Interactive Remote Shake Table Laboratory for Instruction in Earthquake Engineering

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Abstract

Bench-scale shake table is an engaging tool to conduct hands-on experiments for educating students about the importance of earthquake engineering by demonstrating how structures respond to earthquake ground motions. Through these hands-on experiments, students may easily build or modify scaled structural models to test theories and implement their own innovations to examine how these structures behave. A collaborative effort was initiated in 1998 to establish the University of Consortium of Instruction Shake Table (UCIST) which endeavored to enhance the education of students through the procurement of instructional bench-scale shake tables, the development of curricula, and the dissemination of these tools to other institutions. Partnered with a former NSF-sponsored premier cyberenvironment project, the George E. Brown Network for Earthquake Engineering Simulation (NEES), UCIST developed a shake table laboratory, which allows the remote control and participation of the shake table for hands-on experiments. In this study, a modified version of the remote shake table laboratory which adopted the more widely used Transmission Control Protocol/Internet Protocol (TCP/IP) as the communication protocol is developed. The modification allows a much more user-friendly set up process and opens up opportunities to connect the shake tables with modern mobile devices such as smartphones, tablets and wearable devices for potential control and participation of the shake table experiments. Thanks to the versatility of the TCP/IP, a mobile remote shake table laboratory is further proposed to meet the learning style of the new generation. In this paper, the developed interactive remote shake table laboratories will be discussed in detail and a corresponding teaching module for the proposed mobile shake table laboratory is demonstrated.

Introduction

History frequently reminds us how destructive earthquakes can be. For example, the Loma Prieta earthquake (magnitude 6.9) in 1989 caused an estimated $6 billion in property damage and took away 63 human lives. The Northridge earthquake (magnitude 6.7) in 1994 brought an estimated of $20 billion property damage and claimed the lives of 57 people with more than 5,000 injured. To design and build safer and more sustainable structures for the future, it is essential to educate the younger generations to better understand earthquakes and study the responses of structures under such an extreme loading. A good environment for engineering learning is created when a course incorporates theory, practical applications, and hands-on experiments. Lack of theory severely limits the ability to practicing engineers by the inability to organize facts and use them in new circumstances; without practical applications, on the other hand, theory has little meaning and value to practicing engineers. Hands-on experiments are an effective means to consolidate the theory and provide insight to challenges in practical applications. Bench-scale shake table is an engaging tool to conduct hands-on experiments on physical structures using modern instrumentation (e.g. sensors and data acquisition system) and educate students about the importance of earthquake engineering and how structures respond to earthquake ground motions. Through these hands-on experiments, students may easily build or modify scaled models to test the theories and implement their own innovations to examine how structure behaves.
The University Consortium of Instructional Shake Tables (UCIST) was developed in 1998\textsuperscript{3-4} and aimed at enhancing undergraduate and graduate education in earthquake engineering by using the bench-scale shake table. It was originally a consortium of 23 universities associated with the three U.S. national earthquake-engineering centers, namely the Pacific Earthquake Engineering Research Center (PEER), the Multidisciplinary Center for Earthquake Engineering Research (MCEER), and the Mid-America Earthquake Center (MAE), and had expanded to include over 100 institutions. Even in those universities that have the shake tables, the instrument may not be available to students due to many restrictive factors such as room capacity, testing schedule, accessibility of the facility, and safety considerations. In a later effort, UCIST partnered with the George E. Brown Network for Earthquake Engineering Simulation (NEES), a former premier cyberenvironment project funded by the NSF, to develop a collaboratory of bench-scale earthquake engineering facilities available for remote participation (teleparticipation) and operation (teleoperation) of the shake table via the internet.\textsuperscript{3-4} These capabilities have been incorporated into formal laboratory exercises in which most students agreed or strongly agreed that the shake tables improved their understanding of earthquake engineering, structural dynamics and structural vibrations.\textsuperscript{5}

As part of the original development team, the author had first-hand experience of setting up the remote shake table system. Although the system showed great potential in engineering education, the configuration process can be a difficult task to educators without in-depth programming background. Especially, the installation of a critical component, the NEESGrid Teleoperations Control Protocol (NTCP) server, which was used to receive remote control commands from the end users, required detailed case by case guidance. Furthermore, the recent replacement of NEES by the Natural Hazards Engineering Research Infrastructure (NHERI) program makes the installation of NTCP server nearly impossible due to the lack of technical support and the incompatibility of the necessary software to newer operating systems. To continue UCIST’s efforts on offering the state-of-the-art laboratory experiences to students and facilitating the national dissemination of remote shake table laboratory (RSTLab) experiments, modified versions of the RSTLab, which have adopted the more widely used Transmission Control Protocol/Internet Protocol (TCP/IP) as the communication protocol, are developed in San Francisco State University (SFSU). The TCP is a core protocol of the Internet protocol suite. It originated in initial network implementation in which it complemented the Internet Protocol (IP). Therefore, the entire suite is commonly referred to as TCP/IP.\textsuperscript{6} TCP/IP is one of the most prevalent communication protocols that major Internet applications such as the World Wide Web, email, remote administration and file transfer rely on. Replacing the obsolete NTCP with the TCP/IP will allow a much more user-friendly set up process and open up opportunities to connect the shake tables with modern smart portable devices such as smartphones, tablets and wearable devices for potential control and participation of the shake table experiments.

