Remote Observation and Control of a Shake Table Experiment

Vernon C. Matzen, Scott Wirgau, and Abhinav Gupta

Professor of Civil Engineering and Director, Center for Nuclear Power Plant Structures, Equipment and Piping, North Carolina State University/ Graduate Student, North Carolina State University/Assistant Professor of Civil Engineering, North Carolina State University

Abstract

Laboratory experiences, i.e. visualization of material covered in class and hands-on use of equipment, are especially advantageous to engineering classes such as structural mechanics. Unfortunately, it can sometimes be difficult for on-campus students to be given sufficient laboratory time and it may be impossible for those already using distance education due to work, disabilities, or other complexities. The project describes a shake table experiment that is being converted to a distance-learning environment. This will include remote access, control, and protection from misuse. An aspect of the project that differentiates it from simple remote viewing of a lecture or experiment is the ability to control the experiment and to protect against the possibility of damage occurring to this particular setup if left unmonitored. This last point necessitates the inclusion of sufficient safety protocols. The environment must allow remote controlling of the system, multi-user viewing, data saving, and download capabilities. The technology selected for use in this project is the LabVIEW programming environment in conjunction with its real time counterpart, LabVIEW RT. By using this language, practical and intuitive control panels coupled with easy to follow data flow block diagrams are made possible. The LabVIEW code likewise handles the data acquisition. The setup in this project connects the host computer to a DAQ accessory device by way of a PXI card, which combines the PCI bus with integrated timing and triggering. The information sent and received through the DAQ card is processed by LabVIEW code embedded in the real time processor. The information is then sent to the host Windows 2000 processor for saving, visualization, and distribution to remote clients. This visualization includes an oscilloscope displaying the accelerations from both the table and the structure residing on the table. Further visualization will be made by way of a video camera. Finally, the code must be made safe from unauthorized usage and the university network must be protected. This paper outlines the implementation of the project using the vibration experiment.

Introduction

Use of laboratory equipment is essential in allowing students to visualize and better understand the concepts taught in classes such as structural mechanics. In a conventional classroom setting it can be hard for students to grasp the actual material or structural behaviors being described.

Unfortunately it is often impractical for each student to be taken to a lab setting and shown examples. However, through the use of a distance-learning lab, these concepts can be conveyed while students remain in the classroom. The educational opportunities of such a lab are great. The following sections will illustrate the educational benefits of such a lab devoted to a structural mechanics shake table experiment as well as describe previous work regarding similar distance-learning laboratories.

Overview of Recent Work

Many universities in the US and abroad have already seen the importance of distance learning associated with their classes. However only a few have done similar work with experimentation. These examples, including those in a research setting, provide a useful insight into the application of a remote site solution towards the shake table experiment.

Remote research collaboratories have been developed to accelerate research and share resources. These collaboratories allow for groups to use equipment that was previously inaccessible. The Network for Earthquake Engineering Simulation (NEES)[1] is one of the most prominent in the structural field. The NEESgrid associates with both the earthquake engineering research community and the information technology community. Most of the engineers involved are structural, geotechnical, and tsunami researchers, and they reside at participating universities across the USA. This group's objectives include setting up "collaborative capabilities [that] will allow analysts and experimentalists to work together in ways that were not previously possible. Tele-observation, data streaming and video streaming will provide access to data, access to state-of-the-art equipment, and the capability to cooperate across distance and time[1]." The shake table experiment is one of the experiments that the NEESgrid is addressing. Additionally, NEES is doing work on supporting hybrid experiments combining elements of the shake table experiment with centrifuge, tsunami wave basin, and reaction wall experiments. Their success dependencies are outlined as:

- Productive communications environment for collaboration
- Acquisition, management and visualization of massive amounts of digital, video, photo, and numeric data
- Reliable distribution of real-time data
- Synthesis, analysis, management, mining, dissemination and findings from various experiments and comparisons.

