

Remote Experimentation with a Wind Tunnel System for Controls Education*

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In this paper, we describe the initial phase of our attempt at identification and development of commonly available hardware and software components to fully exploit the idea of tele-operation or remote access to control systems over the Internet. We also present the results of a student evaluation of the system and its concept, as well as the results of a locally-organized faculty workshop and discussion on remote experimentation.

INTRODUCTION

TWO MAJOR EVENTS that have greatly impacted human society during the 1990s were the end of the Cold War and the advent of the World Wide Web. In the United States (US), one side effect of the former development has been the reduction of government spending for university research, which typically has led to reduced university budgets for education infrastructure such as instructional laboratories and equipment. Unfortunately, this has coincided with a period of strong enrollment growth and improved retention for the College of Engineering at The University of Texas at El Paso (UTEP) brought about by such diverse factors as the inception of the North American Free Trade Agreement and the introduction of innovative student programs [1], respectively. Consequently, budget, space and scheduling problems especially with regard to instructional laboratories are growing concerns for this institution, just as they are at other institutions around the world.

Meanwhile, the World Wide Web has led to the incredible popularization of the Internet as an alternate means of personal and mass communication, information assimilation and dissemination and, more recently, distance education and research. As the related technology improves in speed and performance, and becomes less expensive and more universally accessible by the general populace, the use of the Internet for distance education will continue to grow at a rapid pace as educational providers, students (particularly those that have work commitments, like the majority of UTEP's students) and students' employers alike see its advantages for each of them from their own different perspectives.

It was against this backdrop that a remote experimentation project was initiated at UTEP late in the year 1999 aimed at providing a springboard for

improved distance education in the fields of Engineering and the Sciences, and the more effective utilization of scarcer, thus more valuable, hardware resources. Although the idea of tele-operation or remote access to and control of hardware systems over the Internet is not new (for example, some Web-controlled robots [2–4] and Internet-based engineering laboratories [5–9] have been around for a few years), we came to the realization that these systems were developed to be different from each other and also are difficult, if not impossible, to duplicate by people not involved with those systems because of reasons such as intellectual property rights restrictions and/or technical complexity. What appeared to be needed to popularize this concept and achieve the goal of ubiquitous remote access experimentation systems was the identification and/or development of a set of generic and commonly available hardware and software components that would address the various functions inherently needed by such experimentation systems, especially those used for instructional purposes.

In this paper, we describe the initial phase of our attempt at such an identification and development. We first discuss the selected experiment and approach, with the emphasis being on interactive-type remote experimentation systems rather than on the batch-type systems described by Knight and DeWeerth [7], and Esche *et al.* [10], and then the various hardware and software components of this system. Finally, we present the results of a student evaluation of the system and its concept, as well as the results of a locally-organized faculty workshop and discussion on remote experimentation.

SELECTED EXPERIMENT AND APPROACH

The development of this system was a collaborative effort by UTEP's Electrical Engineering (EE) and Mechanical Engineering (ME) faculty members, and leveraged the recent establishment

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Fig. 1. Wind tunnel.

of a US National Science Foundation, (NSF)-funded, multidisciplinary Dynamic Systems and Controls laboratory (EE led), and development of a NASA-sponsored wind tunnel for research purposes (ME led). Details of these activities can be found in [11] and [12], respectively. We decided that this small wind tunnel (shown in Fig. 1) located in the UTEP Controls laboratory (see Fig. 2) could function not only as an important tool for studying the aerodynamic properties of various automotive and aerospace structures, but also as an excellent platform for Control Systems education (a field of study that cuts across several engineering disciplines). Moreover, the proportional-integral-derivative (PID) controller that it requires for adjusting the voltage of the fans for wind velocity regulation is a common component found in many other systems relying on automatic feedback control. Finally, since the wind tunnel was already fully operational, we seized the opportunity to invest the incremental amount of time and effort needed to augment it with remote experimentation capabilities.

