Development of a Web-Based Control Laboratory for Automation Technicians: The Three-Tank System

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Abstract—This paper introduces a Web-based control laboratory for experimentation on a nonlinear multiple-input–multiple-output (MIMO) system: the three-tank plant. Using this application, automation technician students can learn in a practical way many fundamental aspects of control processes. The client-side of the virtual laboratory has been developed using the programming support provided by *Easy Java Simulations* (EJS), an open-source tool for teachers with limited programming skills who want to create Java applications and applets. The lab has been integrated in the collaborative Web-based experimentation environment *eMersion* which provides more flexibility for the students performing the laboratory experiments.

Index Terms—Collaborative learning, distance learning, interactive systems, laboratory education, virtual laboratory, Web-based experimentation.

I. INTRODUCTION

AN automation technician is a technician in control process who has undergone two to four years initial vocational training (upper secondary education), often combined with an apprentice in a private enterprise. These technicians play an important role in the day-to-day operation and maintenance of automation equipment and control systems in all process and manufacturing industries. Automation technicians do acquire basic understanding and knowledge of automation and control systems in the initial vocational training courses in automation. However, specialized and ongoing training and practice, in addition to basic education, need to be documented. This situation may also be a result of the organizational characteristics of many companies.

- Compared with university graduates, automation technicians often have less opportunities to attend training courses to update their skills.
- Even in large companies, often only a small group of people have an automation and control background. Therefore, the automation technicians do not have much opportunity of discussing problems related to their profession with inhouse personnel.

Industry constantly puts pressure on educational institutions to produce automation technicians with sufficient basic knowledge and experience so that in-company formal and/or nonformal learning is kept to a minimum. Consequently, a need exists to provide learning materials and contents that are relevant to industry and to update and modify these continuously to match industrial equipment.

To provide solutions to this problem, five European universities are running a pilot project entitled "AutoTECH: Automation Technicians Vocational Training Repository," which is part of the European "Leonardo da Vinci" program [1].

The specific aim of the project is to develop and disseminate a set of new and innovative software packages for vocational training in automation and control. These tools would not only be of interest to the automation technicians but also to faculty teaching who want to extend their work to the production and application of educational deliveries for nonuniversity education. The training packages will improve quality and increase motivation in vocational training. Each of these packages will consist of different types of Web-based learning resources: theory, exercises, interactive simulations, and virtual and remote laboratories. As a result of this project, automation technicians will acquire knowledge and practical experience in the design, tuning, and troubleshooting of industrial control systems.

From a pedagogical perspective, a flexible education scheme is an important issue for providing students with extended accessibility to learning resources [2], [3], or for allowing them to work in virtual teams [4]. For this reason, the laboratory, which was developed using *Easy Java Simulation* (EJS) [5], a software package used to create interactive simulations, has been integrated in *eMersion* [6], a Web-based collaborative environment. Using this laboratory, students should acquire the knowledge and skills of control system modeling required to develop and test controllers that meet certain performance requirements. The interactivity of the laboratory encourages students to play a more active role and to get involved in their control engineering learning process [7].

The paper is organized as follows. Section II describes the course and the required pedagogical features. Section III briefly discusses the three-tank system. Section IV describes the Web-based learning environment. Section V discusses the control required for the plant. Section VI introduces a Web-based laboratory exercise using the laboratory developed. Section VII discusses the evaluation methodology and the results obtained. The paper ends with some concluding remarks and considerations about further works.

II. DESCRIPTION OF THE COURSE AND PEDAGOGICAL FEATURES

Table I summarizes the contents and the learning approach of the module "Measurement and regulation systems," which

TABLE I
BRIEF COURSE DESCRIPTION AND LEARNING ACTIVITY

Contents	Description	Activity type
Fundamentals of process control systems	Processes, dynamic characteristics, manual and automatic control, feedback, analog and digital controllers.	Intro- 5% Theory- 55% Lab- 30% Quizzes- 10%
Data adquisition and processing systems	The data adquisition path. Sensors and actuators. Signal conditioning. Transmitters. A/D and D/A conversors. Devices and instrumentation. Industrial buses. Programable instrumentation. Supervision systems. SCADA programs ("Supervision, Control and Data Adquisition"). Applications.	Intro- 5% Theory- 45% Lab- 40% Quizzes - 10%
Structure of the control loop	Open loop and closed loop. Feedback systems. Response and characteristic parameters. Components of a control system. Controllers. Controller tuning methods.	Intro- 5% Theory- 45% Lab- 40% Quizzes - 10%
Introduction to the multiple-loop control systems. Classification, functions and characteristics	Ratio control. Cascade control. Override control. Split control. Feedforward control. Applications.	Intro- 5% Theory- 40% Lab- 45% Quizzes - 10%
Introduction to advanced process control techniques	Hydraulic proportional. Electronic control. Devices and elements. Fuzzy controllers. Distributed control. Applications.	Intro- 5% Theory- 45% Lab- 40% Quizzes - 10%
Procedures and practices used in measurement and control systems	Configuration of measurement systems for continuous processes. Instrumentation and measurement procedures. Functional analysis of control systems in continuous processes. Configuration of control systems with a limited number of control loops. Specifications. How to select technologies, instrumentation, and devices. Graphical representation of automatic control systems using different technologies. Standards and regulations. Tuning of controlled processes. Analysis of malfunctions and diagnosis of failures in controlled systems. Maintenance of industrial equipment.	Intro- 5% Theory- 45% Lab- 40% Quizzes - 10%

is part of the Spanish syllabus for the automation technicians studies.