The research outlined in this paper has the same initial three goals but places the highest importance on developing educational abilities. These abilities include the expansion of benefits gained from laboratory experience to a larger audience. Such benefits include hands on experience, better visualization, and practical knowledge towards applications. Most of the NEES related research is ongoing at the time that this paper is being written. SUNY Buffalo and the University of Nevada at Reno are both working on research that will allow remote access to shake table experimentation[1,2]. However, as implied earlier, the NEESgrid differs from the research addressed by this paper in that distance learning and education applications are not a goal of that project.

Southern Illinois University has also done research involving remote testing of a scale model building attached to a shake table simulating earthquake excitation. This is similar to the shear building model in the shake table experiment focused on in this paper. One similarity lies in the need for inputting varying waveforms, frequencies, and amplitudes[3]. However, the research done at Southern Illinois is different from that being done in this study, as it did not address remote control. Once the input values were set, remote viewing and analysis were the only objectives. Changes to the inputs were not needed. "The Web pages created allowed students and interested engineers to remotely access the website and learn by watching the 3D graphics model[2]."

Educational Value

Converting our conventional teaching laboratory into a distance-learning lab will result in significantly increased educational value. Not only will the quality of learning for present students be increased by this change, but also the number of students reached, and the diversity of this group, will be enhanced. Through distance learning, non-traditional students such as underrepresented minorities, working parents, part-time students, students with disabilities, and career changing adults could all benefit from the exercises.

Learning and retention of lecture material can be improved through allowing active participation by the students. The use of observation, control, and analysis of experiments are each beneficial towards increased learning and can be used in conjunction with or as an alternative to passive listening and reading exercises. In fact, some studies have shown that students do more critical thinking in their online exchanges than in face-to-face classroom discussion[4]. By using a distance learning laboratory students will gain hands on experience while the need for an instructor is optional. Outside of the classroom environment, students will still have the opportunity to view and study the procedure. Furthermore, they will have the ability to actually control the shake table giving them hands on knowledge of vibration experimentation.

This type of implementation holds additional appeal for non-traditional students. By placing courses online, students no longer need to commute to a campus. This can save both time and monetary resources, thus opening the door for those who otherwise would not be able to gain further education. Those with physical disabilities would benefit from the same factors. Lessons and experiments could be accessed from their own homes.

The development of collaboratories mentioned earlier also has educational value. The use of a remotely operated structures lab would allow stimulated development of shared resources between other institutions and colleges. Students at community colleges and smaller schools would have an opportunity to use equipment previously inaccessible to them.

Present Lab Setup and Procedure

The first stage of the implementation process shown in figure 1 is observation of the present lab setup. The Structural Behavior Measurements Laboratory at NC State University, which is used for undergraduate studies, contains, among other facilities, a small, one-dimensional table with a 50 lb. electromagnetic shaker as depicted in figure 2. The primary use of this equipment is for introductory dynamics exercises in the lab. The "Free and Forced Vibrations of a Single Story Shear Building" lab acquaints students with concepts in the theory of vibrations and requires them to determine the natural frequency and damping ratio of a shear building. The shear building has two thin columns supporting a steel girder. It is then bolted to the shake table and accelerometers are connected to both the girder and the table. These, in turn, are connected through use of a DAQ accessory and desktop computer system to display software running

National Instrument's Virtual Bench software[5]. Currently, a function generator is used to produce the desired excitation.

The procedure for this experiment can be generalized into four steps:

- Theoretical calculations
- Static testing
- Free vibration testing
- Forced vibration testing

The theoretical calculations step necessitates weighing of the girder assembly and obtaining geometric properties. These properties are then used with known dynamic equations to find the stiffness, period, and frequency.

