Expanding the Undergraduate Laboratory Experience Using Web Technology

Sven K. Esche, Dennis J. Hromin
Stevens Institute of Technology

Abstract

Stevens Institute of Technology is currently implementing a new undergraduate engineering curriculum. This curriculum reflects the recent nationwide trend towards enhancement of traditional lecture-based courses with a design spine and a laboratory experience that propagates through the entire educational program. In the course of the curriculum development, it was recognized that the incorporation of design and laboratory components into all engineering courses places a significant strain on the spatial, temporal and fiscal resources of the institute. In order to accommodate the anticipated student enrollment, creative concepts for the implementation of affordable integrated experimental and design laboratories have to be developed. Without compromising the intended educational objectives, these laboratories must allow for the required student throughput using the limited existing laboratory space.

This paper presents the recent development and implementation of a student laboratory approach that is founded on Internet-based, remotely accessible experimental setups. In this approach, the students' experimental experience is greatly expanded by allowing them to not only use the experimental facilities in the traditional on-sight fashion but also to remotely access the computer controlled laboratory setup of interest through the Internet. In addition to the facilitation of asynchronous student learning patterns, this approach also enables instructors to include demonstrations of sophisticated laboratory experiments into their lectures. As is discussed in detail in this paper, the main benefits of the laboratory implementation discussed are the exposure of a potentially large student body to adequate experimental experiences, the promotion self-learning of the students, and the significant alleviation of strain on laboratory class schedules. In addition to making the laboratories available to students at any time from anywhere, this approach also serves as the basis for the affordable integration of laboratory experiences into the lecture environment.

A laboratory sequence that accompanies a sophomore-level course on dynamical systems was recently augmented by this approach. This paper focuses on the integration of remote experimentation into the undergraduate learning environment and analyzes the advantages and shortcomings of such remote laboratories. The cross-fertilization between abstract physical concepts and experimental validation achieved through the integration of lecture and laboratory material is highlighted using the experimental setup of a mechanical vibration system.

I. Introduction

Today, all constituents of academia are recognizing the hands-on activities typically associated with educational laboratories as imperative and integral elements of modern engineering curricula. The new review criteria applied by educational accreditation boards such as ABET and recent funding initiatives of governmental, charitable and industrial foundations as well as corporate and alumni sponsors are clear evidence of this trend.

A new undergraduate engineering curriculum is currently being implemented at Stevens Institute of Technology. In this curriculum, the recent nationwide trend of enhancing traditional lecture-based courses with a design spine and a laboratory experience that propagates through the entire curriculum is acknowledged. At the same time, it is recognized that the incorporation of design and laboratory components into all engineering courses places a significant strain on the spatial, temporal and fiscal resources of the institute. Therefore, new concepts for the implementation of affordable integrated experimental and design laboratories have to be developed in order to accommodate the anticipated enrollment. These laboratories must allow for the required student throughput using the limited existing laboratory space without compromising the educational value.

This paper presents the development and implementation of a student laboratory approach that is founded on Internet-based, remotely accessible experimental setups. Besides making the laboratories available to students at any time from anywhere, this approach also serves as the basis for the affordable integration of laboratory experiences into the classroom. This approach has recently been implemented at Stevens into a laboratory that accompanies a sophomore-level course on dynamical systems. The discussion in this paper will focus on the integration of remote experimentation into the undergraduate learning environment and analyze the advantages and shortcomings of such remote laboratories. The experimental setup of a mechanical vibration system will be used to highlight the cross-fertilization between abstract physical concepts and experimental validation achieved through the integration of lecture and laboratory material.

In the context of recent major Stevens initiatives on e-learning and virtual classrooms, the implementation of this remote experimentation concept has sparked considerable excitement amongst the Stevens faculty, staff and students involved in the development, building and testing of the experimental setups.

II. State-of-the-Art in Approaches for Educational Laboratories

Traditional educational laboratories are typically characterized by the following elements: preparatory instruction, preliminary student performance assessment, hands-on experimental work, data analysis, and reporting of the experimental findings. As the first step, the students are familiarized with the educational objectives of the experiment as well as with the underlying theoretical background. Typically, some type of preliminary student performance assessment is then conducted in oral or written form in order to assure that the students are prepared to correctly carry out the experimental work. Where appropriate, the students are also tested on their awareness of safely concerns related to the experiment. The experimental work itself comprises the setup and calibration of the equipment followed by the data acquisition, filtering and postprocessing. An out-of-classroom assignment is finally given to report and discuss the experimental findings.

