Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1373

TELE-OPERATION SHAKE TABLE EXPERIMENTS IN EARTHQUAKE ENGINEERING FOR UNDERGRADUATE EDUCATION

S. J. Dyke[1], R.E. Christenson,[2] and S. Courter[3]

ABSTRACT

For nearly ten years the University Consortium of Instructional Shake Tables has worked toward improving educational opportunities related to earthquake engineering. More recently, the suite of educational opportunities has expanded to include the use of teleoperation experiments for education at the undergraduate level. Through a partnership with an NSF-sponsored cyberenvironment project referred to as the Network for Earthquake Engineering Simulation (NEES), 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. A collaboratory of teleoperated bench-scale instructional shake table deployment sites has been established. Two initial laboratory exercises have been developed to educate undergraduate students in the fundamentals of earthquake engineering (e.g. structural engineering, structural dynamics). Future plans are also in place to extend and enhance the reach of the collaboratory.

Introduction

The University Consortium of Instructional Shake Tables (UCIST) was developed 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 (Dyke et al., 2002, 2003). This collaborative effort in engineering education, now headquartered at Purdue University (http://engineering.purdue.edu/ucist/), has since expanded to over 100 institutions around the 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, and a wide range of undergraduate research opportunities became available.

[1]Professor, Dept. of Mechanical Engineering, Purdue University, West Lafayette, IN 47907
[2]Assistant Professor, Dept. of Civil Engineering, University of Connecticut, Storrs, CN, 06269
[3]Professor, Dept. of Eng. Prof. Development, University of Wisconsin, Madison, WI, 53706

Through a partnership established in 2006 with the George E. Brown Network for Earthquake Engineering Simulation (NEES), a premier cyberenvironment project funded by the National Science Foundation, UCIST has been expanding its scope to include the use of virtual presence technologies within the experiments developed. We are focusing on 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 (Dyke et al., 2007a-d).

Figure 1. Shake Table Experiment

Students using the teleoperation tools have indicated that they enjoy using this technology for classroom experiments. For instance, one student said "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 someplace else, and actually view it through live streaming video." Another student felt "[It] Was very hands on, and many people learn better by doing and seeing than just calculations." This type of feedback has encouraged us to expand the use of these experiments to reach broader audiences and a variety of students.

Educational Equipment and Teleoperation Implementation

The UCIST equipment consists described here 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 viewing 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 of the UCIST shake table using the NEES cyberinfrastructure was first accomplished by the authors 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 (Dyke et al., 2007a-c). 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.

The components that allow for teleoperation and teleparticipation are illustrated in the diagram shown in Fig. 2, and include:

- 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.

