Implementing a Remote Laboratory Experience Into a Joint Engineering Degree Program: Aerodynamic Levitation of a Beach Ball

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Implementing a Remote Laboratory Experience Into a Joint Engineering Degree Program: Aerodynamic Levitation of a Beach Ball

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***Abstract*—This paper details a successful and inexpensive implementation of a remote laboratory into a distance control systems course using readily available hardware and software. The physical experiment consists of a beach ball and a dc blower; the control objective is to make the height of the aerodynamically levitated beach ball track a reference trajectory by manipulating the voltage to the blower. MATLAB/Simulink coupled with xPC Target serve as the controller platform, while Microsoft NetMeeting and standard Internet video conferencing equipment are used to interface the distance-learning students with the laboratory equipment. Both local students at North Carolina State University's campus in Raleigh and distance students at the University of North Carolina at Asheville completed the laboratory experiment. In a student survey, distance students participating in the lab remotely rated the experience as favorably as local students. Course grades, including the design project grade, were similar between the two groups.**

***Index Terms*—Control, distance education, e-learning, joint degree program, levitation, remote laboratory.**

I. Introduction

RECENT advances in communications technology have triggered widespread changes in engineering education, especially in the realm of distance learning. These technologies have enabled the synchronous transmission of lectures through "video over Internet" protocol (or their later viewing over the Internet at the learner's convenience), the efficient transfer of course-related materials, and a variety of communications options between the student and instructor. Despite these technological breakthroughs, administering undergraduate degree programs in engineering disciplines remains a formidable challenge due to the need for "hands-on" laboratory experiences. Laboratory experiences enhance the student's ability to grasp subject material and demonstrate practical applications of course topics. Effective laboratory experiments are characterized by: 1) an intriguing physical system; 2) the ability to interact with the system; 3) real-time visualization of the system for direct performance evaluation; and 4) human assistance from a knowledgeable source (course instructor or teaching assistant). Exposure to these components facilitates professional and scholarly development.

The costs associated with implementing, staffing, and supplying separate laboratories at distance sites often prevent these being established. Requiring that distance students travel to the host institution, or purchase experiment kits to conduct laboratory exercises, clearly diminishes the benefits of working remotely from the academic institution. As with other aspects of distance education, the Internet offers solutions to the distance-education/laboratory-experience dilemma. The Internet now enables students to interact with laboratory simulations or with actual laboratory equipment (remote laboratories) and observe the simulated or actual system's response to various student-dictated inputs.

North Carolina State University (NCSU) in Raleigh, has a long and successful history of distance education through its joint engineering degree programs. Since 1982, NCSU has granted students at the University of North Carolina at Asheville (UNCA) the flexibility of completing the first half of their coursework at the UNCA campus and the second half at the NCSU campus. Building on the success of this program, the two universities launched in 2004 a joint-degree program (B.S. in engineering, Mechatronics Concentration) in which UNCA students can complete all of their undergraduate degree requirements at the Asheville campus. In this program, the core engineering courses are taught from NCSU via Internet-based distance education methods while the core science, mathematics, and general education courses are taught conventionally at the UNCA campus.

One of the required courses in the Mechatronics joint-degree curriculum is MAE 435, Principles of Automatic Control, typically taken in the student's senior year. As stated in its syllabus, the chief objective of this course is "to facilitate the student's ability to analyze and design control systems for various electromechanical engineering systems." Specifically, students must demonstrate knowledge in the following tasks: 1) modeling electromechanical systems using mathematical equations; 2) analyzing the system's stability and sensitivity to parameter changes; 3) predicting and interpreting the system's behavior using classical analysis tools; and 4) designing controllers to modify and improve the system's stability and response characteristics. Laboratory experiences in this course are critical to understanding the application of control systems to real-world applications, while fully engaging the imagination and intellect of the student. MAE 435 culminates in a design project, where

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small teams of students (three-four per team) apply their modeling and control design skills to a "real world" (inherently nonlinear and unstable) system. This project addresses several educational objectives more effectively than lectures and homework exercises: it addresses conflicts between student perceptions and the reality of "true-to-life" engineering problems (physical disturbances, limitations of mechanical and electrical components, and so on). This paper details a successful and inexpensive implementation of a remote laboratory into the MAE 435 curriculum using readily available hardware and software.

II. Background

Some of the earliest Internet-based attempts at providing distance engineering students with lab experience involved Internet-accessible simulations [1]–[5]. These simulations allow the distance student, using his/her own Internet-equipped personal computer, to observe and often interact with a simulation that models an actual physical system. One controls simulation cited by Michau *et al.* involved a ball balanced on a pivoting beam; the position of the ball was controlled by adjusting the inclination of the beam [4], [5]. Remote users could modify various control parameters and observe the system response via continuously updated graphs and an animation of the physical device. Recently, an open source software tool, *Easy Java Simulations (Ejs)*, was developed to facilitate the creation of Java applets for controls simulations [6]. In spite of their utility, simulations often ignore real world nonlinearities and disturbances, and do not provide the experience of operating actual equipment. Simulations also tend to give the student limited control of system parameters.

