Automatic Control Lab: A Pilot System for Simulation and Remote Performance of Experiments

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Abstract: - In this paper we propose a methodology for the development of educational systems that allow for simulation and remote performance of laboratory experiments. The proposed methodology is developed with primary interest in the experiments of the Automatic Control Laboratory in the Department of Electronics, TEI Piraeus, Greece; yet, it is generic and could be easily modified for application to other engineering / technical instruction or training fields as well. We present here the development of a pilot system for a liquid level control experiment, which has recently become operational and open to remote access, either through the departmental LAN or over the Internet. Access and successful experimentation statistics show that the proposed approach constitutes an attractive and advantageous alternative to the conventional hands-on experimentation practice in an engineering lab.

Key-Words: - Educational software, Tele-education, Automatic Control Systems Lab, simulation, performance of experiments, remote experimentation, Internet.

1 Introduction

In the recent years there has been an increasing research interest in alternative forms for education and training. These would exploit technological advances in fields such as computers, communications and networking, in order to provide forms of instruction more attractive, flexible (free of time and space constraints) and personalized (dynamically adaptive to the specific student’s needs or weaknesses), [1]. Conventional education methods have been supplemented by computer-aided education / instruction (CAE/CAI), while educational material in electronic form allowed for the development of the tele-education paradigm, which made Open and Distance Learning (ODL) study programs possible. More recent research was aimed towards the integration of Artificial Intelligence elements into the CAE systems, in order to help them adapt dynamically to the individual student’s progress through the educational material, [2], [3]. This attempt has given birth to the field Intelligent Tutoring Systems (ITS), which incorporate advances in software engineering and database technology for their educational purposes, [4]-[6].

Today, tele-education and ODL systems constitute well established and technologically mature paradigms. Their focus, however, remains mainly on theoretical instruction, either synchronous or asynchronous, leaving actual laboratory work to conventional instruction methods. This is mostly due to technical complexity, cost and safety issues arising when equipment is manipulated remotely. However, as educational methods and technologies mature, remote instruction and actual laboratory practice on technically demanding material constitute an interesting challenge.

Automatic Control Systems address problems in diverse scientific / technical fields, ranging from electronics, mechanics and fluid mechanics / hydraulics to biology, economics and social / behavioral sciences, [7]. This is made possible by placing all paradigms under a common abstract set of theory and practice; critical in the latter is the notion of the system, as well as that of feedback. Automatic Control is therefore a domain where laboratory experimentation is of critical importance, as it helps students substantiate abstract ideas into real world procedures and practices.

Laboratory experimentation, on the other hand, is a major educational aid in technical instruction and training, regardless of any specific technical area. Hands-on laboratory work allows students to integrate theoretical knowledge with practical skills and experience, indispensable for their first professional steps. Laboratory experimentation can
either be performed on actual technical equipment or simulated by appropriate software. It is worth mentioning here that, in an engineering context, simulation is not able to provide the student with the experience and expertise offered by the actual instruments or devices. Therefore, neither conventional nor intelligent instruction will provide quality education or training, if based solely on simulation. Studies have shown that a combination of both approaches is the educationally optimal way to go.

In light of the latter result, we propose here a method for the step-by-step development of an educational system through which students will be able (i) to study a specific experimental setup by simulation and (ii) to actually perform the experiment remotely. Our work was motivated by the need for such an educational environment, realized while teaching the Automatic Control Systems Lab to undergraduate students of the Department of Electronics, TEI Piraeus, Greece. The pilot system we have developed for that purpose is built around the Liquid Level Control experiment of the lab. However, the proposed methodology is generic and might serve as a basis for the deployment of instruction courses on other technical subjects as well.

2 System Design Methodology

We propose a three-steps procedure for the design of a remote experiment performance educational system.

- The first step focuses in the automation of the specific experimentation procedure, aiming at a result where equipment can be operated “hands-free”, through commands issued to the appropriate software / hardware interfaces. This is made possible thanks to analog-to-digital conversion cards and interface cards, that provide bi-directional low level communication between the user, interacting with a user-level application software, and the actual devices he/she intends to operate during the experiment. In the user – to – device direction, user commands are issued to the software interface, passed on to the interface cards and translated to analog signals that trigger the target device via actuators. In the reverse direction, sensors capture signals of interest, produced by an operating device; interface and conversion cards translate these signals to digital information and pass it on to the software, in order to inform the user on the experiment progress or results.
- The second step focuses on the communication between the user site and the experimental equipment site, these two now considered as being physically separate. Standard software development procedures, such as the client–server architecture, are exploited to transform the application software appropriately, so as to run in the two separate sites and provide satisfactory communication. This step is not straightforward, because the experiment time constants might pose restrictions on the communication channel parameters.
- The final step of the procedure involves connection of the user site and the equipment site over a communication network (LAN / WAN / the Internet). Again, standard computer network technologies are employed to proceed from the second to the third step, [2]. However, this step incurs an even higher risk than the second step, as quality-of-service issues are not fully resolved over Internet communication channels. In fact this step currently attracts significant research interest and activity.

