MECHANICAL STRUCTURES INTERACTIVE LAB

Carlos E. S. Cesnik[1] and Torrey Radcliffe[2]

Abstract *— The Mechanical Structures Interactive Lab is one of a number of new remotely accessible WebLabs being developed at the Massachusetts Institute of Technology. The Lab is a modular framework for allowing remote experimentation on elastic structures for all levels of instruction. The users are only required to have a computer connected to the World Wide Web through any commercially available browser. By using the same computer to both model the beam and perform experiments, the students receive rapid feedback on the accuracy of their numerical models. All of the software was created using the National Instruments LabView. The system has both static and dynamic actuators and various sensors. The system has been used by a small graduate course to determine the frequency response of a beam. While most of the feedback was positive, there are still a number of areas for system improvement.*

Index Terms — Active structures, distance learning, remote laboratory, structural dynamics.

INTRODUCTION

Under the MIT- Microsoft Alliance iCampus program, the I-Lab project was conceived to develop a new framework for science and engineering education [1]. The main focus of I-Lab is the concept of web-accessible remote laboratories (WebLabs) that allows real-time experiments from anywhere at anytime and coupling them with simulation tools. Several WebLab concepts are being pursued in different disciplines, from microelectronics to chemistry. This paper describes the development of one such concept, the Mechanical Structures I-Laboratory (MSI-Lab). Reference [2] provides more detailed information on the MSI-Lab project.

The MSI-Lab was created because mechanical structures courses can greatly benefit from having experimental projects. However, these projects, while relatively simple to operate, are often time consuming to setup. As a result, only one of the numerous mechanical structures courses offered by the MIT Department of Aeronautics and Astronautics nominally conducts experiments.

MSI-Lab allows students to have access to laboratory equipment at all times. The student will have real-time data from the laboratory displayed on the same platform they create and run their analytical simulations. Having both the analytical and physical results from an experiment side by side allows for quick feed back and evaluation of the analytical models developed in the classroom. It also allows for the study of error sources in the physical setup.

A WebLab has several practical advantages over a traditional laboratory. A WebLab can also be leveraged by multiple courses, in multiple departments, and over multiple universities. The long-term work-model proposal is to have several universities participating in a "WebLab Consortium." Thus, instead of each school spending time and effort creating and maintaining dozen different labs, they build one (or a few) elaborate experiments and share it with a dozen different schools. Additionally, due to the remote nature of the system, more users can access one piece of laboratory equipment over given amount of time than a traditional laboratory. For example, consider a class with two hundred students all required to perform the same experiment in a given week. A traditional laboratory would require the students to come in at specified time slots and either work in very large groups using one piece of equipment, or in smaller groups with numerous pieces of identical equipment. The former solution does not allow for more individual access to the laboratory equipment and the latter does not efficiently use space or financial resources. However, a WebLab can be accessible twenty-four hours a day, seven days a week. Thus, student usage can be spread over more time requiring less laboratory setups. This can actually be the enabling feature of an academic laboratory, which requires a large amount of capital to create a single experimental setup. WebLabs can also operate near autonomously for long periods of time requiring almost no staff time, but for regular maintenance. It takes up much less space as no people need direct access to its facilities. There is no chance of user injury, nor can the user harm the laboratory itself.

It is recognized, however, that WebLabs will not replace the physical experience of a student in a real laboratory environment. But it will complement that. Students should be given the opportunity of a "hands-on" laboratory experience targeting specific learning objectives only attained when in physical contact with an experiment. However, as other attributes in the educational curriculum, this does not need to be exercised in every experimental assignment. There are important curricular issues that must be addressed by experimental assignments that WebLabs can provide so effectively. The WebLab can also allow for a more comprehensive laboratory setup than what can be created in the time constraints of a normal lab assembly.

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OBJECTIVES

The objective of the MSI-Lab project is to design a platform for easy creation of remotely operated mechanical structures experiments. It is created to allow better access to and improved quality of mechanical structures experiments. To accomplish this task several key goals were decided upon..

