

Remote Experimentation on a Three Coupled Water Reservoirs

Adolfo BAUCHSPIESS¹, Member, IEEE, Bruno GUIMARÃES², and Hugo L. GOSMANN³

^{1,2,3}LAVSI/ENE, UnB, Brasília, Brazil, e-mail: {Adolfo, Bruno, Gosmann}@ene.unb.br

Abstract— A remote laboratory for long-distance education is presented: the level control of three coupled water reservoirs. This process is non-linear and multivariable so that different control problems and strategies can be shown. The user can control and visualize the experiment in real-time using a standard Web browser; no additional software is required. PID, state-space, Fuzzy and Exact Linearization have been implemented on this process. Multivariable PID with the most common references are already available for remote experimentation.

Index Terms—Multivariable Level Control, Teleoperation, Educational aids.

I. INTRODUCTION

Internet with WWW has made possible long distance education becoming a reality for students, teachers and researchers in, allowing them to interact remotely using the resources already available [3], [1], [9].

A **remote laboratory** means the remote experimentation on real processes. In opposition, a **virtual laboratory** is based strictly on software simulations. It is well known that a simulation is quite often far from the reality; it depicts “only” the underlying mathematical model. For a good education it is necessary to be faced with real signals: noisy and reflecting lots of non-linear effects that are neglected in under-graduated control courses. The use of remote laboratories allows the sharing of expensive experiments between different educational institutions.

The presented architecture for remote labs goes beyond the universe of long distance education. In the long distance education context, remote laboratories are known as very efficient, due to the high level of interaction with the user. The main idea of the proposed remote lab is to use the *World Wide Web* as supporting communication platform and a *Web Browser* as its interface [8]. The client software required to run the experiment is the everywhere available *Web Browser*. The Web server implements the interface between the remote client and the physical experiment in the laboratory.

The developed remote lab allows the teleoperation of the level control of a three coupled reservoirs process at the University of Brasília [7]. In real-time the user can adjust controller parameters, reference signals and see them on a dynamically updated plot of chosen signals and on a 2-D visualization of the water levels.

II. THE THREE COUPLED RESERVOIRS

In the technical literature level control has been often used for educational purposes due to easiness of construction and the visualization appeal for students. Each process aims to show a slight different control theory concept. For example, [5] describe a system with two reservoirs, one in a higher level feeding a lower with variable cross-section. [6] shows a four tank system in two levels that can be configured to be minimum- or non-minimum phase.

In the following the model of the three coupled reservoirs process at University of Brasilia will be presented. It was build to show simple concepts as PID control at different operation points, fuzzy logic control [7] and also to verify more complex algorithms as non-linear decoupling and exact linearization of multivariable systems [4].

Dynamic model of the process

The process is composed by three interconnected water reservoirs and two pumps, as illustrated in Fig. 1. A schematic is given in Fig.2. The two input signals are the water flow of two pumps. The state of this system is given by the three water levels in the three reservoirs. Two levels can be controlled in this configuration, the third level will be considered as an intermediate variable.

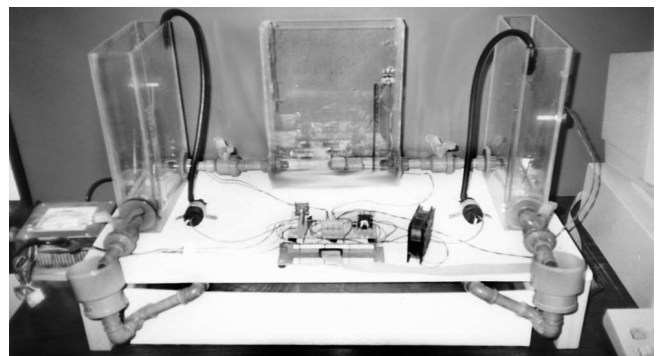


Fig. 1. The three coupled reservoirs process.

Process parameters

Each of the three reservoirs has a volume of 4500 cm³, and is coupled by means of valves, as shown if figure 2. The reservoirs 1 and 2, located outer, are supplied by water pumps. These pumps are driven by power transistors commanded by a 0-10V signal that came from a D/A card in the Personal Computer (PC). Each reservoir is equipped with a potentiometer-floater based level sensor.

