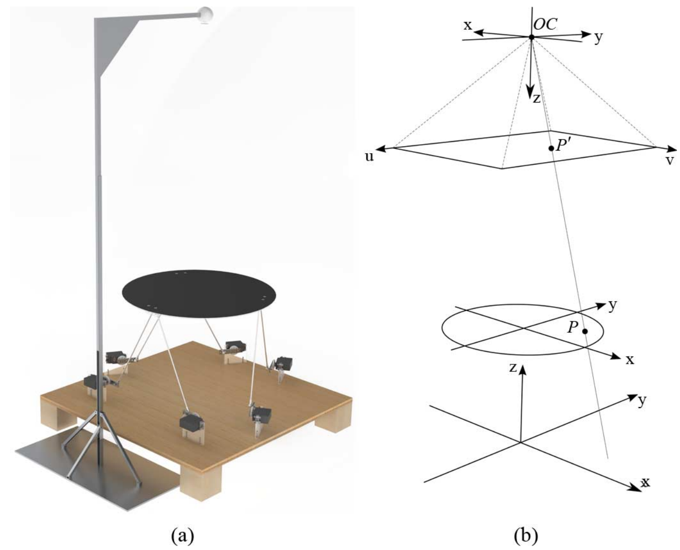

Fig. 4. Ball-and-plate system. (a) Six-degrees-of-freedom motion platform with camera for visual feedback. (b) Schematic diagram of assigning a pixel to a 3-D position on the platform.

The frames are interpreted by a specially written vision algorithm that, after calibration, determines the position of the ball on the platform.

V. Examples of Applications

Using this environment and the two available setups, multiple experiments can be performed. Furthermore, it should be noted that the particular structure of this remote lab allows an easy extension to incorporate other setups.

A. Mobile Robots

The control approach consists of two distinct levels: an upper level that controls the direction (lateral and longitudinal) of the robot based on the data extracted from image processing, and a lower-level inner loop that controls the angular speed of the tracks of the robot.

The model of the robot is found by using a step-response identification process. Since the robot is a simple process, based on dc motors and only proportional controllers, its dynamics can be represented by a first-order transfer function $K/\tau s + 1$. The resulting transfer function between the reference speed and the output speed is given by $K = 1.24$ and $\tau = 0.1$, to which the integrator from the position output is added. This transfer function includes the lateral control. Obviously, the result obtained in such a way is not accurate and introduces a difference between simulations and real robots. Nevertheless, it gives insight into the process and makes the controller design more reliable.

After performing the identification task, the student has a model of the dynamics of the robot. Therefore, the tuning of the PID controller can be done offline, using any desired method. As an example, the Frequency Response Tool (FRTool) [17] is used, and the results for a 33-cm reference distance are shown in Fig. 5 for initial startup.

If a model of the robot is not available, control can be applied by auto-tuning algorithms. The remote laboratory environment allows the possibility to the student to carry out a relay test.

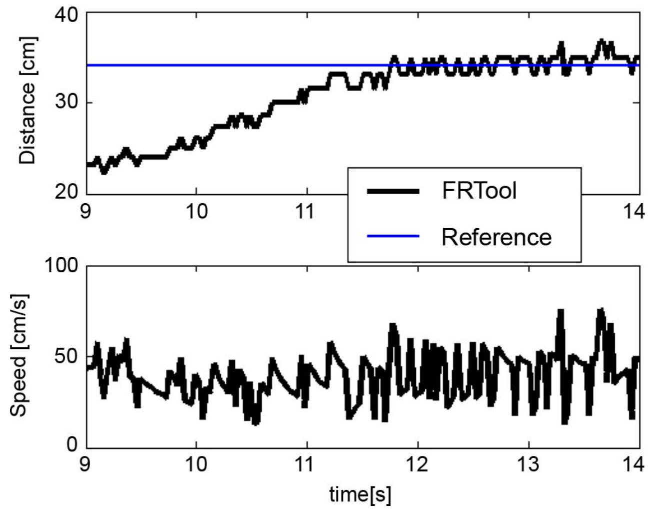

Fig. 5. Example of reference trajectory following. Measured output (distance [cm]) and controller output (speed [cm/s]) for a PID control designed via the FRTool.

Based on the results of the relay test, the PID controller can be computed using various algorithms. In the Bachelor's course, several methods are presented to the students [19]–[21]. From a simple relay experiment, the student can extract the amplitude a and the period T_c of the output of the system. The amplitude is used to calculate the critical gain of the relay experiment $K_c = 4d/\pi a$. These parameters then enable the student to calculate the controller coefficients based on phase margin, gain margin, and robustness specifications. Here, the student can conclude that if analysis is not required (i.e., stability), then the auto-tuning controllers provide performance to that of the model-based PID control, and the task of identification can be avoided.

B. Ball and Plate

The second application, the ball-and-plate system, allows students to perform identification and design controllers. Based on a pseudo-random binary signal input signal, the identification delivers a second-order transfer function as a first order plus integrator $K/s(\tau s+1)$. For the transfer function from position to angle of the plate in degrees, $K = -1.641 \cdot 10^{12}$ and $\tau = 8.77 \cdot 10^{9}$. Since the system has already an integrator, a proportional-derivative (PD) controller suffices, designed also using the FRTool interface. The result in closed loop for a step response in position of the ball on the plate is shown in Fig. 6. Here, the students can observe the effects of stabilizing feedback control.