From an educational standpoint, the data collection, interpretation and correlation with theoretical formulations presented in the classroom should be the main focus of the students' attention in connection with any laboratory. On the contrary, in the classical educational laboratory approach students are often forced to spend a disproportionate amount of their total allotted laboratory time on assembling the particular experimental setup and calibrating it, especially when sophisticated equipment is involved. The students' educational experience is then usually reduced to a phase where they follow a recipe-type experimental tutorial in collecting the required data. The analysis of the experimental results, which due to the required analytical thinking represents the most challenging component of the entire laboratory experience, is then left as a homework assignment.

It can thus be argued[1] that this traditional closed educational laboratory setup, where students first spend time in the laboratory facility and then conclude the laboratory by a report written outside of class, is not an arrangement that is particularly conducive to learning. The remotely accessible laboratories discussed in this paper appear to be a better alternative where students can return at any time to repeat and refine their experiments.

Accessibility and affordability represent further severe limitations of the traditional educational laboratories in addition to their closed nature. A significant commitment of personnel and other resources are required to satisfy the needs of large student populations. Usually laboratory space is limited and the students are accommodated by dividing the classes into multiple laboratory sections, both for the preparatory instruction as well as for the experimental work itself. In addition, each section is broken up into groups where in most settings teams of three to four students have been found to work most effectively. Due to scheduling constraints, it is not uncommon that some of these laboratory sections will be forced to undertake experiments out of tune with the lecture which they are to accompany[2], and thus the intended educationally benefit is not attained to the full extent. The size of the laboratory sections is limited by number of identical experimental stations available. In most educational institutions, budgetary constraints prevail, and therefore, the number of student groups that can perform any given experiment concurrently is very small. This limitation is especially stringent for sophisticated and therefore costly experimental setups. In order to resolve this constraint, the time allotted for the students to perform their experimentation is reduced to the bare minimum, and as a result, the students are not exposed to the laboratory equipment to the extent that would be desirable from an pedagogical standpoint. Modern undergraduate engineering curricula as they have been devised recently at many schools nationwide tend to further intensify this problem since they are increasingly focusing on laboratory activities and experimental demonstrations during lectures.

Educational laboratory facilities that effectively address these shortcomings of the traditional laboratory environment are still in short supply. Therefore, the development of alternative approaches to laboratory education has recently become the focus of numerous initiatives involving educational institutions, governmental agencies and professional societies. Upon examining and assessing the current state, it has become increasingly clear that a shift of paradigm in laboratory instruction must be seriously considered. New laboratory approaches should allow for more flexibility in administering preparatory instruction for the laboratory experiments as well as in performing the experimental laboratory work itself. Furthermore, they should fully exploit the recent technological advances in information technology and communications. As a review of current laboratory instruction approaches reveals[3], a multitude of instructional tools using computer software and multimedia-type technologies has been developed and implemented into the classroom environment recently. Studies on the effectiveness of these tools have indicated a measurable improvement in student achievement and performance outcomes (e.g., information retention, learning time) compared with traditional instructional methods. This improvement is at least partly being attributed to the ability of the students to proceed at their own pace and to obtain online help and background information beyond the classroom material, the possibility for active student interaction, and the inherent stimulation of audio- and video-based learning patterns. In many cases, today's students who are accustomed to heavy computer usage in all spheres of their lives demonstrate a positive learning attitude when exposed to computer technology in the learning process.

III. Undergraduate Laboratory Approach

At Stevens Institute of Technology, an approach to undergraduate laboratories is currently being implemented and tested, in which both students and instructors are able to access the laboratory facility remotely at any time and from anywhere through the Internet. The laboratory architecture allows one to connect to the interactive, computer-controlled laboratory setup of interest as shown in Figure 1.

In the first phase of a typical laboratory experiment, the students get re-familiarized with the underlying physical phenomena of the particular experiment to be performed. In addition, the appropriate documentation is available online to the students to acquaint themselves with the experimental equipment. Where deemed appropriate by the instructor, the students can be asked to successfully complete an online competency test on the underlying fundamentals and the specific equipment to be used before coming to the laboratory session.