A more recent development is the introduction of "remote laboratories," in which distance students interact with physical systems through the Internet. An extensive review of virtual/remote laboratories has been conducted by Bencomo [7]. The physical system is equipped with one or more sensors to monitor the pertinent states and relay the data to the student. The user is frequently given the ability to execute and terminate the experiment and change system parameters. Early remote labs required distance students to purchase and install specialized software [4], [5]. More recently, remote labs have been configured for operation through Java applets [8]–[11], allowing access through a standard web browser and eliminating the need for additional software downloads.

Many remote laboratories provide live video and/or audio feeds, allowing sensory feedback of system performance and in some cases interaction with the professor and/or pupils at the host site [4], [5], [9], [11]–[14]. A remote telecommunications lab described by Scheets *et al.* includes one of the most advanced systems for student interaction, in which a lightweight headset containing a camera, headphones, and microphone is worn by the instructor, and video cameras controlled by the distance student are spread throughout the classroom [14]. The equipment enables remote students to conduct two-way conversations with both the instructor and local students.

Although the remote laboratory can be very effective, its establishment often entails high costs and experienced computer programming personnel, especially in the case of teleoperated 24-hour-accessible sites [9], [10], [12]. Due to the lack of direct supervision at the host site, precautions must be taken to prevent injury to students in the vicinity of the equipment, as unexpected start-ups can injure room occupants. At one remote lab facility, sensor-laden floor mats were installed to disable equipment when a room occupant was standing within a certain range of the device [12]. Another remote lab facility included light controls [9] to provide proper lighting at all hours of the day while conserving energy when the system was not in use. The costs of equipment, laboratory space, and personnel deter many institutions from providing remote laboratories for controls courses.

A low-cost, low-skill alternative to the Java applet remote laboratory involves using application sharing programs, such as NetMeeting, and video conferencing equipment (microphones, webcams, speakers, and/or earphones) to interface the distance student with the local laboratory. Like the applet-driven approaches, the application-sharing remote laboratory can contain a realistic physical system, interaction with local instructors and students, and high levels of control for the remote student. Swamy *et al.* [15] described in detail an automatic controls experiment that benefited from Microsoft's NetMeeting program-sharing features. This freeware application allows distance students to control programs running on the host institution's computer. The addition of video conferencing equipment (microphones, webcams, speakers, and/or earphones) allows interaction between the distant student and local parties and provides audio/visual feedback of the working experiment. Swamy aptly described the procedure of setting up the remote laboratory, but did not include a substantial assessment of the laboratory outcomes.

The goal of this study is to demonstrate that low-cost remote laboratories using shared applications can be effective alternatives to local laboratories. Specifically, this study will evaluate how effectively distance technology enables: 1) interaction with a physical electromechanical system; 2) implementation of control algorithms; 3) real-time communication with a local operator (course instructor or teaching assistant); and 4) a laboratory experience equally satisfactory and motivating as that of local counterparts. The success of this approach, assessed by student surveys and course grades, will motivate other instructors to provide lab experiences for distance students. The functionality, low cost, and ease of use of this approach has made it a feasible solution for integrating a remote laboratory experience into the MAE 435 curriculum.

III. Methods and Materials

In the spring semester of 2006, students enrolled in MAE 435 (Principles of Automatic Control) built an aerodynamic beach ball levitation system (Fig. 1). The primary components of this system are an inflatable plastic ball and a dc blower. The blower ejects a vertical stream of air which levitates the ball at a height dependent on air velocity. The control objective is to make the height of an aerodynamically levitated beach ball track a reference trajectory as closely as possible by manipulating voltage to the blower. A Jabsco 12-V dc Flexmount marine blower $(\text{maximum output} = 7.0\ \text{m}^3/\text{min})$ provides aerodynamic levitation forces [Fig. 1(a), (b)]. A fitting attached to the outlet nozzle tapers the outlet diameter from 102 to 64 mm, while an array of plastic drinking straws placed in the outlet distributes