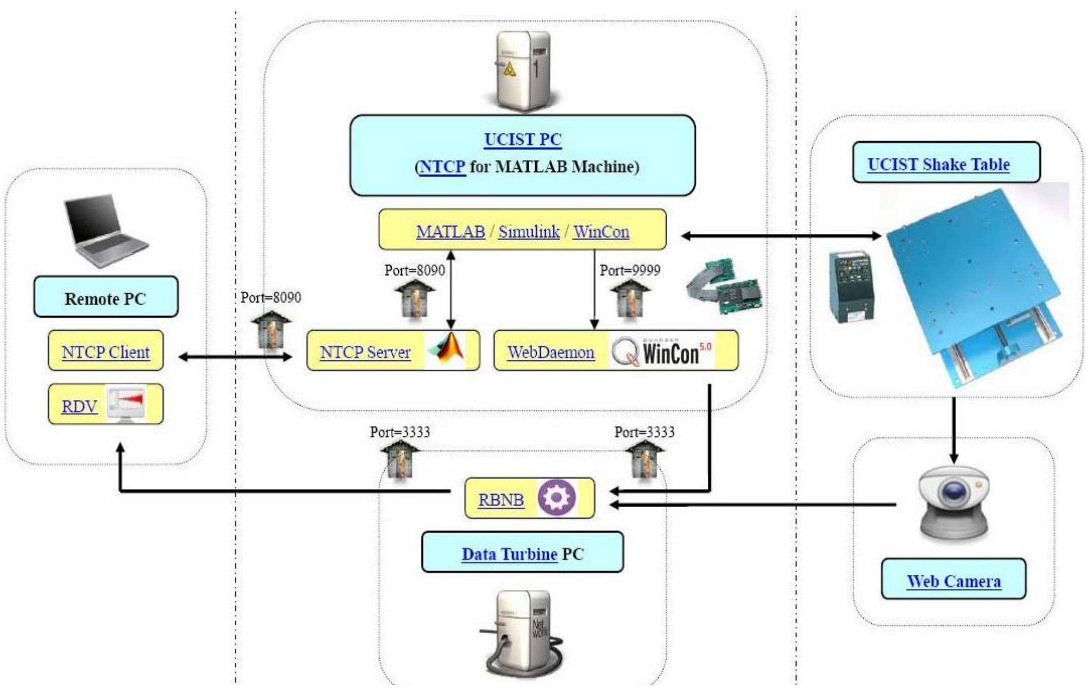

Figure 2. Diagram of the Teleperation Implementation Using NEES tools.

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) is shown in Fig. 3. A Java applet serves as the NTCP Client graphical user interface (GUI) located in the upper right corner of the RDV, and provides remote users a direct means to control the experiment by adjusting the frequency and amplitude of the sinusoidal excitation and pressing start. Several other applets have been developed for various experiments and purposes, including running earthquakes, swept sine waves and

Instructional Materials Developed to Date

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. Most of the modules contain 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.

Freshman Level Introduction to Earthquake Engineering Module

A freshman level module was developed which 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 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 in St. Louis (Dyke et al., 2007b-c).

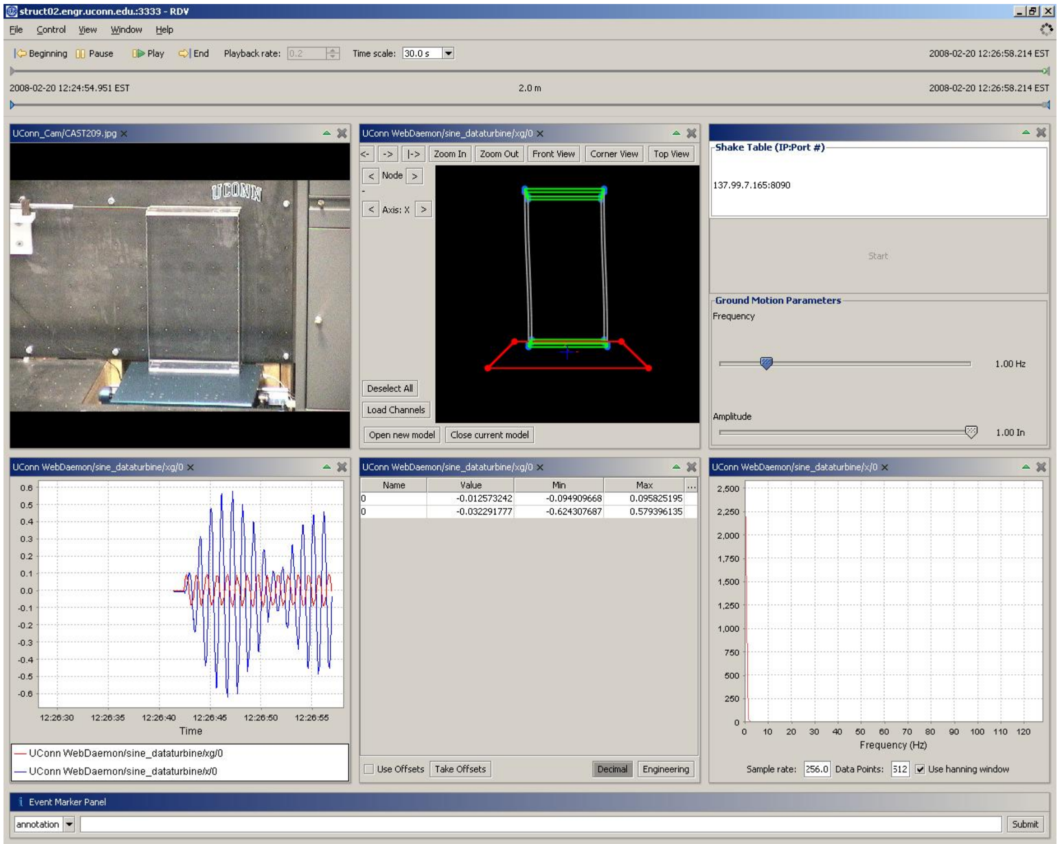

Figure 3. Real-time Data Viewer Connected to the University of Connecticut Deployment Site.