Later when coming to the laboratory facility, the students have the opportunity for a limited amount of direct interaction with the laboratory setups. They can be asked to calibrate the equipment and perform a limited set of experiments. The remote accessibility of the experimental setups then allows them to continue more detailed experimental studies in a remote fashion. This approach gives tremendous flexibility to the instructor in leveraging a limited number of experimental stations for a wide variety of studies. It thus greatly enhances the scope and value of the experimental experience for the students.

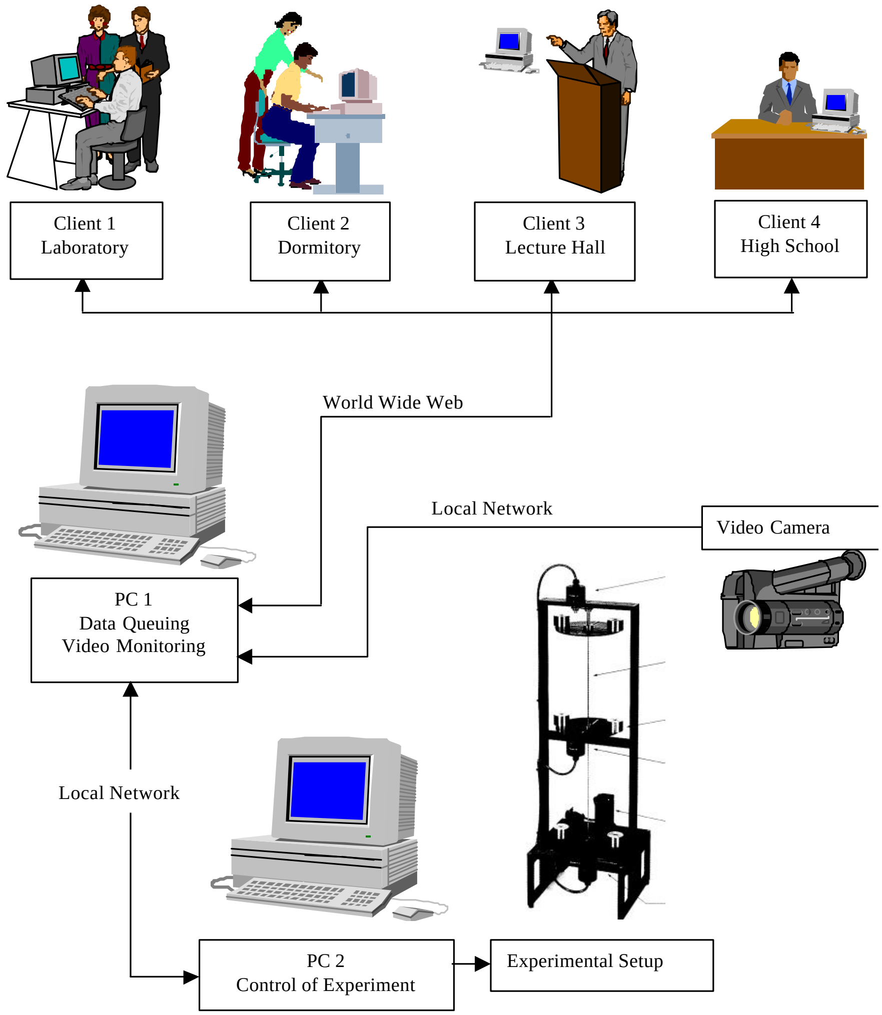

Figure 1: Setup of undergraduate laboratory

During the remote experimentation, the students interactively submit sets of input data for the selected experiment to a web server, which controls a queue. Individual data acquisition terminals then extract the input data files one by one from the queue and initiate their processing by the appropriate computer-controlled laboratory equipment. The experimental procedure is recorded by video cameras and saved in electronic form as a video file. Both the numerical results of the experiments and the video files are finally made accessible through the Internet for the remote and time-independent inspection and/or post-processing by the user.

IV. Benefits and Shortcomings of the Laboratory Approach

The approach described in this paper takes advantage of a variety of existing and emerging communication technologies. All activities associated with the laboratory courses are guided through web pages. These web pages can be implemented using WebCT, a software package that is currently being adopted in various courses at Stevens. This package offers functions to support various activities of the laboratory framework described here. In addition to the functionality of conventional HTML-based web pages, the capabilities integrated in this package comprise among others a tool to track the student page views, several communications tools (e.g., chat room, e-mail, white board, bulletin board), an online quiz feature and a grade database. All preparatory instructional materials (enhanced by visual tools such as drawings, photographs, computer animations, audio and video files) as well as testing and self-assessment tools for the students can thus be provided in electronic form on the Internet. The Internet-based communication tools will conveniently enable team-based learning activities for students that are exposed to spatial and temporary constraints in their study techniques.