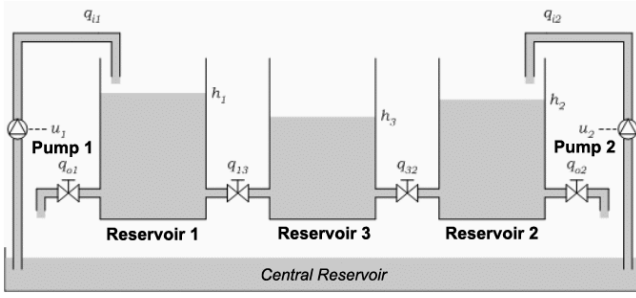


Fig. 2. Schematic representation of the process.

Considering the process in Fig. 2, the following variables can be defined:

q_{i1}, q_{i2} = input flow [cm^3/s] in reservoir 1 and 2;
 q_{13}, q_{32} = flow [cm^3/s] between reservoir 1-3 and 3-2;
 q_{o1}, q_{o2} = output flow [cm^3/s] of reservoirs 1 e 2;
 h_1, h_2 e h_3 = water level [cm] in reservoirs 1, 2 e 3.

Applying the mass balance in each reservoir, we have:

$$\begin{aligned} A \frac{dh_1}{dt} &= q_{i1} + \text{signal}(h_3 - h_1)q_{13} - q_{o1}, \\ A \frac{dh_2}{dt} &= q_{i2} + \text{signal}(h_3 - h_2)q_{32} - q_{o2}, \\ A \frac{dh_3}{dt} &= -\text{signal}(h_3 - h_1)q_{13} - \text{signal}(h_3 - h_2)q_{32}, \end{aligned} \quad (1)$$

where A is the cross section of the reservoirs and $\text{signal}(\cdot)$ is the function that returns -1 if the signal of the argument is negative, 0 if it is zero and 1 if it is positive.

The valve characteristics, considering turbulent flow, were obtained experimentally, $k = 8.2094$:

$$\begin{aligned} q_{o1} &= k\sqrt{h_1}, \\ q_{o2} &= k\sqrt{h_2}, \\ q_{13} &= k\sqrt{|h_3 - h_1|}, \text{ and} \\ q_{32} &= k\sqrt{|h_3 - h_2|}. \end{aligned} \quad (2)$$

Substituting equations (2) in (1) we get the following non-linear state space representation of the reservoirs system:

$$\begin{aligned} A \frac{dh_1}{dt} &= q_{i1} + \text{signal}(h_3 - h_1)k\sqrt{|h_3 - h_1|} - k\sqrt{h_1}, \\ A \frac{dh_2}{dt} &= q_{i2} + \text{signal}(h_3 - h_2)k\sqrt{|h_3 - h_2|} - k\sqrt{h_2}, \\ A \frac{dh_3}{dt} &= -\text{signal}(h_3 - h_1)k\sqrt{|h_3 - h_1|} \\ &\quad - \text{signal}(h_3 - h_2)k\sqrt{|h_3 - h_2|}. \end{aligned} \quad (3)$$

The student to design a PID controller can linearize these equations. In that case the coupling can be considered a perturbation signal. The student can also design a state-space controller for the multivariable system. And it is also possible to use the non-linear equations to design exact-linearizing controllers [4].

As a multivariable process the remote lab should provide the user with independent choices for the controller parameters associated to reservoir levels 1 and 2. It is also expected that the experiment could be on-line monitored by their associated references, control and measured variables.

Level Sensors. The level sensors installed in the three reservoirs have been build using $4.7\text{k}\Omega$ linear potentiometers connected by a metal rig to a floating element, as shown in figure 3.

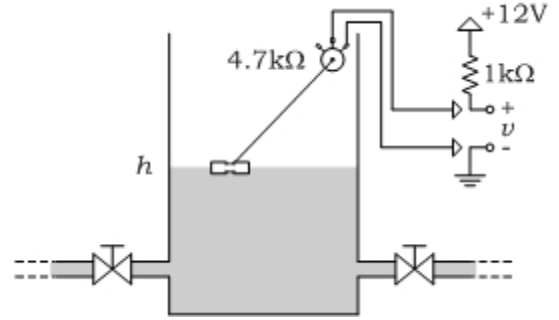


Fig. 3. Schematics of the level sensor.