Senior Level Design Exercises

Two additional exercises have been developed for integration into a senior level structural dynamics and vibrations course. These were implemented in the Fall of 2007 and 2008 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 sinusioidal 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 sinuisiodal 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 4). 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.

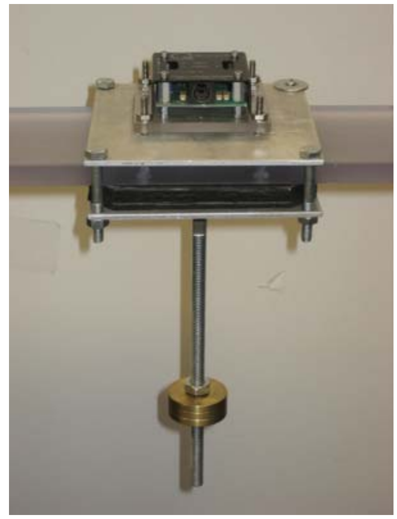

Figure 4. Vibration Absorber for Senior Level Exercise.

Webinar for Engaging Faculty in Instruction Using Teleoperation

On August 31, 2009 a webinar entitled "Learning and Teaching Using Teleoperated Shake Tables" was held with support from NEESinc and NEESit. This event was designed to engage faculty in the use of these shake tables for instruction. Approximately thirty individuals attended this online workshop, which is archived at https://www.nees.org/news/webcasts/. The workshop focused on the experiments and teaching modules developed, as well as the evaluation outcomes from these exercises. At the end of the webinar we had a question/answer session, followed by an offer from the project team to make the teleoperated shake tables available to faculty across the country for use in their classroom in the 2009-2010 academic year.

Future Plans

Our vision with the teleoperation experiments 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 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.

The operation and management of the NEES network has recently been relocated to Purdue University under the name NEEScomm. One of Purdue's strengths in information technology is in the development of hub technology, allowing the user to utilize simulation tools through a web portal without necessarily installing or supporting the software locally. NEEScomm is moving toward integrating education, outreach and training efforts of the NEES network into NEEShub, and will be generating what will be called the NEES Academy.

Through the partnership of NEES and UCIST, the teleoperation tools for the shake table developed by UCIST are being incorporated into NEEShub. A prototype of this implementation has been developed and shown in Fig. 5. Although this tool is not publically available yet, it offers a number of options for usage of the shake tables in the future by a wide variety of students.