The benefits of this laboratory approach are, among others, that:

- larger numbers of students can be exposed to a more comprehensive experimental experience (including students with physical disabilities, non-traditional students, part-time students, students undergoing continued education, participants of on-site industrial training courses),
- asynchronous learning is encouraged, which is especially suited to fit the needs of non-traditional, commuting part-time students,
- it is a much closer approximation to hands-on experience compared to purely numerical experimentation and simulation,
- it promotes student self-learning,
- it renders itself as a tool for integrated student performance assessment and self-assessment,
- it captures the spirit and imagination of the students who nowadays tend to be increasingly technologically inclined,
- instructors are enabled to include demonstrations of laboratory experiments into their lectures,
- the strain on laboratory class schedules is alleviated significantly, and
- budgetary constraints are overcome.

As it was rightfully pointed out by the reviewers of the original NSF proposal leading to partial funding of this activity by the NSF-ILI program as well as by other individuals involved in the planning and implementation of this project, this laboratory approach does not only offer important benefits but also exhibits some drawbacks. The significant investment in the up-front development effort and time required is one of the main disadvantages compared with traditional laboratory setups. In contrast to the original plans for developing a laboratory to be accessed exclusively in a remote fashion, the development team changed to the hybrid on-site / remote approach described here. This modification of the original plans takes into consideration the valuable opinions of various people with whom the initially conceived fully remote laboratory approach was discussed and the majority of whom found that direct hands-on student interaction with the experimental equipment is of paramount importance for the educational success of the experimental experience that the students gain. The authors believe that the modified approach to student experimentation as presented in this paper has the potential to enhance engineering curricula by facilitating improved access to better laboratory equipment by a broader student audience. Another key concern frequently voiced related to the perceived difficulties in enforcing the independence of student work when performed remotely. While at other institutions this issue might pose a challenging problem without an obvious solution, at Stevens there exists a student honor code that entirely removes any need for student proctoring.

V. Technical Realization of the Laboratory Architecture

The laboratory approach presented here was realized using a client-server network architecture that allows the concurrent execution of multiple experiments using separate experimental setups. Experiments that require the same setup are queued and executed in the order of the incoming requests. The connection from the laboratory to the outside world is established using a Linux-enabled web server. This server hosts the process queue, the data input and output files generated, and the graphical user interface that was developed using conventional HTML pages, Java applets, and CGI/Perl scripts. The web server is networked to individual data acquisition terminals running Windows NT. These terminals execute LabVIEW VI scripts that control the experiments and report the experimental results back to the web server.

After downloading the main web page of the online laboratory using any web browser, the user first selects a particular experiment from the list of available offerings. Then the user fills out the corresponding input form, which contains some personal information (name, affiliation, e-mail address) as well as the necessary input data for the experiment. Subsequently, the user receives an e-mail message, which provides the estimated execution time for the experiment, the necessary access code and URL where the output data (numerical results in ASCII format, video file in real media format) can be picked up at any time after the completion of the experiment.

A unique process identification number is then automatically generated, an entry in the process queue residing on the web server is made, and the user is informed about the estimated waiting time until completion of the experiment. The individual data acquisition terminals check continuously for new entries in the process queue. When detecting a new relevant entry, the input data are retrieved from the corresponding user input form and parsed. Subsequently, a series of scripts are executed that perform a variety of subtasks involved with the execution of a particular experiment. The list of actions initiated by LabVIEW VI scripts includes but is not limited to:

- parsing the input data file,
- switching on/off the power and/or lights,
- activating/deactivating the video capturing,
- initializing the experimental setup,
- executing the experiment and acquiring the resulting output data, and
- transferring the resulting output data back to the web server.

The numerical data can finally be imported into any software that the user selects for postprocessing purposes. Replaying the video file requires the RealPlayer software that is distributed by RealNetworks.

VI. Sample Implementation of the Laboratory Approach

The laboratory approach described in this paper was initially developed and implemented into one course of the new Stevens undergraduate engineering curriculum on dynamical systems. So far, the four types of systems available are mechanical vibration systems (with one degree of freedom and two degrees of freedom), a liquid level system, an acoustic system (simplified muffler with adjustable expansion chamber) and electrical systems (inverting and non-inverting amplifier, low pass and high pass filter). In addition, an electro-mechanical system is currently under development. Each system allows for a variety of individual experiments to be performed.