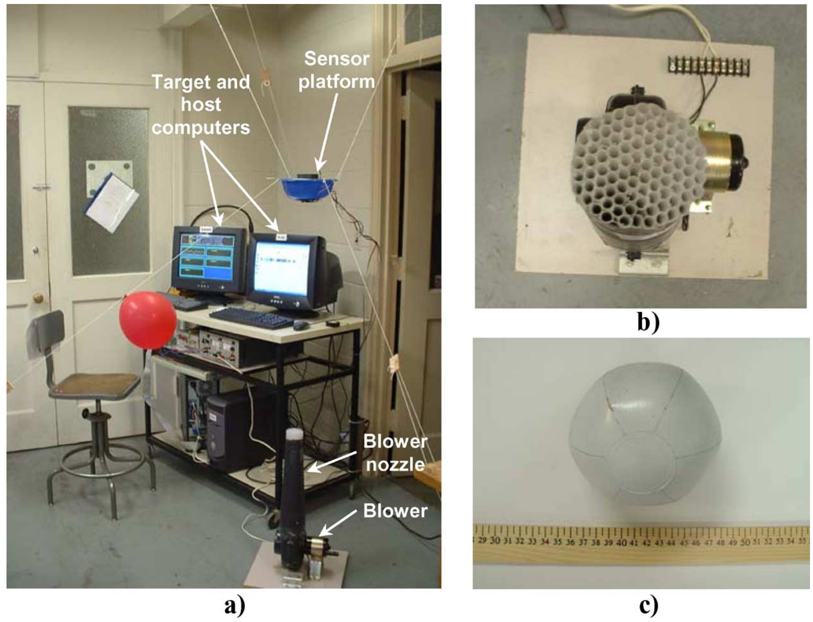

Fig. 1. Customized blower/ball test rig. (a) Blower and sensor assembly. (b) Detail of blower nozzle. (c) Inflatable ball.

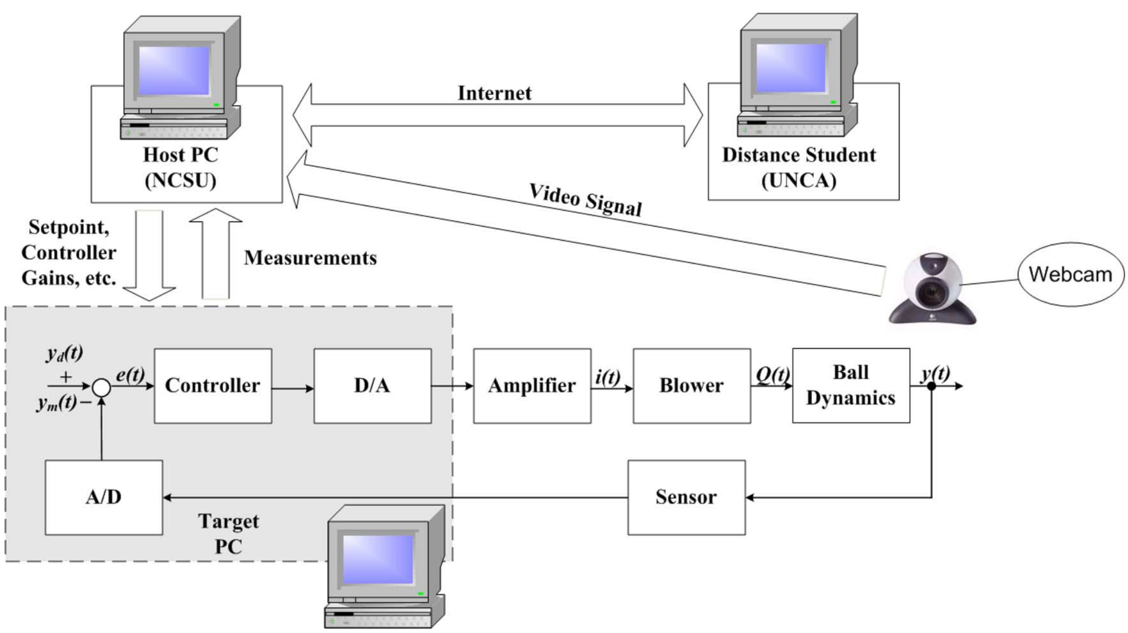

Fig. 2. Block diagram of ball/blower remote laboratory showing interaction of host, target, and remote computers.

the airflow across the nozzle. The moving air column levitates the miniature inflatable beach ball ($\mathrm{diameter} = 12.0\ \mathrm{cm}$, $\mathrm{mass} = 13.0\ \mathrm{grams}$) shown in Fig. 1(c). An array of Sharp GP2D12 infrared distance-measuring sensors [Fig. 1(a)] is mounted to a measurement platform located above the blower to provide position feedback.

The real-time control environment consists of a "host" running Windows XP Professional 2002 and a "target" computer (Fig. 2), linked by a direct Ethernet connection. The host computer runs MATLAB 7.0, Simulink 6.0 and xPC Target 2.5, and generates run-time code using xPC Target's Real-Time Workshop. This code is downloaded onto the target computer for execution, which is controlled by the host computer. Using a National Instruments PCI-6024E multifunction data acquisition (DAQ) card, sensor data is acquired and a control voltage is generated. This voltage is amplified using a Kepco 20-10M Bipolar Operational Power Supply which powers the blower. The blower voltage dictates the fan speed and thus the lift forces exerted on the ball.