The potentiometers are connected in series with a $1\text{k}\Omega$ resistor, as a voltage divider, driven by $+12\text{V}$. The voltage of each potentiometer is connected to an A/D channel of the acquisition board in the PC. The operation range of this sensor is 0 to 28 cm .

Pumps. The actuators of the system are two pumps driven by a voltage in the range 0 - 10V .

The pump control is implemented by a power electronic circuit commanded by D/A channels of the PC acquisition board, as shown in figure 4.

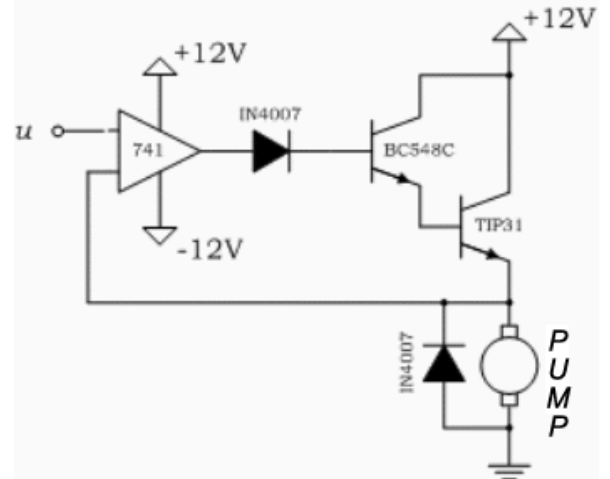


Fig. 4. The pump driver circuit.

III. DYNAMIC CHARACTERIZATION

The three coupled reservoirs process modeled in the previous section was first submitted to a series of experiments with different controller strategies. Some of these local experimentation results are presented in this section.

PI Control

For a PI control a linearization of the process must be carried out. Quite often the analogy to an electrical circuit is used, relating the hydraulic parameters with R and C equivalents [4]:

$$R = \frac{dH}{dQ_o} \quad (4)$$

$$C = \frac{dV}{dH} \quad (5)$$

The capacitance (C) represents the reservoir area and the resistance (R) the “load loss” of the fluid until reaching the main reservoir. This resistance also determines the coupling between reservoirs through their corresponding connecting ducts. With these parameters the linearized one-reservoir process became [4]:

$$\frac{H_1(s)}{Q_{i1}(s)} = \frac{R_1}{R_1Cs + 1} \quad (6)$$

If we consider a two-reservoirs process then the coupled system became:

$$\frac{H_3(s)}{Q_{i2}(s)} = \frac{R_2}{R_{32}R_2s^2 + C(R_{32} + 2R_2)s + 1} \quad (7)$$

The “R” parameters must be determined experimentally [4], while de Capacitance “C”, is simple the area of the transversal section of the reservoir.

In the frequency domain the PI controller can be described by:

$$\frac{U(s)}{E(s)} = \frac{K_p \cdot (T_i \cdot s + 1)}{T_i \cdot s} \quad (8)$$

The PI design was carried out using the root locus procedure and the following specifications

- $M_p=0\%$ (overshoot);
- $T_r=20s$ (rise time).

Fuzzy Control

Fuzzy control is a control technique that uses “rules” of an expert to create a inference system that produces a non-linear systems without extensive mathematical modeling. If the rules are well defined the result of a fuzzy controller is better then a liner controller. The price of avoiding the non-linear modeling and non-linear controller design is that some “trial” and fine tuning of the fuzzy rules are necessary [7]. The tuning of the rules was done using Mat-Lab’s Simulink® to simulate the process and the fuzzy logic Toolbox, as shown in Fig. 5. The idea was try to obtain the same dynamic specifications of the PI for any operating point of the system.