Below, a brief description of the one-degree-of-freedom mechanical vibration system is given together with three potential experiments. The system consists of a metallic mass that is supported by a linear helical spring. The mass is guided by low-friction linear bearings and actuated by a magnetic coil. Within engineering accuracy, this experimental setup can be approximated as a linear second-order spring-mass-damper system whose schematic representation is shown in Figure 2.

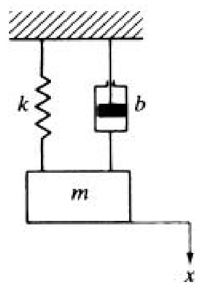

Figure 2: Schematic representation of a one-degree-of-freedom free vibration system

The vibration system as described here is a mechanical system that lends itself nicely both into on-site and remote experimentation as will become clear in the discussion to follow. This system can be used on several occasions throughout the course on dynamical systems. In the first laboratory session devoted to system identification, free vibrations induced by imposing an initial displacement condition on the system are analyzed. From the measured amplitude versus time curve (see Figure 3), the students are asked to determine the damped period T_d, the damped natural frequency f_d, the damped circular natural frequency w_d, the logarithmic decrement L, the damping ratio z, the damping coefficient b, the undamped circular natural frequency w_n, the undamped natural frequency f_n and the undamped period T_n.

Upon inspection of the results for different initial displacement conditions, it becomes clear that the damping ratio of this one-degree-of-freedom system depends slightly on the amplitude of the vibration. It is this fact that makes this experiment into a prime candidate for a laboratory that can start in the on-site hands-on mode and can then be finished in remote fashion. Initially, the experiment can be carried out on-site for one given initial displacement value. The repetitive procedure of determining the dependency of the damping ratio on the vibration amplitude can then be left for remote exploration.

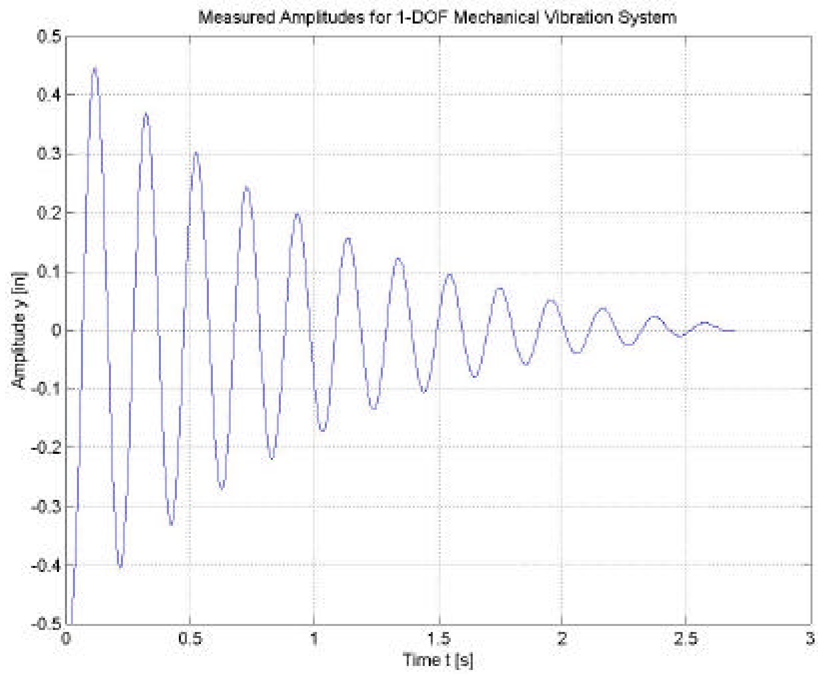

Figure 3: Measured amplitudes for one-degree-of-freedom mechanical vibration system

In the second laboratory session involving the one-degree-of-freedom mechanical vibration system, the forced vibration response to a step function force input is investigated. The excitation force is imposed upon the mass by the magnetic coil as schematically shown in Figure 4. The experimental amplitude vs. time curve (see Figure 5) allows the students to determine the delay time t_d, the rise time t_r, the peak time t_p, the maximum percentage overshoot m_p, and the settling time t_s. Again, after completing the step response experiment in the on-site mode, additional experiments such as the ramp response, impulse response etc. can then be assigned to the students for remote experimentation outside of the allotted laboratory time.

