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An architecture for multi-user remote laboratories

Sven K. Esche†, Constantin Chassapis†, Jan W. Nazalewicz† & Dennis J. Hromin‡

Stevens Institute of Technology, Hoboken, United States of America†
JDS Technologies Inc., Ridgefield, United States of America‡

ABSTRACT: The emergence of new fields is forcing engineering educators to constantly reconsider both the content and means of delivery of modern curricula, which requires the conception, implementation and assessment of innovative pedagogical approaches and technical realisations. Many Internet-based tools are currently being introduced that promise to enhance the educational experience of on-campus students and expand the reach of unique educational offerings beyond the local campus. A laboratory approach based on remotely accessible experimental set-ups was developed and piloted at Stevens Institute of Technology (SIT), Hoboken, USA. This paper discusses the development of an architecture for remote laboratories, which enables the interaction of many users with a network of spatially distributed experimental devices. The paper concludes with an outlook on possible directions for future remote laboratory developments based on an assessment of the current system.

INTRODUCTION

Stevens Institute of Technology (SIT), Hoboken, USA, recently implemented a new undergraduate engineering curriculum, which was designed with a significant design thread and a comprehensive laboratory experience propagating through the entire educational programme. In the course of the curriculum development and implementation, it became increasingly apparent that the incorporation of laboratory components into all engineering courses places significant strains on an institute's spatial, temporal and monetary resources. Thus, creative concepts for affordable laboratories had to be devised that accommodate large student enrolment without also compromising the intended educational objectives. SIT has been an early adopter of computers; all undergraduate students own a PC/laptop and the campus is fully networked. This excellent information technology infrastructure and the superb computer savvy of the student body at SIT were identified as strong assets in the development of innovative laboratory facilities that leverage the available resources.

In this context, a student laboratory approach that is founded on Internet-based, remotely accessible experimental set-ups was proposed [1]. As shown in Figure 1, the experiments can be carried out by the students as laboratory exercises, by instructors as lecture demonstrations or by outside clients such as high schools.

It was decided to first apply this approach in a pilot project for a laboratory on dynamical systems. This laboratory component accompanies a corresponding sophomore-level lecture course taken by all engineering students as a core requirement (approximately 100 students per class). These development activities were partially funded by the National Science Foundation (NSF) through the Instrumentation and Laboratory Improvement and Research Experiences for Undergraduates programmes [2][3]. The initial plan called for the implementation of a laboratory that is accessed exclusively in a remote fashion [4]. This concept was later modified to include both on-site as well as remote components of the experimental student experience as part of a laboratory course on machine dynamics (with a typical class size of 20 students) [5][6].

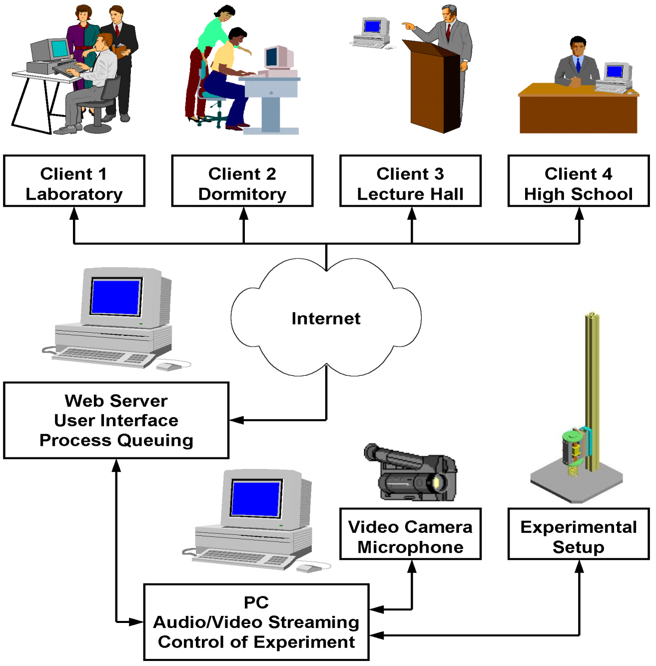

Figure 1: Set-up of an Internet-based remote-access interactive educational laboratory.

