Cyberinfrastructure Tools in Engineering Education for Teleoperation Experiments

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Abstract — Hazard mitigation and structural dynamics have been important additions to the undergraduate civil engineering curriculum. UCIST (University Consortium on Instructional Shake Tables) has worked toward improving educational opportunities in this area for nearly 10 years. For the past 8 years, the US National Science Foundation has sponsored a cyberenvironment project referred to as the Network for Earthquake Engineering Simulation (NEES). Through a partnership between NEES and UCIST, we are working to enhance earthquake engineering education around the world. The development of teleoperation and teleparticipation exercises for bench-scale instructional shake tables based around the NEES suite of tools will allow future civil engineers to learn fundamental concepts in structural dynamics. This paper will discuss the establishment of a collaboratory of bench-scale instructional shake table deployment sites. This collaboratory provides for real-time online laboratory experiments, leveraging the unique capabilities of the NEES initiative to offer experiences previously unavailable to undergraduate students. The paper will describe two of the initial laboratory exercises developed to educate undergraduate students in the fundamentals of earthquake engineering (e.g. structural engineering, structural dynamics). In addition to direct educational benefits, the indirect outcomes of these exercises include an introduction to virtual presence technology and collaborative computing tools, broadening their exposure to tools that will become essential for future engineers.

Index Terms — Earthquake engineering; Shake table; Teleoperation; Virtual Experiments.

INTRODUCTION

In recent years bench-scale shake tables have proven to be an engaging tool for educating students at all levels about fundamental concepts in earthquake engineering. Shake table laboratory stations (see Fig. 1) allow for demonstrations and hands-on experimentation on physical structures. The station will typically include the shake table, accelerometers, versatile software to create various input motions, and a model of a building structure. At advanced levels, undergraduate and graduate students can conduct experiments to test their knowledge of fundamental concepts in structural dynamics [1,2]. Students may easily build or modify the size and behavior of models of structures to experiment with their own innovations. The use of realistic sensors allows students to gain experience with modern instrumentation. Furthermore, demonstrations for K-12 students allow students to gain an understanding of earthquake motions and how structures can be designed or retrofitted to better withstand seismic motions.

The University Consortium of Instructional Shake Tables (UCIST) was developed by Prof. Shirley Dyke in 1998 to enhance undergraduate and graduate education in earthquake engineering through the incorporation of bench-scale instructional shake table experiments into the undergraduate curriculum [4,5]. This consortium, headquartered at Washington University in St. Louis (http://ucist.cive.wustl.edu/), has since expanded to over 100 institutions around the world.
world. UCIST has endeavored to enhance the education of undergraduates through the procurement of these shake tables, the development of curricula, and the dissemination of these tools to other institutions. Additionally, outreach activities targeting K-12 students and the general public were encouraged [7,8], and a wide range of undergraduate research opportunities became available.

Through a recent partnership with the George E. Brown Network for Earthquake Engineering Simulation (NEES), a premier cyberenvironment project funded by the NSF, UCIST is expanding the scope to include the use of virtual presence technologies within the experiments developed. We are focusing on the leveraging the geographically-distributed network of world-class experimental facilities, its connecting cyberinfrastructure, and its extended community of engineering and cross-disciplinary faculty from academic programs across the nation to provide undergraduates with exceptional learning opportunities. Partnering with NEES provides an excellent opportunity to increase the impact of UCIST exercises, and to develop a virtual collaboratory in earthquake engineering education. NEESinc is also heavily involved in earthquake engineering education; it has developed a NEES Education, Outreach and Training (EOT) Strategic Plan in parallel with its establishment (Grant CMS-0337808). The plan calls for the development of a Coordination Framework for all of the EOT activities related to NEES, encompassing activities at the sites, by the PIs of research projects, by NEES EOT staff and by external PIs who have a particular interest in earthquake engineering or cyberinfrastructure education initiative [5]. An Execution Plan, intended to accompany the Strategic Plan, will provide a detailed roadmap to the NEES community for helping them to achieve the goals of the NEES EOT Program.

