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Developing and Implementing Virtual and Remote Labs for Control Education:
The UNED pilot experience

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Abstract: Last years, research efforts on the development of virtual and remote laboratories in control engineering education have been reported in many conferences, workshops and journals. However, it is observed that pilot experiences about the utilization of web-based laboratories are not habitual practices. In this paper it is described the pilot experience of the Department of Computer Science and Automatic Control of the Spanish University of Distance Learning (UNED) about the introduction of three web-based laboratories in a course on process control. This experience begins with descriptions of the tools employed to develop client and server-sides and the collaborative environment used to publish the labs in Internet. Attention is due to the concept of *task protocol*. It consists essentially of an ordered list of activities that students must execute in the virtual and remote mode of each one of the three web-based laboratories. To conclude, results of the pilot experience are given by means of evaluation questionnaires.

1. INTRODUCTION

Currently, it is a reality that the development of web-based laboratories in some technical and scientific disciplines can already be considered as a mature and well-established technology. This statement is especially true and relevant in the control engineering field where there is a narrow and clear link between graphical representations (Nyquist, Bode, Nichols) and the mathematical expressions of systems. It has allowed the rising of new concepts in the development of either virtual or remote labs: interactivity (Dormido, 2004) (Sánchez *et al.*, 2004a) (Guzmán, 2006), augmented reality (Gillet *et al*., 2001), networks of labs (Casini *et al*., 2005) (Pastor *et al*., 2003), etc. A proof of that is the regular celebration of international congresses, workshops and seminars devoted to the development, deployment and utilization of virtual and remote laboratories using Internet as the connecting channel among clients, that is, students, and servers, that is, real processes or models.

Yet, until now, it was not less true that in many cases the development of a web-based laboratory was just a final point, and its application in the regular teaching with students was not considered. Fortunately, this aptitude of the university teaching staff is steadily changing and the release and use of web-based labs and the learning resources associated to them (quizzes, assignments, lectures, practice homework, etc.) is becoming both a reality as a research topic. And this situation must be considered as the best one since a feedback loop is closed: experiences derived of the application of web-based labs show up the necessity of research in new tools, techniques and learning processes, and, as direct consequence of that, the availability of new tools and design techniques produces improved web-based labs, and so on.

UNED is the Spanish university for distance education and it is on charge of the higher education of nearly 120.000 students distributed all around the country. Up to recent years, the UNED's distance methodology was exclusively based on traditional tools (phone, electronic mail, postal mail, face-to-face laboratories, etc), although recently a great institutional effort is been accomplished to introduce in the teaching process learning content management systems (WebCT, Alf) specially adapted to fulfil the particular necessities and functionalities of our university. Also, lastly this effort is being increased as consequence of the put in the stage of the Bologna process.

The adaptation of the UNED's distance methodology to the Bologna requirements is not very difficult since there are many points in common. But, however, the transformation of the current conception of the engineering laboratories to Bologna is not solved by now and, here is where virtual and remote laboratories play a crucial role.

Now, when UNED students must follow out practical experiences to complete some engineering and science courses, they have to stay in Madrid for one or two weeks to attend the laboratories every day (like students of traditional universities). To get that, many students have to spend some holidays with the inconveniences generated in the family and working life. For example, to get the degree in Physics from the UNED, students must complete an introductory course on process control (Automatica I, 2007) and they have to attend the laboratory for a week, eight hours per day to complete the hands-on experiments on system identification and control.

In a try to adapt this introductory course on process control to the future European Space of Higher Education and to apply our experience on virtual and remote laboratories in control engineering, last academic year these control laboratories were transformed into web-based and pilot experiences were

carried out with students. So, it meant for students that their stays in the labs at Madrid were removed and the time to complete the practical assignments was up to them, obviously with some deadlines to send the final reports to instructors and some constraints regarding the remote laboratories (for instance, reservation of time-slots since real processes are real resources and they can not be shared for many students at the same time).

