Web–Based Remote Laboratory

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INTRODUCTION

From the angle of computer-based education, the Internet extends the power of the personal computer (PC) from being a standalone machine to one that is connected to the world with uncountable resources. Applications such as library access, information search, educational material download, online tutorials, and even examinations can now be routinely carried out by a low-cost PC with an Internet connection at anytime from practically everywhere.

Most applications are, however, software oriented and do not involve experimentation through remote access to physical hardware or equipment. While it is natural and easier for more flexible software to establish links and communicate with each other, these setups do provide a good learning experience in many situations. However, as pointed out by Antsaklis, Basar, Carlo, McClamroch, Spong, and Yurkovich (1999), it is commonly recognized that effective and complete learning, especially in engineering and science, requires a mixture of theoretical and practical sessions. In particular, to appreciate and use theoretical knowledge to solve real-world problems, practical exercises are indispensable.

From the angle of evolution, once problems involving software and communications protocols and standards have been established, the next stage of Internet development may see more applications where hardware can be controlled or accessed, enabling us to have a better working, living, and learning environment.

This article gives an overview of the design and use of Internet remote experimentation for the purpose of education. Following a brief survey of some related systems and their design philosophies, the architecture for a typical Web-based laboratory will be presented. The important software and hardware components and subsystems that are needed to develop a user-friendly system will be discussed, followed by some example implementations where the impacts of using such setups on remote technical education will be highlighted.

OVERVIEW

Internet Education

Developed within the midst of universities and government agencies, the Internet has been used for a variety of purposes in education. It serves as a convenient multimedia communication channel between teachers and students, and scholars and research centers, and has hosted many new, immersing, and innovative ways to enhance learning and expand educational opportunities. Distant education and nontraditional classrooms can reach more students with specialized instruction and self-paced learning, while student projects, virtual field trips, and online journals may complement available local resources.

In general, the Internet can be used for education in the following manners.

- Delivering content from a course Web site where various teaching materials and course-management functions are hosted
- Delivering programs in which multimedia animation or simulation is provided to replace physical experiments

- Providing access to a Web-based laboratory that enables students to set up parameters and undertake experiments from a remote location

Web-Based Course

This is the simplest and most common way in which the Web is used for education. In fact, most universities in the world have systems that utilize the Internet as a general communication tool and aid for material download and general learning.

In particular, Simione and Tuttle (1997) presented a user-centered Web-page-construction and maintenance model to develop Web-based course materials, while Pascoe (1997) developed several methods, including interactive exercises, course-note annotation, and automatic tailored feedback, to enable students to interact with the course site to enhance learning. Rosenblum and Healy (1996) described some Web-based collaborative learning communication tools through a CGI (computer-generated image) program that provides instructors with private course discussion areas. With an intuitive chat interface, these areas allow the instructors to give students a platform-independent ability to communicate in as many groups as is needed by the class.

Recently, Tartaglia and Tresso (2002) explored a Web-based evaluation system for technical education, while Ko and Cheng (2004) designed and developed a secure Web-based test system where a camera at the client computer is used to capture and deliver images of the student's face and postures at random intervals during the assessment. This scheme overcomes the hurdle of verifying the identity of the student by using just a simple user ID and password.

Internet Simulation Laboratory

This is the second most common way to utilize the Internet for education, and is especially beneficial in helping students to obtain a deeper understanding of hard-to-grasp topics. As an example, the concept of frequency components in a time-domain signal can be much better appreciated by using an interactive multimedia approach where students download and run a program from the Web, play around with the amplitudes of the various spectral components of an audio signal, view the resulting waveform, and listen to it at the same time.

Software-based demonstrations can be passive or interactive. The former is simpler in structure but only allows students to play back prerecorded audio or video. The latter is more interesting from a learning viewpoint, but is also more complicated to be developed. It can in general be divided into those that need to be downloaded for execution on a local machine running software such as MATLAB, or those that run directly on the Web using Java applets.