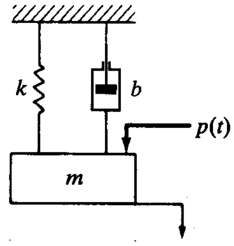

Figure 4: Schematic representation of a one-degree-of-freedom forced vibration system

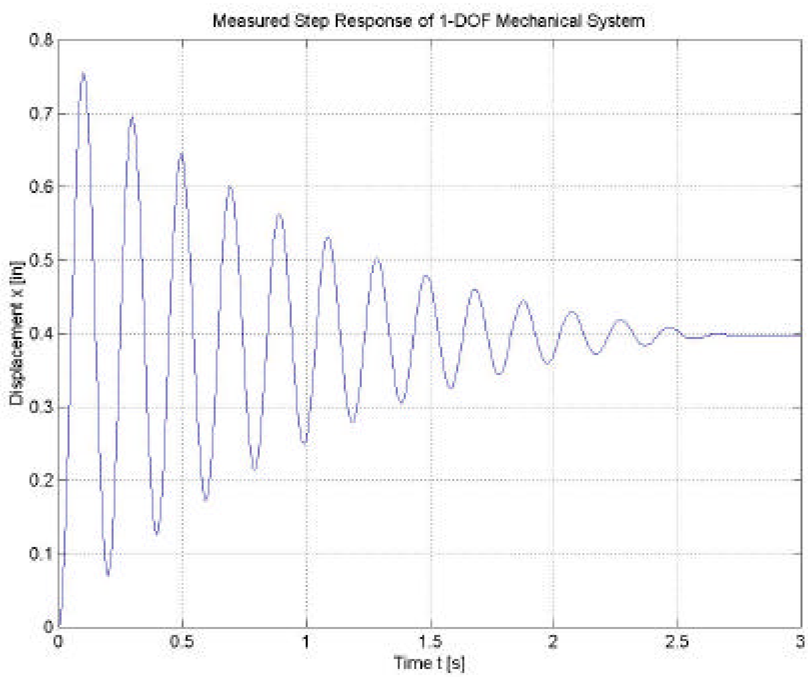

Figure 5: Measured step response for one-degree-of-freedom mechanical vibration system

The third laboratory session that is based on the one-degree-of-freedom mechanical vibration setup investigates the frequency response of the system. Here, a sinusoidal force of varying frequency is applied onto the mass and the resulting vibration amplitude is recorded as a function of the excitation frequency (see Figure 6). From the resulting experimental data, the students are asked to determine the resonance frequency f_{res}, the amplitude at resonance x_{res} and the static deflection x_{st}. As for the two laboratory sessions described above, this experiment can be carried out for a limited number of excitation frequencies during the allotted laboratory hours, and later the frequency response diagram can be completed in remote mode. Alternatively, other more detailed studies (e.g., analyzing the dependency of the results on the excitation force amplitude) can be performed later in remote fashion.

It should be noted that the remote accessibility of all experimental setups described here provide the instructor the opportunity for including experimental demonstrations into the traditional lecture environment. Stevens has invested significant efforts and funds into the networking of classrooms, thus enabling the integration of web based instructional tools into the learning process in a seamless fashion.