Our vision is to develop an international collaboratory of bench-scale earthquake engineering facilities that will engage a broad range of students by creating a series of shared laboratory exercises available for remote operation via the internet. This educational collaboratory will leverage the cyberinfrastructure, coordination capabilities and educational goals of the NSF-sponsored NEES initiative. Implementation of the extensive array of cyberinfrastructure tools developed for NEES research will enhance the learning process at the undergraduate level. Most of these tools are opensource and are being continually updated and improved by NEES, ensuring that updated, secure tools will be available for our needs. Existing state-of-the-art cyberinfrastructure tools developed by NEESit (NEES Information Technology, it.nees.org), the technical support and development component of NEES, for NEES research activities will be utilized. Tools have been developed recently for the remote control (teleoperation) and the viewing and analysis of streaming data and video (teleparticipation) for the instructional shake tables over the internet. These capabilities have been incorporated into two formal laboratory exercises and one 3-week teaching module, and in the Fall of 2007 we will be deploying these exercises to several universities within the US. Over the next couple years, several new exercises using these capabilities will also be developed. Information on how to join this collaboratory is available at the end of this paper.

LABORATORY EQUIPMENT

The equipment used for these instructional materials consists of a Shaker IV system from Quanser Consulting (www.quanser.com). The bench-scale seismic simulator has a 46x46 cm slip-table driven by a ball-screw mechanism with an operating frequency of 0-20Hz, a +/-7.6cm stroke and a peak acceleration +/-1g with an 11.3kg payload. The Shaker IV interfaces with a PC through the Quanser Q4/Q8 board and is controlled using WinCon real-time software. This shake table is a powerful tool for high fidelity and controllable reproduction of seismic motions. Accelerometers are available for measuring the responses of the structure and recording the measurements. Data can also be streamed in real time to remote users for plotting and analysis. This equipment is ideal for educational uses, and has also been used widely for K-12 outreach, demonstrations, and small scale research projects. A prior NSF-funded cooperative project to establish these shake tables at universities across the country facilitated the dissemination of the proposed project to universities nationwide.

NEES cyberinfrastructure tools now make it possible for earthquake engineering researchers to remotely participate and control experiments, facilitating new testing methods such as distributed hybrid testing where various components of a single structural system are tested at geographically distributed sites. Video and data can be transferred in real time to laboratories and users around the country for analysis and simulation. These teleparticipation capabilities are being employed here for educational uses by UCIST through the development of a series of new educational exercises. These exercises will allow a broader set of students and institutions access to use the shake tables for education and training, and will facilitate national dissemination of real-time online laboratory experiments to offer state-of-the-art laboratory experiences previously unavailable to undergraduate students.

Remote operation the UCIST shake table using the NEES cyberinfrastructure was first accomplished by Prof. Richard Christenson in December 2004. More recently, an expansion of this effort has been undertaken involving teleparticipation by adding functionality to stream data and video through existing NEES cyberinfrastructure tools. The UCIST PC is configured as a server to receive commands. Commands to the shake table originate by the remote user through the graphical user interface running at the client (remote) end. The NEES Real-time Data Viewer (RDV) is then used to view the time synchronized streaming video and data from any PC over the internet.
There are several components that allow for teleoperation and teleparticipation, which are illustrated in the flow chart in Fig. 2. In this configuration a Remote PC, any PC with internet access, uses a teleoperation java applet as an NTCP Client. NTCP is the NEESGrid Teleoperations Control Protocol where the NTCP Client is the front end client that provides teleoperation commands. Telepresence is achieved through the Real-time Data Viewer (RDV). The RDV is a NEES tool that allows for viewing of synchronized streaming data and video.

The Ring Buffered Network Bus (RBNB) program, running on a Data Turbine PC, buffers and streams data and video to the RDV. The shake table PC has three main functions: control of the UCIST shake table through the WinCon real-time software; receiving NTCP commands, through the NTCP Server, for teleoperation; and streaming data to RBNB, through the WebDaemon program, for teleparticipation. A Panasonic BL-C1A web camera provides streaming video to the RBNB. A view of the portal seen by a remote user while streaming data and video from the RBNB using the NEES Real-time Data Viewer (RDV), shown in Fig. 3. A Java applet serves as the NTCP Client graphical user interface (GUI). This GUI is shown in Fig. 4, providing remote users a direct means to control the experiment by adjusting the frequency and amplitude of the sinusoidal excitation and pressing start.

Instructions on how to set up the RBNB server and NTCP on a Windows-based PC, and how to enable teleparticipation and teleoperation of the UCIST shake table are available on the UCIST website: http://ucist.cive.wustl.edu/.

Figure 2 Flow Chart of the Teleoperation Experiment.

Figure 3 Real-time Data Viewer connected to University of Connecticut deployment site.