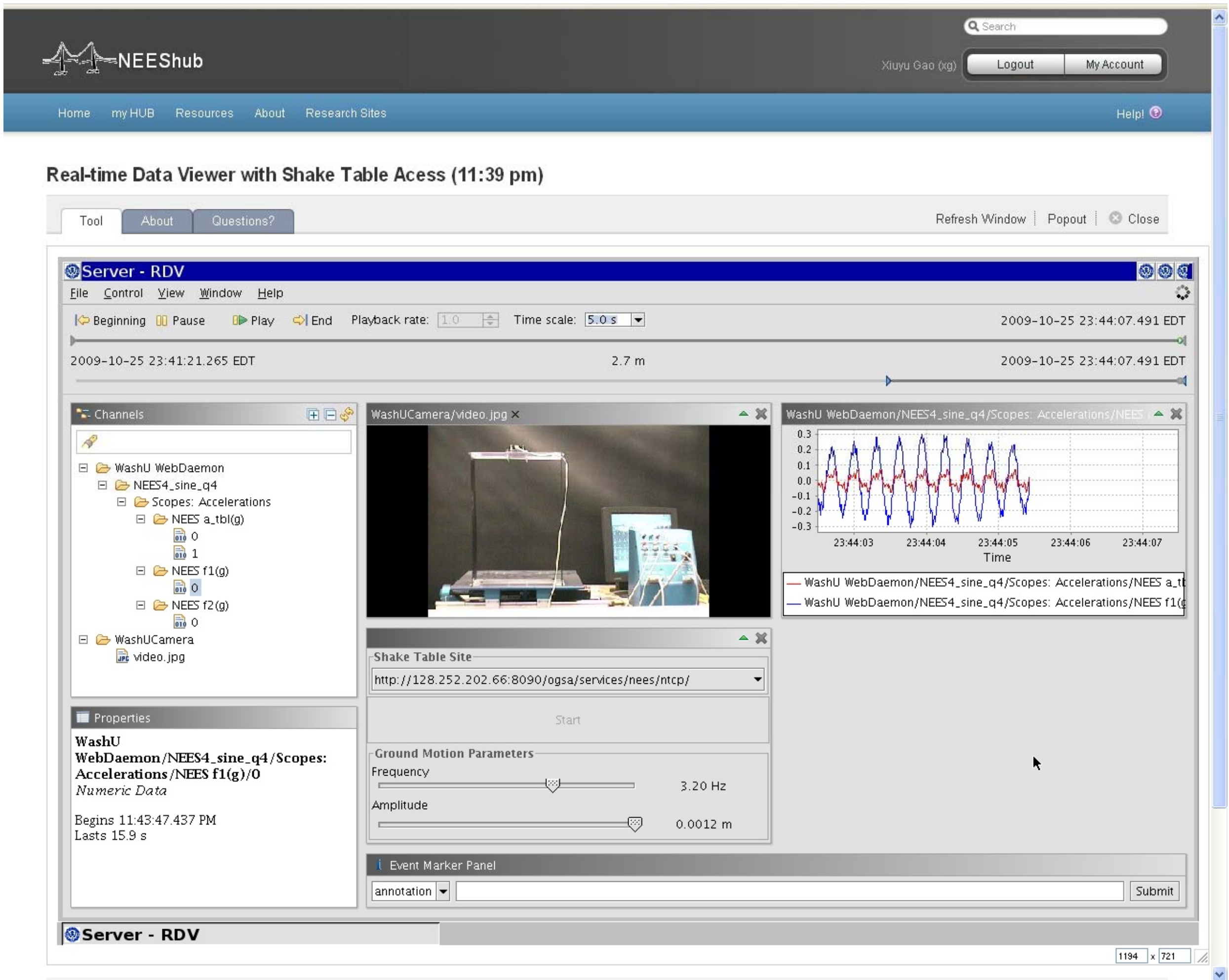

Figure 5. NEEShub Implementation of Teleoperated Shake Tables.

We are planning other opportunities to explore the use of these teleoperated shake tables for education. For instance, prepared videos about the experiments might be created for faculty to use to engage students in experiments or to use with large classes. Interactive exercises within the NEEShub framework culminating in the use of a teleoperated shake table learning experience would be attractive as materials to supplement course lectures. Additionally, faculty development activities will be expanded, engaging participants through the NEES Annual Meeting to prepare faculty in the use of these experiments. We also anticipate formalizing some of the additional educational exercises that have been developed around the use of the shake tables. Undergraduate researchers will also be engaged in the summer NEES REU program for research and development activities.

Summary

The use of modern internet capabilities such as teleoperation represents an exciting new alternative in the education of our students. Students at institutions without shake tables will be able to perform real-time exercises in structural dynamics and earthquake engineering. 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. A partnership between UCIST and NEES was developed to engage a broad group of students in learning exercises through the use of teleoperation. Faculty guidance in the use of such tools is available. Through this partnership, UCIST is extending its reach to impact students across the US, and potentially around the world.

Further information about the UCIST, as well as all of the educational modules are available at: http://engineering.purdue.edu/ucist/. For more details on how to participate in or partner with this educational collaboratory please contact Prof. Shirley Dyke at sdyke@purdue.edu.

Acknowledgments

Partial support for this project is provided by the National Science Foundation, DUE 0618605. Support for original development of the UCIST was provided by the NSF, DUE 9950340. The assistance of NEESit and NEEScomm staff is also appreciated. All of this support is gratefully acknowledged.

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