The table shows the emphasis placed on laboratory-based education, which accounts for approximately 40% of the overall program content. Lectures, which are divided in two main parts (introduction and theory), account for 50% of the course content, and quizzes account for the remaining 10%.

This course takes a total of 160 h. Four different training packages have been developed to cover the contents shown in Table I. Points of the module in which this work focuses appear underlined in the description.

Each training package is composed of different activity types. Students start with introductory text, which introduces the topics to be studied and also establishes the objectives to be reached. Later, lectures are used to expose to students the relevant theory in a conceptual way. Practical activities for automation technicians are as important as theoretical ones. The Web-based laboratories developed by this project are to improve the understanding of the theoretical contents. The laboratory activities are conducted in a collaborative setting and have been de-

signed to be followed by students interacting in groups using *eMersion* [6]. At the end of each module, a quiz about the subject studied in the module is given in the laboratory.

The laboratory assignments are structured in two parts. The first part is dedicated to a preliminary analysis and design activity called prelab. Prelaboratory assignments help assure that the student is ready for hands-on experiments. The student must submit a prelab document to the teacher. Only when this document is successfully evaluated, will the laboratory experience take place. In their laboratory work the students can validate the preliminary design on the physical device.

When students finish the complete training package, they go through a compulsory evaluation. The evaluation consists of questions in which the collaborative activities, such as case studies developed in the laboratory, will also be ranked.

III. THE THREE-TANK SYSTEM

To develop the Web-based laboratory, a laboratory plant was modeled (Fig. 1). The plant corresponds to the DTS200 three-tank system manufactured by Amira GmbH [8].
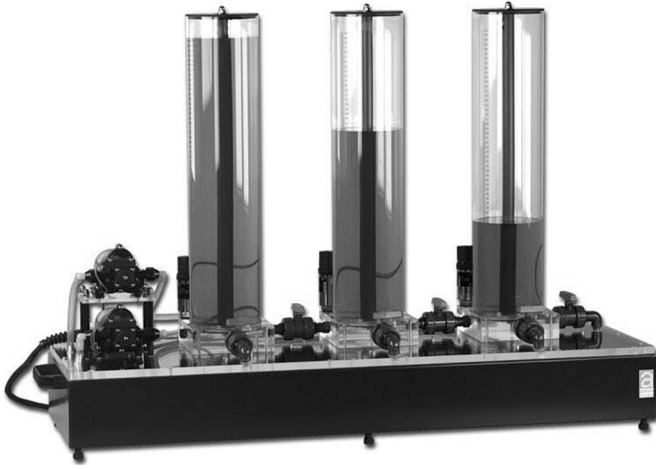
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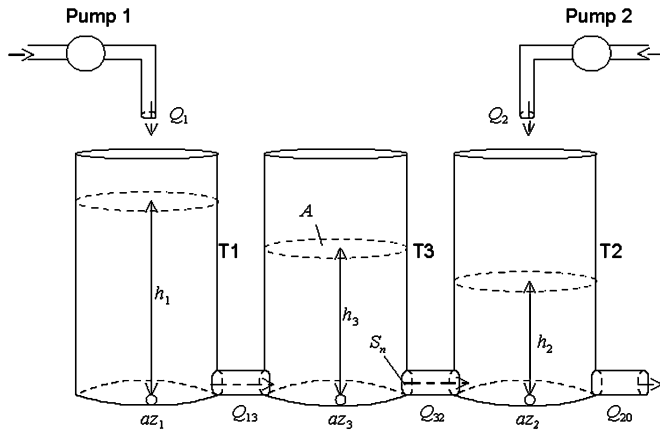Fig. 1. The three-tank system by Amira.

Fig. 2. Full structure of the plant.

A. Description of the Plant

The three-tank plant consists of three cylinders T1, T2, and T3 with the same cross *Section A*. These cylinders are connected serially to each other by pipes of cross section S_n. The tank on the left is T1; the tank in the middle is T3; and the tank on the right is T2. The complete structure of the plant is shown in Fig. 2.

On the right side of tank T2 is the outflow valve, a circular cross section S_n. The outflowing liquid from the system is collected in a reservoir located under the three tanks. This reservoir supplies pumps 1 and 2 with liquid which returns to the system. Pumps 1 and 2 represent the input flows of tanks T1 and T2. The plant is a closed system, where the liquid that enters the reservoir from the tanks returns to the tanks via the pumps. However, these pumps will be switched off automatically when the liquid level of T1 or T2 exceeds a given upper limit.

Besides the outflow valve on T2, the system includes five additional valves. Two of them are used to connect each pair of neighboring tanks (one for the T1-T3 connection and the other for the T3-T2 connection), and can be manually adjusted to close the connection between the two consecutive tanks. The other three valves are at the bottom of each tank. These leak valves can be used to manually drain each tank.

In the global system, the pump flow rates correspond to the process input signals and the levels of tanks T1 and T2 are the output signals. All of them can be used for control purposes.