Numerous demonstration-based laboratories, such as those by Crutchfield and Rugh (1997) and Tilbury, Luntz, and Messner (1998), can be found on the Web on a variety of topics all over the world. A good example is the simulation laboratory developed in Carnegie Mellon University, where an effective paradigm to use the Web for tutoring students on the use of MATLAB and SIMULINK is provided. Students are expected to run MATLAB or SIMULINK in one window of their own computers and a Web browser in another. While surfing the tutorial, the student can download examples from the Web page and run them locally. This helps students learn how the analysis and design of control systems can be carried out.

Web-Based Remote Laboratory

The above setups provide students with useful theoretical and simulation materials. However, in science and engineering especially, it is universally recognized that effective and efficient learning requires a mixture of both theoretical knowledge and experimental work or exercises. Essentially, effects due to nonideal operating conditions, practical components, noise, and interference just cannot be taken into full consideration in any simulation. Simulations are based on the use of models that by and large approximate real physical systems. Even the most complicated models, such as those used for pilot training, assume certain operating parameters and conditions that may be violated in actual operation or flights. In fact, the most important stage in the design of a good simulator is to study the actual system for the purpose of extracting the most important essence that needs to be taken into account in the simulation. From this angle, a Web-based experiment is much more valuable than a Web-based

simulator. It is impossible for the latter to derive the former, but it will be a very valuable experience to design a simulator from getting actual data from a Web-based experiment.

Nevertheless, some basic resource issues have to be resolved in conducting laboratory-based experimentation sessions. First, physical space must be available for developing the experimental setups and for students to carry out the experiments in a conductive environment. Second, technical manpower has to be deployed to ensure safety and proper equipment handling. Third, appropriate time scheduling has to be in place to ensure maximum usage of the laboratory.

In the context of teaching, where the various topics to be covered usually follow a certain sequence, it is often desirable and sometimes necessary for certain experiments to be carried out by the entire class within a short span of time, say, a few weeks. This places a lot of constraint on resources, which will inevitably be poorly or not even utilized when the experimentation session is over. Also, students taking courses part time, in the evening, or through distant learning may not have the chance to carry out an experiment due to the unavailability of technical personnel and the closure of laboratories.

As illustrated by Foss, Eikass, and Hovd (2000), Gillet, Salzmann, Latchman, and Crisalle (2000), and Travis (2000), the use of Web-based remote laboratories corresponds to an attempt to overcome these constraints, and may well be the next important step in remote distant learning. Such a system will enable students to gain access to laboratory apparatuses anytime, anywhere via the Internet, allowing them to conduct experiments in as realistic a manner as possible. An advanced system may even have software that monitors logging on and how the instruments are used, enabling the experiment to be graded in a semiautomatic fashion. In addition, a Web-based remote laboratory may allow researchers or students in different locations to carry out research and design work cooperatively and remotely at the same time, including the remote monitoring or observation of vital changes at various stages of the experiment over a long period of time.

SYSTEM ARCHITECTURE

Performing experiments from a remote location is a form of remote access that allows interaction with the physical world through the use of appropriate electronic control and monitoring systems controlled by computers. Typically, after logging on through the Internet, a user will be able to control both the computer and the various equipment in the remote laboratory through an appropriately designed graphical user interface (GUI) running on the client computer. The interface may include image or video captured in real time in the laboratory resulting from adjustments made to some apparatus or changes in the dynamics of the objects being studied. A microphone may also be placed at interesting locations to pick up acoustic signals or vibrations in the experimental setup, and data may be captured by some instruments or sensors to be displayed or downloaded for further analysis by the user on the client computer.

For illustration, Figure 1 shows the hardware architecture of a typical Web-based laboratory in an experiment involving the use of a test circuit board as described by Ko, Chen, Hu, et al. (2001). Since multiple computers performing different functions may be needed, the system is hosted on and connected to the Internet through an intranet. The system may include a number of analog and digital control DAQ (data acquisition) cards for acquiring signals and controlling the various nonprogrammable instruments and the circuit board, while the other programmable instruments may be connected through the use of GPIB (general-purpose interface bus) or other appropriate cards to the instrument-controller PC. When the need arises, video and audio feedback may be provided by using a video server system that is connected to the intranet. Since video feedback is bandwidth intensive and more complicated to set up, this may be left as an optional item in the Web-based laboratory.