The remote operation described above, however, would not be recommended for untrained users, as it would not meet basic lab safety requirements. Besides safety, cost and availability of certain devices or materials place constraints on their remote use. A viable and educationally advantageous alternative is to simulate the experimental setup to the desired degree of detail. The simulated environment can then be used either for training prospective users of the actual setup, or as a substitute of the actual experiment for educational purposes, so as to avoid heavy use and damage risk of critical equipment.

3 Development of a Pilot System

An experiment of liquid level control is selected as a pilot for the application of the developed remote experimentation solution. This choice provides a suitable educational example, thanks to its clear structure and relatively simple dynamics, [7] (chapters 4 and 5). In addition, the time constants and moving parts of this experiment do not pose critical requirements on the communication channels. This choice allows us to focus on the educational rather than the technical aspects of the developed system.

The open-loop system, shown in Fig. 1, consists of a liquid tank equipped with a filling valve and a
draining pipe with a valve. This is an elementary hydraulic system of the 1st order. Indeed, the level of the liquid in the tank at time $t$, $h(t)$, is connected to the liquid filling rate, $q_{in}$ (in litres/min), and the liquid draining rate, $q_{out}$ (in litres/min), through the 1st order differential equation

$$q_{in} (t) - q_{out} (t) = A \frac{dh(t)}{dt},$$  \hspace{1cm} (1)

where $A$ denotes the rectangular tank surface.

As the major components of this system are (approximately) linear, the system transfer function, $G(s)$, can be obtained in the Laplace domain, in the following form

$$G(s) = \frac{H(s)}{Q_{in}(s)} = \frac{R}{1 + sAR}$$  \hspace{1cm} (2)

where $H(s)$ denotes the liquid level, considered as the system output, $Q_{in}(s)$ denotes the liquid filling rate, considered as the system input, (both expressed in the Laplace domain) and $R$ denotes the draining pipe resistance. It is clearly a linear, time invariant, single time constant system, with time constant $AR$. The block diagram of the open-loop system is shown in Fig. 2.

![Fig. 2: Liquid level control system (open-loop, block diagram).](image)

In order to control the level of the liquid in the tank, $h(t)$, a negative feedback loop is added to the open-loop system. The schematic and block diagram of the closed-loop system are shown in Figs. 3 and 4, respectively.

![Fig. 3: Liquid level control system (closed-loop, schematic).](image)

![Fig. 4: Liquid level control system (closed-loop, block diagram).](image)

After the closed-loop system output $h(t)$ will have reached steady state, it should ideally follow as close as possible the reference liquid level, $h_r(t)$, provided as the closed-loop system input (Figure 4, left). In the closed loop system, a floater is used as the level sensor, to monitor $h(t)$, and an electric liquid supply pump along with an electric draining valve are used to control $h(t)$. Drained liquid is reused: the draining valve sends liquid through a draining pipe to a reservoir from which draws the liquid pump. It should be noted here that the system is hydraulic; yet, the liquid level is controlled electronically, by potentiometers and voltage / power amplifiers.
4 Student Access and Instruction

Student interaction with the experiment equipment is organized in steps for educational purposes. Our intention is to study the educational efficiency of the system both in each individual step and across the whole process.

A graphics interface has been developed that leads students into the steps of the experiment, either when they simulating or actually perform the experiment. This includes a detailed block-diagram screen, showing all physical objects as blocks, along with all possible interconnections. The screen is shown in Fig. 5. The graphics interface software allows the student to select and connect blocks graphically as well as to connect measurement equipment like voltmeters at selected points, in order to measure output quantities or view results in graphs. Equipment not connected is shaded in the background, for clarity.

Fig. 5: Screen view of the closed-loop system showing all possible interconnections.

1. The student is first asked to study Figs. 3, 4 and 5 in parallel, in order to identify all physical parts and quantities involved in the experiment from Fig. 3, and relate them to blocks and quantities in Fig. 5. The closed-loop block diagram of Fig. 4 helps the student identify the main feedback path involved in the experiment.

2. In a second step, students are handed with a list with the required experiments, tests and measurements they should perform on the specific setup, and are given time to study the list and decide their path through that. A sample list along with the associated interconnections is shown in Table 1 (connection endpoints are numbered as in Figure 5). As it can be seen, the first six steps in the list study the behavior of individual blocks, whereas the seventh step requires measurements on the output of the fully interconnected, closed-loop system.

3. In the next step, students proceeds to interconnect specific blocks and take measurements at appropriate points, in order to identify the block transfer function (e.g., amplifier gain), time response, or other useful characteristic, required in the list.
Table 1: Sample list of experiment steps along with associated interconnections.