A. System Modeling

Students first create mathematical models of this nonlinear system which must incorporate the electrical, mechanical, and aerodynamic effects. The aerodynamic lift can be modeled using a standard drag force relationship [16]

$$F_d = \frac{1}{2} C_d \rho A (v_{\mathrm{air}} - v_{\mathrm{ball}})^2 \tag{1}$$

where F_d is the drag force, C_d is the drag coefficient (nominally 0.38 for a sphere in turbulent flow), ρ is the density of air

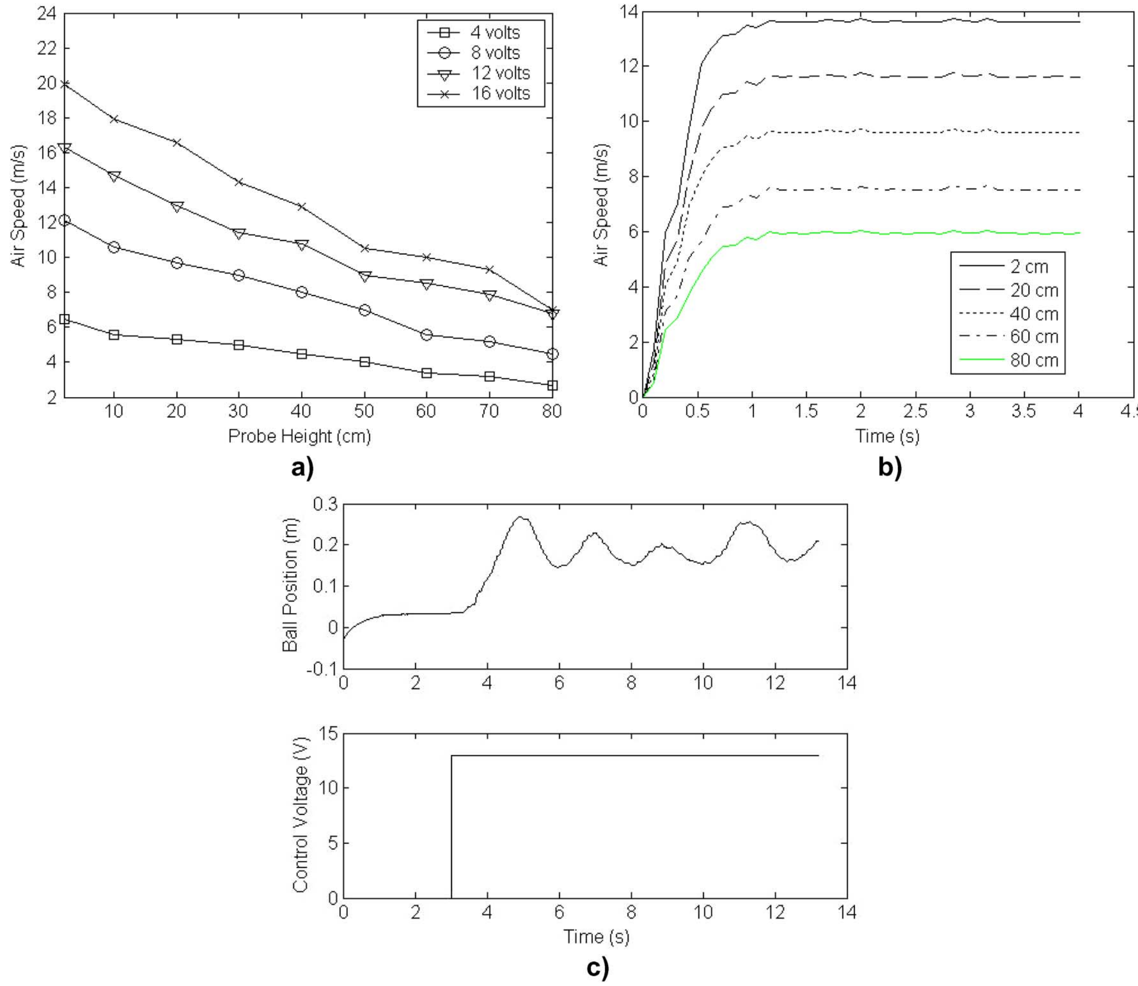

Fig. 3. Experimental data for the ball/blower system. (a) Steady-state air velocities for various blower voltages and probe heights above the nozzle. (b) Air speed response to a step input of 10 V at various probe heights above the nozzle. (c) Ball response to a step input of 13 V.

($\sim 1.2\ \mathrm{kg/m^3}$), A is the frontal area of the ball ($0.0113\ \mathrm{m^2}$), v_{air} is the mean velocity of the air column, and v_{ball} is the absolute ball velocity. Air velocity is a function of the height above the nozzle exit and the blower's rotational speed. To model these relationships, students measure air velocities at specific blower voltages and heights above the nozzle [Fig. 3(a)]. Variations in air speed [Fig. 3(b)] and ball height [Fig. 3(c)] to step changes in blower voltage are also recorded. This data can be incorporated into two-dimensional lookup tables and transfer functions to characterize the blower dynamics.