Based on the hardware structure outlined, Figure 2 shows the corresponding software structure and tools for the development of the remote laboratory. On the top level, a WWW (World Wide Web) server with, for example, Red Hat Linux 5.2 and Apache HTTP (hypertext transfer protocol) Server hosts the Web pages that contain Java applets for the experiments. At the same time, an mSQL database system may be installed to manage user authentication, while a GNU C program transits command strings from the client side to the instrument-controller PC and passes experimental data in the reverse direction. Depending on the user inputs,

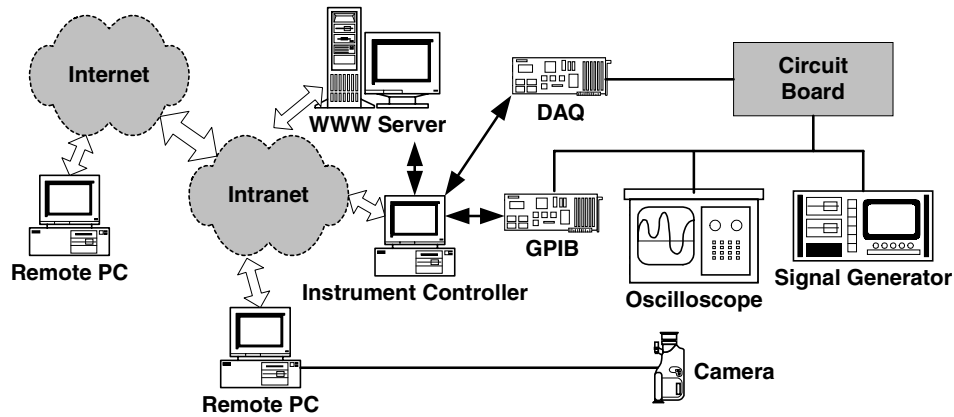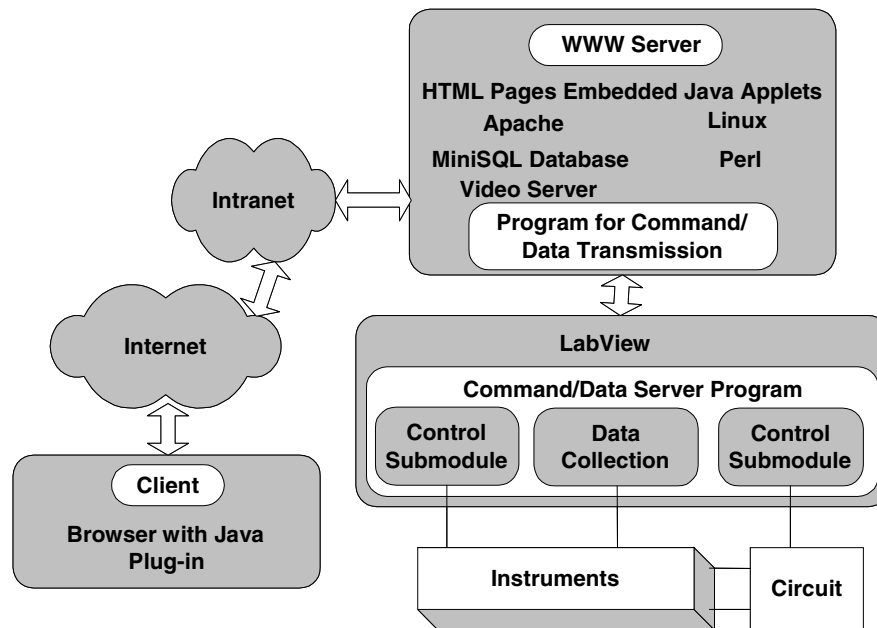*Figure 1. Typical hardware architecture*

*Figure 2. Typical software structure*

Java applets embedded in HTML (hypertext markup language) files may be downloaded for running on the client machine. At a lower level, the control of real instruments in the physical laboratory can be conveniently implemented by using LabVIEW, a graphical programming language that can provide real-time support for a rich array of cards, buses, and instruments. For every instrument under control, a submodule will need to be created to process the commands from the user.

GUI DESIGN

The user interface of a remote laboratory should be as realistic as possible to impress on users that they are actually operating on real physical apparatuses. A user-friendly interface will also enable the user to conduct the experiments conveniently and efficiently. The creation of vivid control and parameter-adjustment components such as buttons and knobs are thus essential in any Web-based laboratory.

Figure 3. Client GUI and instrument panel for an oscilloscope experiment
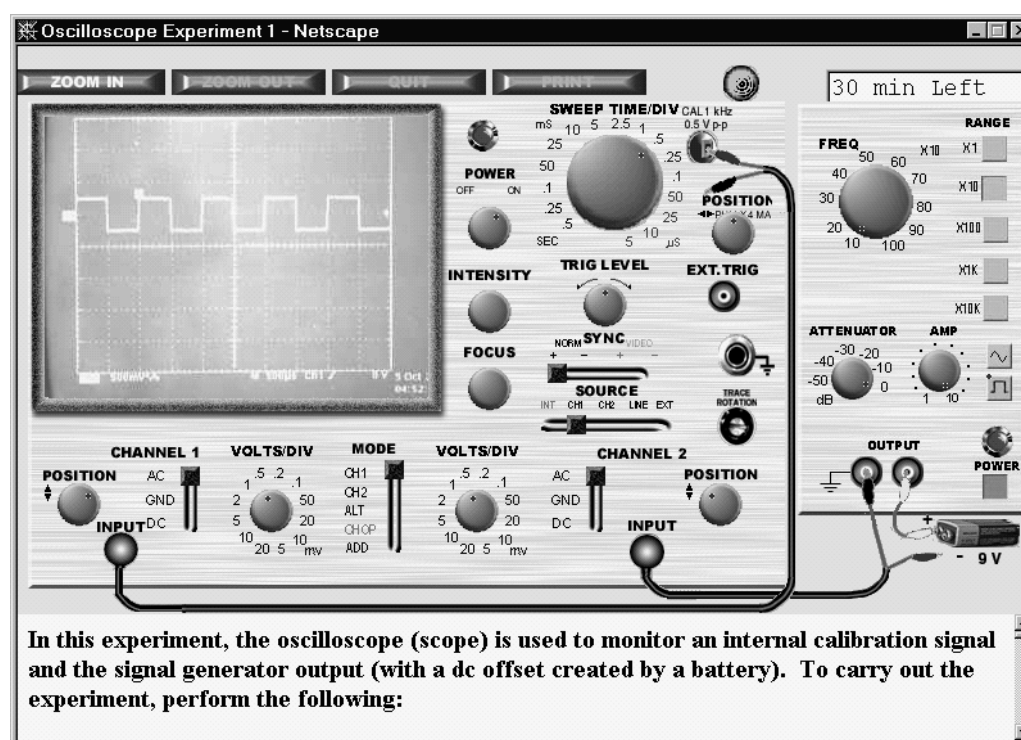
As examples, Figures 3 and 4 show the client GUI designs in two Web-based laboratories involving the use of an oscilloscope for studying an electronic circuit and the use of an expensive spectrum analyzer in a frequency modulation experiment. As described by Ko et al. (2000) and Ko, Chen, Hu, et al. (2001), the former involves the use of real-time video feedback, while the latter is a less bandwidth-intensive application that constructs the analyzer display form data sent by the instrument in real time.

Typically, after a successful log-on to the Web-based laboratory, the user will be shown the GUI, which may include several instrument panels, graphs, or tables showing experimental results, as well as windows containing various support information such as experimental procedures, instrument usage, the time elapsed, and communication status. Each instrument panel may consist of several moveable components such as buttons, knobs, terminals, and plugs, as well as appropriate displays. On the panel, buttons may be pressed or released, knobs may be turned through dragging with the mouse, plugs may be plugged or unplugged, and cables may be dragged

to connect or disconnect relevant input or output terminals. The display may be numeric in nature and constructed from real-time data sampled from the instrument, or it may correspond to a video streamed from a camera in the physical laboratory.