Also, for the teaching staff the pilot experience meant not only the programming of the experimentation and e-learning layers. Also, new learning materials had to be written to explain the issues derived of this new concept of laboratory: the access to the labs, the graphical user interfaces, the task protocols, etc.

Before beginning the description of our pilot experience, it is needed to define what we do figure out for laboratory and experiment. Any of the web-based laboratories reported in this paper allows the implementation of two basic components: the laboratories and the experiments. A laboratory is a container for experiments, while an experiment is a specific procedure for using a physical device available in the laboratory.

The paper is organized as follows. Section 2 describes the design and programming of the two basic elements that compound the experimentation layer of each one of our web-based laboratories, that is, the interactive client interface and the server running the real-time control loop. Also, in this section a brief description of the three processes and laboratories offered in the course will be given. Section 3 presents the eMersion-based e-learning layer, which implements the complementary web resources that every student needs to make a correct use of the experimental applications. Section 4 lists the steps of the task protocol to be followed in order to complete the practical experiences of the course by using the web labs. Section 5 provides information about the qualitative and quantitative methods used to review and evaluate the results of this pilot experience and its perceived effect on learning. Finally, some conclusions and considerations about further work are given.

2. BUILDING THE WEB-BASED LABORATORIES

For researchers and engineers who design distributed systems, one of the main challenges is to build effective communication protocols using appropriated software tools which allow enhance the maintainability, usability, performing and scalability of the system.

Based on the above idea, TCP/IP has been the protocol of communication chosen for developing the data exchange between server and clients. On the other hand, LabVIEW by National Instruments is, without any doubt, the tool used for the majority of programmers which need flexibility to manage external instrumentation, to analyse data, or to develop real-time system and communications. Thus, the server side has been developed by using LabVIEW. Finally, Java based applications are, nowadays, the natural way of thinking when portability and independence of the operating system are fundamental issues. On this line, Easy Java

Simulations (*Ejs* by short) provides all the necessary elements to develop Java applets which can be published over Internet embedded in standard HTML pages. For these reasons, all the client side applications have been developed with *Ejs*.

2.1 Experimental application structure

Fig. 1 (image extracted from http://www.ni.com) shows the communication architecture used to develop the experimentation layer. This framework takes advantage of the design pattern named "*Command based architecture*" provided by National Instrument for the remote control of embedded applications by using LabVIEW.
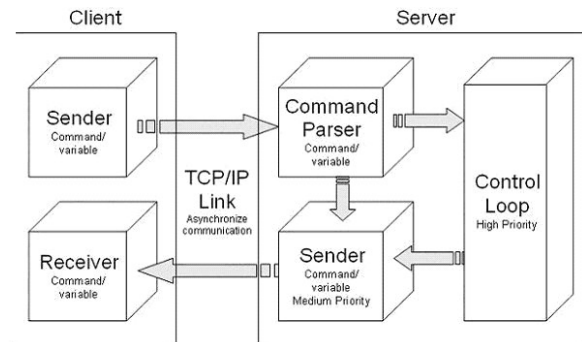

Fig. 1. Command based architecture

The command based architecture is focalized on high-performance applications where both the minimization of the network traffic and the ability to manipulate different data types using a naming convention to the variables are the fundamental objectives. The communication protocol covers the following characteristics:

- Minimize network traffic by sending data only when it is needed.
- *Set* and *Get* parameters with different data types from client side through the use of variable names hiding the TCP implementation details.
- Ability to send *metadata* information to ease the packaging and parses data.

The virtual and remote control applications used in the pilot experience implement this mechanism of communication using LabVIEW in the server side and *Ejs* in the client side. Next section discusses details of the implementation.

2.2 Server – Implementation overview

In order to decrease the delays introduced by the communication network and to make a better use of the bandwidth, the exchange data is done *asynchronously*. This "key idea" is that users do not interact with the application every time. Due to this, the communication between client and server will be unidirectional in most part of the evolution steps, being bidirectional only when user interacts with the graphical interface. In the unidirectional case, the server will send to the client the output values of the real process, while

client will send input variables only when user makes an interaction over the simulation.