PREVIOUS REMOTE LABORATORIES

With the advent of the Internet, remotely accessible student laboratory facilities have become feasible and are gaining increasing popularity. The underlying fundamental promise of such Internet-based laboratory approaches lies in students' abilities to connect to the computer controlled laboratory set-up of interest at anytime from anywhere, thus sharing existing limited resources in a more efficient manner than would be possible with the traditional on-site laboratory approach.

The general concept of remotely controlled devices has a long-standing history. In fact, the roots of such systems were tracked back to a master-slave teleoperator developed at Argonne National Laboratory in 1954 [7]. Even the idea of sharing student laboratory facilities remotely by using modern communication technology is not new. A remotely accessible control systems laboratory based on networked engineering workstations was proposed as early as 1991 [8].

Since then, remotely shared experimental facilities have emerged as one innovative solution for educational laboratories with reduced resource needs. This trend is witnessed by a variety of related test implementations [9-16] and investigations [17-24]. More recent developments include, for example:

- A low-cost system to control microcontrollers over a touch-tone phone [25].
- A remotely accessible real time manufacturing automation laboratory [26].
- A system architecture for remote experimentation with power electronic devices [27].
- A simulation-based method for mitigating the impact of temporary network overloading on real-time remote experiments [28].
- A remote laboratory set-up where a multi-circuit board contains various components and the students wire up electrical, electronics and power electronics circuits through a graphical wiring environment [29].
- A variety of remotely accessible experimental test-beds for aerospace, mechanical, electrical, civil and chemical engineering [30].
- A remotely controllable four-axis robot [31].

DESIRABLE ATTRIBUTES OF REMOTE EDUCATIONAL LABORATORIES

From the very beginning of the remote laboratory development at SIT, the focus was on developing a platform that would enable potentially large numbers of students with diverse needs to utilise a wide range of educational experimental resources in a concurrent and interactive fashion. A number of desirable features (most of which were not found in previously existing remote laboratory implementations) were identified for the development of this remote laboratory architecture.

In the conceptualisation and implementation of this technology, a strong emphasis was then placed on the following technical characteristics:

- Modularity and expandability;
- Scalability;
- Usage of, and compatibility with, existing communication standards;
- Computer platform independence.

Acceptance of remote laboratories by the academic community is expected to hinge on the following attributes:

- Correlation with curricular needs;
- Compliance with ABET requirements;
- Pedagogical soundness;
- Affordability;
- Ease of use;
- Reliability.

SYSTEM IMPLEMENTATION

The overall hardware architecture for the remote laboratory system developed at SIT is shown in Figure 2. The system was realised using a client-server network approach that allows the concurrent execution of multiple experiments using separate experimental set-ups. Experiments that require the same set-up are queued and executed in the order of the incoming requests.

The connection from the laboratory to the outside world is established using a Linux-enabled Web server. This server hosts the process queue, the data input and output files generated, as well as the graphical user interface, which was developed using conventional HTML pages, Java applets and CGI/Perl scripts. The Web server is networked to individual data acquisition PC terminals running Windows NT. These terminals execute *LabVIEW* VI scripts that control the experiments and report the experimental results back to the Web server.