These aerodynamic and electromechanical effects are combined using Newton's second law to model the vertical dynamics of the beach ball:

$$\begin{aligned}\sum F_y &= m_{\mathrm{ball}}\frac{d^2 y_{\mathrm{ball}}}{dt^2} = m_{\mathrm{ball}}\frac{dv_{\mathrm{ball}}}{dt}\\ \frac{dv_{\mathrm{ball}}}{dt} &= \frac{1}{2m_{\mathrm{ball}}}C_d\rho A(v_{\mathrm{air}} - v_{\mathrm{ball}})^2 - g\\ \frac{dv_{\mathrm{air}}}{dt} &= \frac{f(V, y_{\mathrm{ball}}) - v_{\mathrm{air}}}{\tau_{\mathrm{air}}}\\ \frac{dy_{\mathrm{sensor}}}{dt} &= \frac{y_{\mathrm{ball}} - y_{\mathrm{sensor}}}{\tau_{\mathrm{sensor}}}\end{aligned} \tag{2}$$

where $\sum F_y$ is the sum of forces in the vertical direction, m_{ball} is the mass of the ball (13.0 g), y_{ball} and y_{sensor} are the heights of the ball and sensor above the blower nozzle, g is the gravitational constant (nominally $9.81\ \mathrm{m/s^2}$), τ_{air} is a first-order time constant determined from air speed response profiles [Fig. 3(b)], V is the blower input voltage, $f(V, y_{\mathrm{ball}})$ is a nonlinear function relating the steady-state air velocities to input voltage and ball height [Fig. 3(a)], and τ_{sensor} is a first-order time constant associated with the infrared sensors. Each student group incorporates its nonlinear system (2) into a Simulink model (Fig. 4).

Next, students linearize their model about a nominal operating point (a specific ball height, airspeed, and blower voltage) and use linear control techniques (root locus compensation, frequency response methods, etc.) to design controllers. By incorporating their nonlinear system model (the plant) and controller into a high-level Simulink block diagram (Fig. 5), students are able to simulate and observe closed-loop behaviors and iteratively adjust the controller parameters until an acceptable level of performance is achieved. A controller that performs satisfactorily in an accurate simulation environment is expected to perform equally well on the physical ball-blower system.

B. Experimental Validation

To test their controllers on the physical system (Fig. 1), local and distance students schedule laboratory time with

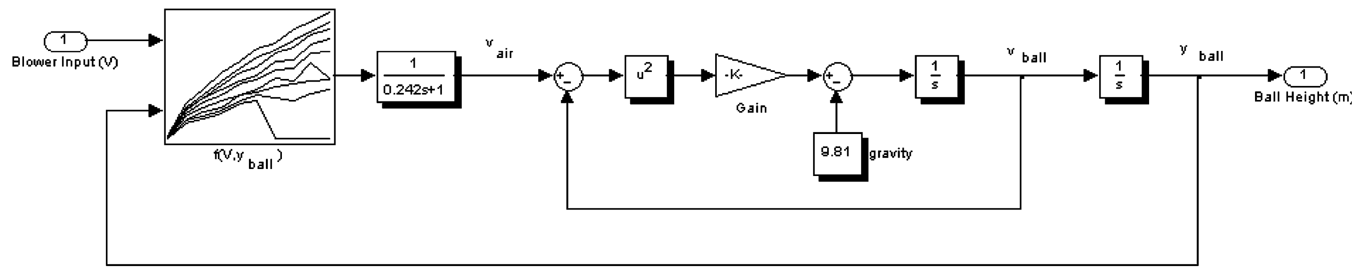

Fig. 4. Simulink model of blower/ball dynamics (plant).

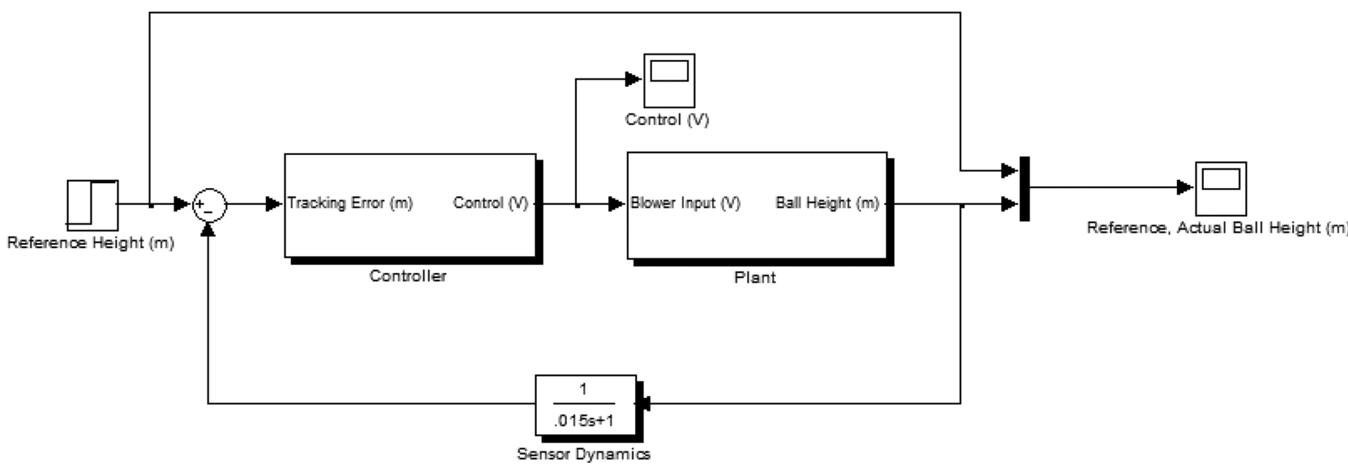

Fig. 5. Simulink model of blower/ball control system.