Our scheme differences three main tasks in the server side: *Command Parser*, *Sender* and *Control loop*. Each element is encapsulated within a while loop structure of LabVIEW. The *Command Parser* receives instructions coming from the client, interprets them and executes the action requested. While the loop does not receive any request, it will be waiting, leaving the processor to other tasks. The *Sender* is a task of medium priority (similar to the *Command Parser*) since it runs when the *Control loop* is sleeping. The function of this component is to send to the client the system state and other output variables. Finally, the *Control loop* represents the deterministic part of the application. So, it runs with the highest execution priority in relation to other tasks. Typically, it includes the data acquisition and the closed-loop control.

2.3 Client – Implementation overview

An important characteristic of the *Command based architecture* is the ability to share *metadata* information between client and server previous to the continuous data exchange. By doing this, both parts can know the exchange format, i.e., which variables will be written and read, and what are their data types and order. Thus, the task of packaging and decoding one variable value is simple and known by both sides (server and client) in the first step of the communication. Fig. 2 shows the metadata information for two sets of variables: "time" and "speed".
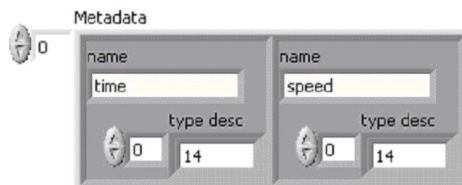

Fig. 2. Metadata information in LabVIEW

There are also two main tasks in the client side of this architecture (as shown Fig. 1): *Sender* and *Receiver*. Both components run as independent Java threads in *Ejs*. The *Sender* writes variables to the TCP channel whenever the user interacts with some of the controls available in the *Ejs* view (sliders, text fields, buttons, etc.). The *Receiver* reads continuously the data sent by the *Sender* block of the LabVIEW server.

The reading and writing of variables at the client side is developed by *set* and *get* commands. These commands are interpreted and executed in the *Command Parser* block of the server, taking into account the data types included in the metadata information.

More information about *Ejs* and its use in the building of virtual and remote control laboratories can be found in (Esquembre, 2004) and (Sánchez *et al*., 2004b).

2.4 Developed prototypes

Three virtual and remote laboratories are developed following the previous approach: the three-tank system, the heatflow system, and the DC current motor. Each one presents the possibility of working in *simulation or virtual mode* (with a mathematical model of the process) or *remote mode* (accessing across Internet to the didactical setup located in the remote laboratory).

The *three-tank system* has been selected to test different control strategies for the learning of classic and advanced multivariable control systems. Fig. 3 shows the user interface developed using *Ejs*. (Duro *et al.*, 2005). The view of the application contains a diagram of the process whose behaviour changes according to the system state. When the system works in remote mode, this simulation is replaced by video images and the system state is recovered from the real didactical setup.
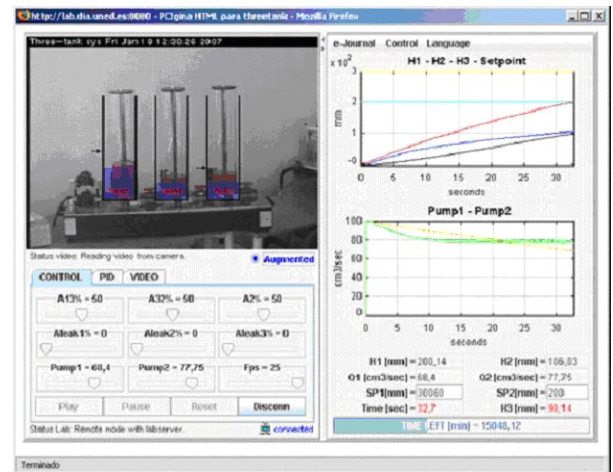