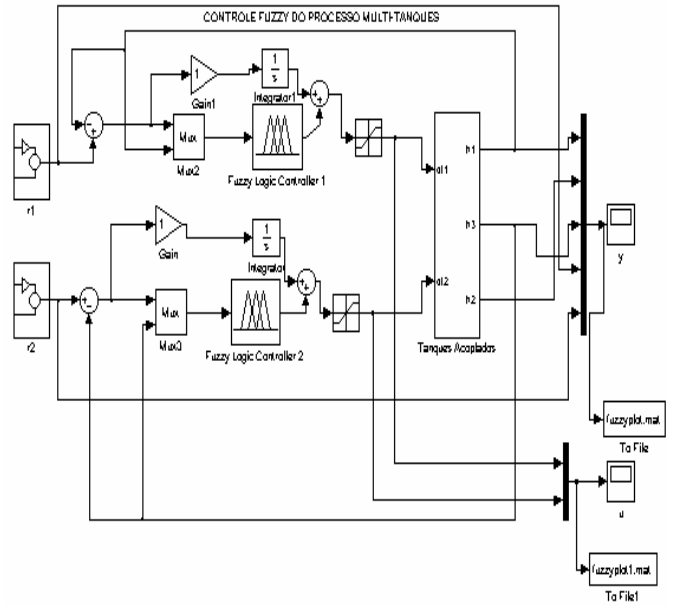


Fig. 5. Simulation of the system using fuzzy control.

Experimental “Local” Results

The controllers where implemented in Borland C++ on a Pentium 90 PC running DOS 6.2. This mono-task solution is very inexpensive when compared with real-time OS based solutions. The program reads the voltage signal associated with the water levels and delivers voltage signals to be applied to the power drivers of the hydraulic pumps.

An AD/DA board is used to interface the continuous process signals to the digital computer.

The following figures show the response of the system to test signals: Fig. 5 for PI control and Fig. 6 for Fuzzy control. The test signal consists on a “square wave” with period 100s and amplitude 1cm that is applied on different operating points: 16cm, 20cm e 24cm.

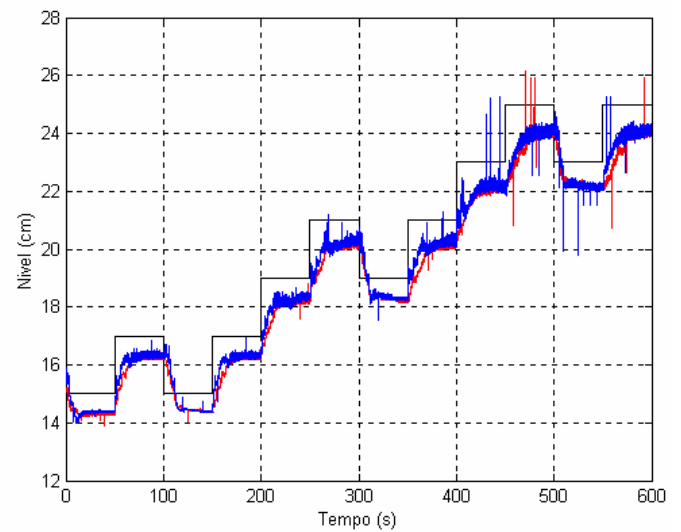


Fig. 6. Response of the system for the PI control. Reservoir 1 – Blue, Reservoir 2 – Red.

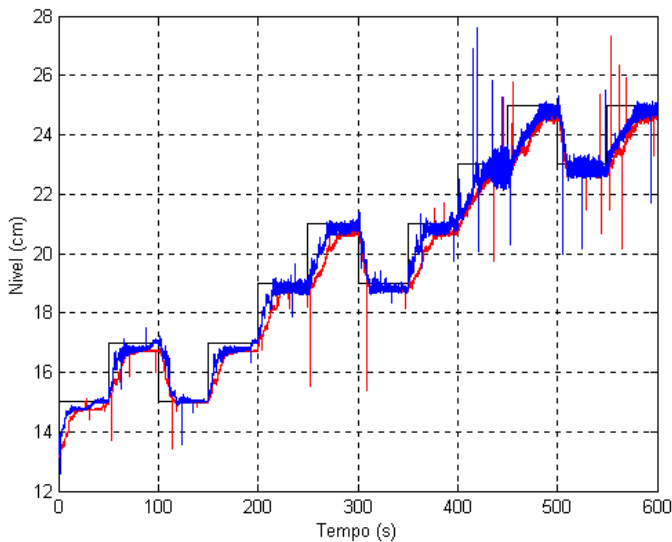


Fig. 7. Response of the system for the Fuzzy control. Reservoir 1 – Blue, Reservoir 2 – Red.

IV. REMOTE LAB ARCHITECTURE

Remote laboratories can support one or more on-line experiments [2]. Fig. 8 shows a possible solution for a remote lab with an arbitrary number of experiments, based on a unique Web server.