<table>
<thead>
<tr>
<th>Step</th>
<th>Step description</th>
<th>Interconnections (Figure 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Preliminary step: Measurement of the pump motor starting voltage.</td>
<td>10-to-9</td>
</tr>
<tr>
<td>2</td>
<td>Pump-interface block: Measurement of the-pump interface output as a function of the reference level voltage</td>
<td>10-to-7 8-to-M3</td>
</tr>
<tr>
<td>3</td>
<td>Loop gain amplifier block: Measurements for the calculation of the block gain.</td>
<td>10-to-5 6-to-M3</td>
</tr>
<tr>
<td>4</td>
<td>Pump and pump-interface seen as one block: Measurements for the calculation of the block gain.</td>
<td>10-to-7 8-to-9</td>
</tr>
<tr>
<td>5</td>
<td>Liquid level sensor (floater) block: Measurements for the calculation of the block gain.</td>
<td>10-to-7 8-to-9 1-to-M3</td>
</tr>
<tr>
<td>6</td>
<td>Tank and draining pipe seen as one block: Measurements for the calculation of the block time constant.</td>
<td>1-to-11</td>
</tr>
<tr>
<td>7</td>
<td>Closed loop system: Recording of the system dynamic response, $h(t)$. Study of the effect of loop amplifier gain, $K_c$, on the liquid level error.</td>
<td>10-to-3, 1-to-2, 4-to-5, 6-to-7, 8-to-9, 1-to-11, 6-to-M3</td>
</tr>
</tbody>
</table>

When the student selects experiment simulation rather than experiment performance, the whole experimental setup and steps remain conceptually the same. The system operation is simulated in the Matlab / Simulink software environment. Student views measured values in simulated voltmeters and the recording of dynamic curves produces plots shown on the computer screen.

Furthermore, no actual difference can be seen when the student either performs or simulates the experiment over the departmental LAN or over the Internet. After connecting to the Automatic Control Lab website, the student follows the instructions given regarding certain parameter settings and then starts “running” the experiment through the common graphics interface mentioned earlier.

5 Results and Discussion

The instruction system presented here has been made available for open experimentation over the departmental LAN and the Internet during the academic years 2003-2004 and 2004-2005. It has offered our students a unique experience of computer aided instruction and laboratory experimentation, and as such it has been continuously attracting their intense interest.

Table 2 shows access statistics for a 10-months period in 2004, as an example. As it can be seen in Table 2, access percentages have been [21.02% / 65.83% / 13.14%] for [LAN / international non-USA / USA] user sites, respectively.

In absolute numbers, approximately 550 unique visitors have visited the experimental web site during this period of time; out of them, around 30 unique visitors per month (average value across the ten months) have successfully reached the point of remote experiment performance.

Table 2: Access statistics over a 10-months period in 2004.

<table>
<thead>
<tr>
<th>Access originating from</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>National access (includes departmental LAN)</td>
<td>21.02%</td>
</tr>
<tr>
<td>International, non-USA access</td>
<td>65.83%</td>
</tr>
<tr>
<td>USA access</td>
<td>13.14%</td>
</tr>
</tbody>
</table>

Fig. 6 shows access statistics per month (January 2004 to October 2004), while Fig. 7 shows visit “depth” statistics for the same period of time. In Fig. 7, when moving from back layer bars to front layer bars, we can see statistics for the access of four different web site pages, which signify the progress of the visitor in the performance of the experiment. Bars in the back layer correspond to access to the Automatic Control Lab introductory page, bars in the next two layers correspond to the introductory page for the liquid level control experiment and the performance of the first six steps of Table 1, while bars in the foremost layer correspond to performance of the seventh step of Table 1, i.e., to the successful completion of the whole experimental procedure.

These strongly encouraging results exhibit the potential of the developed system for technical instruction, including laboratory experimentation, either local or remote.

Remote performance or simulation of laboratory experiments, as presented in this work, is made possible only after having successfully addressed certain technical problems. Predominant among
them is the issue of safety while operating equipment remotely. As soon as an acceptable level of safety is established, educational quality arises as the next major target. Along this line, we are currently working on the improvement of the educational aspects of the system.

For this purpose, we first have to assess the educational efficiency of the developed remote instruction system and then address its weak points for improvement.

- Assessment involves a systematic measurement of specific educational efficiency parameters, [3], on each experimental step and on the overall procedure as well, for a period of academic time, in order to estimate weak points.

- Improvement, on the other hand, might require re-engineering of the technical solution (hardware and software platform) on which the system is built, along with re-engineering of the educational approach offered to the students.

Another educational aspect sought is the integration of the remote experimentation system presented here into a more general and generic instruction framework, such as the Intelligent Tutoring System (ITS), which is currently under development in the Department of Electronics in TEI Piraeus. An initial report on the progress on the ITS software developed in the Department of Electronics along with the perspectives of integration with the remote laboratory experimentation system can be found in [8].

References:


