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A Remote-Access LabVIEW-based Laboratory for Environmental and Ecological Science*

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Distance learning in laboratory science and engineering has been enhanced in recent years by making instruments accessible and remotely controllable on the Web. User-friendly technologies such as those of LabVIEW software have greatly facilitated this process. This paper reports the use of these technologies for online experiments in environmental and ecological science. Remote monitoring and control is provided through LabVIEW, AppletVIEW and live streaming video. Experiments are a collaborative effort of undergraduate and high school students and of college and high school faculty. Reduction of the technical demands of these experiments allows us to focus more attention on pedagogical issues.

INTRODUCTION

THE IDEA OF World Wide Web access to instruments in engineering and science has been pioneered at several sites around the world. Projects based on this idea have greatly broadened the community of undergraduate and even high school student users of complex instruments such as a scanning probe microscope (Arizona State University http://invsee.asu.edu/) or a telescope (University of California—Santa Barbara http://www.deepspace.ucsb.edu/rot.htm). LabVIEW has been used in some of these projects, for example, in remote control of a laser laboratory (Dalhousie University, Halifax, Nova Scotia, http://vll.phys.dal.ca/) and of various engineering systems (University of Tennessee—Chattanooga, http://chem.engr.utc.edu/). The versatility of LabVIEW for these purposes has been well documented [1, 2].

A common feature of the projects just cited is their high demand for equipment and technical staff resources. Note also that these projects are devoted to distance learning either of engineering or of physical science though it seems quite possible that Web access to instruments would have many applications in other domains. The project discussed in this paper is based on a belief in the value of adapting the ideas of Web access to instruments in a manner that is less demanding of technical expertise. This approach may allow wider application to distance learning of the technologies for remote monitoring and control of experiments, providing enhanced opportunities for aspiring engineers as well as scientists.

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DISTANCE LEARNING THROUGH ONLINE EXPERIMENTS AT BETHEL COLLEGE

Here we report on the adaptation of remote access to instruments for investigations in chemistry, biology, and psychology (http://escience.bethelks.edu). Recent publications on science education by the United States National Research Council [3, 4] have emphasized the importance of experience in the process of scientific inquiry for both undergraduate and pre-university students. The National Research Council [3] has also encouraged the involvement of college science faculty in pre-service teacher education and the engagement of undergraduate students in interdisciplinary laboratory science, approaches that are pursued in this project. Recent studies of human learning indicate that learning environments must be learner-centered, i.e., that we must strive to help students to integrate new knowledge with what they already know [5]. Hence, in this project students are introduced to problems that are somewhat closer to their everyday experience than are those in the examples cited above. Special attention is given to actively involving the student in the design and execution of the experiments and in analysis and presentation of the results.

A crucial software package in this project is LabVIEW (National Instruments, Austin, TX), to which students are introduced through a lower-level interdisciplinary course in scientific computing. LabVIEW (currently version 6.0) is used in laboratories by all the departments participating in this project. See [6] for a description of early LabVIEW use at Bethel College.

In an effort to further develop the uses of LabVIEW in our courses, create opportunities for our pre-service secondary school science teachers, and enhance the recruitment of good students for our departments, we are using the Internet capabilities of LabVIEW to make our laboratory instruments available via the Web to high school students and teachers. We are conducting experiments in collaboration with high school teachers and students using these procedures. We have also established a relationship with an education service center that serves many secondary schools. They assist us in establishing a clientele for our Web-based services and advise us in working with this clientele.

Our project is focused on environmental and ecological science as it is taught in three core introductory laboratory courses—Environmental Chemistry, Environmental Science, and Animal Behavior. In addition to the content that unifies these courses, we are developing them as Web courses. All three courses already utilize similar LabVIEW-based measurement technologies in experiments conducted online. These experiments examine changes that occur relatively slowly, over hours or days, and so online access is extremely useful in allowing students both on and off campus to monitor these changes regularly. The project affects about 25 lower level students per semester (not counting high school student participants) in addition to 10–15 upper level students in coursework or assistant roles.

The fundamental hardware and software for the workstations in each department are the same. We employ Macintosh G4 computers with National Instruments PCI-6052E data acquisition boards. Signal conditioning is accomplished with various National Instruments SCXI modules in an SCXI-1000 chassis. In Environmental Chemistry and Environmental Science we use two input modules, one for thermocouples (SCXI-1121) and a second for pH, oxygen, and carbon dioxide (CO_2) probes (SCXI-1120 with BNC connector block). These probes allow continuous long-term monitoring of chemical solutions and aquatic environments. Each SCXI chassis also contains an output module (SCXI-1161) for control of external devices, in particular a peristaltic pump for adding substances to solutions that are being monitored with the probes. The workstations for the Animal Behavior course employ the same computers, data acquisition boards, and signal conditioning chassis. In this case the chassis is equipped with high voltage input (SCXI-1162HV) and output (SCXI-1163R) modules to allow communication with the animal training equipment (levers, food and water dispensers), which operates at 28 VDC.

LabVIEW virtual instruments (VIs) for all experiments have been created by our faculty and student assistants using the LabVIEW examples as points of departure. Examples designed for our particular SCXI modules are especially helpful in solving the problems of low-level communication with data acquisition hardware. All these VIs write data to spreadsheet files at regular intervals, selectable by the user according to the needs of each particular experiment (see Fig. 1).

Making the experiments available online is accomplished in several ways (see Fig. 2). Dynamic displays are made available by means of AppletVIEW (Nacimiento Software, Austin, TX). The AppletVIEW server software runs on a separate Linux computer (700 MHz Pentium III, 256 mb RAM, 18 Gb SCSI hard drive). AppletVIEW subVIs are incorporated into each of the data acquisition VIs. These subVIs pass data to and from the AppletVIEW server software via the local area network. Web displays are designed with AppletVIEW tools, which handle all the Java programming. Displays with controls and indicators similar to those on a LabVIEW front panel can be created. We have created various such displays for each of our experiments. The displays are posted to the Web by an Apache Web server running on the same Linux computer. Displays that incorporate controls require a password in order to gain access; password access is managed with the standard capabilities of the Apache server.

Preliminary work with clients at remote sites indicated a demand for at least two additional forms of communication. Since the experiments that we are conducting involve long-term monitoring and changes that occur over rather extended periods of time (hours to days), there is a need for

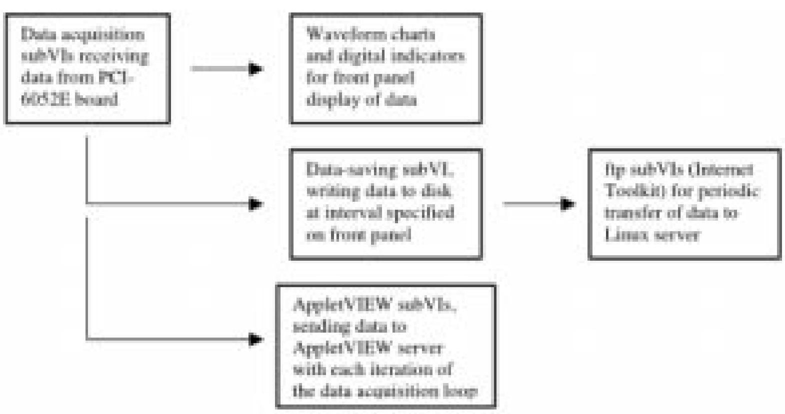

Fig. 1. A general flow diagram for our LabVIEW data acquisition VIs.

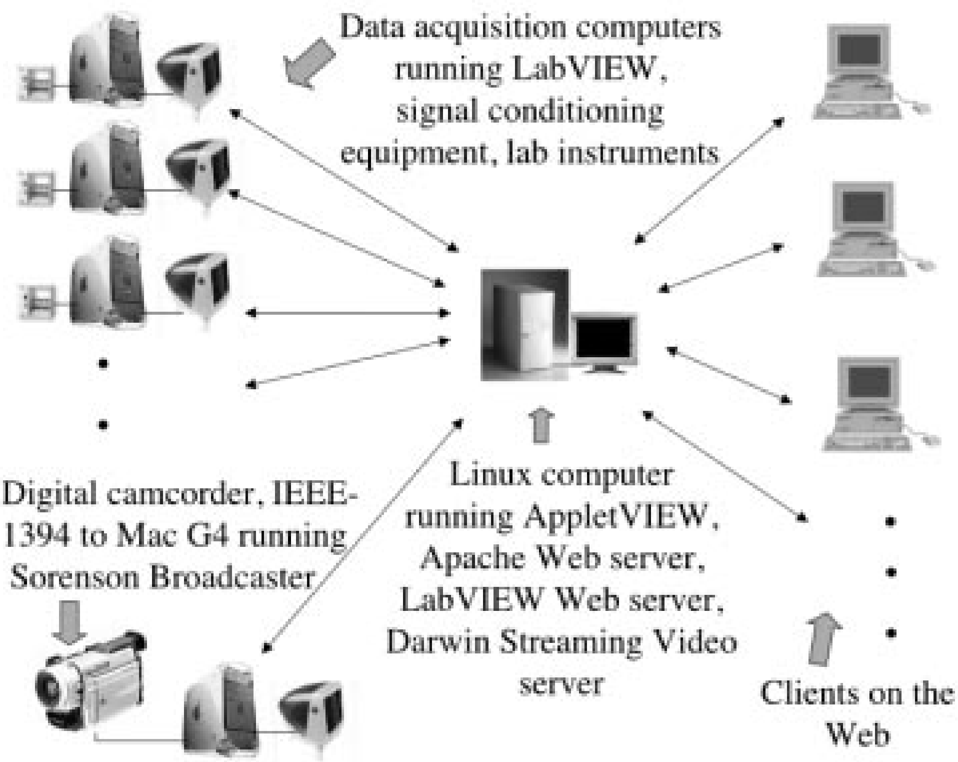

Fig. 2. Diagram of major data acquisition and server components.

graphical display of the cumulative results of experiments. These results are saved in files that grow throughout the experiment at each data acquisition workstation. The files are periodically sent to the Linux server through the ftp capabilities of the LabVIEW Internet Toolkit. These ftp sub-VIs are incorporated into the data acquisition VIs at each workstation. LabVIEW VIs running on the Linux server read these files on an hourly schedule and post them on the Web using the http server built into LabVIEW.

A second form of communication requested especially for the animal experiments is video. This request is consistent with the argument of Salzmann *et al.* [2] that video is needed for experiments entailing rapid changes. This problem has been addressed by running video streaming server software (Darwin Streaming Server 3.0, available free from Apple Computer) on our Linux server. A Macintosh G4 is connected via firewire (IEEE-1394) to a Sony camcorder (DCR-TRV900). Sorenson Broadcaster software (version 1.1, Sorenson Media, Salt Lake City, Utah) running on this G4 sends live video via our local area network to the Linux server. Links to these live images are easy to incorporate into the pages served up by the Apache server.

Upon completion of experiments or individual experimental sessions, the data are made available for downloading over the Web. The data are in the form of tab-delimited text files. In many instances these are the files that are saved at each workstation by our LabVIEW virtual instruments, sometimes with minor editing. For some experiments (e.g. those on animal foraging) preliminary averaging across experimental sessions may be needed. All posted data files can be opened and analyzed with spreadsheet software. Since our distance-learning clientele consists of high school students, we assume that most analyses will be in the form of graphical displays of data columns from these spreadsheet files. Students are encouraged to look for patterns over time and to compare different experimental conditions visually. However, the raw data for more quantitative analyses are also available if they or their classroom teachers so choose.

SOME EXAMPLE RESULTS OF ONLINE EXPERIMENTS

Environmental chemistry

An important topic in the Environmental Chemistry course is the natural regulation of pH in fresh waters [7]. Students are introduced to acid-base equilibria that are important in determining pH and various ion concentrations in natural waters. The CO_2/carbonate system is discussed in some detail, and calculations are carried out that show equilibrium concentrations in H^+, Ca^{2+}, and HCO_3^- ions close to those found in fresh water lakes and streams. What is difficult to convey to students is the length of time for equilibrium to be reached (may be hours or days) and how human activity can impact the process.

To help students gain a better understanding of the acid-base chemistry in natural waters, we have constructed a model natural fresh water system. The system consists of an open tank holding about 8 L of water. The chemical species in the water are monitored with pH, dissolved CO_2, and temperature probes. Acids, bases, or other reagents are added to the system using a peristaltic pump, and temperature is controlled using an electrical immersion heater. All inputs are monitored and output devices are controlled with LabVIEW.

This model system is used to compare the changes over time in several experimental conditions:

1. Neutral deionized water adjusted for ionic strength (necessary for proper probe response).
2. The same water with a limestone rock ($CaCO_3$) added.
3. Condition #2 with an 'acid-rain' event—addition of 10 ml of 1.0 M HNO_3 or H_2SO_4 by peristaltic pump.
4. Condition #3 but with no limestone present.

Data collection in this experiment is monitored dynamically on the Web through AppletVIEW displays, and cumulative results are posted hourly by the LabVIEW Web server. The acid-rain event can also be initiated over the Web through AppletVIEW by activating the peristaltic pump. Results from one such experiment, conducted in collaboration with a high school teacher and students, are shown in Fig. 3. The rapid pH decrease at the time of the acid rain event was followed by a gradual recovery to near neutrality over a 24-hr period. The buffering role of limestone is further documented by the accompanying large increase in carbon dioxide concentration with a gradual decline to baseline during the same period.

Environmental science

For many years, life scientists have used microcosms, essentially small, containerized ecosystems, originally as a way to bring nature into the classroom and, more recently, as a major research tool for studying and modeling the way natural ecosystems work [8, 9]. Microcosms can simulate a variety of aquatic and terrestrial ecosystems, and are particularly valuable where large-scale or long-term experiments are not feasible due to time or cost constraints. Their conditions can be carefully controlled, they can be replicated at reasonable cost, and they can yield data within periods of weeks or months rather than years [10].

Microcosms are well suited to classroom application for several reasons. First, they can provide a biologically meaningful link between the relative simplicity of mathematical models and the complexity that characterizes the natural world. Second, microcosms allow levels of control and replication that are not possible in the field. In particular, the initial conditions and all subsequent inputs of energy, materials, and organisms can be manipulated by the experimenter. Finally, because such systems can run faster than natural systems, a great deal of experimental work can take place on academic time scales for classroom demonstrations or as ongoing laboratory exercises.

A large component of the Environmental Science course is a survey of global environmental problems and their effects on natural systems. We have designed experiments to investigate the effects of several types of anthropogenic environmental change on model living systems (changes in temperatures or pH, or introduction of nutrients or pollutants). All of these manipulations involve aquatic microcosms comprising deionized water in 38-liter glass tanks, a source of photosynthetically active radiation, submersible water circulation pumps, and a simple community consisting of aquatic plants (e.g., *Elodea*, *Cryptocoryne*), small fish (e.g., comet goldfish or guppies), and invertebrates (e.g., pond snails and mussels). Each experiment employs a control system and a treated system. Initially, the two tanks are set up using identical conditions, and are monitored until we are satisfied that the systems are operating at equilibrium. Then, one of several treatments is applied to one of the microcosms, and changes in system parameters are monitored over time. In the example shown here to model the effects of global warming, temperature was elevated by 5°C above ambient through a thermostatically controlled submersible heater (not yet controlled by LabVIEW and AppletVIEW but could be). To assess the health of these biological systems, dissolved oxygen, dissolved CO_2, pH, and temperature were monitored on the Web through LabVIEW and AppletVIEW. Results of this

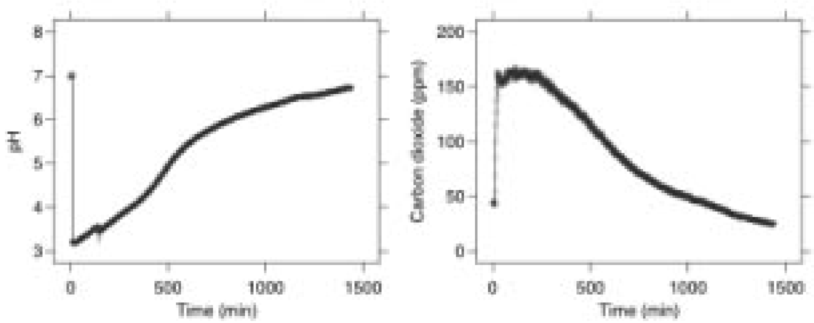

Fig. 3. Changes in pH and ppm CO_2 after an 'acid-rain' event.

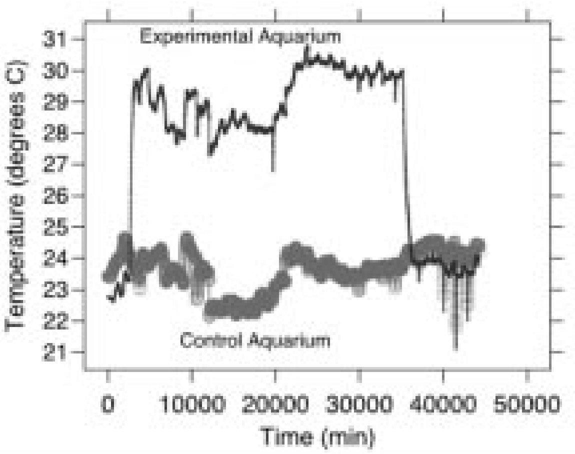

Fig. 4. Changes in aquarium temperature in the temperature experiment.

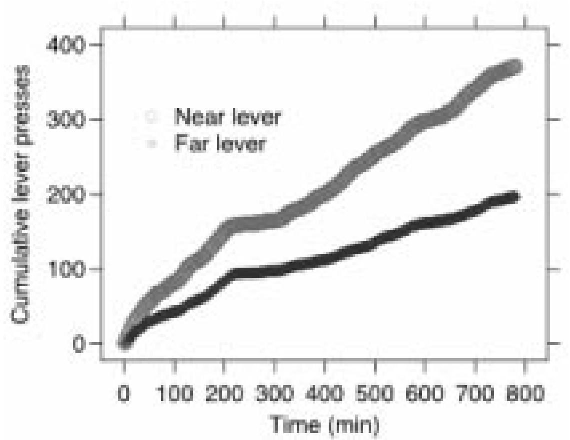

Fig. 6. Mean responses showing the animals' preferences for the near lever in spite of lower payoff.

experiment demonstrated a large increase in carbon dioxide concentration during the temperature elevation (Figs 4 and 5), presumably due to the elevated metabolic rates of ectothermic organisms living in the aquarium. The gradual overall increase in CO_2 may be due to gradual accumulation of CO_2 at the higher temperature, but drift in the calibration of the probe cannot yet be excluded.

Animal behavior

An important topic in behavioral ecology is evolutionary optimality. This issue is evident in the numerous tradeoffs that animals encounter as they select among behavioral options to search for food, defend a territory, avoid predators, etc. [11]. The best studied examples of optimality are in food search and consumption (optimal foraging); a variety of methodologies have been employed in this research, including the study of choice behavior in laboratory operant conditioning environments [12].

These experiments entail collaboration among students in an advanced psychology course, students in Animal Behavior, and high school students off campus. Advanced students initially trained rats to a high level of performance in moving either of two levers to activate a food-pellet dispenser. Then 24-hour sessions were undertaken to further study the allocation of responses to these two levers, one of which required considerably greater effort. Data collection was again monitored on the Web through LabVIEW and AppletVIEW displays, and payoffs at each lever could be altered over the Web through AppletVIEW controls. The results show a very strong preference for the less effortful response that is very hard to overcome by increasing the payoff for the more effortful response. (See Fig. 6 for data averaged across eight laboratory rats on the third day of sessions in which the payoff for the far lever is twice that of the near lever.)