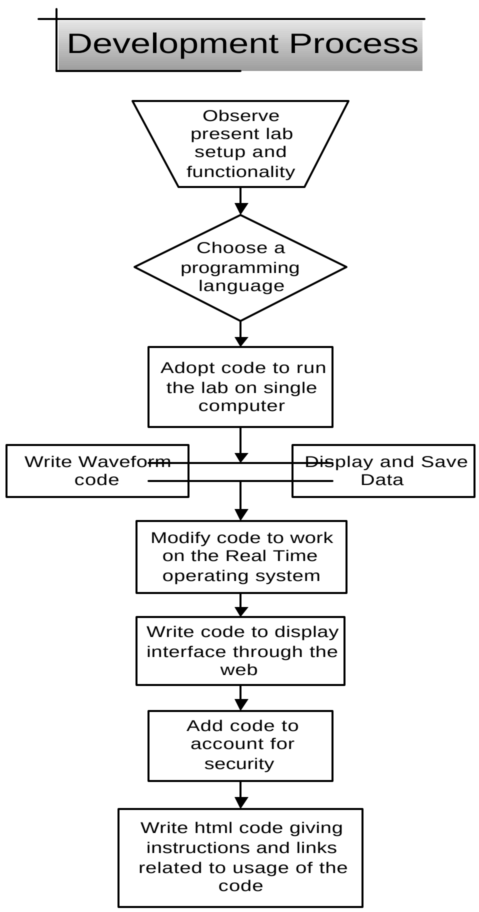

Figure 1 – Flowchart for the implementation process.

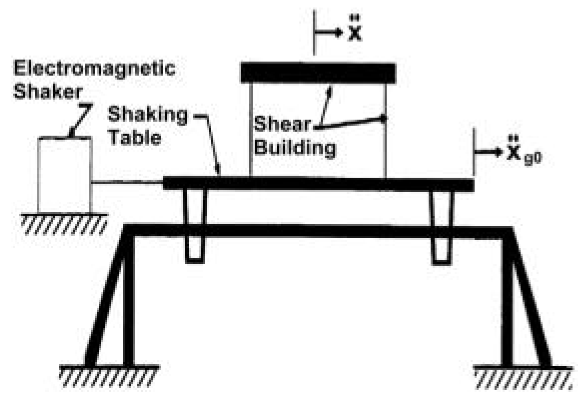

Figure 2 – Diagram of the shake table setup.

For the static testing portion of the lab, the shear building is bolted vertically to a stiff column. An LVDT is then calibrated and set up to measure vertical displacement of the girder. Initial voltages are read and weights are added incrementally to the girder and then removed in the same increments. Voltage readings are recorded at each increment. By plotting the aforementioned data as load versus displacement, the slope can be used to find the static stiffness. Values for stiffness, period, and frequency are found. These lab values are compared with the theoretical values previously calculated.

In the free vibration-testing phase, the LVDT is removed and the structure is excited by applying an initial displacement. An oscilloscope is used to obtain the period and the damping ratio. All three sets of data are then compared.

Lastly, the shear building is placed on the shake table and excited at various frequencies. At resonance, the period of excitation and the maximum accelerometer voltages of the structure and table are recorded. These data then allow the natural frequency and damping ratio to be calculated. By comparing the various sets of results, the students are exposed to differences between the various lab techniques.

Overview of Improved Lab Setup with Distance Learning Support

In order to make the shake table lab ready for a distance-learning environment, certain additional pieces of hardware were necessary. The first was a computer with a real-time processor and a Windows operating system. Here, real-time is in reference to actions taking place in a deterministic manner where code is executed in predictable time intervals as opposed to with a Windows operating system where timing is unpredictable. In addition, the real-time hardware allows code to be downloaded to and embedded upon an independent hardware target with a real-time operating system. Each hardware target has a dedicated processor running a real time operating system independently from Windows[6]. Any Windows related difficulties or even a Windows reboot would have no negative consequences associated with the equipment. A Windows 2000, 1.26 Gigahertz Pentium III system with a real-time PXI card from National Instruments was used in this research. An E series DAQ card capable of analog to digital and digital to analog conversions was also required along with LabVEIW 6.1 and a web camera. This system allows the shake table excitation signal to be generated by LabVIEW rather than by a function generator. By embedding this code onto the real-time board, the mouse and keyboard interface are able to take the user commands and send a signal out of the PXI card into the E-series DAQ device. This in turn sends the desired waveform to the shake table. Accelerometers attached to a power source and to the shake table then send data back to the analog input channels on the DAQ board. Future steps will allow viewing via a camera set up that can be connected to Microsoft Netmeeting software embedded in the html code.