The GUI may be implemented by using Java, JavaScript, and HTML technologies, most of which are supported by popular Web browsers such as Microsoft Internet Explorer and Netscape Navigator. Specifically, Java applets embedded in HTML pages can be easily used to construct the main interface of the experiment. It is a natural choice on the client side because of its flexibility in GUI design, convenient network-programming capability, and platform independence. Platform independence, the last feature, is most significant since it allows the same applet program to run on client machines with different platforms.

In addition to being visually similar to those of actual instruments, the user interface must also be designed to work logically. For example, the frequency counter should show an appropriate reading only after the user has connected the frequency counter to a certain point where there is a signal.

Figure 4. Client GUI and instrument panels for a frequency modulation experiment
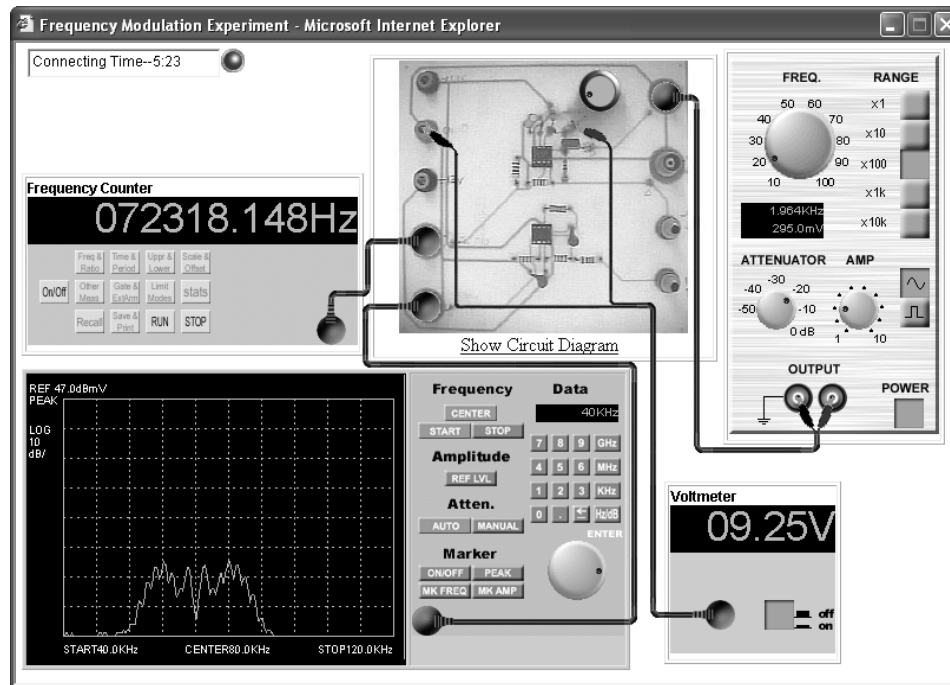
DISPLAY OF EXPERIMENTAL RESULTS

Apart from control buttons and knobs, the display of experimental results is another crucial component of the GUI. While the display and refreshment of numerical results is straightforward, the display of graphical information may be complicated and bandwidth consuming.

The simplest setup involves the use of Microsoft NetMeeting, a typical audiovisual application that uses the H.323 standard [39]. With NetMeeting, audio and video captured by a microphone and a camera can be streamed to the client side and played through the use of appropriate video and sound cards. Figures 5 and 6 show two Web-based experiments that use NetMeeting to let the user see the status of a coupled-tank apparatus and an experimental helicopter in the remote laboratory as these are being controlled. Specifically, a window on the right shows the water levels in the coupled tank in Figure 5, and a window on the left shows the moving helicopter being controlled in Figure 6.