B. The Mathematical Model

The mathematical model of the plant is given by the following balance equations:

$$A\frac{dh_1}{dt} = Q_1 - Q_{13} - Q_{1\text{leak}} \tag{1}$$

$$A\frac{dh_3}{dt} = Q_{13} - Q_{32} - Q_{3\text{leak}} \tag{2}$$

$$A\frac{dh_2}{dt} = Q_2 + Q_{32} - Q_{20} - Q_{2\text{leak}} \tag{3}$$

where t represents time, h_1, h_2, and h_3 represent the liquid levels in each tank; A represents the cross section of the tanks; Q_1 and Q_2 denote the flow rates of pumps 1 and 2; Q_{ij} denotes the flow rates between tank T_i and T_j ($j = 0$ represents the system output) and Q_{ileak} ($i = 1$ or 2 or 3) represents the output flow of the respective tank when the leak valve is open. These three balance equations make explicit that the volume variance in each tank is equal to the sum of the flow rates that enter and leave the tank.

The flows Q_{13}, Q_{32}, and Q_{20} in (1), (2), and (3) are calculated using Torricelli's Law

$$Q_{\text{ij}} = az_i S_n \text{sgn}(h_i - h_j)\sqrt{2g|h_i - h_j|} \tag{4}$$

where az_i is the outflow coefficient, $\text{sgn}(z)$ is the sign of the argument z, and g is the acceleration as a result of gravity. The resulting equations to calculate the partial flows are as follows:

$$Q_{13} = az_1 S_n \text{sgn}(h_1 - h_3)\sqrt{2g|h_1 - h_3|} \tag{5}$$

$$Q_{32} = az_3 S_n \text{sgn}(h_3 - h_2)\sqrt{2g|h_3 - h_2|} \tag{6}$$

$$Q_{20} = az_2 S_n \sqrt{2gh_2}. \tag{7}$$

The valves of the pipe connections, the pumps, and the leaks were modeled using the usual relationships [9].

IV. WEB-BASED THREE-TANK SYSTEM LABORATORY

A. Web-Based Learning Environment

The Web-based learning enviroment used is *eMersion* [6]. It has been developed at the Ecole Polytechnique Fédérale de Lausanne. *EMersion* allows combining traditional lectures and written exercises with additional Web-based learning resources. The environment features two main parts: the experimentation console (Fig. 3) and the laboratory journal (Fig. 4). The experimentation console is an interactive Java applet that enables the actual realization of experiments, in simulation mode or as the result of a remote access to real online equipment. In this case, the applet has been developed using EJS. Different toolkit consoles are displayed using options available in the experimentation console (see part B of this section).

The laboratory journal, called eJournal in *eMersion*, plays the role of an asynchronous collaboration artifact. It facilitates reporting, knowledge integration, and sharing among groups of students or with professors. Using the eJournal's common workspace, students can store, retrieve, share, and exchange
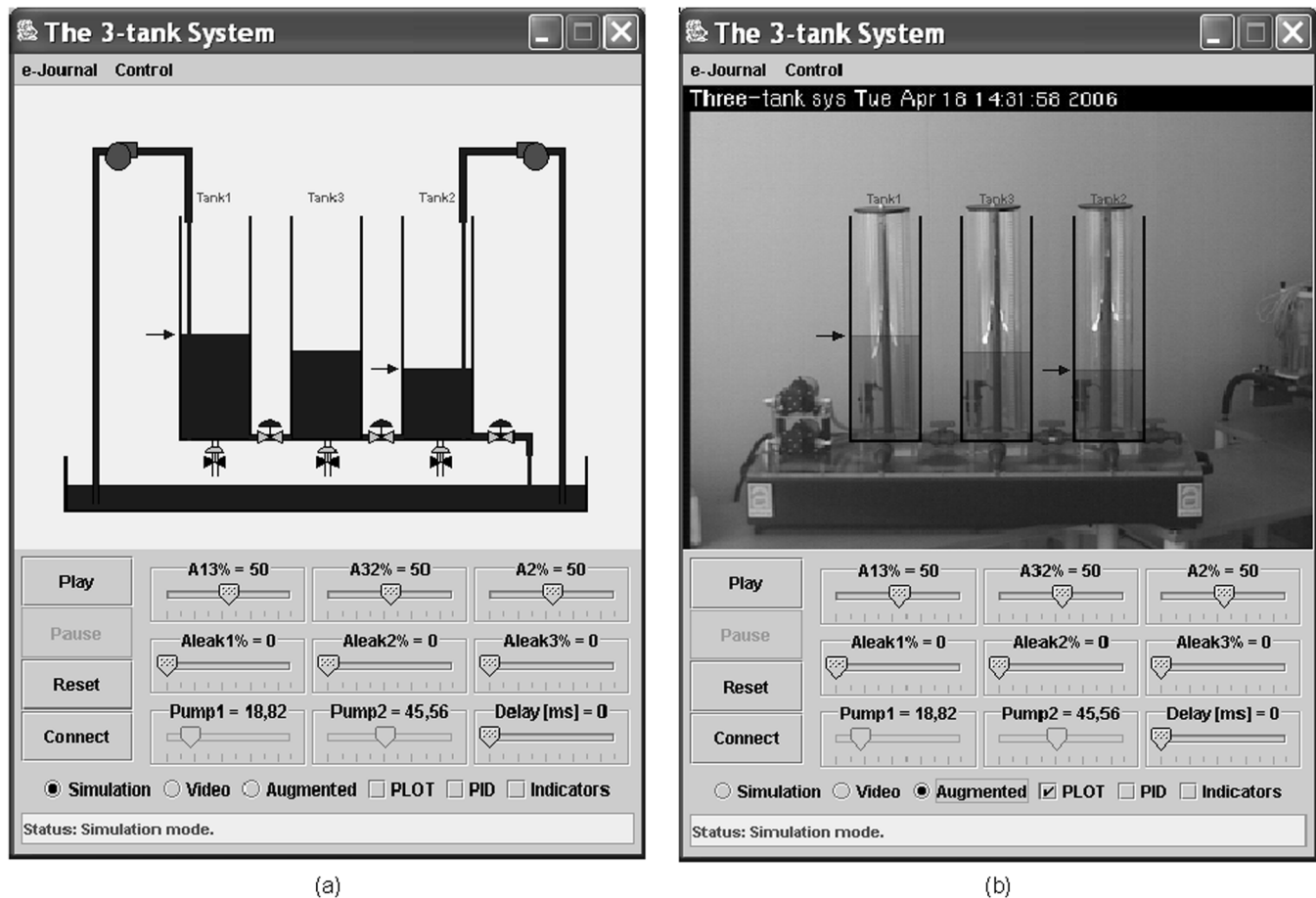
Fig. 3. Experimentation console integrated in the *eMersion* enviroment developed with EJS. (a) Simulated plant. (b) Real plant using reality augmented.

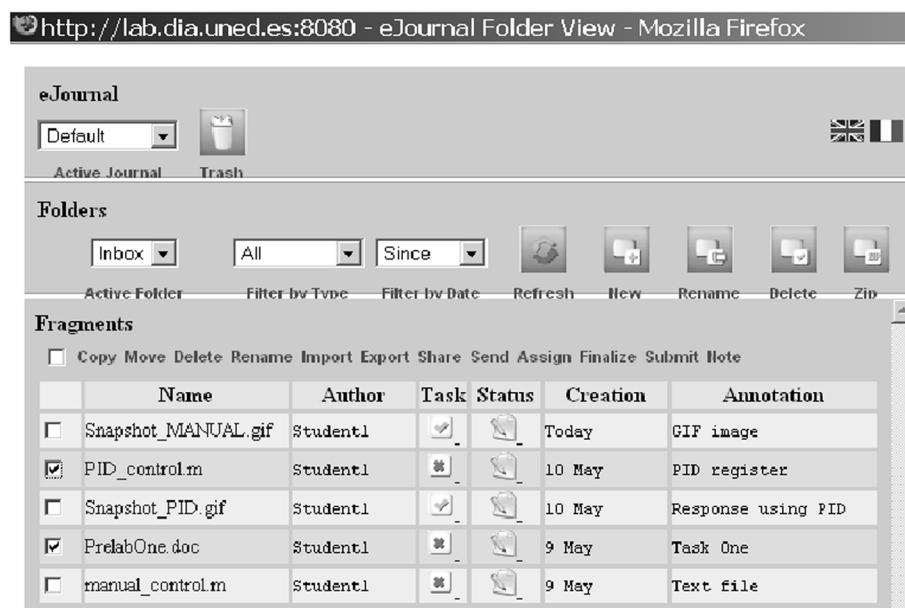Fig. 4. eJournal collaboration space integrated in the *eMersion* environment.

group documents while preparing and performing the experiments. The eJournal also allows students to submit their results to the professor via an integrated e-mail system.

Supplementary information, such as the experimentation protocol or the theoretical description of the system, can also be accessed online by students using *eMersion*.
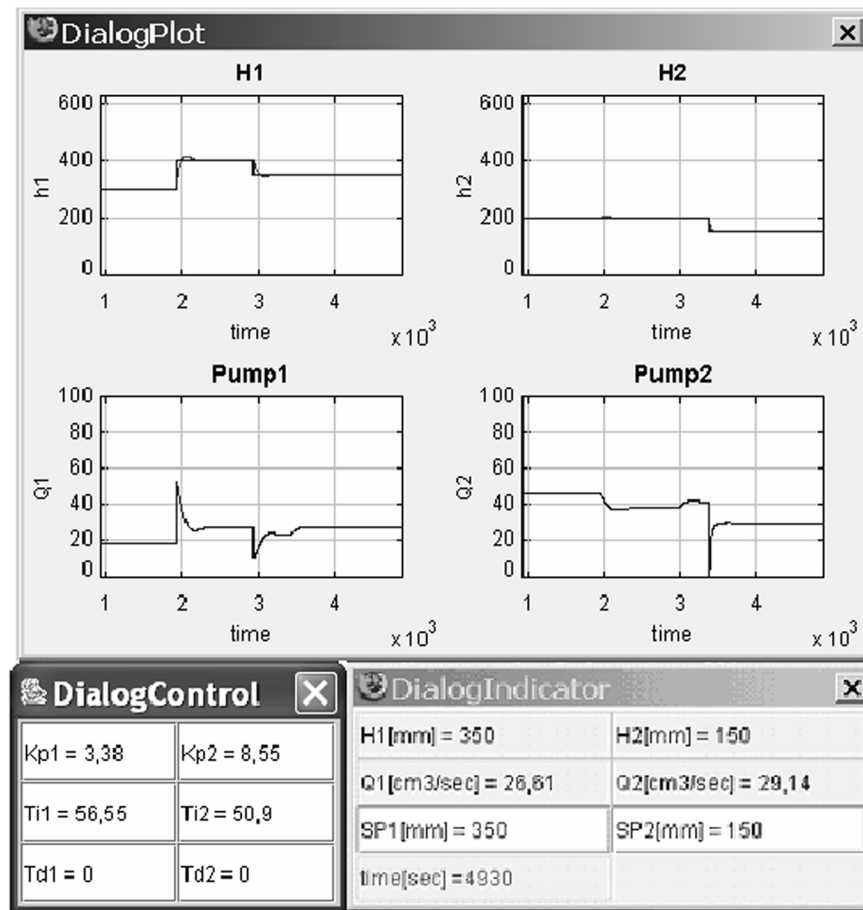
Fig. 5. Dialog windows.