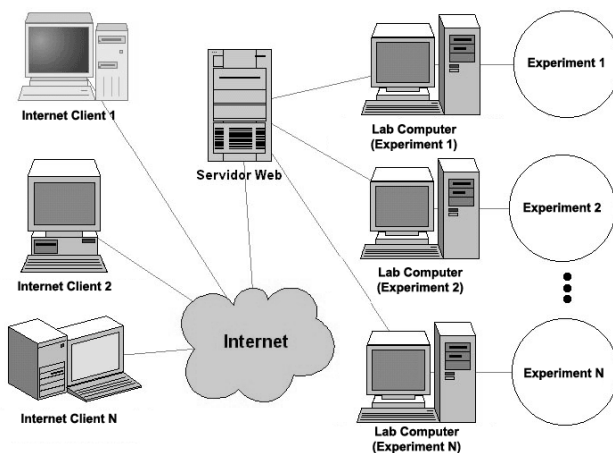


Fig. 8. Generic architecture of a remote laboratory with different experiments and one Web server.

The different client stations shown in Fig. 8 reveal the necessity for user hardware independence, so that the remote lab can be widespread accepted.

Requirements analysis

A remote laboratory requires some features to guarantee quality and effectiveness to the learning process. So, from the communications architecture point of view, the following characteristics should be given/maximized:

- ✓ High portability: Allow highest compatibility using the minimum remote user resources.

- ✓ System updating: self-sufficient architecture, that is, the updating of the system should not depend on the user and every modification should be immediately available.
- ✓ Robustness: Computational tools to protect against any physical damage or system integrity threat. Restart capacity, if necessary.
- ✓ Low cost: Students, in general, are not willing to install specific software to experiment remotely. They also don't want to pay for additional software. So, the remote lab should be based on freeware and conventional Web browsers.
- ✓ User identification/usage limitation: Remote lab through internet demands user control/registration when accessing the experiments. Once experimenting, other connected users should not have capacity to adjust the controller parameters. The time limitation is also important to let other users gather access.
- ✓ Educational efficiency: Provide high interactivity, technical information about the experiment, modular learning, etc. It is also very important that the experiment data are made available to the user after a run. So the signals should be stored on the server during the experiment run and the user can request the download afterward.

Communication structure

Three computers, at least, are involved in the remote lab, Fig. 9: Client (remote user), process controller and Web server. So, two communication paths are necessary and run in parallel during the experiment execution. The first is between the process control and the Web server, through a LAN. The second between the Web server and the client, through the internet.

Fig. 10 shows the communication structure of the system. This structure is based on client/server architecture and uses essentially *Java*. The Web server is the only interface with the experiment. First, a HTML page arrives at the user. Asking for an experiment start, a HTML form in conjunction with a *JavaScript* and PHP register the identification data. If valid, the *Java Applets* in charge of the experiment control are downloaded from the Web server to the user. The proposed communication structure, Fig.10, is generic, supporting different experiments.



Fig. 9. Remote level control experiment: The three computers involved. From left to right: client, process controller and Web server. In this case the client is in the laboratory, but accessing the site as would any other internet connected user.