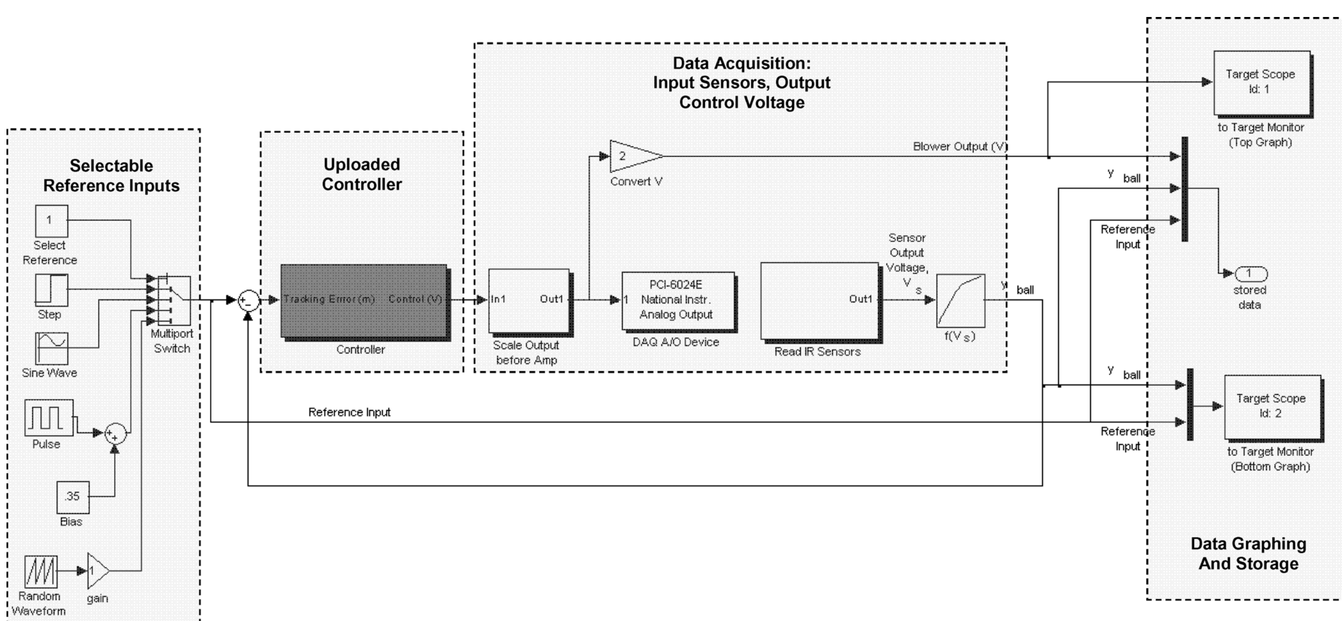

Fig. 6. Simulink block diagram for controlling the physical system.

the instructor. For the remote lab, the UNCA students establish contact with the NCSU laboratory using standard video conferencing equipment, in this case VCON ViGO hardware and VCON vPoint 5.1 software. Next, both parties initiate a NetMeeting session, and the distance students are granted control of the host laboratory computer. The students load their controller into a high-level Simulink program (Fig. 6) which acquires data from the infrared sensors, computes the tracking error, calculates the corrective control action, and outputs a control voltage to the amplifier. This program is compiled and loaded onto the target computer using MATLAB's Real-Time Workshop. The execution of this real-time code (and hence the

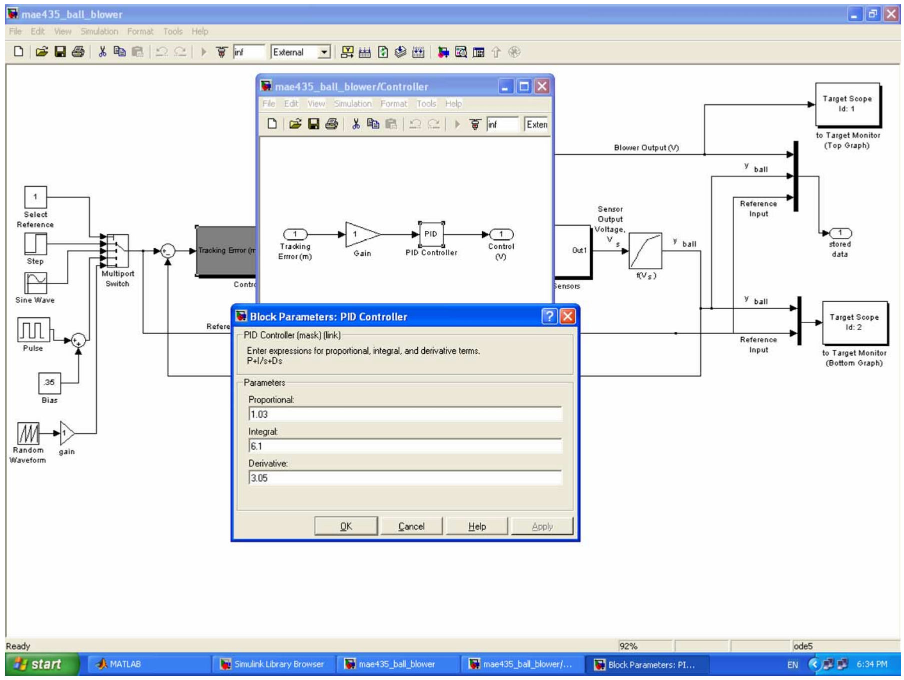

Fig. 7. Real-time adjustment of control parameters in the Simulink block diagram.