Considering the particular experiment and its desired educational outcome (detailed below), we

decided to develop and implement an interactive-type remote access experimentation system as this seemed to be the more effective learning approach. Thus the system was to allow the remote user to iteratively adjust parameters, perform the experiment and observe the result during one continuous interactive session instead of a series of discontinuous batch sessions. More specifically, the system was to allow the remote user to vary the three gains of the PID controller for the wind tunnel's fans and then from the observed response learn about the effect of such variations on the transient and steady-state responses of the wind velocity in the tunnel.

REMOTE ACCESS APPARATUS SELECTION, DEVELOPMENT AND IMPLEMENTATION

The main design objective for the remote experimentation apparatus was to enable a remote user (student client) to perform the experiment via the Internet through a Web browser, with near-real-time data from that experiment displayed for viewing by the same means. The user should require no other software in order that any device with a Web browser and Internet access anywhere can be used by him/her. A block diagram of the different functional components of a system that would accomplish this is shown in Fig. 3.

Our principal criteria in selecting the embodiment of these functions in our remote experimentation system were availability, flexibility, usability and cost. We ultimately selected hardware and software products from National Instruments



Fig. 2. Wind tunnel system in UTEP Controls lab.

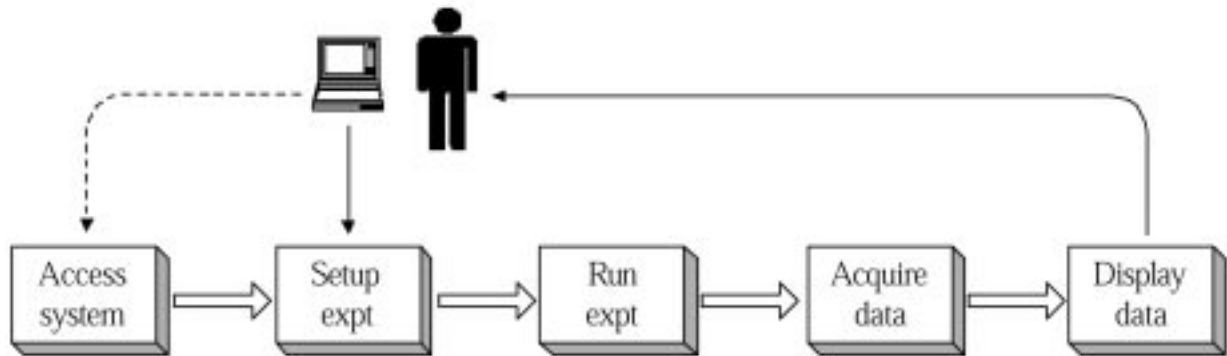


Fig. 3. Block diagram of the functional components of an interactive-type remote experimentation system.

(NI) to implement our system. The specifics of the various NI hardware linking the software to the wind tunnel and their functions are described below. All of the software-enabled functions in this remote experimentation system described in the following were performed by Virtual Instruments (VIs) or programs developed using NI's LabVIEW[®] v5.1 and Internet Developers Toolkit for G v5.0. The cost of the hardware and software constituting the remote experimentation system (excluding the host PC, the wind tunnel and its power supplies) is summarized in Table 1.

Access system

The first function necessary for the proper usage of this experimentation system and for achieving its intended purpose is access control. It is currently accessible through the Controls lab Web site located at <http://129.108.38.158/>. However, access to this system is limited, based on user name and password, to a specific group of approved users; for now, that group consists of only those students enrolled in the Controls lab. We chose this restriction in order to prevent improper usage by simply anyone with Internet access leading to excessive wear and tear of the system. In addition, access to this system has been deliberately limited to one user at a time (the default is multiple user access) to avoid the confusion resulting from several users adjusting the experiment's parameters and controls simultaneously. However, a timer is also used to limit each experimenter's session (20 minutes from the instant of successful login is the present setting) to prevent any one person from 'hogging' the system.