B. The Experimentation Console: The Three-Tank System in EJS

The experimentation console (Fig. 3) was first developed using EJS. The resulting simulation has then been integrated into the *eMersion* environment.

EJS is a freeware, open-source tool developed in Java, specifically designed for the creation of interactive dynamic simulations [5], [10]–[15]. EJS simulations are created by specifying a model to be run by the EJS simulation engine and by building a view to visualize the model state that readily responds to user interactions.

As recommended in [16], the physical system should be realistically displayed so that students more easily understand the virtual laboratory. In this sense, an effort has been made to make the interface of the simulation as self-explanatory as possible, so that students can quickly become familiar with the system.

The interface of the simulation enables the user either to run a local simulation or to perform a remote experiment on the real equipment. Both alternatives can be exercised at the same time. The console can also be visualized in three different modes: displaying only the simulated plant, displaying the real-time image of the real equipment obtained using a Webcam connected to the Internet, or, finally, superimposing the simulated plant to the image of the real plant (thus obtaining an *augmented reality* visualization).

Students can operate the system in an intuitive way. For instance, they can interactively change the set points for tanks T1 and T2 by dragging two level arrows up and down to set the desired levels in the controlled tanks. The opening and closing of the different valves, leaks, and pumps in the system can also be operated using different sliders.

Three additional dialog windows (toolkit consoles) provide full control of the operations (Fig. 5). In the DialogPlot console students can observe changes in the levels (controlled variables) of the two tanks (T1 and T2) or in the voltages applied to the pumps (manipulated variables). Experiences using either manual or proportional-integral-derivative (PID) controls are possible. The parameters of the PID controller can be adjusted during the experiment using the DialogControl. At last, other relevant values, such as the simulation time, the level of the controlled tanks, the value of control signals, or the set points, are also provided in the DialogIndicator console.

The interface also allows students to save measurements, to take snapshots of the evolution of the main variables of the process, or to record Matlab data files (.m files). With these data, using Matlab or SysQuake, students can analyze their experimental data stored in the eJournal or use them to prepare experiments.

V. REQUESTING CONTROL OVER THE PLANT

The objective of a controller for this system is to control the level of the liquid in both T1 and T2. A schematic graph of a

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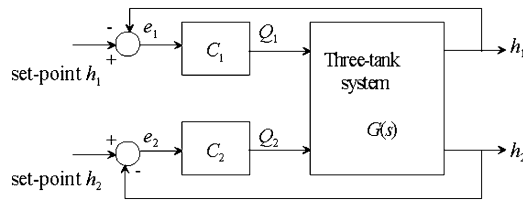

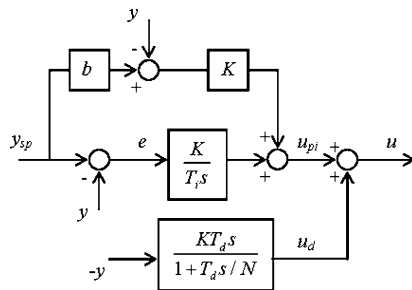Fig. 6.   Control strategy for the three-tank system.

Fig. 7.   PID control for the three-tank system.

possible multiloop control strategy is shown in Fig. 6, where C_1 and C_2 are the controllers.

The control strategy implemented is a decentralized PID controller (one for each loop). The detailed block diagram structure is given in Fig. 7, where K is the proportional gain; T_i the integral time; T_d the derivation time; N is a parameter to limit the high frequency gain ($N \in [2, 20]$); and b is the set-point weighting parameter ($b \in [0, 1]$).

By properly modifying the parameters of the PID controller, other variants, such as PI, PD, or P, are easily obtained.

Manual control is also possible in this laboratory. Using it, students can clearly observe that the system is nonlinear, since the flow of the system is a function of each of the tank heights.

Others alternative controller design strategies have been developed, such as a Model Predictive Control [17] or a Decoupled PI Control [18]. These strategies have not been included in this laboratory because PID controllers are enough for the automation technicians to understand the more relevant control principles. PID controllers are formed in a large number in all industries. These controllers have several important functions: they provide feedback; they have the ability to eliminate steady-state offsets through the integral action; they can anticipate the future through the derivative action; and they can cope with actuator saturation. Much good control practice is engineered into them. They are thus important components in the automation technicians' toolbox.

VI.   PRELABORATORY ASSIGNMENT AND STUDENT EXERCISE

Before performing the Web-based laboratory, students are required to complete a set of prelaboratory assignments. The experimentation protocol is available in *eMersion*. This set of prelaboratory assignments provides a good fundamental and theoretical background for the design of a controller for the system, which can later be remotely tested on the Web.

The assignments include the following.