VI. Evaluation

Previously, students had to perform a number of tasks to prepare for the laboratory work. They had to study and analyze the theoretical concepts and study the properties of the test system (i.e., thus preparing the experiment that they were supposed to perform in the lab). Then, they had to attend the laboratory in the university campus, conduct experiments on the real plant, and discuss their results. Finally, students submitted a report containing the results and insight gathered during the experiment. This report was then evaluated by the teaching assistant and the

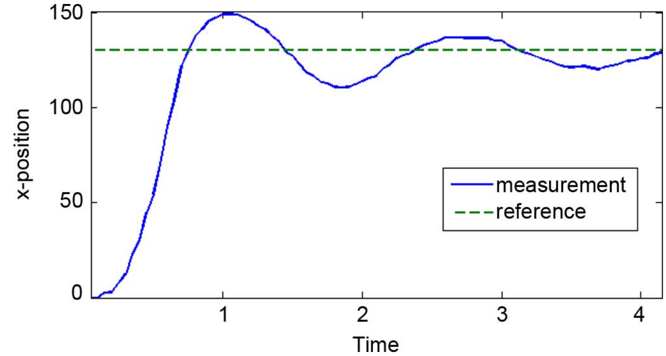

Fig. 6. Closed-loop step response of the position of the ball on the plate using a PD controller.

professor. This pedagogical method is no longer feasible in view of the high number of students and the quality requirements for teaching tools. Traditional laboratory practice has now been complemented, step by step, with virtual and remote labs. The use of remote labs as a platform for students to perform real-life experiments at a distance reduces the cognitive load required to acquire new knowledge of control theory [32].

These types of laboratory incorporating various remote applications have been used for several years in the Bachelor's and Master's automatic control courses of the Computer Science Engineering program at the UNED in Spain. At the end of each course, students were invited to evaluate the use of remote labs as emerging teaching tools. The main purpose of these evaluations was to gauge their perception of the possible contribution of the remote labs to their development as engineers.

The results of these evaluations indicate that most students consider that the laboratory with remote applications offers good support to understanding the relevant concepts of process communication and control. Furthermore, they found that these remote labs were complementary to the traditional labs. This indicates that the remote/virtual activities should be considered as a complement (and not a replacement) in teaching control engineering. The general opinions of the students who used the labs can be summarized as follows.

- Having more time to interact with the systems through remote access to the real plant gives them a better understanding of physical phenomena that may occur.
- Remote access is an efficient tool in the learning process that enhances their understanding of control concepts.
- The availability and intrinsic flexibility of these tools results in more commitment and more time to perform the experiments.
- Remote experimentation allows a better analysis of the theoretical and practical concepts.

As a result of the past expertise at UNED, a pilot remote lab, consisting of the mobile robot formation only, was previously implemented at Ghent University [33]. This was first used in a Bachelor's control engineering course and received positive student feedback. Although no survey evaluation was done, student comprehension improved, as demonstrated by improved examination results, an increase of about 15% in the distribution of grades toward the highest score. Based on the encouraging results of this pilot test, it was decided to expand the remote lab to include the ball-and-plate system. By providing multiple applications within the same remote lab platform, more students can work in parallel on similar tasks.

While experiments are being performed, however, the course assistant must be available in the lab in case any technical support is necessary. This is not a problem since these experiments can be made available during the teaching staff's working hours and can be monitored by the remote lab's security log-file since all students need to log in in order to manipulate the application. Students not being physically present reduces the teaching assistant's load to general supervision of the application. Once safety loops are attached to the plant, supervision can be further improved, and the teaching staff can focus their attention on other pedagogical/research tasks, which addresses the imbalance between the teaching and research workload encountered in the modern academic context.

The remote labs can be used for a high (but finite) number of students; experiments cannot be performed in parallel, but several (groups of) students can be logged in at the same time to manage, analyze, download data, or perform other tasks. Since the IP camera is always available, a student who is not conducting an experiment can watch the student who is carrying out an experiment. This allows interaction between the students and exchange of information, which may speed up the cognitive process.

VII. Conclusion

This paper summarizes the development, the architecture, the implementation, and two (of many possible) applications of a remote laboratory for teaching control engineering concepts to undergraduate students. These two applications are in-line formation control of mobile robots and a ball-and-plate system. Two further applications envisaged for the same remote lab, quadruple-coupled tanks and temperature control by flow regulation, would allow the use of the remote lab at the Master's level to teach the control aspects of transmission zeros, multivariable interaction, and variable time-delays.

The topics taught to undergraduates with the current remote lab are: 1) identification of real processes (i.e., dealing with noise, choosing the sampling time, observing the nonlinear effects at startup, pairing the input–output variables); and 2) the advantages and disadvantages of PID auto-tuning techniques over model-based PID control design, the use of feedforward control, and disturbance rejection. Feedback from both students and academic staff is positive and encourages such practice as a good pedagogical tool.

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