Instead of NetMeeting, other commercial video server software such as Inetcam can be also used for video feedback, and this may sometimes provide more flexibility and the possibility for customization. With Inetcam, the video stream is pushed to the client using JPEG (Joint Photographic Experts Group) server push technology. The user requires merely a Netscape Communicator browser to carry out the experiment with no additional plug-in that needs to be installed. An example for using this is the oscilloscope display as shown in the remote experiment in Figure 3.

In addition to streaming video, results captured from the instruments can be sent to the client GUI and an appropriate display constructed. This may sometimes save network bandwidth and give faster responses. As shown in Figure 4, the power spectrum shown on the spectrum-analyzer display is constructed from real-time data collected from the actual instrument. Since the spectrum may only change slightly due to noise and other effects, refreshing of the display may not require the transmission of the entire spectral curve.

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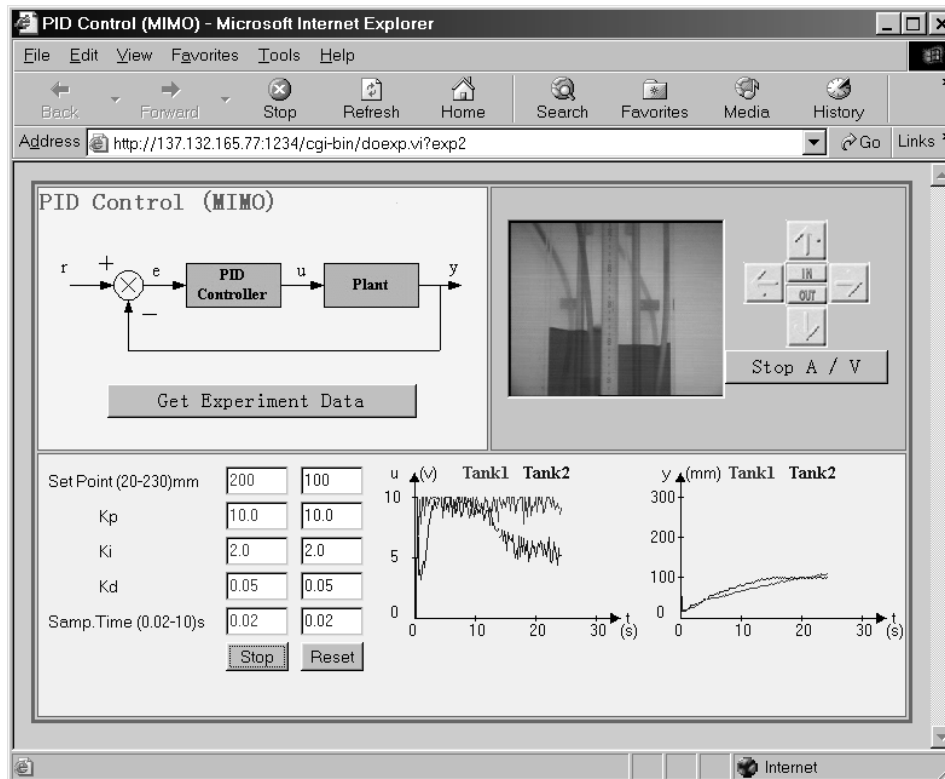*Figure 5. Web-based coupled-tank experiment illustrating the use of NetMeeting*