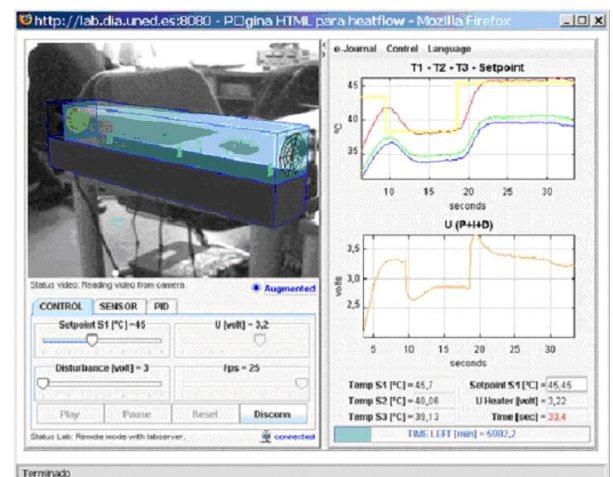Fig. 3. Interactive interface of the three-tank system

Fig. 4. The heatflow system created with *Ejs*

The *heatflow system* is used to study both some concepts related to the temperature flow control in presence of delays and identification techniques. Fig. 4 shows the laboratory

developed with *Ejs* to control the plant. Similar to the three-tank system, in remote mode the view is replaced by video images captured from a remote IP camera and the system state of the laboratory.

All the laboratories incorporate the augmented reality feature by which a graphical representation of the system is overlapped to the video image. In the heatflow system this feature is particulary useful because users can appreciate the heating process inside the duct since the colour of the air changes from blue to red gradually.

The DC current motor allows making speed and position control of a steel disc plugged to a DC motor. Fig. 5 shows in the central window the view with *Ejs* of the application connected to the remote plant in the laboratory.

The left side contains a location reserved to the simulation and a control panel to change different parameters of the system. The virtual representation is developed copying the front view of the real motor. Thus, either change of the state system during simulation mode is observed as a rotational movement of the disc. Of course, remote mode is also allowed for this system.
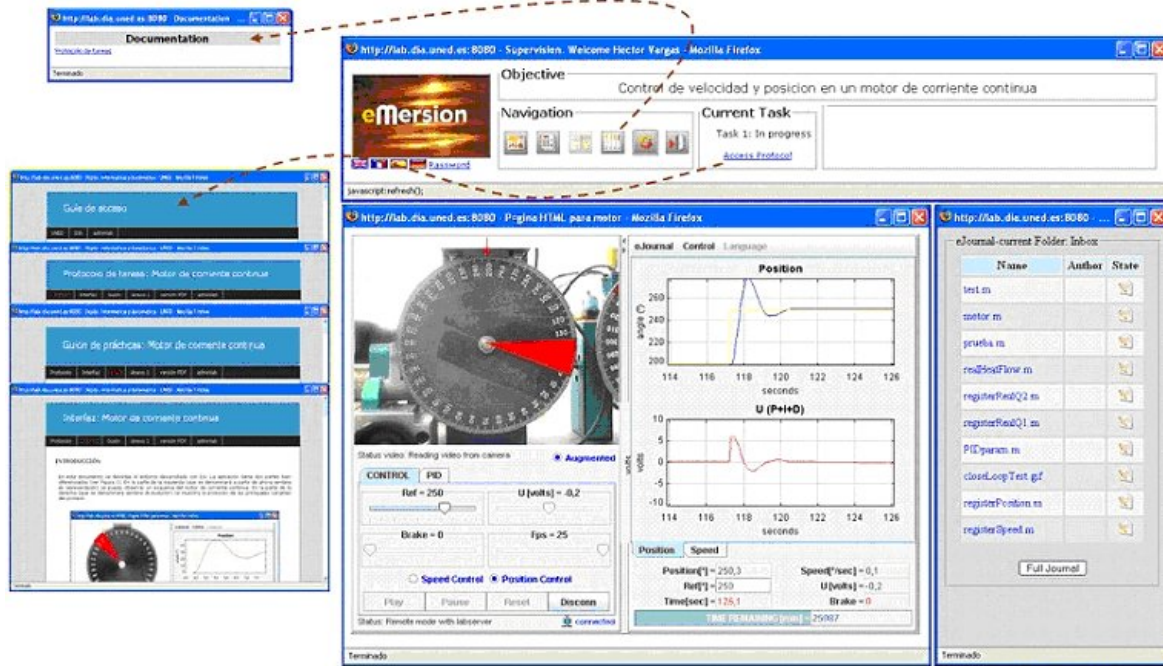