Most of the activities mentioned in the previous section are attainable with the current setup. Notes and instructions will be placed on the web so that the theoretical calculations may be evaluated and so that each control on the graphical user interface is understood. The forced vibration phase is also implemented using this setup. LabVIEW and the World Wide Web are used to allow students to request control of the experiment and run the test with variable waveforms. The web camera and Netmeeting software will let the remote user view the experiment and sketch the lab setup.

LabVIEW and the Real-Time Board

In order to convert the existing lab into a suitable environment for distance learning, a medium for control of the equipment was needed. As outlined in figure 2, this necessitated the choice of a programming language. LabVIEW was chosen because it allows for a high level of control and flexibility.

Like C, C++, and Java, LabVIEW is a programming language. However, lines of code are not used. Instead, graphics and logic diagrams are used with programming objects such as loops to produce the desired results. An example code can be seen in figure 3. Due to these differences compared to a more traditional programming language, LabVIEW is referred to as a graphical programming language, or "g" programming. LabVIEW provides a more intuitive environment for creating controls due to the ability to drop dials, switches, buttons, etc. directly onto the LabVIEW front panel. These front panels are used as the user interface. Two front panels are shown in figures 5 and 7. This functionality allows an easy-to-use, professional looking interface to be quickly constructed. The programs produced are called virtual instruments or vi's. Vi's are portable between system architectures such as PC, Mac, or Sun. The aforementioned graphical user interface and its intuitiveness along with the ability to program many different instruments are other reasons for using the g programming system.

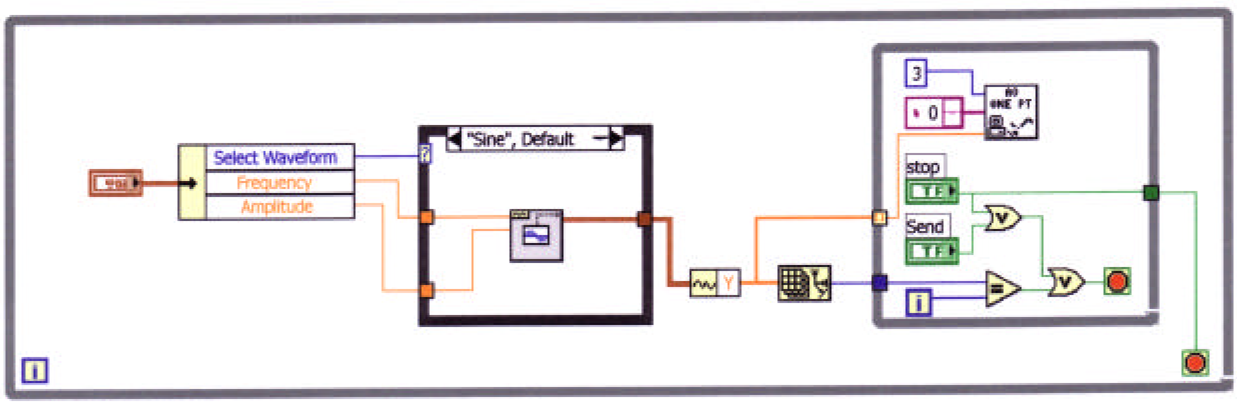

Figure 3 – Example LabVIEW code for a remote front panel waveform generation solution.

LabVIEW 6.1 has a built in web server that allows for ease of placing vi's onto the web. With this ability, it was easy to see and set up tests for remote controlling of various experiments throughout the development process.

The real-time PXI board and accompanying real-time vi's were also a good match for this research. The PXI board combines the high-speed PCI bus and integrated timing and triggering in order to provide improved performance when compared to older setups[7]. The real-time architecture is necessary so that reliable timing and updating will take place. It also allows for increased ability to quickly shut down the experiment if a problem were to arise. By writing handshake functions between LabVIEW Real-Time and the Windows 2000 system, the shake table can be made to stop if certain safeguards are not met. The real-time architecture also allows the system to keep running during a crash of the supporting CPU. This is due to the compiled g code being embedded within the real time controller itself. The Windows 2000 machine accompanying the PXI RT board can therefore run other tasks such as web serving while the RT board handles the LabVIEW code and DAQ functions. The PXI board has a connector for a DAQ accessory to allow for the process of these functions. This is essential for sending analog waveforms and receiving displacement data.