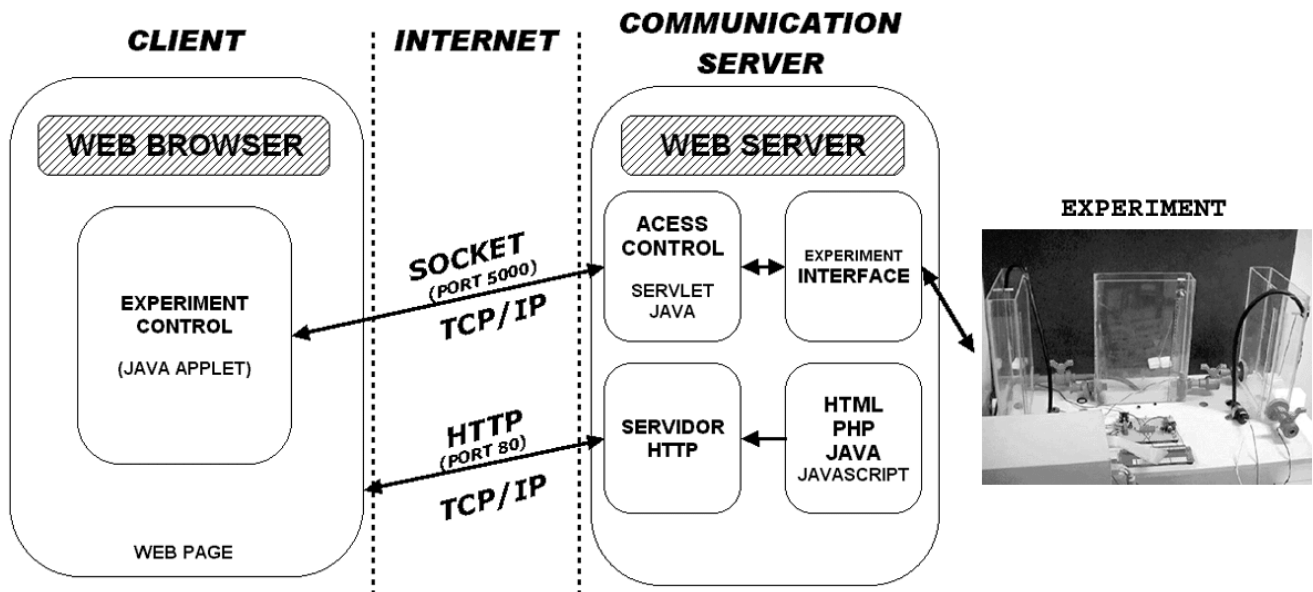


Fig. 10. Communication architecture adopted in the remote laboratory.