Fig. 5. Virtual and remote experimentation environment (eMersion) for the DC current motor laboratory

3. PUBLICATION AND STRUCTURE OF THE LABS

The access to our web-based laboratories is available at *http://lab.dia.uned.es*. Fig. 6 shows the home page. This web contains information about virtual and remote laboratories. For instance, concepts like virtual and remote experiments are introduced to students before they begin to work with the real processes located in the laboratory.

Our department is using the eMersion environment to support the experiments carried out by the students across Internet. eMersion is a collaborative environment developed at the Ecole Polytechnique Fédérale of Lausanne (EPFL). This tool supports all the fundamental aspects related to the Web-based collaborative works existing among students and instructors.

From a pedagogical perspective, eMersion is a very convenient environment for distance learning in engineering disciplines because it incorporates all the elements needed to complete an experimental session emulating the work carried out in the traditional laboratory (Fakas *et al.*, 2005), (Gillet *et al.*, 2005). Fig. 5 shows the functional structure of the collaborative environment for the DC current motor laboratory. The experimentation environment is composed of four parts: the eJournal, the experimentation console, the on-line documentation and the navigation bar.

Fig. 6. Home page of the web-based laboratories

The eJournal module provides a shared space to facilitate the communication and collaboration among students and instructors during the learning process. In this shared space students can store, retrieve, and exchange their experimental results and documents. Documents and files stored in the eJournal are called fragments. The experimentation console module contains the Java applet developed with *Ejs*. Using it, students can perform their experiments in a similar way to a traditional laboratory by accessing to the real laboratory resources through a local network (remote laboratory) or by simulating the physical phenomenon using a mathematical model (virtual laboratory). Additionally, the eMersion environment provides tools to simplify the organization of work-groups and offer asynchronous messaging, news, and e-mail notification services.

Each laboratory includes a set of activities named *task protocol*. The aim of this protocol is to specify the sequence of logic actions that a student must accomplish one he/she enters in the system.

Once the student chooses a laboratory the list of tasks to carry out in the virtual laboratory and/or remote laboratory are available. Moreover, the student will find on-line documentation which provides a portfolio with theory, familiarization with the safety rules, user's manuals of the environment, user's guide which describes the tasks to be performed by students during the laboratory session plus any additional information needed to successfully complete the experiments. The tasks belong to two groups: *prelabs* and *labs*. The first ones are assignments that students must carry out in simulation mode, such as identification or parameter estimation activities. Once the real process is modelled, it is necessary to tune the controller parameters to achieve the desired control objective. Only when the prelabs have been successfully finished up, the student will be granted with remote access to the didactical setup. Now, it is already possible to compare and contrast the results obtained during the simulation mode. In addition, a video window is provided to watch the remote laboratory in real time. Unlike virtual laboratories, based only on simulations, the presence of a video window is an important feature because the user can keep an eye on the real process, having a most sense of physical presence in the laboratory.

Finally, a lab report is required for each experiment or experiment block. The lab reports must comprise the following sections: a background with the theory, experimental procedures and collected data, results and discussion including answers to questions and conclusions.

4. ASSESSMENT AND EVALUATION

4.1 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 pilot experience reported in this paper is based on the study presented in (Schoner *et al.*, 2005). Students were required to submit electronically a questionnaire data to the teacher.