a) b)

Fig. 8. Scenes viewed alternately by the distance student through the webcam. (a) Levitating ball. (b) Monitor of target computer.

experiment) is controlled entirely by the distance students, who simultaneously view video of the levitating ball and updated graphs of its measured height and control voltage.

The performance of each controller is assessed by how well the beach ball tracks a variety of reference trajectories; typical reference inputs include sine, square, and sawtooth waves (Fig. 6). A particularly beneficial feature of xPC Target is that it enables control gains and tracking inputs to be adjusted while the real-time kernel is running (Fig. 7), making it unnecessary to compile and download new run-time code for every adjustment. With this capability, local and distance students can note the effect of controller adjustments in real-time.

For the distance student, access to Simulink is provided through NetMeeting's program sharing feature. With this feature, the desktop of the local computer is shown on a window in the distance student's monitor, enabling the distance student to directly access and control the application running on the local host computer.

The distance student receives real-time confirmation of controller performance through a webcam, which displays video of the ball/blower [Fig. 8(a)], and the target monitor [Fig. 8(b)].

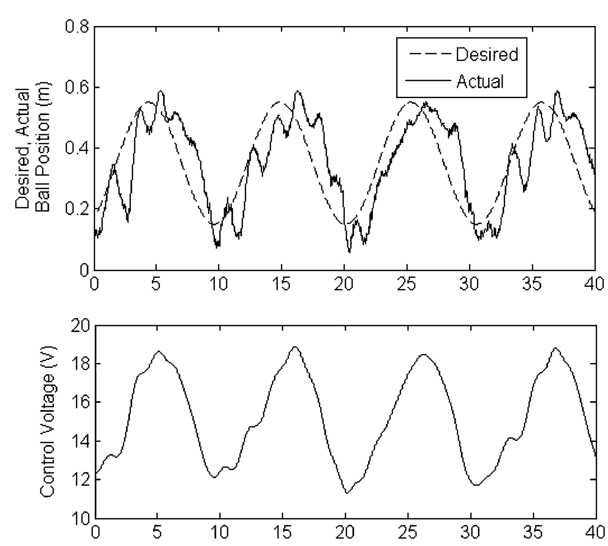

Fig. 9. Typical data collected during a laboratory exercise: desired and actual ball positions (top) and control voltage applied to the blower (bottom).

TABLE I
SURVEY RESULTS: COMPARISON BETWEEN LOCAL AND DISTANCE STUDENTS

	Local			Distance			Difference		
Item	n	M	SD	n	M	SD	M	SD	p
1. Overall, the lab was a good learning experience.	33	4.48	0.71	6	4.83	0.41	+0.35	-0.30	0.26
2. The lab increased my practical skills in controller design.	33	4.30	1.05	6	5.00	0.00	+0.70	-1.05	0.11
3. The lab helped me understand how controllers can be implemented and evaluated experimentally.	33	4.45	0.75	6	4.67	0.52	+0.21	-0.24	0.51

n= number of participants, M= mean, SD= standard deviation, p calculated from 2-sample equal variance t-test

TABLE II
SURVEY RESULTS: EVALUATION OF REMOTE LAB BY DISTANCE STUDENTS

Item	n	M	SD
4. The audio/video hardware provided adequate communication with the local experiment operator (Dr. Buckner and/or teacher's assistants).	6	4.50	0.55
5. The audio/video hardware provided adequate visualization of the levitating ball.	6	4.50	0.55
6. The audio/video hardware provided adequate visualization of the "target" computer screen (scrolling graph showing actual vs. desired output).	6	3.67	1.37
7. Viewing video from two cameras simultaneously (as opposed to one camera) would greatly enhance the quality of the laboratory experience.	6	3.83	1.47
8. Hypothetically speaking, I would prefer an automated remote lab (no local assistant) with 24-hour Internet access over the current system (scheduling a time with the local operator).	6	2.67	0.82
9. Interaction with the local operator, provided by video conferencing software, enhanced the quality of the remote laboratory.	6	4.50	0.55

n = number of participants, M = mean, SD = standard deviation

The upper graph on the target monitor shows the control voltage applied to the blower, while the lower graph shows the reference and measured ball positions.

Upon completion of the experiment, the user can download data from the target computer and reproduce performance plots for the entire data collection period (Fig. 9). Local students transfer data files to USB flash drives, while distance students transfer files using NetMeeting for further analysis and inclusion in final reports. If controller performance is less than desirable, students use this data to identify deficiencies and redesign their controllers. The process of laboratory assessment and controller modification is iterated until a satisfactory controller is produced.