- *Theoretical analysis of the system based on the mathematical model*. Students must notice that the system, although nondifferentiable, may be regarded as a flat hybrid system. Indeed, students need to realize that the system has four possible state locations. In each location a differentiable model is obtained. By analyzing the equations of the model, students must note that there must be enough head between the set points of tanks T1 and T2 so that each of the tanks can reach the set point independently.
- *Open-loop identification based on real registers of the plant*. The open-loop dynamics of the system are so slow that the identification procedure would take too long for a laboratory session. Consequently, the real registers of the time responses are recorded offline by the teacher and included in the eJournal where students can analyze these data and determine the model.
- PID *control design*. Students must select the values of the parameters of each PI controller to meet the following specifications: an overshoot of 20% and settling time of 1000 s in T1 and an overshoot of 15% and settling time of 500 s in T2.

In the laboratory exercise, students observe and record waveforms to perform the following experiments.

A.   Process Identification

Students are asked to identify the open-loop transfer function model of the system. The tanks are approximated by simple first-order lags. The gains of the process and the time constants can be determined by simple open-loop step testing from the registers obtained in the simulation. Students are expected to compare the model obtained and the model identified in the prelaboratory task based on the real registers of the system. Since registers are saved as .m files, students can use Matlab to perform any calculation required.

B.   Manual Control

Setting both controllers to manual mode, students have to adjust the pump flow-rates to achieve a specified steady-state level in T1 and T2. Then, a leak valve of one of the tanks can be opened to observe the effect on the levels of the tanks. The opening of this valve could be viewed as a disturbance. The difficulty of achieving good control of the tank levels using manual control must also be analyzed.

C.   Reference Tracking and Disturbance Rejection

In this exercise, students are required to verify in simulation mode that the values of the PI controllers' parameters determined in the prelab task meet the given specifications. These specifications are an overshoot of 20% and settling time of 1000 s in T1 and an overshoot of 15% and settling time of 500 s in T2. Students have to simulate the time response of the system using Matlab, and check that the requirements are met (Fig. 8).

Students must analyze the second-order system step response noticing that it is a function of both the system-damping ratio and the natural frequency. Comments on the responses obtained when control parameters are changed are also interesting, paying particular attention to the crosscoupling effect.

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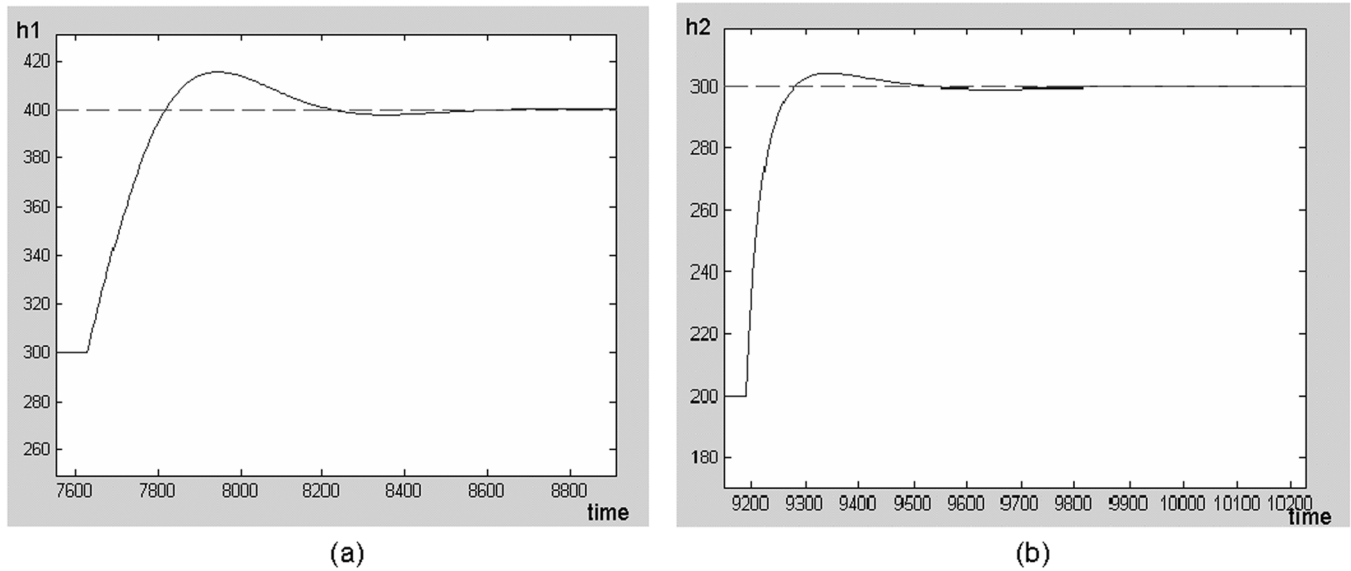DORMIDO *et al.*: DEVELOPMENT OF A WEB-BASED CONTROL LABORATORY 7