- The user experience should be as close as possible to actually being at the laboratory.
- The user should have access at any time from any computer with a commonly available web browser.
- The laboratory should be flexible enough to allow for different levels of mechanical structures classes to utilize it.
- No special manual adjustments should be needed for the normal operation of the system.
- New laboratory realization should be easily deployed within the platform.
- The system should be secure from outside tampering.

SYSTEM LAYOUT

The MSI-Lab can be divided into three basic areas: hardware, lab controlling software, and user interface. While the first two areas are common to other computer-controlled labs, the user interface is what allows the MSI-Lab to be operated remotely. However, all three areas were designed such that the goals of the project could be achieved. Figure 1 shows the basic scheme of the system.

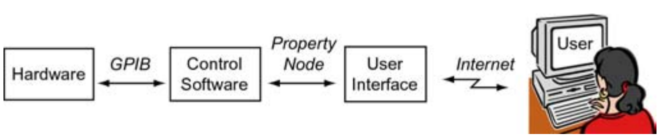

FIGURE 1
MSI-LAB SYSTEM LAYOUT

Hardware

The MSI-Lab hardware includes sensors, actuators, and testing elastic structure in addition to the conditioners and amplifiers required to convert digital from analog information and visa-versa. Figure 3 shows all of the hardware that is used by the current system and how it is connected.

All of the experiments are conducted on slender structures because they fit into the mechanical structures curriculum of the Aeronautics and Astronautics department of MIT. Almost all of the courses study beams at some point due to their relatively simple nature. Moreover, they are simple to construct and provide a natural proof of concept for the experiment. The beams currently used in the MSI-Lab are made from either steel or graphite epoxy composite. Composite beams were custom manufactured with two layups chosen to demonstrate a bend-twist coupled composite structure and a pseudo-isotropic structure. The beams can have either a cantilever or a pinned/roller end condition, both of which are statically determinate. The cantilever end condition has the advantage of a larger amplitude displacement for a given load and beam length.

The MSI-Lab proposes to have two types of actuators, one static and one dynamic. Currently only the dynamic actuator has been realized. Dynamic actuation is performed using ACX QP20N piezoelectric actuators [3]. When bonded to a beam and actuated, the piezoelectric actuator induces a moment, which causes the beam to deform. The actuators are placed near the root of the beams to cause maximum beam tip deflection. The analog input signal to the actuators comes from a high-voltage amplifier.

Various sensors monitor the state of the beams. The available sensors are able to measure displacement, acceleration and strain. This gives the students the chance to study the advantages of measuring each attribute. The signals generated by the sensors are passed through conditioners mounted in a SCXI mainframe [4].

Strain gauges are the most common sensor used to monitor structures. They can determine the surface strain of the object to which they are attached. Strain gauges are inexpensive, but have a relatively low signal-to-noise ratio. Strain gauges are mounted along the length of the beam, as shown in Figure 2. A rosette of three gauges is mounted to the composite beams to allow for twist measurements at the roots. The thermal drift corrections are processed at the software level.

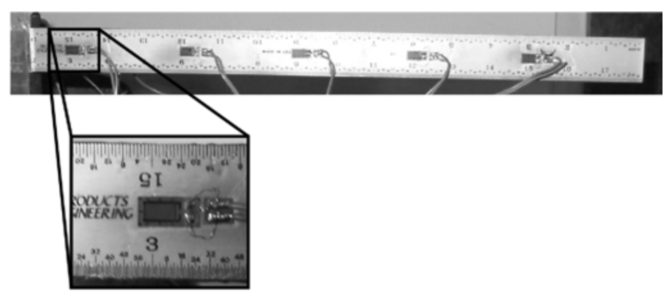

FIGURE 2
STEEL BEAM WITH ATTACHED STAIN GAUGES

Accelerometers are able to capture the motion of a system by measuring the accelerations it undergoes. The accelerometers are placed where the motion is expected to have the greatest amplitude, near the free tip of the cantilever beams and at the middle of the pinned/roller beams. The Keyence LB-70 laser sensor allows for accurate displacement measurements of a single point of the structure [5]. Finally the user would also have the ability to view the structure using a video camera. Currently the camera does not have enough resolution to provide much quantitative data, however it does allow the user to observe the beam's behavior during the experiments. A grid is placed behind the beam to give the user a frame of reference for any beam motion. Still under implementation is the addition of a strobe