Figure 4 Java NTCP Client.
DEVELOPMENT OF INSTRUCTIONAL MATERIALS

Several early experiments that use this shake table lab station are available on the UCIST website for downloading and implementation. Experiments consider structural dynamics, soil-structure interaction, bridge design, torsional responses of structures, etc. The website contains laboratory manuals for instructors and students, drawings for building experimental components, and sample data. These experiments have been used at institutions across the US to educate undergraduate and graduate students in earthquake engineering topics. Users who may be interested in posting new experiments to share with the earthquake engineering community are welcome to contact the authors.

More recently a K-12 teaching module has been developed as part of a NSF-funded GK12 site at Washington University. Furthermore, to date, one formal NEES-based telepresence experiment has been conducted in a classroom setting. A freshman level experiment has been developed to introduce earthquake engineering concepts through teleparticipation experiments utilizing the bench-scale shake table. All of these activities are summarized below, followed by a description of the future activities of the UCIST.

Teleparticipation and Teleoperation at the Freshman Level

The module consists of a series of 8 lectures. Students are introduced to structural engineering topics, mathematical modeling of dynamic behavior, MATLAB simulation tools, and NEES capabilities and research through a series of lectures. Then the students use the teleparticipation tools to conduct an experiment using the shake table. A one-story (single-degree-of-freedom) structure with light inherent damping is used (as shown previously in Fig. 3). A linear voltage differential transducer (LVDT) is used to capture structural response data for a sinusoidal excitation. Video and data are observed and downloaded through RDV for analysis and comparisons to mathematical models. The students are introduced to structural engineering and vibration concepts as they are asked to model the structure and analytically determine the natural frequency and response at various sinusoidal excitations, through a series of three homework assignments. The module culminates with the students conducting experimental tests online to observe the structure’s actual natural frequency and response to various sinusoidal excitations. The students prepare a laboratory report documenting their efforts during the module. This experiment has been implemented at the University of Connecticut and Washington University. Evaluation of the tools is now underway, and the tools will be disseminated on the UCIST and NEES websites in the Fall of 2007.

Evaluation Procedures and Outcomes

The evaluation plan for this exercise considered multiple approaches. For the first experiments at the University of Connecticut and Washington University, students completed an online survey at the end of each module. Faculty used the web-based Student Assessment of Learning Gains (http://www.wcer.wisc.edu/salgains/instructor/); this survey instrument was designed by Elaine Seymour, author of Talking about Leaving: Why Undergraduates Leave the Sciences, and is available to all faculty through multiple NSF funded projects and the ExxonMobil Foundation. Eighty-three students from the two institutions have responded; fourteen were female.

Preliminary results indicate that peers are important to student learning and that the shake table experiments are “amazing;” the experiments help them “see the way a structure physically, as opposed to analytically, moved and reacted to vibrations.” Across both institutions and three implementations of the initial module, students ranked working with peers outside class the most important support they had as a learner. When asked about what they liked about the shake table learning experience, students wrote:

- I liked how we actually ran a real experiment and were able to run it from our dorm rooms even though the shake table was somewhere else, and actually view it through live streaming video.
- [It]Was very hands on, and many people learn better by doing and seeing than just calculations.
- It was a very interesting experience. The fact that you could manipulate a structure in another building across campus from your room is amazing.
- You go to see live footage of what was actually happening to the structure under vibrations of differing magnitudes and see how your frequency matched up to the real structure

When asked what improvements they would suggest, students wanted more control of the table plus more time and more explanations. They commented:

- Give the students a chance to control the table to find the frequency that produces resonance, rather than just showing pre-formulated simulation.
• More time and more thorough explanation of what we were actually doing. We were thrown head first into the deep end with no help aside from our peers.

On-going formative evaluation will ensure that the project effectively achieves its goals in a timely way. Using outcome measures, the ongoing assessment of the project’s progress will enable the project leaders to make midcourse corrections and improvements. As part of a continuous improvement management model, faculty will use the data to improve the modules for students on the initial two campuses as well as at the other network institutions that will implement the modules in fall, 2007.

Senior Level Teleoperation Exercises

Two additional exercises have been developed for integration into a senior level structural dynamics and vibrations course. These are being implemented in the Fall of 2007 at Washington University as a laboratory component to a course in structural dynamics. These exercises focus on understanding both time and frequency domain behavior of discrete parameter dynamic systems. The first exercise focuses on a single degree of freedom, and the second focuses on multiple degrees of freedom. These exercises are discussed in the following paragraphs, and will also be available on the UCIST website.