The layout of the paper is as follows. The architecture and system components of the modified RSTLab are first described. Secondly, a newly developed RSTLab allowing the use of mobile devices to meet the younger generations’ learning style is introduced, after which a teaching module utilizing the mobile RSTLab is shown as an example. Lastly, the paper will be closed with conclusions and future development plans.
System Components of RSTLab

The schematic of the RSTLab that allows for teleoperation and teleparticipation through TCP/IP is shown Figure 1.

Figure 1 Schematic of the Modified RSTLab

The main component of this remote laboratory is the Quanser Shake Table II. The Shake Table II consists of a 46 x 46 cm top stage driven by a 400W high-powered 3-phase brushless DC ball-screw motor, allowing it to achieve an operating frequency of 0 – 20 Hz, a +/- 7.6 cm stroke and a peak acceleration +/- 1 g with a payload of 11.3 kg. The Shake Table II interfaces with a Control PC through the Quanser Q4/Q8 data acquisition board and is controlled through Quanser QUARC real-time control software. Besides the control of the shake table, the Control PC is also used to host the TCP/IP server to receive the control commands from remote end users and stream the measured data to the DataTurbine (DT) program through the NEES Daemon program for teleparticipation. The open source DT program, running on the Data Turbine PC, is provided by Open Source DataTurbine Initiative.

Accelerometers mounted on the Shake Table II and the structural models are available to measure the responses of the top stage and the structures. An Axis 214 PTZ network camera is used to capture the view of the experiments. The collected data and video will then be streamed in real-time to the DT program for synchronization and prepared for remote users to access. The synchronous video and data can be viewed by any computer over the Internet with the NEES Real-time Data Viewer (RDV). Developed as part of the NEES cyberenvironment project, RDV provides an interface for viewing and analyzing live or archived data and video either locally or across a network from the Data Turbine PC. The playback rate can be adjusted so that data and video are presented slower or faster than real time to aid in analysis. Besides the data and video, RDV is also capable of displaying numeric, textual, still images, 3D visualization and spectrum analysis results. Individuals can develop new panels according to their needs, thanks to the open source initiative. As an example, a customized remote control panel has been developed to send control commands to the Control PC for teleparticipation. The RDV connecting to the Data
Turbine in SFSU is shown in Figure 2.

The RSTLab set up at SFSU is shown in Figure 3. Strong floor and strong wall with equal spacing connection screws are designed within the shake table stand to allow for flexible mounting of specimens and sensors. To support the two shake tables at SFSU running simultaneously or individually, two side by side shake table placement slots are incorporated in the design. The modified RSTLab is compatible with the educational modules developed by UCIST. These modules range from introduction level to advanced level and from K-12 learning to graduate courses (available for download at https://nees.org/resources/929). With Quanser shake tables existing around the world, the authors hope that the user-friendly installation process will facilitate the adoption of the RSTLab and promote further development of the corresponding teaching modules, thus better educating students on earthquake engineering. The detailed instruction and necessary installation files for the modified RSTLab will be available online and free to download at http://sfsuslab.org/RemoteST/ in Fall 2016.
Mobile RSTLab