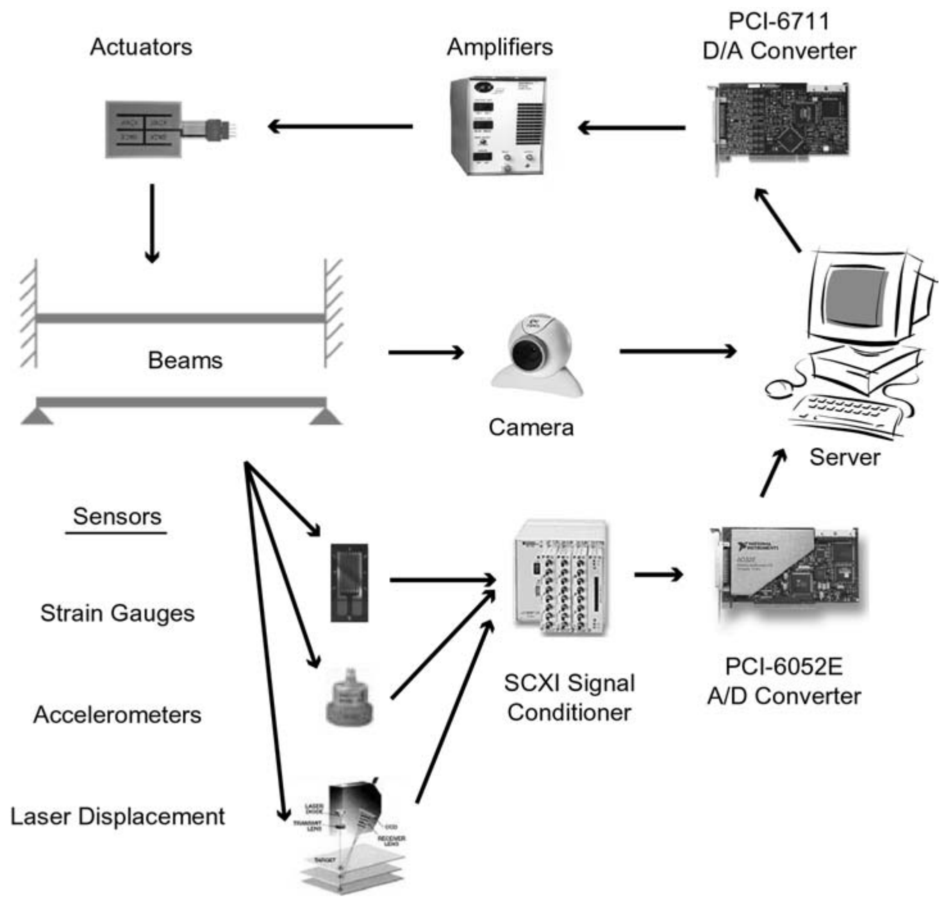

FIGURE 3
SCHEMATIC OF HARDWARE LAYOUT

light to the system to allow the user to "slow down" the motion of the beam and help in the visualization of the motion.

Laboratory Controlling Software

The structure is controlled using a set of Virtual Instrument (VI) applications created in the G language using National Instruments Lab View version 6i [6]. The structure controlling VI program is essentially a "while loop" that contains five actions: signal generation, signal output, sensor input, graphic creation, and optional file generation. Whether or not the user has control over each of the various inputs is determined for each possible experiment and set in the user interface.

Each time the VI is started or the output signal type is changed, the mean value of each input is determined over a period of two seconds. These mean values are then subtracted during all other iterations. This method removes the output bias that is generated over time due to thermal drifts. Both the output signal and the sensor inputs are buffered. Buffering ensures that no data is lost. This allows for smooth output signal generation. However, both the output file and the graphical display can only present what is in the buffers. Because of this, the input data and the output data are out of phase. That is to say, at a given point, the input buffer has what the sensors just read, while the output buffer has what is next to be sent to the actuators.