In the first exercise the students use the shake table to experimentally observe transient and forced vibration of a single degree of freedom (SDOF) dynamic system. A SDOF system representing a one story building is used as the test specimen. Accelerometers are placed on the base (shaking table) and on the floor of the building. The input is a sinusoidal excitation, but the frequency and amplitude can be controlled by the user. The students use teleoperation tools developed within this project to remotely control the shake table. Streaming video is available, and the students use RDV to view the data and video in real time. In this exercise the students first observe the transient response by examining the motions of a structure during startup of the table. In the second portion of the exercise the students obtain a frequency response function for the SDOF system by measuring the response of the system to a series of sinusoidal inputs at various frequencies. The input of the system is the acceleration of the base, and the output of the system is the acceleration of the floor mass. Using the resulting frequency response function the students are also required to compute damping levels. The students also compare a numerical model to the experimental data.

In the second exercise the students have a multi-degree-of-freedom (MDOF) system. Their objective is to design a vibration absorber for a 2 story building model. The vibration absorber consists of a pendulum that can be adjusted to ‘tune’ it to the natural frequency of the primary system. The mass and length of the pendulum can be varied within a wide range of values (see Figure 5). The students are provided with some information about the building before the lab, and will email their designs (length and mass) to the TA for the course prior to the laboratory time. The TA must set up the pendulum according to their designs so that when they connect remotely, the experiment is available for them. The students are expected to build a numerical model of the system and compare the experimental behavior of the system to the theoretical model.

This Fall (2007) we are working on extending the evaluation plan to assess and improve these exercises. In the near future both of these exercises will be made available on the UCIST website listed in the summary of this paper for downloading.

Overview of K-12 Materials Available

In addition, an Earthquake Engineering Module for K-12 Education has been developed around the use of this shake table lab station. The module contains a series of lessons that have been developed and refined over the course of several years [7,8]. In principle, any of the ‘modules’ could be used as a stand alone, one-time lesson to supplement one specific academic area such as forces and vectors or building fundamentals. Alternatively, the full module could be used as a continuous series of lessons over an 8-10 week period. Supplemental worksheets, learning activities and presentations are included to provide opportunities for active learning. The final lesson involves a design project incorporating all of the materials learned within the module. Teams of students design and construct a balsa wood building. A scorecard is provided for students to encourage them to be creative and yet understand practical issues associated with construction and design. Ideally this module, presented as a whole or individually, will satisfy some of the educational requirements and standards of the K-12 classroom in which it is offered.
Next Steps in Developing and Deploying Experiments

To deploy the shake tables to other sites within the project, documents have been prepared for distribution and feedback to lead the remote deployment sites through the setup process. Subsequently the updated documents will be posted to the UCIST website and made available through the NEES central site for this project. By the end of the summer of 2007 we anticipate all sites being operational. Either the Freshman level module or the senior level exercises will be implemented at most of these deployment sites during the 2007-2008 academic year.

An undergraduate structural design competition will be implemented with the instructional shake tables to engage students in learning more about earthquake engineering and introduce them to the broader earthquake engineering community. Activities such as the well-recognized Steel Bridge and Concrete Canoe competitions by ASCE have long-proven that these types of team-building exercises promote technical interaction and excitement in civil engineering among undergraduates, while stimulating life-long learning in those students that participate in the events. In this spirit, the networked shake tables provide a unique opportunity to engage civil engineering undergraduates by providing students a challenge to innovatively design model structures to withstand strong ground motions.

SUMMARY

The use of emerging technologies such as teleoperation capabilities represents a new and flexible mechanism for educating students. This partnership between UCIST and NEES was developed to engage a broad group of students in learning exercises through the use of teleoperation. Through this partnership with NEES, UCIST is extending its reach to impact students across the US, and potentially around the world. Students at institutions that are not able to acquire shake tables will be able to perform real-time exercises in structural dynamics. The integration of typical sensors used in the real world is also an essential component of such exercises, engaging individuals in the use of modern engineering tools.

Further information about the UCIST, as well as educational modules, lab exercises, teleparticipation and teleoperation tools, and all documentation for these activities will be made available at: http://ucist.cive.wustl.edu/. For more details on how to participate in or partner with this educational collaboratory please contact Prof. Shirley Dyke at sdyke@seas.wustl.edu.

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REFERENCES