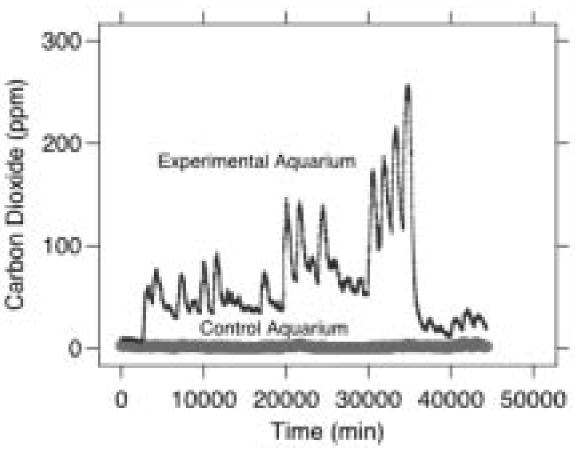

Fig. 5. Increased CO_2 during the period of elevated temperature.

Remote monitoring of the animal behavior experiments is enhanced through live streaming video, allowing students to observe the animals during the experiment.

OUTCOMES

We have found that the data acquisition systems work extremely well. We have been able to complete a number of experiments in each of the three areas mentioned above. Since the experiments unfold over a period of days to weeks, we usually find that the most useful method of monitoring the experiments is to examine the cumulative graphs that are posted on the Web. These displays provide a quick overview of the entire pattern of results that is useful both to faculty and to on-campus and distance learning students. Because of the long-term timeline of the experiments, the synchronous displays provided through AppletVIEW are less valuable for monitoring the data acquisition than they are for allowing control of experimental parameters.

Our collaborating high school teachers report considerable enthusiasm about participation in the experiments and analyzing the results. Student and high school teacher participation in the design phase of the experiments has been quite significant in some instances and not in others. Time constraints are often limiting in this planning process as it is difficult to plan with sufficient lead time to fit the particular demands of their curricular schedules. Much of this planning has been conducted through electronic mail contact. We can now supplement these contacts with live chat sessions using our course management software, so we look forward to a more efficient experimental design process in the future.

Conducting the experiments has generally been quite trouble-free at the data acquisition workstations, but the remote connections for manipulation of experimental parameters have posed problems. These problems center around the introduction of firewalls and proxy servers at the remote sites, which then deny access to certain of our resources since not all our Web pages are posted through the standard port 80. We believe we now have solutions to these problems but have not yet had the opportunity to test them extensively.

Downloading and manipulating the data files appears to be rather straightforward for both teachers and students. The computing power of common personal computers now makes rapid manipulation of files with thousands of data entries a fairly simple matter, so we find that teachers and students can easily discover the main patterns in the data and are adept at posing questions for follow-up experiments. They have responded very favorably to the opportunity to design original experiments, to the immediacy of access to the results, and to freedom from cookbook designs prescribed by laboratory manuals.

What we are able to achieve with these technologies is clearly beyond anything that we could do previously. We had no method of providing remote access to experiments previously, so our work with high school teachers and students is now possible for the first time. In addition, we find that there are some very significant benefits for students on campus. Our goals with distance learning students have forced us to think about experiments with a relatively long timeline so that we and students at remote sites need not often be present at our workstations at the same time. These experiments have turned out to have many interesting features for students on campus as well. The ability of on-campus students to monitor ongoing experiments without coming to the laboratory has added an important new dimension to the laboratory experience of several courses.

EQUIPMENT COSTS

The greatest costs for the systems we use are in the data acquisition workstations. The combination of a computer in the midrange of prices, a National Instruments 6052E board, an SCXI-1000 signal conditioning chassis, and signal conditioning modules costs about US$6000–$7500, depending on the particular signal conditioning modules needed. A LabVIEW departmental educational license, which allows installation on multiple computers on any platform, is US$995 per year. AppletVIEW software is currently priced at US$895; other software running on Linux is freeware (Apache; Darwin Streaming Server). A Linux server with the specifications indicated earlier was about US$1500, though, of course, a much more powerful computer could now be had for a similar cost. A high-end digital camcorder is about US$2000, while Sorenson Broadcaster and QuickTime Pro software (Macintosh) cost only about US$230. These are the principal equipment and software costs in developing a comparable system. We incurred additional expenditures for probes, pumps, operant chambers, etc., which would presumably be different in another application of this approach.