The approach presently adopted to 'gracefully'

disable system access when the system is being used either by a remote user or by people in the lab is to automatically redirect the potential users to a 'temporarily busy' Web page that also tells them to try again in 15 minutes. Other possible options, including redirecting them to an online tutorial on PID control or letting them 'look at but not touch' the active session, were also considered. However, the latter appeared technically difficult to achieve satisfactorily with the available set of software tools.

Setup experiment and run experiment

The next system function should be to enable the user, after successful system access, to adjust the experiment's setup (controller gains) and to execute commands to start and stop the experiment. LabVIEW was used to develop VIs for ensuring the proper transfer of information between the user and the experiment via the Internet. The main VI controls the wind tunnel's fans; its front-panel (shown in Fig. 4) acts as the user interface for starting, stopping and adjusting the parameters of this VI as well as displaying the data after it has been acquired and processed. A second, specialized, VI available in the Internet Developers Toolkit functions as the link between the main control VI and the image of its front-panel as seen by the remote user so that she/he can adjust the experiment's parameters, start and stop it, as well as view its results from his/her remote location. An HTTP server acts as the go-between for this VI and the Internet. Once the experiment is started, the main control VI is responsible for processing the wind velocity error through the PID control algorithm and determining the appropriate signals to be sent, by an NI AT-GPIB/TNT card mounted within the host PC, to the two General Purpose Interface Bus (GPIB)-addressable power supplies applying voltage to the four electric motor-driven fans that create the air flow through the wind tunnel system. That VI also limits the voltage that is sent to the power supplies, for protective purposes. Further details of the LabVIEW program and control system layout and design can be found in Hennessey *et al.* [12].

Table 1. Cost of remote experimentation system (excluding PC, wind tunnel and power supplies)

Item	Cost
NI LAB-PC-1200AI TM with LabVIEW (v5.1) TM	US\$995
NI AT-GPIB/TNT TM	US\$446
NI Internet Developers Toolkit for G (v5.0) TM	US\$322
Total	US\$1,763