Tasks Accomplished for Distance Learning Lab Setup

With the intention of creating a distance learning version of the original shake table lab, many tasks were required. First, proper software had to be written to drive the shake table itself. This would need an intuitive interface and allow inputs to be received and sent to the DAQ board. A functional oscilloscope was also essential to display data received from the DAQ board while allowing for triggering and cursors. Also, the data presented needed to be saved for further analysis. Safety precautions including input limits and handshaking where placed within the code as well. These aspects followed the middle set of nodes in figure 2.

The procedure for creating the waveform generation and controlling code for the shake table is shown in figure 4. Amplitude, frequency, and waveform type input controls were placed on the user interface displayed in figure 5. The interface used is the LabVIEW front panel diagram itself as discussed in the LabVIEW and Real time board section. This allows for easy placement of buttons and switches. The code runs on the real time (RT) operating system due to the need for data acquisition. The DAQ controller is located within the RT system architecture and cannot be initialized from the Windows system.

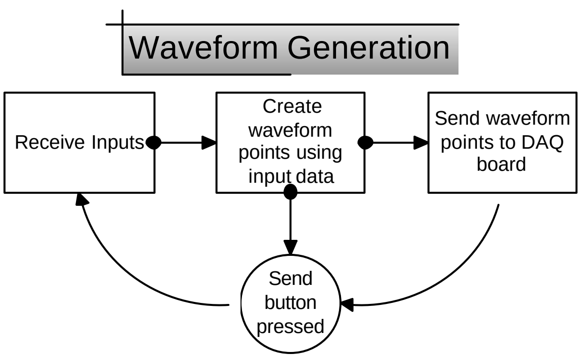

Figure 4 – Functionality diagram for the waveform generation code.

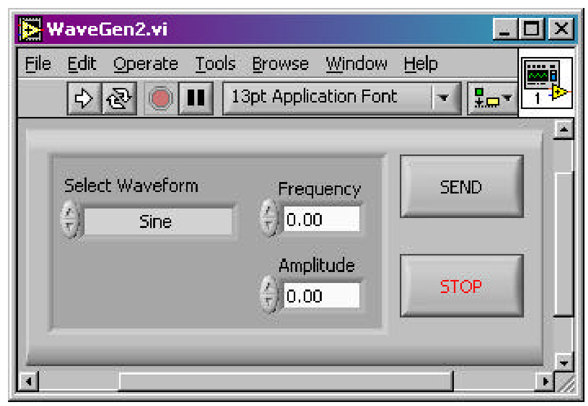

Figure 5 – Example Front Panel (GUI) for the waveform generation code.

The oscilloscope interface was created in a manner similar to the waveform generation code. The steps followed are shown in figure 6. Since data were taken in by the DAQ accessory, this code must reside on the RT board as well. Sample code from LabVIEW 6.1 was taken and modified to create the oscilloscope shown in figure 7. Cursors, triggering, vertical resizing, and time-span control are all functionalities included as part of the scope. This portion of code also sends all of the numeric data to the screen where it can be copied and placed into a spreadsheet program for further analysis. The data logging was a major portion of the conversion of code to the RT setup. More efficient implementations for saving data are presently being addressed. These include the use of TCP/IP and shared memory VI's instead of the LabVIEW remote front panels solution.

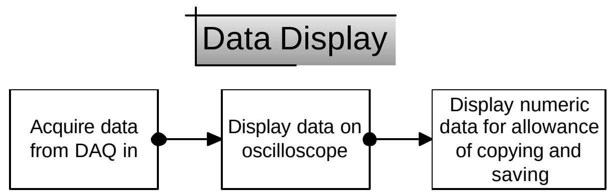

Figure 6 - Functionality diagram for the display code.