The structural controlling VI creates a graphical image of both the input and output signals. The created image is multi-colored with each color corresponding to a specific actuator or sensor. The time axis scale is controlled by the user, while the data axis is auto-scaled. Additionally, the user can control what data is shown on the plot. The user can choose to either have each sensor and actuator shown or hidden.

The output data file created by the VI consists of a date and time stamp for each line of data, followed by both the actuator and the sensor readings at that time. The data is presented in a spread sheet-like format.

User Interface

All of the user's interactions with the experimental setup are handled using National Instruments G Web Server [7] that makes Hypertext Markup Language (HTML) and other documents available on the Internet. The user accesses the server from a client computer using a web browser.

The user accesses the laboratory through a web site (layout shown in Figure 4) that is divided into two areas: the secure and the unsecured areas. The unsecured side of the site has various pages describing the layout of the system and its capability. The password protected secured pages allow the user to control the experiments and access experiment specific downloads. These downloads can include Matlab scripts which an instructor can provide to help create a model of the experiment or to analyze collected data.

Any user connected to the Internet can access the unsecured "Home Page." From there they can go to a page offering an overview of the MSI-Lab layout, which in turn links to a number of pages which give detailed information on the various subsystems. From the Home Page, users with the proper password can reach the experiment pages. Each experiment being hosted on the MSI-Lab has its own page and user/password combinations.

When the user tries to gain access to the experiment, the system checks to see if any of the structures requested is available. If all of the possible structures are currently in use, the user enters a queue. The user's client displays the queue HTML page which simply has the statement: "You are currently number *X* in line," where *X* is replaced by the number of people waiting in the queue ahead of the user in question. This page reloads itself every five seconds to update for changes in the queue.

When the user is at the front of the queue (or if there is no one using the system) they are redirected to a page with three frames distributed vertically. The topmost frame contains the queue page from before. The middle frame contains all the controls for the actuator input. In addition, the middle frame contains links to the various visualization options: animated output data, static output data, and video feed. The graphic outputs are created using specialized LabView VIs. The bottom frame contains the file generation control where the user can create and download sensor data files. The user can only download the most recently created data file.

All user inputs are provided through form fields that transfer data to Common Gateway Interface (CGI) applications [8]. These CGI applications then modify the input property nodes of the laboratory controlling software. The form field / CGI interface was chosen to maximize compatibility with the various web browsers and to avoid downloading specialized clients.

When the system has detected that the user is no longer connected, it stops the experiment, deletes any user created data files and records the usage in a data log file.

PLATFORM TEST

When the MSI-Lab had reached a developmental state where it was thought possible to use in a class, it was deployed in a small graduate course. This test of the MSI-Lab gave insights into its performance that would not be otherwise possible.

Student Assignment

The students were given a handout describing the experiment and how to use the MSI-Lab, and were allowed two weeks to complete the assignment. The class consisted of six graduate students, and the assignment was given towards the end of the term. The students were told that the MSI-Lab was in an early stage of development and that they might have problems using it.

The students were given access to a cantilever steel beam to perform structural dynamic studies. They were also given the beam properties and asked to perform an analytical analysis of the beam before carrying out their experiments. The students' objectives were to find the resonance frequencies of the structure both analytically and experimentally and to discuss the results of both methods.

The motivation of such an assignment is that the students would see the limits of the analytical models they had developed in class. By using a remote laboratory, it was expected that the students would perform the experiments shortly after performing the analytical analysis. Perhaps they would have had both results on their computer screens at the same time and were able to make rapid evaluations of the results. If they had done everything as expected, the students would have found that the analytical results consistently over estimated the natural frequencies of the structure. While there are numerous possibilities for the discrepancies, the details are not important. What is really crucial is that the students might have begun to think about these possibilities. The laboratory assignment also asked the students to explore areas of structural dynamics that are difficult to analytically model, such as nonlinear behavior. It also gave them some experience in processing experimental data.