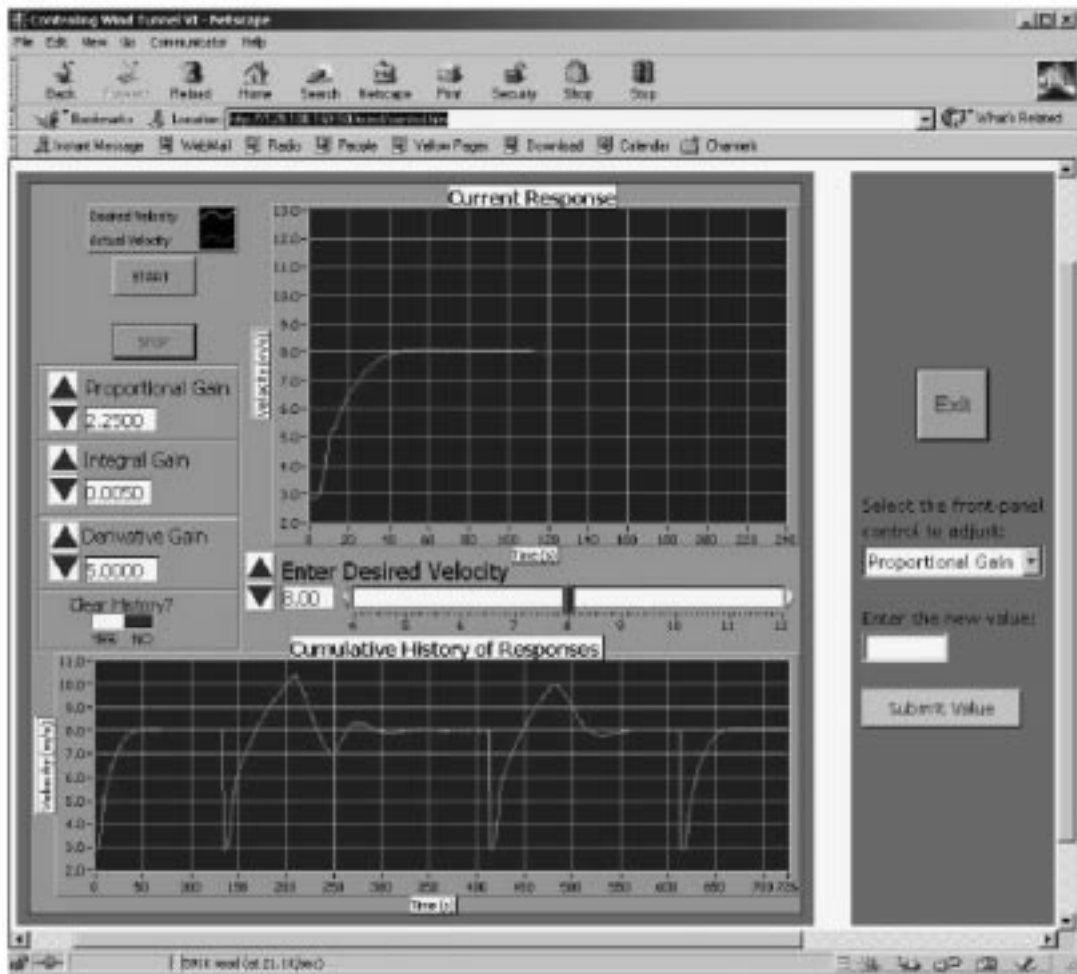


Fig. 4. Image of VI front-panel for wind tunnel control and data display in Web browser window.

Acquire data and display data

Another system function is to enable the acquisition of data and the feedback of the experiment's results to the remote user. The tunnel's wind velocity is calculated from the output voltage of a pressure transducer via a pitot tube located inside the wind tunnel that is 'read' by a NI LAB-PC-1200AI card mounted within the host PC. Presently, feedback to the user is in the form of near-real-time display of a graphical plot of the tunnel's wind velocity versus time as part of a VI front panel image, as shown in Fig. 4. The transmission of this image of the wind tunnel control VI's front panel over the Internet to be viewed with a Web browser by the remote user is handled by a specialized VI available in NI's Internet Toolkit; the HTTP server again acting as the go-between for this VI and the Internet. We point out that the software version used for this system results in the desired animation of the plot only with the Netscape v4.x browser, not with Internet Explorer or the more recent versions of Netscape. Instead, the user needs to manually depress the 'Refresh' or 'Reload' button to obtain the animation effect using the latter browsers. Finally, to 'save' the

experiments' results for later review, the user can perform an image capture of the browser window or of the entire screen.

EXPERIMENT PROCEDURE AND EDUCATIONAL OUTCOME

The objective of the experiment is to investigate how changing the various gains of the fans' PID controller affects the transient and steady-state behavior of wind velocity within the wind tunnel. The educational goal is to have the students understand PID control characteristics through an active learning process. By design, students have not yet had lectures on the theory behind this controller when they are asked to perform the lab experiment. However, they have learnt about step response, steady-state performance (error) and transient performance (overshoot, rise time, etc) by the time they perform this lab. More importantly, they are informed in the pre-lab instructions that one gain primarily affects the speed of the transient response, another the oscillation of the transient response whereas the third

primarily affects the accuracy of the steady-state response. In the lab procedure, the students are provided upper and lower limits for each of the three gains to assist them in their determination of the set of optimal gains. This is done to avert long and frustrating sessions as well as the nonlinear behavior that results from encountering the power supply voltage limits. They are also asked to identify which of the three gains mainly affects which characteristic of the step response; the main goal of this experiment.

As illustrated in Fig. 4, the cumulative history graph showing the results of a series of experiment runs with increasing values of the derivative gain indicates the role of that gain in damping out the oscillation of the response. Moreover, the current response graph in Fig. 4 shows the 'optimal' step response afforded by this controller, with a short settling time and negligible steady-state error. Note that the educational purpose of this experiment is clearly better served by an interactive-type remote experimentation system rather than a batch-type one.