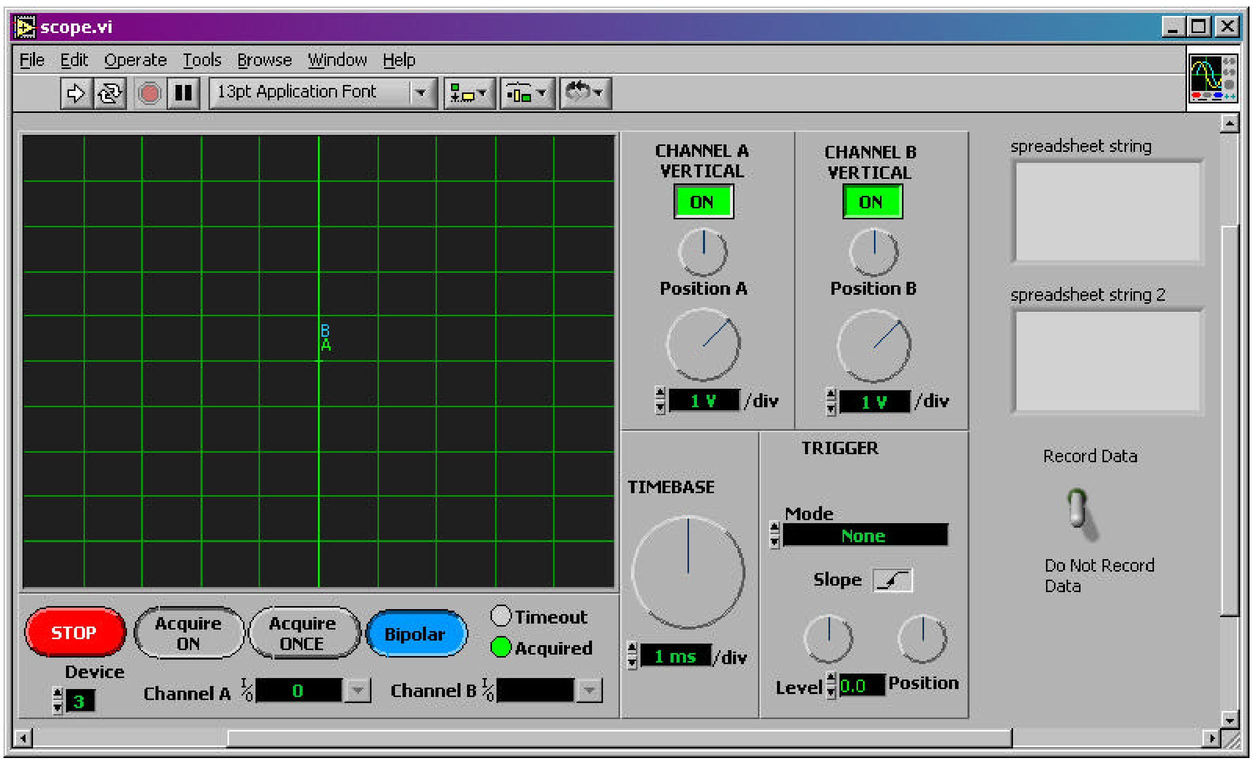

Figure 7– Example Front Panel for the display code.

Another concern for the setup was safety. Certain aspects pertaining to safeguards were exercised in each portion of the code. The waveform generation section of the code had limits added to the inputs. This was done within LabVIEW and was set so that any values outside the specified range would be limited to the closest allowable value. These input limits were placed upon the amplitude and frequencies. Data from tests conducted on a shear building similar to the one used in the experiment together with professional judgment was used to determine a range for the various limits. Changing these values for different structures is a simple task for the administrator. Feedback using the data in the display code is also a safety protection that is presently being implemented. The data received will stop the code if the amplitude values are found to be too large. A final precaution presently being added is a handshaking function. As depicted in figure 8, this function sends a signal from the Windows operating system to the RT system saying that it is working properly. In the case of a system crash the RT board would remain active however, the remote user would lose access to the interface. If this occurred, the RT board would no longer receive the “OK” signal and would safely shut down the experiment.