Fig. 8. Simulation response. (a) Tank 1 Level. $K_p = 1,0945$; $T_i = 71,4623$. (b) Tank 2 Level. $K_p = 5,19$; $T_i = 53,8377$.
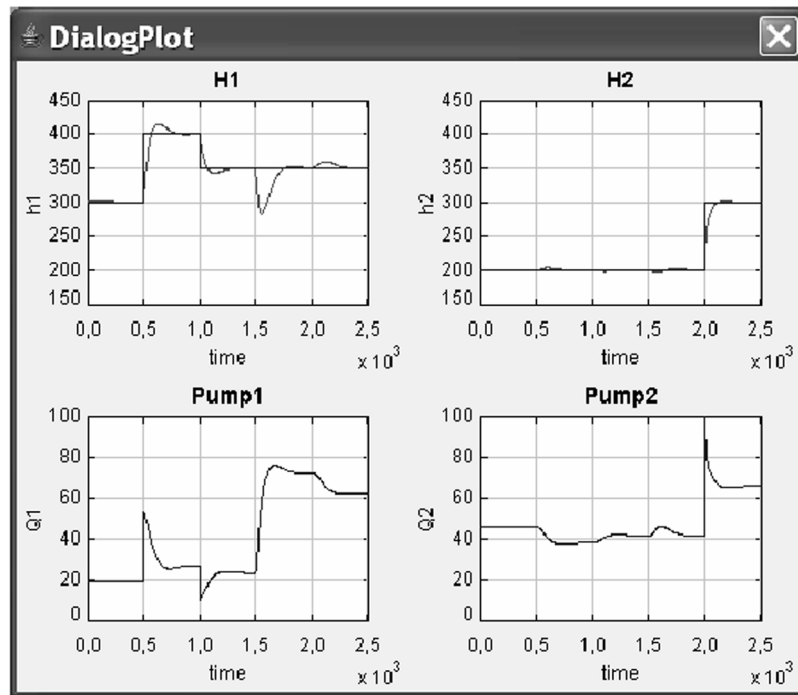

Fig. 9. Disturbance rejection: Evolution of the main process variables using PI controllers with $T_{i1} = 56.55$ and $K_{p1} = 3.38$ and $T_{i2} = 50.895$ and $K_{p2} = 8.55$.

By changing the three system leaks, students can introduce disturbances in the process. Fig. 9 shows an experiment that begins with the system working in manual mode, and is then switched to automatic mode at time equal to 150 s. At 500 s, the set point of tank T1 is changed to 400 mm, then it is allowed settling, and at 1000 s the set point of T1 is fixed to 350 mm. At time equal to 1500 s, the leak valve of T1 is opened at 37%. In other words, a disturbance is added to the system at this moment. The reference in T2 is set to 300 mm at 2000 s. As it is displayed, when a set point change occurs if a disturbance is introduced into any of the tanks, the controller used causes the controlled variables to move in the right direction towards the set point.

D. Remote Laboratory

Students can remotely perform the same experiment on real equipment using the three-tank system running at the laboratory in the university. Fig. 10 shows the responses corresponding to the reference tracking experiment proposed. The results are similar to those obtained in simulation mode (see Fig. 8).
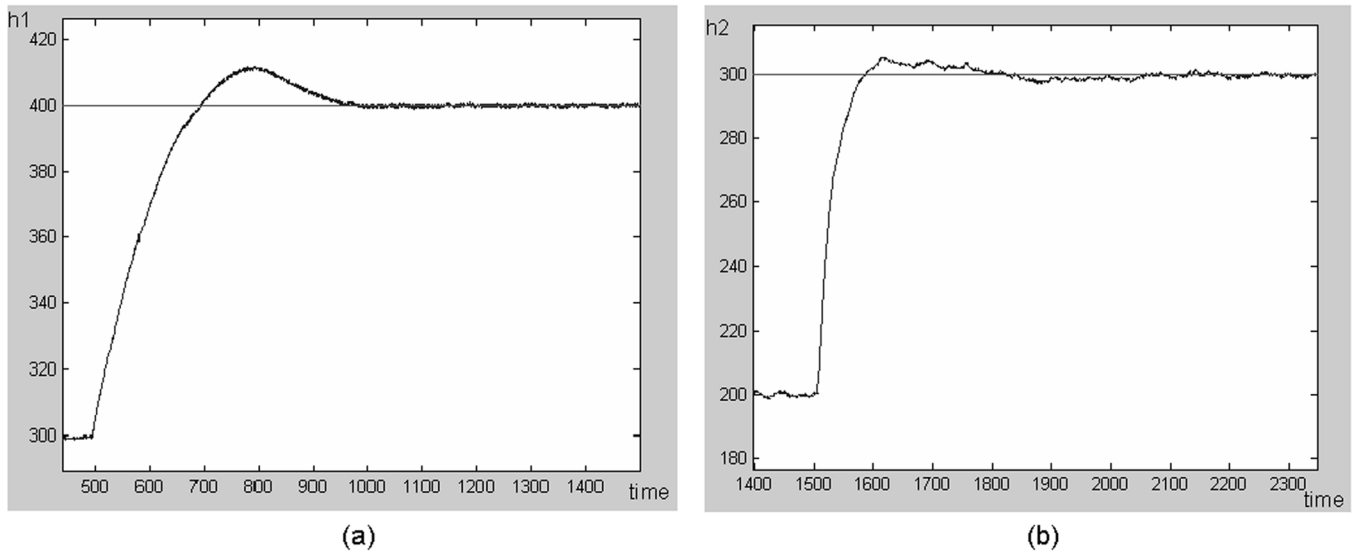
Fig. 10.   Real response. (a) Tank 1 Level. $K_p = 1,0945; T_i = 71,4623$. (b) Tank 2 Level. $K_p = 5,19; T_i = 53,8377$.