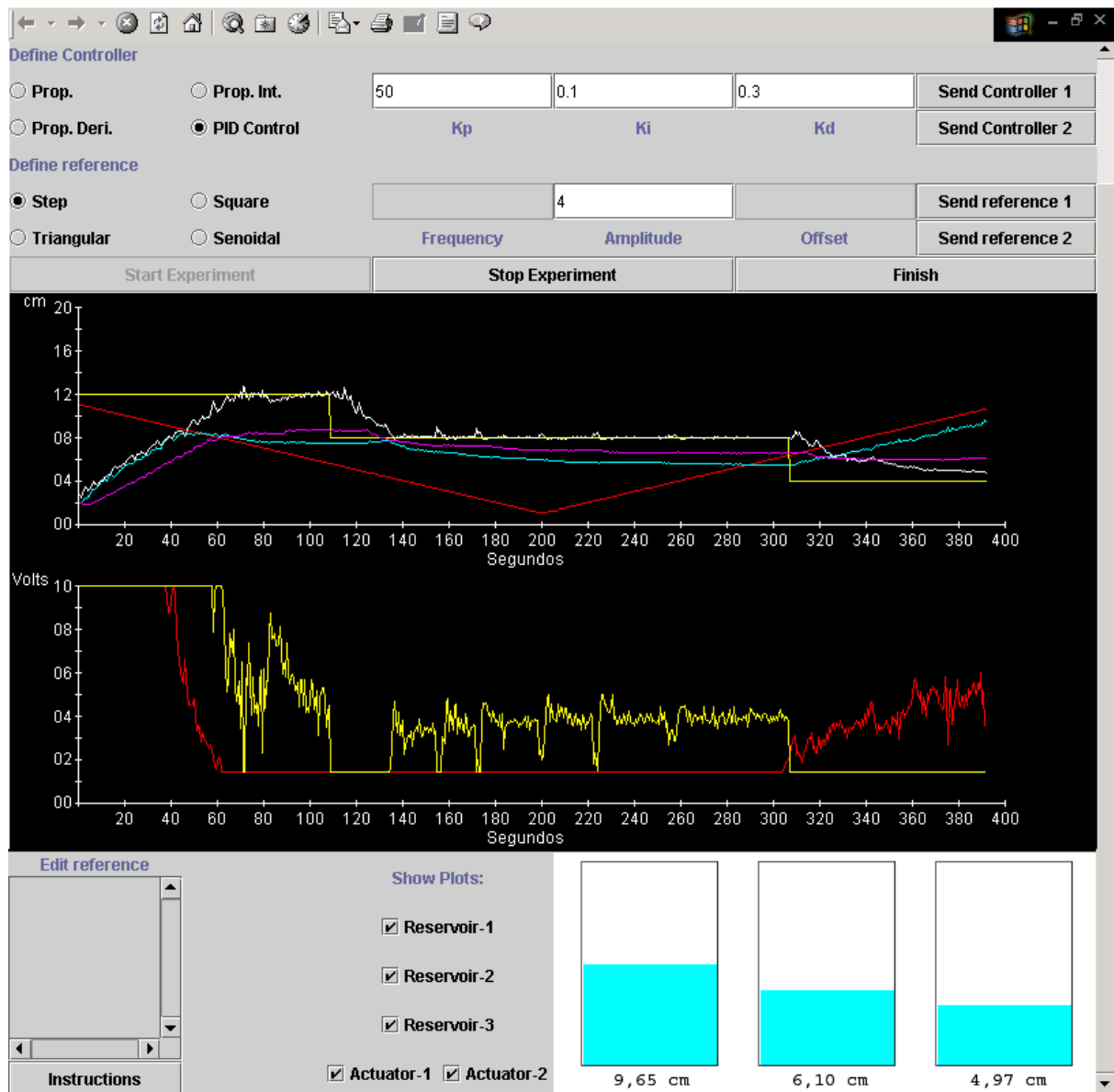


Fig. 11 – Web Browser operating the remote laboratory over a 56 kbps dial-up connection. <http://164.41.49.94/lab/>

After setting the controller parameters and the reference signals (step, sinusoidal, triangular, square or piece-wise) for the reservoirs 1 and 2, the *start* button put all to run. A *Java Applet* opens a TCP/IP connection at port 5000 with the Web server (that runs continuously the *Java Servlet*).

The process control computer runs DOS 6.22, what guarantees “near” real-time, because of its single-task nature. The *Microsoft Lan Manager 2.20* is used to support the LAN connection to the Web server. The controller is implemented in C++. The communication between the Web server and the process control computer is through ASCII files hosted on the Web server. The specific data structure used simplifies the interaction between both communicating tasks.

By the fact that control loops can demand high sampling rates, any cyclic read/write on hard disk is not acceptable (high access latencies of the mechanical hard disk heads). To avoid this, a RAMDRIVE (RAM-based virtual drive) was configured on the Web server to host the ASCII files. High data rates can so be obtained because no disk accesses are needed. Disk access functions are used but in fact RAM operations are carried out.

To start an experiment, a *Java Servlet* writes an ASCII file with the corresponding parameters. Periodic checks of the control and the data files are taken while the experiment is running. The *Java Servlet* also continuously furnishes data through TCP/IP to the remote user, closing so the loop of the remote experimentation.

If the user stops the process or exceeds the time limit the experiment is finished. A PHP *script* provides a copy of the data file that is made ready to be downloaded by the user.

Fig. 11 shows a typical result of a PID control for a step reference. The upper graphics show the levels of reservoirs 1,2 and 3. On the lower we have the voltage values applied to actuators 1 and 2.

The result window of a network tool to measure the bandwidth is superimposed on this picture. The result was obtained using a 56 kbps dial-up connection, that is, the worst case (smallest bandwidth). For the client the experiment brought 110 bytes/sec and delivered 56 bytes/sec. It is worth to mention that the experiment sampling-rate is much higher, but to present the result to the user a smaller data rate is quite sufficient.

A “reality-feeling” enhancement for the remote experiment is the use of a graphical representation of the current process state [2], in our case the water level in each reservoir. Three rectangular blue bars are drawn using Java to present the three water levels (this information is already available at the Java user interface).

V. CONCLUSION

This paper shows that real experiments in laboratories can be adapted to be shared as long distance education tools. The internet provides world-wide access.

For the client, only a conventional Web browser and the *Java Run Time Environment* is needed. In the laboratory, the experiment interface and the network structure can be implemented as shown, to allow the remote experimentation. The system as a whole could be implemented using freeware. In particular we point out the *Java* language. It is highly portable and is available without charge.

The implemented three reservoirs level control is a very handsome process because it allows a visual monitoring of the state variables of the process while the experiment is running. Beyond linear PID, state-space, “intelligent” fuzzy and Exact-Linearization have been implemented. They are now being integrated in the remote laboratory.

As future directions we mention the “reality-feeling” enhancement that can be obtained using video *streaming*. A freeware solution offered by Real Player® (*RealProducer Basic* e *RealServer Basic*) could produce and grant the access to only one user a time. The data rates obtained without *streaming* are low enough to allow, even in the worst case, that the remote user could benefit from the real-time experiment monitoring: signal graphics, 2-D level representation and video *streaming*. So the implemented remote laboratory is effectively a promising tool for long distance education.

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