EVALUATION

User survey

Evaluation of this remote experimentation system was accomplished through a survey of Controls lab students during the Spring 2002 semester. They were questioned about its availability, usability and overall quality. The students were also asked about their attitudes regarding various aspects of remote experimentation and about the level of their enthusiasm for this form of education. The highlights of the data compiled were that students are overwhelmingly positive about the concept of using a remote-access system for lab experimentation 'at anytime from anywhere' and are strongly in favor of implementing such a system for performing experiments in other Science and Engineering lab courses (see Fig. 5). They are also strongly in favor of having a lab fee assessed to support the development and maintenance of such similar systems and somewhat willing to pay a reasonable amount to support such efforts (see Fig. 6). It was also noteworthy that the students' responses as to when they began working on this lab were fairly uniformly distributed over a week's period, so they did not all wait until the last minute to perform this experiment. Asked about other opinions, one student wrote, 'I believe remote experimentation is a good idea. It would be awesome if the Controls lab could be used to develop other remote controls experiments by the students enrolled in the class.' Complete details of this survey can be found at [13].

Faculty workshop

In addition to the user survey, a mini-workshop and discussion session was held in early 2002 to

discuss and obtain feedback about remote experimentation as part of a locally-organized conference on teaching and learning [14]. The objectives were to raise awareness on the UTEP campus about remote experimentation systems, to discuss their impact on teaching and learning, and to facilitate the local development of a greater number of such systems. Eight faculty members from diverse Science and Engineering fields were in attendance in addition to the first and third authors of this paper who conducted the workshop. The main points discussed were with regard to the trade-offs between a traditional lab and a remote-access lab, remote-access system implementation and operation, the students' feedback and possible candidates for new system development. The primary conclusions of this session were that remote experimentation is still a novel idea to many Science and Engineering faculty members, that there is widespread agreement about its stated advantages for targeted applications and that more work needs to be done to evaluate its effect on student learning.

CONTRIBUTION

Judging by the student and faculty feedback, this system is making a positive contribution to the infrastructure for education. Students have benefited, and will continue to benefit, from the use of this system. It will also have a positive impact on the public's awareness of how science and technology affects our daily lives. These points are elaborated upon as follows.

Impact on the infrastructure for education

This remote experimentation system is now operational and being used for instructional purposes. A brief guide describing the wind tunnel system and the experiment, along with step-by-step instructions for the remote user, has been developed and student-tested. In addition, documentation of the development and implementation of this remote experimentation system, in the form of a developer's guide, has been prepared in keeping with the subsequent goal of enabling the hardware and software package to be ported for use by similar systems or modified with minimal effort for various other systems adopting the same approach to remote experimentation. This documentation and the various software programs that have been developed for this remote experimentation system can be obtained upon written request to the first author of this paper.

Impact on students and the public

This system has benefited and will continue to benefit UTEP's Controls students. Those undergraduate and graduate students working on Senior Design or research projects related to the wind tunnel will also benefit from this system. In