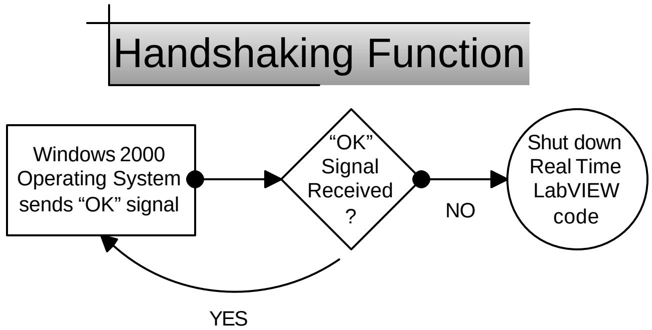

Figure 8 - Functionality diagram for the handshaking code.

Web Setup

In order to allow for distance access to the shake table experiment, an Internet setup is instituted. A client-server setup of the type shown in figure 9 is used for this purpose. The controlling computer runs LabVIEW and has a DAQ card that is attached by coaxial cable to a DAQ device. Not only is LabVIEW used to control the experiment, but the built in web server is also used to place the vi onto the World Wide Web. HTML code is automatically generated by LabVIEW and can be modified as needed. The client computer only needs a web browser with the LabVIEW run time module downloaded from the National Instruments web site to access the system.

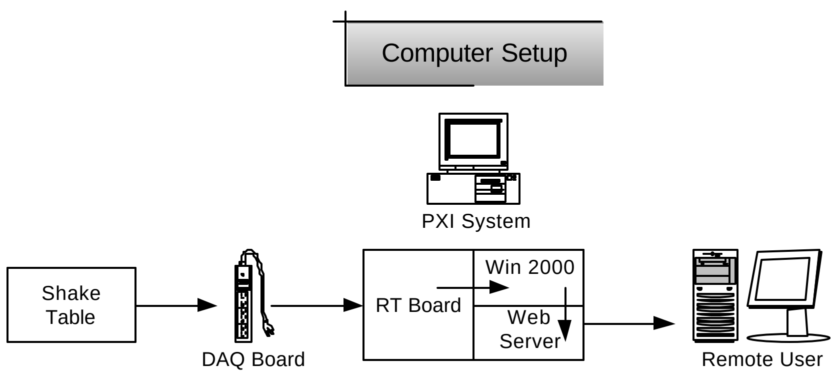

Figure 9 – Communication between laboratory equipment and the web.

The LabVIEW code is run on the RT board and remote front panels are used to see the code on the Windows 2000 system. The use of remote front panels is an option within LabVIEW that allows any front panels to be seen by way of the internet. This simplifies programming so that the transfer of information no longer needs to be hard coded. The RT controller being used cannot be directly used as a web server by itself. However, when the RT board is targeted by LabVIEW, the vi's being used are placed into virtual memory on the Windows 2000 system. This allows the web server on the Windows 2000 system to distribute the code. The use of remote front panels required additional licenses from National Instruments. Given the additional licenses and proper configuration, the lab was structured so that there could be as many remote viewers as there were licenses but that only one could control the experiment at a single time.

TCP/IP protocols are used for dealing with communications. TCP/IP is a family of protocols often called the “internet protocol suite” that allow computers to share resources over a network. These deal with file transfer, remote login and execution, as well as other events. By only allowing certain IP addresses access to the interface, a greater level of security is gained.

Associated Web Documentation

With the use of LabVIEW programming on the server machine, it is important that any client computers have software that can read the g language. To do this, the client must have either LabVIEW or a LabVIEW run-time module installed on their machine. Assuming that most users will not have LabVIEW existing on their computer, an accompanying website is offered as the easiest primer for downloading all of the necessary components. This website specifies input limits and includes a brief description of the lab as well as instructions on use of all virtual instruments. There will also be a link to National Instruments site for free downloading of the run-time module. Once the camera is added, a link to the Netmeeting download site will be included.