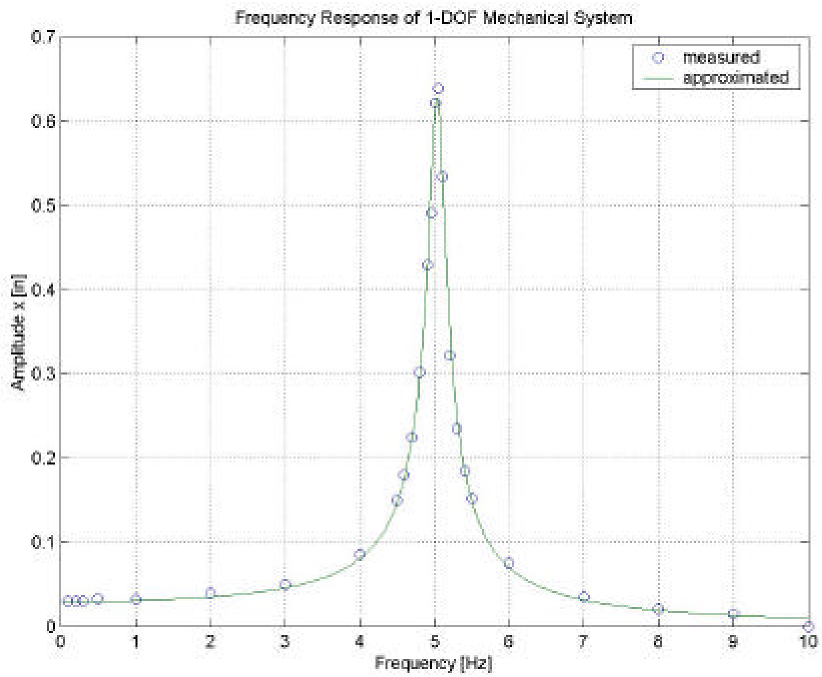

Figure 6: Frequency response for one-degree-of-freedom mechanical vibration system

VII. Future Plans

Currently, the one-degree-of-freedom mechanical vibration system, the liquid-level control system, the acoustic system and the electrical systems are fully functional while the two-degree-of-freedom mechanical vibration system is still in the development phase. Furthermore, an electro-mechanical system is currently under development, and it is foreseen to extend this laboratory approach in the future to other applications of dynamical systems rooted in mechanical, electrical, civil, and chemical engineering.

It is furthermore planned that at a later time the possibility of integrating remotely accessible experiments into other educational laboratories at Stevens will be explored as well. In addition, some of the laboratory setups developed for the undergraduate laboratory on dynamical systems can potentially provide for classroom demonstrations in graduate courses in controls, fluid mechanics, vibration and noise control and others. Besides the proposed application for remote-access interactive laboratory training, it is envisaged that this Internet-based technology will find other fields of application such as the remote access of expensive research equipment and facilities.

VIII. Summary

An approach to laboratory instruction based on Internet technology is presented in this paper. In this approach, the students' experimental experience can be greatly expanded by allowing them to remotely access the laboratory facility and connect through the Internet to the computer controlled laboratory setup of interest. This approach enables and encourages instructors to include demonstrations of sophisticated laboratory experiments into their lectures and provides for asynchronous learning. Therefore, the main benefits of the proposed laboratory implementation are that more students can be exposed to adequate experimental experiences, self-learning of the students is promoted, and the strain on laboratory class schedules is alleviated.

Acknowledgements

The development of the Dynamical Systems laboratory is partially funded by the National Science Foundation through NSF Award #9851039 for which the first author is the principal investigator. This financial support by the NSF is gratefully acknowledged. In addition, the collaborative efforts of Dr. M. Prasad and Dr. M. Tsatsanis who are co-investigators for the NSF project are appreciated. Furthermore, it should not go unmentioned that the implementation of this laboratory approach into the system dynamics laboratory would not have been possible without the vast design and manufacturing expertise of Mr. Jan Nazalewicz and his colleagues in the Stevens Department of Engineering Services.

Bibliography

1. Knight, C. D. & DeWeerth, S. P. (1996). A shared remote testing environment for engineering education. *Proceedings of the ASEE 1996 Annual Frontiers in Education Conference*, Session 8c1, November 6-9, 1996, Salt Lake City, UT, USA, pp. 1003-1006.
2. Chan, W. L. & So, A. T. P. (1994). A cost effective interactive multimedia system for electrical undergraduate laboratory sessions. *Proceedings of the 1994 IEEE 1st International Conference on Multi-Media Engineering Education*, July 6-8, 1994, Melbourne, Australia, pp. 219-224.
3. Esche, S. K., Prasad, M. G. & Chassapis, C. (2000). Remotely accessible laboratory approach for undergraduate education. *Engineering Education Beyond the Millennium, Proceedings of the 2000 ASEE Annual Conference and Exposition*, St. Louis, Missouri, June 18 - 21, 2000.

SVEN K. ESCHE
Sven Esche currently holds a position as Assistant Professor of Mechanical Engineering at Stevens Institute of Technology. He received his undergraduate degree in Applied Mechanics in Germany and his M.S. and Ph.D. degrees in Mechanical Engineering from The Ohio State University.

DENNIS J. HROMIN
Dennis Hromin will receive his undergraduate degree from the Department of Electrical and Computer Engineering at Stevens Institute of Technology in Spring 2001. Over the past two years he has designed and implemented the remote-access features of the dynamical systems laboratory described here.