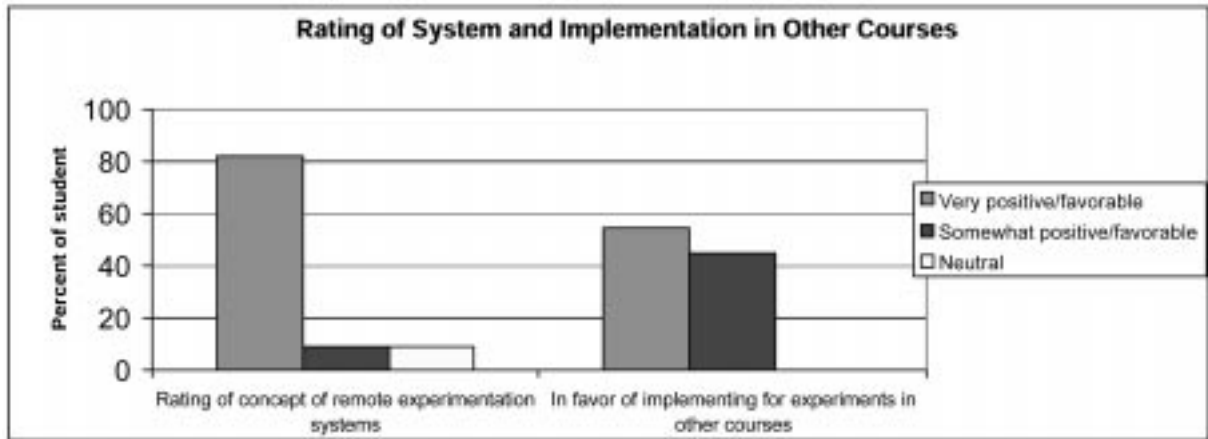


Fig. 5. Rating of remote experimentation concept and implementation in other courses.

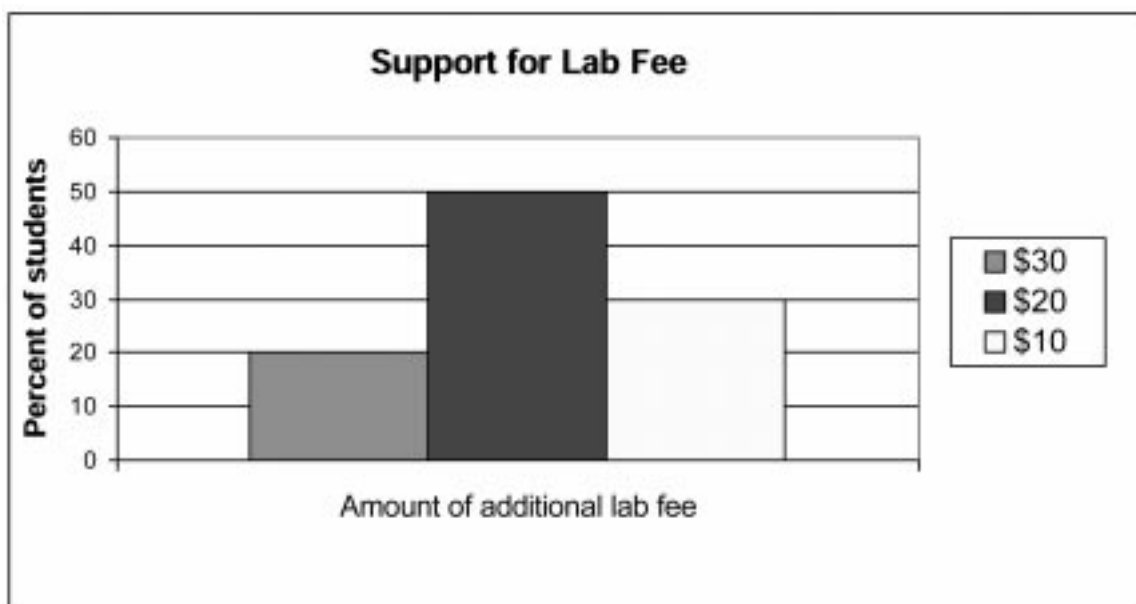
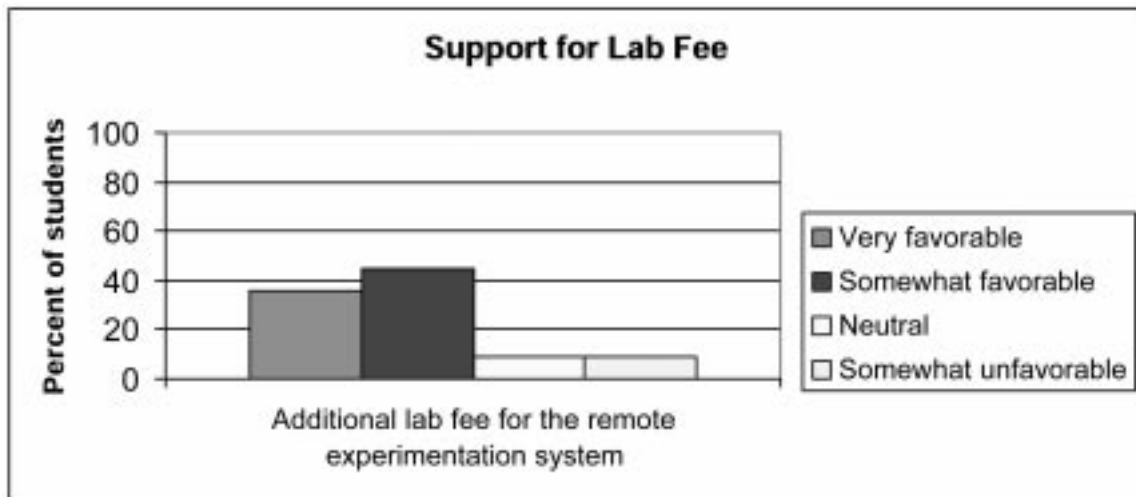