Learning style changes from generation to generation. Gioia and Brass\textsuperscript{7} in 1985 noted that the college students being taught then were a “TV Generation”, who were raised in an environment dominated by visual images. In early 2000, the new “Virtual Generation” appeared with the prevalent virtual media such as Internet and videogames\textsuperscript{8}. The current and incoming tech-savvy learners grow up with the digital world. The advancement of technologies makes learning more accessible. Mobile learning has become a commonly accepted and embraced concept among the younger generations.\textsuperscript{9} Keegan anticipated that mobile learning would become a harbinger of the future of learning\textsuperscript{10}. Effective learning occurs when the teaching styles align well with the learning styles.\textsuperscript{10} The versatility of the TCP/IP makes the teleoperation and teleparticipation of the shake table experiments through mobile apps feasible, which provides a unique opportunity to incorporate the RSTLab into mobile learning. Through a recent partnership with the world leading educational equipment provider, Quanser, the authors gained access to its new mobile development platform qdex. Qdex offers the fastest and easiest way to transform conventional static training documents into highly interactive, concept-rich knowledge apps that fully exploit the convenient and powerful mobile devices (http://qdexapps.com). A mobile knowledge app has been developed at SFSU using qdex to remotely conduct shake table experiments. This app allows users to send different control commands to the shake table and receive sensor measurements in real-time through TCP/IP. Screenshots of the typical control interface of the app for sine wave, sine sweep and earthquake inputs are shown in Figure 4. By pressing the different input signal buttons, corresponding control elements (e.g. sliders and toggles) associated with the input signal chosen will be displayed which allow users to interact with the app and customize the control signal to be sent.
After the user selects the desired input and presses the send button, the control commands will be sent to the Control PC and the app will prompt the users to the data viewer page to display the sensor measurements automatically in real-time. Screenshots of the data viewer page for different excitation frequencies, $\omega$, vs structural natural frequency, $\omega_n$, are shown in Figure 5.

Figure 4. Typical Mobile Shake Table Control Panel

Figure 5. Data Viewer
The RSTLab allows students to participate and conduct shake table experiments without the need of being physically present in the laboratory. However, as other virtual laboratories, it is “virtual” and focuses on the experiment already set up. To actively engage students and provide them a real sense of presence and participation, we attempt to incorporate a telepresence robot into the mobile RSTLab. The telepresence robot, Double, is built by a technology startup company, Double Robotics (http://www.doublerobotics.com). It is a remote-controlled robot stand that works together with an Apple iPad to provide real-time control and communication. Through an app in a mobile device, users can remotely control the Double to move around and communicate interactively with its surroundings in real-time. By adopting the Double, students will be able to interact with the lab assistant to set up the experiment, move around to observe the physical testing from different places and angles, and even modify the set up on the fly (with the help of the lab assistant), as being actually present in the laboratory. The schematic of the mobile RSTLab with the telepresence robot is shown in Figure 6. Through the mobile RSTLab, an experiment can be initiated from a few clicks on the user’s mobile device. The TCP/IP control signals will then be passed to the TCP/IP MATLAB server set up in the Control PC, which will be directed to control the Quanser Shake Table II through the QUARC real-time control software. In the meanwhile, the sensor measurements will be streamed back to the mobile devices using TCP/IP. Before, during and after the experiments, users can use the telepresence robot to move around and interact with the surrounding.

Figure 6 Schematic of the Mobile RSTLab with Telepresence Robot

From the surveys conducted on the users of the UCIST remote shake table system, it clearly demonstrated how important the robustness of the system is for a good user experience. System malfunctions frustrate students as well as the instructor and limit the learning experience. To build a safeguard for unforeseen system breakdown, Belkin WeMo remote power controls are
used to enable the remote powering on/off the Control PC and Shake Table II. If an unexpected break down occurs, a hard reboot can be launched by the administrator of the laboratory from a few clicks through the WeMo app on a mobile device, after which the whole RSTLab system will be reloaded automatically and be back online after a few minutes. In addition to the unexpected system break down, it is always a challenge to enforce the allowable time for each remote user and ensure that only one user is controlling the shake table at a time. Taking advantage of the powerful qdex mobile platform, it is a relatively simple task to incorporate a booking system where the user will be assigned with a unique access code according to the time slot reserved on the booking system. The user will be allowed to control the shake table only when the correct access code is entered during the reserved time. The developed booking system, a typical email with the access code and the interface allowing users to input the access code are shown in Figure 7.

This implementation prevents multiple inputs that could potentially confuse and crash the remote shake table system. The detailed instructions and necessary installation files for the mobile RSTLab will be available for download at http://sfsuslab.org/RemoteST/ in Fall 2016.