Figure 6. Web-based helicopter experiment illustrating the use of NetMeeting
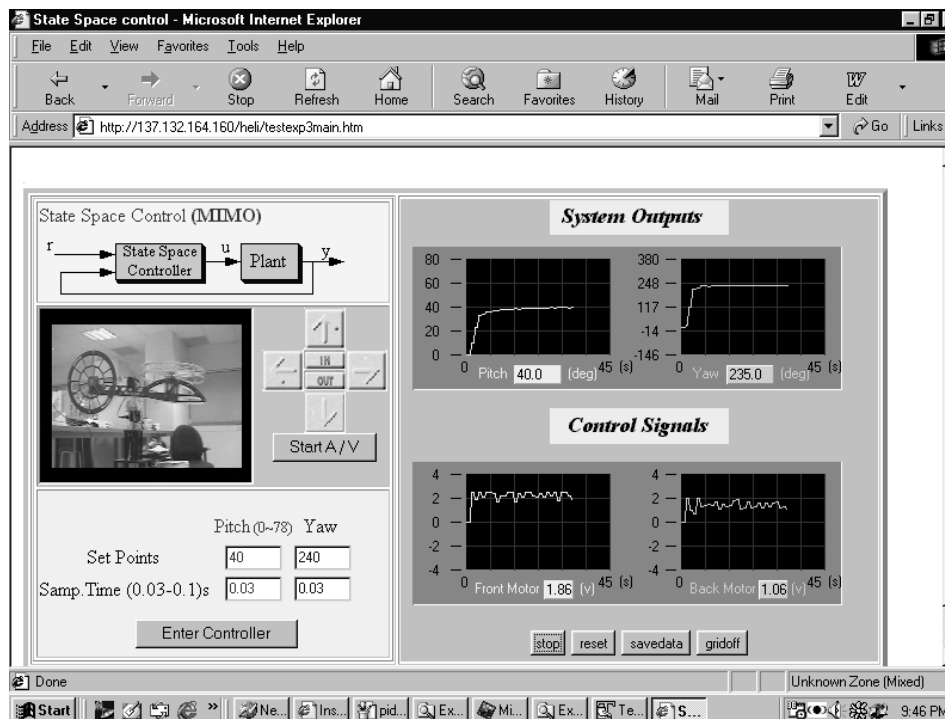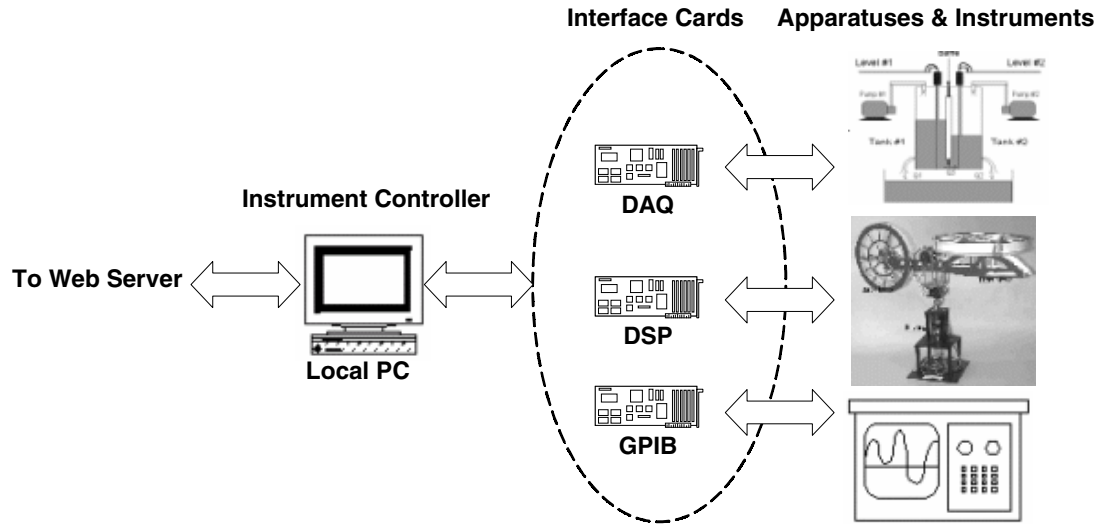
Figure 7. Interface cards for instrument control

INSTRUMENT CONTROL

The main difference between a real remote laboratory and a simulation-type laboratory is that the former is ultimately involved in the control of actual physical instruments and apparatuses. Web control of instruments can be achieved through a variety of PC-based cards, interfaces, and buses. PC-based instruments that are compatible with stand-alone instruments can also be used and are becoming popular.