Fig. 6. Support for additional lab fee and fee amount.

addition, the three students who helped set up the hardware and software and develop the remote experimentation programs all gained valuable training and experience in this new technology. They now possess the expertise to set up similar systems for the University and for their future employers.

Demonstrations of this remote experimentation system will be conducted for visitors, including pre-college students, during Engineering Open House to educate the public (especially young people) on how science and technology affects our daily lives as exemplified by distance education. In addition, public dissemination of the material relating to this system (including system description and evaluation results) is being carried out via a publicly accessible website and this publication so as to make a broader impact.

CONTEMPLATED ENHANCEMENTS

For the experiment described above, we are considering the provision of audio feedback to the remote user as the volume and pitch of the fans' whirring may be a helpful accompaniment to the plotting of the wind velocity information. However, providing near-real-time video feedback is not under serious consideration firstly because there is not much that is 'exciting' for the user to see and secondly since the video quality will be poor (due to bandwidth constraints) for the majority of users. Another enhancement that would be useful, although perhaps more challenging to effect, is to provide the user with an alternative method to performing an image capture to save the experiments' results for later review.

In addition, the system described is presently used for only one experiment, regarding the characteristics of the PID controller. Plans are underway to expand the use of this system for illustrating and teaching other dynamics and controls concepts, such as stability.

Furthermore, regarding this system's educational effectiveness, we plan to have an exam question about the PID controller's characteristics and to compare the performance of the users against the non-users (those enrolled in the lecture but not the lab) on this question to see if there is any significant difference.

Finally, at the time of this paper's writing, the latest version (v6.1) of LabVIEW has recently

become available. Its impact on this work will be evaluated, particularly with respect to the problem of proper animation (continual updating) of the wind velocity plot.

CONCLUDING REMARKS

This paper has described a significant step taken towards the objective of improved distance education by the identification and development of generic hardware and software components for addressing the various functions inherently needed to interact remotely with a large and diverse group of Science and Engineering experiments. The prescribed solution is based on LabVIEW[®], the PID control algorithm and the GPIB protocol. This has been implemented, as a prototype, for a Controls experiment on a small wind tunnel system and used interactively by students to understand the PID controller's characteristics via an active learning process. The results of a survey of these students and of a discussion by UTEP faculty members regarding the remote experimentation concept and this particular system were very encouraging.

The general approach and specific implementation, having now been established, is being considered for adaptation to other Science and Engineering experiments on the UTEP campus, which will result in a broader impact of this work. Our contribution of identifying and developing generic hardware and software components should speed such adaptations. We believe that this in turn will provide greater impetus towards the ultimate goal, which we share with others, of having remote experimentation become a ubiquitous component of education and act as a means to maximize the availability of significant resources.

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