Usage and Performance

While the students had access to the MSI-Lab, several observations were made of the lab's usage and performance. From the usage data it was observed that the lab was used at least once per weekday. The day before the assignment was due had the most number of users, which peaked to four users at the 4 PM hour.

There were two major problems with the MSI-Lab platform that were identified during this test. The first problem was unexpected program errors in National Instruments LabView, which caused the entire platform to stop working. The problem was found to be associated with the LabView software, and not the MSI-Lab itself. At the time of the experiment, the only solution to the problem was to monitor the system and restart it when a crash had occurred. Since then, the source of the problem has been identified and corrected.

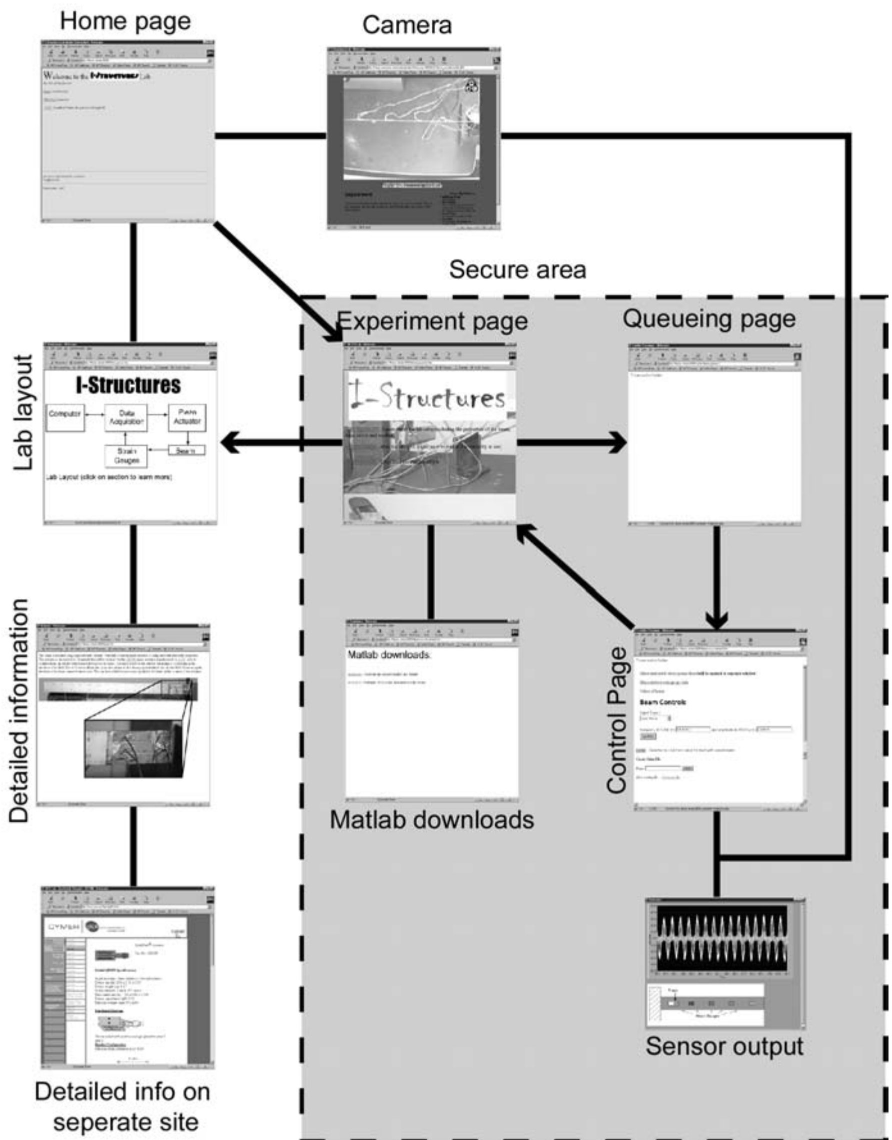

FIGURE 4
LAYOUT OF WEBSITE. SECURED AREAS IN GRAY

The second problem involved the queuing system. When the system was being used to collect data, particularly when a data file was being created, there was a system-wide slow down. The data collection and beam control program were given highest priority to ensure no data was lost. However, the HTTP server would not process requests as quickly as expected. This caused the queuing system to register some of the users as having left the system. As a client is supposed to respond every five seconds, the original time for the queuing system to wait for a response from a client was 15 seconds. To correct for this problem, the user expiration time was extended to 45 seconds. The problem was not noticed and, therefore not corrected, until the last night of the assignment.