IV. EVALUATION

A. Student Survey

Following completion of the course, students were surveyed to assess the laboratory experience, including ease of use of the remote laboratory interface. Survey data was collected 6–18 months after course completion. A five-point Likert scale was used for survey statements: 1) "Strongly disagree," 2) "Disagree," 3) "Neutral," 4) "Agree," and 5) "Strongly agree." A two-sample equal variance t-test was used to evaluate statistical significance. Both local and distance students completed a 3-item questionnaire (Table I), for comparison of perceptions between the two groups.

Of 52 students who completed the course, 33 local (75% participation) and 6 distance (75% participation) students responded to the survey. An additional 6-item questionnaire was given to distance students only (Table II). Neither student group was notified of the purpose of the survey. Results from Questionnaire 1 showed that distance students rated the lab as favorably as or more favorably than local students, indicating that the remote laboratory offered distance students a quality laboratory experience. No statistical significance between local and distance student perceptions was recorded, indicating similar levels of satisfaction between both groups.

Questionnaire 2, given to distance students only, was used to assess specific aspects of the remote laboratory: interaction with the local professor, sensory feedback of controller performance, and accessibility of the lab. Generally, distance students viewed favorably communication with the local operator and visualization of the physical experiment, agreeing that communication with the local operator was very helpful. In fact, students felt that interaction with the operator would be more desirable than having an automated 24-hour-accessible system (with no assistant). Students felt little need for an extra camera. However, distance students expressed dissatisfaction with visualization of the real-time graph via Internet video.

TABLE III
COMPARISON OF COURSE GRADES BETWEEN LOCAL AND DISTANCE STUDENTS

Item	Local			Distance			Difference		
	n	M	SD	n	M	SD	M	SD	p
Design project (ball levitation)	44	85.15	9.22	8	87.42	17.10	+2.27	+7.88	0.59
Final exam	44	68.20	17.64	8	68.00	18.56	-0.20	+0.92	0.98
Overall course grades	44	71.56	18.25	8	76.78	14.11	+5.22	-4.14	0.45

n= number of participants, M= mean, SD= standard deviation, p calculated from 2-sample equal variance t-test

B. Project, Exam, and Overall Course Scores

The effectiveness of the remote laboratory was also evaluated for its impact on course grades for the ball levitation design project, the end-of-semester final exam, and the overall semester course (Table III). Scores for all three items were very similar for local and for distance students, indicating similar learning experiences in both environments. Although not statistically significant, mean projects scores and overall course grades of distance students were higher than those of local students.

V. CONCLUSION

This paper demonstrates one means of conducting controls experiments at local and remote sites with minimal effort and cost beyond that needed for the local laboratory. Lab experiments were conducted for a senior-level controls course locally by students at NCSU's Raleigh campus and remotely by students at UNCA. MATLAB/Simulink coupled with xPC Target served as the controller platform, while Microsoft NetMeeting and standard video conferencing equipment were used to interface the laboratory equipment with the distance students. This technology enabled the distance students to implement, execute, and assess the performance of their control designs in real-time. For the remote laboratory, a local operator was required to place the ball on the blower nozzle before each blower startup; otherwise the distance students worked without any support from the local operator (when support was not desired). Sessions often included long periods of blower operation in which distance students assessed controllers without any intervention from the local operator. Nevertheless, providing personal interaction with the local operator and the course professor is a critical component of distance education; it is not recommended that personal interaction be sacrificed for the sake of fully automated laboratories.

The ball levitation experiment provided an engaging experience for both local and distance students. Students were simultaneously intrigued and challenged by the complex nature of the system, which stimulated much thought and, at times, head-scratching.

Surveys showed that distance students viewed the design project favorably; in some respects more favorably than their local counterparts. Course grades, including design project grades, were also similar between local and distance groups. The controls experiment required no additional funding or services from computer technicians. To provide a duplicate experimental setup at the UNCA campus would have required access to expensive laboratory space, equipment and technical supervision. As revealed in surveys, one drawback of the method is that the video's low resolution made it difficult to see clearly the real-time graphs relayed from the local computer screen. Improved Internet video resolution, along with more thoughtful formatting of the graph, would provide improved visualization for future experiments.

The methods described in this paper can be readily extended to other remote laboratory projects and other courses. The authors have used the same multipurpose hardware (personal computers, data acquisition boards, power supplies, etc.) to control design projects involving inverted pendulums and ball-beam balancing. Although other software applications (Remote Desktop Connection, Virtual Computing Network, etc.) could be used for application sharing, NetMeeting was chosen by the authors because it offers all of the following characteristics: 1) default installation on most Windows PCs (Windows 95 OSR2-Windows XP), 2) simultaneous desktop viewing by both local and remote participants, and 3) overall user-friendliness (no programming or learning curve).

Finally, the remote laboratory methods defined within this paper are not intended as a means to a comprehensive, college- or department-wide "collaborative environment," such as that described by Sivakumar [17]; but rather, as an option for educators who would wish for a remote laboratory but lack the time and resources necessary for a more integrated web-based laboratory environment.

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