Future Considerations and Increased Scope of the Lab

Presently, the static and free vibration tests are difficult to implement with this setup. This is due to the need for fixing the shake table so that it cannot move. At the time of this paper, screws are used to clamp onto the table and must be hand tightened. One option is to replace these screws with pneumatic actuators that will clamp down upon the shake table to make it stationary. Another actuator can be used to apply an initial displacement to the girder of the shear building giving it an initial excitation. The control of these actuators could be implemented in LabVIEW, as was the control for the shake table.

Another future consideration is the use of the web camera. Currently the camera being used has relatively low frames per second with basic usage limited to showing the lab setup and verifying whether or not the table is moving. Purchase of a faster, higher quality camera that will be able to show the video of the experiment more fluently is planned. Furthermore, with a higher quality camera combined with proper software, it will be possible to grab a selected number of frames per second matching or closely matching the frequency of various structural modes. This would produce an effect similar to a strobe light and allow for the user to better see the different structural modes of vibration.

With these changes, the equipment will be usable in a way that closely meets each aspect of the original lab. This will let students learn without the need of being present on campus. The changes made will also make the lab more accessible as a tool for classes other than the structures lab. Graduate level classes such as advanced dynamics could utilize the lab from the classroom. This would allow students to see varying mode shapes and gather data while making calculations away from the clutter of the laboratory.

Conclusion

Through studying the distance-learning laboratories of other institutions and keeping the users needs in mind, a positive distance-learning environment can be achieved. This environment will be able to reach a broader spectrum of students and researchers as well as allow for the eventual formation of collaboratories with other teaching and research-oriented organizations.

Along with the educational and collaboratory benefits, this work will also allow for modifying other experiments in the laboratory. After the setup described has been completed, only the LabVIEW portion of the setup and the placement of the data acquisition tools should have to be changed in order to convert labs with similar data acquisition needs. This procedure shows that proper safety guidelines are required for placement on inputs limits and feedback options. Remote front panels were also seen as the best option for balancing ease of programming and functionality.

Acknowledgements

The authors would like to acknowledge the generous support of the Civil Engineering Department at N.C. State University and of National Instruments, Inc.

Bibliography

[1] http://www.neesgrid.org "NEES Community Requirements Workshop Final Report." Technical Report NEESgrid-2001-03.

[2] http://www.nees.org/EQ/sites/p1_ub.html "Versatile High Performance Shake Tables Facility towards Real-Time Hybrid Seismic Testing." University at Buffalo, State University of New York.

[3] Smith, S. R., C. W. Husted, S. Smith, and B. Cross. "A Web-Based Tutorial and Tele-Operation System for Earthquake Engineering Education." 30th ASEE/IEEE Frontiers in Education Conference, Kansas City, Mo, October 18-21, 2000.

[4] Newman, D. R., B. Webb, and C. Cochrane. "A content Analysis Method to Measure Critical Thinking in Face-to-face and Computer Supported Group Learning." Interpersonal Computing and Technology, Volume 3, Number 2, pg. 56-77, 1995.

[5] http://sine.ni.com/apps/we/nioc.vp?cid=1455&lang=US "Virtual Bench" National Instruments.

[6] http://volt.ni.com/niwc/realtime/what_is.jsp?node=3304 "What is Real-time Control?" National Instruments.

[7] http://sine.ni.com/apps/we/nioc.vp?cid=1525&lang=US "PXI" National Instruments.

VERNON MATZEN is a Professor of Civil Engineering at NC State University, Alumni Distinguished Professor for Undergraduate Teaching, Member of the Academy of Outstanding Teachers, Director of the Center for Nuclear Power Plant Structures, Equipment and Piping and Director of the Structural Behavior Measurements Laboratory. He conducts research in experimental and analytical mechanics, including inverse problems, in civil and nuclear structures.

SCOTT WIRGAU was born in Schenectady, NY, in 1979. He received his B.S. in civil engineering with a minor in computer science in 2001 from North Carolina State University. His research interests include distance learning, LabVIEW programming, and dynamic analysis.

ABHINAV GUPTA is an Assistant Professor of Civil Engineering at NC State University. His research and educational activities have been focused on integration of emerging computing (numerical and information) technologies with the engineering knowledge for improved understanding and visualization of structural performance.