RESULTS AND DISCUSSION

Based upon the feedback provided by a student survey, the MSI-Lab accomplished its goal of providing the students with a mechanical structures experiment, which they could remotely manipulate. The students felt that they had as good of an experience as would have had using a more traditional laboratory setup. Despite not being able to physically see the experiment, they said that they had a good understanding of what was occurring. These statements were made despite the MSI-Lab not being fully functional.

The ability of the lab to log usage was extremely helpful. The usage data showed that, despite being warned that the laboratory was unstable, many students chose to wait until the last possible night to perform their experiments. The students were also using the system longer than expected. As there were only six students in the class, that did not become a problem. However, the student behavior shows that some scheduling scheme must be in place for a larger class. While this might limit the flexibility of having a remote laboratory, not having a schedule risks a logjam of the laboratory on the last night of any assignment. Even with a schedule in use, their usage could still be flexible by giving students a specific 24-hour period to use the system instead of limiting them further.

The use of the platform by an actual class of students showed that there are several areas of improvement that need to be implemented in the next design iteration. The primary corrections to the system are those associated with system stability. The system needs to be stable independent of the number of users on the system and what tasks they are performing. An unstable system leads to student confusion and frustration. Before the MSI-Lab is used again for a class, more tests will be performed simulating large numbers of users. Even so, it will be difficult to predict all states the system could be put in by users.

A number of students who used the MSI-Lab found the structure control interface to be confusing. The user interface is an integral part of the MSI-Lab. One student asked for more explanation of how to use the controls on the control page, while another complained that the page was already too cluttered. While they had access to all controls they wanted, they had difficulty using the controls they had. One exception to this was a student who had seen the MSI-Lab demonstrated and the controls manipulated by one who understood them. Thus, one possible solution is to demonstrate the system for each class that would use it at the time the assignment is given. Ultimately, the controls should be arranged in a more intuitive manner so that such an in-class demonstration is not required. Perhaps a tutorial on the web site might improve user understanding. There was a detailed instruction page on the web site, but the students either did not find that page or had difficulty understanding it. Putting more descriptive information on the actual control interface would lead to a more cluttered interface. Finally, a well developed "help" section and tutorial would solve a number of issues that the students raised.

All these suggestions have been incorporated in the most recent version of the MSI-Lab, and future course deployment is expected at both MIT and the University of Michigan for further validation of the concept.

CONCLUSION

A Mechanical Structures Interactive Laboratory that allows users to have access to mechanical structures experiments via the World Wide Web has been designed, implemented, and tested. This MSI-Lab is a framework that allows structural experiments to be performed remotely at any time for any computer connected to the Internet. The MSI-Lab framework consists of one or more mechanical structures that can be either statically or dynamically actuated. Various sensors are used to monitor the structures' behavior. Remote users can manipulate both the actuator signal and sensor data via the Internet. Most of the software was implemented using National Instruments LabView development tools. The control signals are sent to CGI applications using HTTP form pushes. User access is coordinated using a queuing application and it is continuously monitored.

This system was tested in a small graduate student class. The overall reaction to the lab concept was very positive, and indicated that the setup gave the students a similar experience as if they were in front of the physical experiment. The ability to log the usage showed that, after checking the web site once, the majority waited until the last possible night to perform their experiments. Due to the time required to run a mechanical experiment, bigger size classes will require a specially design scheduling scheme or a change in the students behavior towards last minute approach to week-long assignments. The students feedback also indicated certain areas of improvement, including platform stability, user's web interface, and on-line help system. The suggestions have been incorporating in the current version of the system, which is ready to be deployed in the classroom again.

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