TABLE II
STUDENT QUESTIONNAIRE

Learning Value	
Q1	Did the lab enhance your ability to understand the theoretical material in a new way?
Q2	Did the lab help you to visualize the concept to be learned?
Q3	Did you gain as much information as you would from a lecture explanation?
Value Added	
Q4	Were you able to develop a better understanding of how to control a MIMO system?
Q5	Were you able to work through experiences in a way that would not have been possible by attending a traditional lab?
Q6	Was the level of interactivity in the laboratory adequate?
Q7	Was the feedback from the teacher useful?
Q8	Was the colaboration with students useful?
Usability	
Q9	Was the Web-laboratory easy to understand and use?
Q10	The ideas and concepts incorporated within the laboratory were clearly presented and easy to follow?
Q11	Were you able to fully use the Web-laboratory by following the instructions provided?
Q12	Were laboratory handouts useful?
Technology Function	
Q13	Did you miss important information because the technology did not work correctly?
Q14	Did the software requirements pose a problem for you?
Q15	How was the response time of the laboratory?

TABLE III
STUDENT QUESTIONNAIRE RESULTS IN PERCENTAGE OF TOTAL NUMBER OF ANSWERS PER SUBSCALE $(n = \text{answers})$ $(N = 30)$

Sub-scale	%Strongly Agree	%Agree	%Neutral	%Disagree	%Strongly Disagree	% N/A
Learning Value (n=64)	65.2	23.0	8	3.8	0.0	0.0
Value Added (n = 132)	61.5	27.2	11.3	0.0	0.0	0.0
Design Usability (n = 115)	63	35.2	1.8	0.0	0.0	0.0
Technology Function (n=84)	60	40	0.0	0.0	0.0	0.0

VII. ASSESSMENT AND EVALUATION

A. Methodology

Capturing students' perceptions of their learning experiences on different dimensions is an important issue in the evaluation process of any laboratory. Assessment of the Web-based laboratory developed is based on the study presented in [19].

Students are required to submit questionnaire data electronically to the teacher. Questionnaire items are combined in four subscales: "Learning Value" of the laboratory, "Value Added" by the laboratory, "Design Usability" of the laboratory, and "Technology Function."

- *Learning Value* includes items that reflect students' perceptions of how effectively the laboratory helps them learn the relevant contents.
- *Value Added* by the laboratory reflects perceptions of whether, and to what extent, the laboratory has advantages over other learning materials.

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- *Design Usability* of the laboratory focuses on students' perceptions of the ease and clarity with which they are able to navigate through the laboratory.
- *Technology Function* assesses students' perceptions of how well the laboratory functioned technically, and whether they had the technical knowledge required to use it.

In addition, other perspectives on the evaluation of the laboratory have been provided through a few student and teacher interviews.

B. Results

The questionnaire developed is summarized in Table II.

The first evaluation was conducted in 2006 during an Educational Course on EJS: "Creation of virtual and remote labs" which took place at the Spanish Universidad Nacional de Educacion a Distancia. The 30 learners were teachers responsible for different laboratories; their opinion gave valuable insight and offered the opportunity to make changes to the Web laboratory to improve students' understanding.

Table III shows the percentages of the survey for the 15 aspects of the online laboratory given by the audience, who rated them as *strongly agree*, *agree*, *neutral*, *disagree*, or *strongly disagree*.

Results indicate that technical functionality did not pose usability problems, but that design issues are the most critical feature for learners. Table III shows that Learning Value and Value Added subscales, respectively, were rated in the Agree and Strongly Agree categories 88.2% and 88.7%, respectively. These rates show that Web-based laboratory environments can be used in distance learning courses without compromising quality. The choice for Design Usability and Technology Function correspond to the Agree and Strongly Agree categories with ratings 98.2% and 100.0% of the answers, respectively.

VIII. Conclusions and Further Works

At the university level, the development of virtual and remote laboratories for control engineering education can be considered a mature technology. However, to date, the application of these learning components to nonuniversity education has not appeared in control education journals. This lack of papers means that a wide and significant group of the control engineering community, namely automation technicians, has been ignored. Thus, a primary target of this work is to develop specific advanced learning resources to fulfil the requirements and expectations of these people.

Regarding the laboratory discussed in this paper, its design replaces face-to-face physical experimentation with a computer session using either a simulation or the remote real system. Thus, the traditional way of study changes, which becomes more flexible; learning is more personalized; compulsory attendance to the classroom is no longer necessary; and work is more creative. Experimentation on the laboratory developed also provides a key educational feature: students can immediately observe the resulting dynamics and thus become aware of some physical phenomena that are difficult to explain from just a theoretical point of view.

EJS proven once more to be a suitable tool for developing interactive virtual/remote laboratories. The developer can easily build virtual and remote laboratories with views that match the standards of the industrial process control world. EJS can be freely downloaded from the EJS Web server at [20]. Furthermore, the integration of the EJS applet with the collaborative Web-based environment *eMersion* allows autonomous and collaborative learning activities.

After testing the first versions of the Web-based laboratory described, the feedback received from automation technicians' teachers was really positive. Throughout the academic course 2006–2007, pilot training courses are planned to test, assess, and validate the complete training package with automation students to obtain a final version of these learning resources.

Current and future work includes the building of a set of Web-based laboratories that will offer a complete range of experiments for students (at the moment, two- and four-tank labs already operate). These virtual and remote laboratories will cover topics ranging from basic to advanced control concepts.

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