ADAPTABILITY OF OUR DESIGN TO OTHER PURPOSES

We believe that the most attractive aspect of our approach is the relatively low level of expertise that is required to set up the hardware and software. The National Instruments data acquisition and signal conditioning hardware, while relatively expensive, communicates readily with VIs that are a part of the standard LabVIEW release. Thus, complex and time-consuming low-level programming of hardware drivers is avoided. At the same time this hardware is quite versatile and easily adaptable to a wide variety of engineering and scientific applications. Communication with the AppletVIEW server is largely a matter of incorporating a few basic subVIs into the data acquisition VIs, and ftp functions are similarly straightforward to include. Certainly some knowledge of LabVIEW programming is required, but our applications were all created through modification of example VIs provided with LabVIEW or AppletVIEW.

Setting up the streaming video software requires no programming at all, only setting a few program parameters on Sorenson Broadcaster (Macintosh). QuickTime movies must be ‘hinted’ using QuickTime Pro and ftp’d to an appropriate directory on the Linux server. Broadcast of live video differs in that an appropriate description file, created with Sorenson Broadcaster, takes the place of a stored movie on the Linux server.

Because the software and hardware in our system are so easy to use, we think that adaptation of our approach to other distance learning projects in engineering and science will require greater effort on pedagogical rather than on technical issues. We find great promise for both teaching and learning in the idea of creating a collaboration among students and teachers with different levels of knowledge and differing interests: high school students, beginning college students, advanced students, student laboratory assistants, student programmers, pre-service teachers, high school teachers, college faculty with varying expertise. This is the central vision in our distance learning project that might be adapted to many other settings.

POSTSCRIPT

We should note in conclusion that the most recent version of LabVIEW (v.6.1) promises to simplify our approach even further. Dynamic display of front panel charts and indicators and manipulation of front panel controls are now possible by simply publishing VIs to the Web using the LabVIEW http server on the data acquisition workstation [13]. We have not yet had the opportunity to test these new capabilities and so are uncertain of the degree to which we may wish to maintain the separation of data acquisition and server functions as they exist in our present system. No matter the outcome, it seems clear that the technical barriers to distance learning through online experimentation are rapidly falling. More and more, we believe, the major tasks before those interested in these forms of distance learning will center on the design of collaborative environments and of supporting curricular materials. Now that many fundamental technical issues have become manageable, teachers of engineering and science who work with distance learners can once more devote their energies to pedagogical issues.

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REFERENCES

1. N. Ertugrul, Towards virtual laboratories: a survey of LabVIEW-based teaching/learning tools and future trends, *Int. J. Eng. Educ.*, **16**(3), 2000, pp. 1–10.
2. Ch. Salzmann, D. Gillet, and P. Huguenin, Introduction to real-time control using LabVIEW with an application to distance learning, *Int. J. Eng. Educ.*, **16**(3), 2000, pp. 255–272.
3. National Research Council, *Inquiry and the National Science Education Standards*, National Academy Press (2000).
4. National Research Council, *Transforming Undergraduate Education in Science, Mathematics, and Engineering*, National Academy Press (1999).
5. J. D. Bransford, A. L. Brown, and R. R. Cocking, R. R. (eds.), *How People Learn: Brain, Mind, Experience, and School*, National Academy Press (1999).
6. R. H. Bishop, *Learning with LabVIEW 6i*, Prentice-Hall (2001) pp. 386–388.
7. C. Baird, *Environmental Chemistry*, 2nd ed., W. H. Freeman (1999).
8. R. J. Beyers and H. T. Odum, *Ecological Microcosms*, Springer-Verlag, (1993).
9. J. H. Lawton, The Ecotron facility at Silwood Park: the value of 'big bottle' experiments, *Ecology*, **77**, 1996, pp. 665–669.
10. J. A. Drake, G. R. Huxel, and C. L. Hewitt, Microcosms as models for generating and testing community theory, *Ecology*, **77**, 1996, pp. 670–677.
11. D. M. McFarland, *Animal Behaviour*, 2nd ed., Longman Scientific and Technical (1993).
12. J. R. Anderson, *Learning and Memory: An Integrated Approach*, 2nd ed., Wiley (2000).
13. National Instruments, LabVIEW 6.1 instantly enables Web-based measurements, *Instrumentation Newsletter*, available at http://www.ni.com/news/dlinst.htm (March, 2002).

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