**Teaching Module**

Several teaching modules are being developed for the mobile RSTLab. A teaching module designed for an undergraduate upper division class, Mechanical and Structural Vibration, at SFSU is shown here as an example. This teaching module is built upon a successful educational module: The SDOF System: Obtaining the Frequency Response Function by Dyke and Gao. The developed module as well as the mobile RSTLab will be implemented in Fall 2016.
In this teaching module, a single degree of freedom (SDOF) structure together with the mobile RSTLab will be used to help students better understand the important concepts in earthquake engineering, such as natural frequency, equation of motion, and transfer function. The module will be divided into three sections, namely numerical analysis, simulation and experiment. All the three sections will be realized in a mobile knowledge app. The post-processing of the data will be accomplished in MathWorks MATLAB. In the numerical analysis section, students will be prompted to a SDOF structure after the introduction of the module. The dimensions and material properties of the different structural components will be displayed when clicking on each component of the SDOF structure. The students are expected to calculate the natural frequency of the structure after figuring out the mass and stiffness of the structure using the provided dimension and material information. Experimental data of the free vibration time history of the SDOF is provided to the students to calculate the damping of the system through the use of the half-power bandwidth method. By using the obtained mass, stiffness and damping, students will be taught to derive the transfer function of the system using Laplace Transform. In the simulation section, students will be able to interact with the app and observe the different responses of the structure under sinusoidal ground motions at various excitation frequencies. The simulation results will be verified in the experiment section by conducting shake table experiments through the mobile RSTLab. In the experiment, the same SDOF structure will be placed on the shake table. Students will be able to select the desired excitation frequency of the sinusoidal excitations and verify the observations from the simulation section. After the sinusoidal excitations at specific frequencies, the students will be asked to send in a sine sweep signal with amplitude of 0.02 cm and operation frequencies ranging from 0 – 15 Hz. The sensor measurements from the mass of the structure and from the top stage of the shake table will be streamed back to the students’ mobile device. Students can choose to save the data on the device or send it to a specified email address for post-processing. Once the data is saved, the students can follow the instruction on the mobile devices to perform frequency response analyses on the input (sensor measurement from the top stage) and output (sensor measurement from the mass of the structure) of the system to obtain the natural frequency of the structure and its transfer function by curvefitting the data in MATLAB. The experimental natural frequency and transfer function will then be compared to those obtained from the numerical analysis section. Explanations are expected on the differences that might be observed. A flowchart of the teaching module is shown in Figure 7 to provide a big picture of the module.
The students are required to submit a formal report on this project. The report should contain typical sections such as abstract, introduction, numerical analysis, simulation, experiment, conclusions, and references. The required outcomes for the numerical analysis, simulation, and experiment sections are shown as following.

**Numerical Analysis Section**
- SDOF system schematic diagram and dimensions
- Mass, stiffness and damping calculations
- Equation of motion of the system
- Natural frequency calculation

**Simulation Section**
- Screenshots of the responses of the SDOF system under representative sinusoidal inputs with various exciting frequencies

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Figure 7 Flowchart of the Teaching Module for Mechanical and Structural Vibration
Experiment Section
• Descriptions on the experimental setup (e.g. sensor type, sensor locations, and data acquisition system)
• Plots of the responses of the SDOF at the same sinusoidal inputs as those in simulations
• Plots on the frequency response analyses results
• Plots on the curvefit results
• Comparisons between the numerical and experimental results
• Possible explanations on the differences that might be observed

The objectives of this teaching module are listed as following.
• To illustrate the concept of natural frequency and its effects on the responses of the structure
• To compute and analyze the structural natural frequency and damping numerically and experimentally
• To identify basic operation principles of the sensor (accelerometer) and the data acquisition system
• To participate and operate the shake table experiment through the mobile RSTLab
• To compute and analyze the system transfer function numerically and experimentally

The developed teaching modules for mobile RSTLab will be available for download at http://sfsuslab.org/RemoteST/ in Fall 2016.

Conclusions and Future Work
In this paper, a modified RSTLab which replaced the obsolete NTCP server with the widely used TCP/IP as communication protocol for teleoperation and teleparticipation is described in detail. With the Quanser shake tables existing around the world, the authors hope that the user-friendly installation process will facilitate the adoption of the RSTLab and promote further development of the corresponding teaching modules, thus better educating students on earthquake engineering by offering them the state-of-the-art shake table laboratory experiences.

Thanks to the versatility of the TCP/IP, a mobile RSTLab is further proposed to meet the learning style of the new generations. A telepresence robot is adopted to integrate with the mobile RSTLab to actively engage students and provide them a real sense of in-person participation without the need of being physically present in the laboratory. Remote mobile power control and online booking system are also added to the RSTLab system to build a safeguard for the unforeseen system breakdown and increase system robustness. A teaching module designed for an undergraduate upper division class at SFSU is used to showcase the mobile RSTLab. The teaching module as well as the mobile RSTLab described in the paper will be implemented in Fall 2016 and the robustness of the system will be investigated. Surveys will be conducted in the same course with and without adopting the mobile RSTLab to examine the effectiveness and influence of the mobile RSTLab in student learning.

Looking forward towards future development, more teaching modules utilizing the newly developed mobile RSTLab are underway. The possibility of using the mobile remote laboratory for flipped classroom and fully online course will also be investigated.
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References