Figure 7 shows some typical cards used in a few Web-based remote laboratories. Specifically, a DAQ card is used to give analog voltages to control the pump motors in a coupled-tank apparatus, while reading back the water levels in the two water tanks by sampling the signals from some capacitance probes. For the control of the helicopter, however, a faster programmable digital signal-processing (DSP) card with a high-speed processor has to be used due to the much faster response of the helicopter as it moves. A GPIB card is used to provide support for an IEEE488 bus through which commands for the oscilloscope can be issued and status can be retrieved.

IMPACT ON EDUCATION

While it may not be easy to set up, a properly designed Web-based laboratory can be used for education in a variety of ways for enhancing the experience of learning, for students to learn in a self-paced manner on their own, as well as for an entire course to be designed around the experiment. This is possible because students are no longer limited by the resource constraints associated with traditional physical laboratories.

As an example, the Web-based coupled-tank laboratory has been utilized in the teaching of both undergraduate and postgraduate courses in the Department of Electrical Engineering at the National University of Singapore. The laboratory for the undergraduate course consists of identifying a physical model for the coupled tank and designing a PID and fuzzy logic controller to control the water levels in the two tanks. Due to the complexity in tuning the controller parameters, the membership functions, and the rule bases of the fuzzy controller, students are often short of time in implementing their controllers within a 3-hour laboratory session.

The Web-based laboratory, however, allows each student to carry out the laboratory according to his or her own pace and time schedule. The manual control function in the Internet laboratory also allows students to collect real-time input-output data, which is useful in model identification. Moreover, students can interplay or fine-tune the controller parameters and membership functions, and the resulting control performance could be visualized and compared since they are based upon the same laboratory platform.

In the postgraduate course, students are introduced to solving both classical, optimal control-system-design problems and advanced, robust control problems. Since half the class consists of part-time students holding full-time employment in industry, classes are conducted in 3-hour sessions on evenings once a week. Due to security, manpower, and other constraints, teaching laboratories are generally closed after working hours and it was almost impossible to schedule laboratory experiments or to assign homework assignments on hardware implementations in the past.

With the availability of the Web-based laboratory, a new teaching element in actual experimentation can be introduced. The laboratory is used throughout the course homework assignments, in which students are required to solve an actual problem on the control of the flow levels in the system using techniques learned in the class, and implement their designs on the actual system through the Internet. To part-time students who can log on when they are free, the laboratory provides a highly flexible access to a real experiment. Feedback and comments from the students are generally very positive. Many students feel that it is superb to see that the controllers they have designed actually work in the real system.

The system offers an excellent and convenient platform for researchers to test and implement their new algorithms as well. As an example, based on a robust and perfect tracking technique developed recently by Chen (2000), a controller for the coupled-tank system has been successfully implemented. While the controller is theoretically capable of tracking any reference signal with arbitrary fast settling time from any initial condition, an infinite gain is generally required to guarantee such a performance. With the remote laboratory, certain design parameters can be easily tuned to meet the control constraints of the physical system with some trade-off in overall performance.

CONCLUSION

In this article, an overview on the design and use of Web-based remote laboratories in education has been presented. Specifically, we have discussed the architecture, design considerations, and tools that can be used to create an Internet laboratory that controls real instruments and enables students to have access anytime, anywhere. The advantages and impact of such a laboratory for a more immersive laboratory experience, for the teaching of evening classes and distant learning, for collaborative research involving the sharing of expensive facilities, and for the possibility of having courses centered around an experiment are also outlined. As computer hardware and robotics become more powerful and cheaper, the possibility of controlling a robot remotely to carry out experiments from a distance and with safety may become a reality for more and more applications.

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KEY TERMS

Internet Remote Experimentation: The use of the Internet to carry out physical experimental work at a remote location.

Online Experiment: An experiment that is running and controlled by a computer terminal.

Remote Access: The ability to control instruments or systems and retrieve relevant information at a distance.

Virtual Laboratory: A computer-accessible laboratory that may be simulated by running a software package or that may involve real remote experimentation.

Web-Based Control: The control of instruments or apparatuses through the Internet.

Web-Based Laboratory: A laboratory that typically involves physical experiments and that can be accessed remotely through the use of the Internet.