Questionnaire items are combined in four sub-scales: 'Learning Value' of the lab, 'Value Added' by the lab, 'Design Usability' of the lab and 'Technology Function':

Learning Value includes items that reflect students' perceptions of how effectively the lab helps them learn the relevant contents.

Value Added by the lab reflects perceptions of whether, and to what extent, the lab has advantages over other learning materials.

Design Usability of the lab focuses on students' perceptions of the ease and clarity with which they are able to navigate through the lab.

Technology Function assesses students' perceptions of how well the lab functioned technically, and whether they had the technical knowledge required to use it.

In addition, students were also asked to evaluate other perspectives of the lab through a few open questions.

4.2 Results

A survey of the questionnaire developed is summarized in Table 1.

Table 1. Evaluation questionnaire

Learning Value	
Q1	Did you gain as much information as you would from a lecture explanation?
Q2	Did the lab help you to learn the concepts faster than in a traditional lab?
Q3	Was the level of the experiments adequate?
Value Added	
Q4	Were you able to understand how to control the different systems using the virtual labs?
Q5	Were the capabilities of the laboratory adequate?
Q6	Was the web-lab more useful than the traditional one?
Usability	
Q7	Was the web-lab easy to understand and use?
Q8	The ideas and concepts incorporated within the lab were clearly presented and easy to follow?
Q9	Were you able to use fully the web-lab by following the instructions provided?
Q10	Were the laboratory hand-outs useful?
Technology Function	
Q11	Did the quality of the simulation work correctly?
Q12	Did you have any problem with the remote connection?
Q13	Did the software requirements pose a problem for you?
Q14	Did the hardware requirements pose a problem for you?

The evaluation was carried out during the 2007 summer term with students enrolled in the Physics degree program at the UNED. The process control laboratory is a mandatory course for these students.

The questionnaires returned at the end of the term show the percentages of the survey for the 14 aspects of the online laboratory given by the audience, who rated them as strongly agree, agree, neutral, disagree, or strongly disagree. These answers are summarized in Table 2.

Table 2. Student questionnaire results in percentage of total number of answers per subscale

Sub-scale	%Strongly Agree	%Agree	%Neutral	%Disagree	%Strongly Disagree	% N/A
Learning Value	55.5	33.3	11.2	0.0	0.0	0.0
Value Added	33.3	66.7	0.0	0.0	0.0	0.0
Design Usability	38.8	55.5	5.7	0.0	0.0	0.0
Technology Function	53.3	13.3	13.3	0.0	0.0	20.1

Results indicate that over 90% of students were satisfied with their laboratory experience. Table 2 shows that most of the answers were rated in the *Agree and Strongly Agree* categories. In the *Technology Function* connection sub-scale there is a 20% of non answered questions because not all the students were able to establish the remote connection.

Students were also asked to provide the most positive and negative aspect at the end of the questionaire. The commonest positive comment about the system was its flexibility. Using the laboratory students could connect to the real plant from any place at any time. Students suggested that the live experiment should be available over an extended period to gain full benefit from the experience.

5. CONCLUSIONS AND FURTHER WORKS

Nowadays, the development of web-based laboratories is already considered a mature technology. But more studies have to be done about their adaptation and application in courses using either traditional or distance education methodologies. However, one of the point that restrain teachers of creating their own virtual and remote laboratories is the absence of tools made by and for teachers. In this paper we present a template-based approach consistent in the use of Easy Java Simulations and LabView to develop client and server side, and the eMersion environment to deploy the labs and the learning materials associated to them.

The analysis of the evaluation results of our pilot experience on control process show up that it is a very promising achievement. Regarding that UNED is a relevant distance learning institution in the worldwide context, these experiences and further ones must be repeated, improved, encouraged and taken into account seriously for the preparation of the new master and graduated studies adapted to the near European Space of Higher Education.

Additional improvements for further pilot plans are the inclusion of collaborative activities using the advance features of eMersion, the development of a reservation system where students can book their time-slots for working with the real setups, the widening of the experimental offer by adding new experiments based on other setups.

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