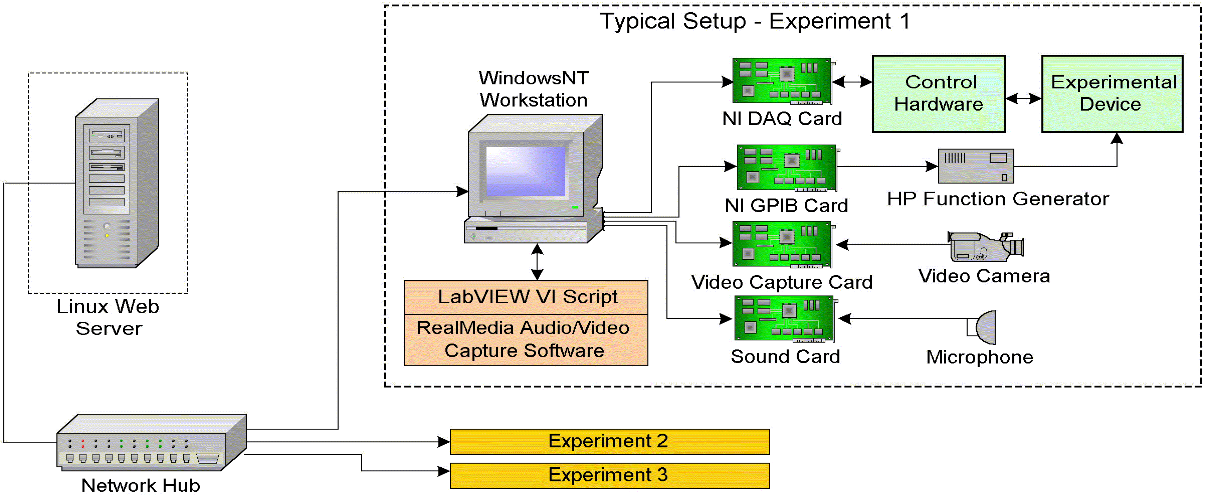

Figure 2: System architecture of remotely accessible laboratory set-ups.

The control software was written using an event driven programme structure. A top-level programme construct idles in an endless loop, waiting for a user request message to be intercepted. Upon occurrence of this event, a low-level subroutine is invoked that parses the message for its meaning. Based on the interpretation of the message, further subroutines are called, which cause some sequence of functions to be performed. After all actions prompted by the original message have been completed, the control programme returns to the top-level loop and waits for the next event.

As an example of a user request, the information flow during the execution of a typical experiment is shown schematically in Figure 3. After downloading the main Web page of the online laboratories graphical user interface using any Web browser, the user first selects a particular experiment from the list of available offerings and fills out the corresponding input form.

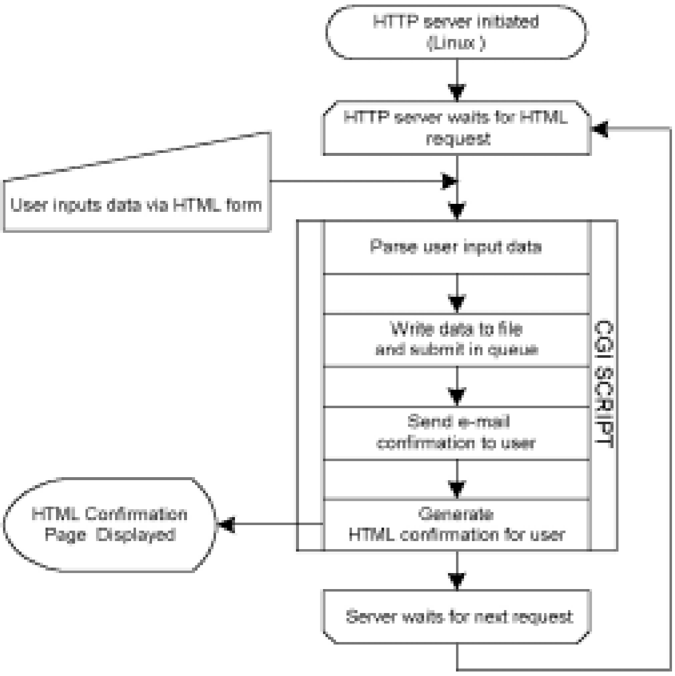

Figure 3: Flowchart for server actions.

This form contains some personal information (name, affiliation, e-mail address), as well as the necessary input data for the experiment. The server then parses the user request, generates a unique process identification number, makes an entry in the process queue and sends an e-mail confirmation message to the user, which provides the estimated completion time for the experiment based on the current queue status, the access code necessary for retrieval of the experimental results from the database at a later point in time and the URL where the output data (numerical results in ASCII format, video file in real media format) can be picked up at any time after the completion of the experiment. Finally, the server returns to waiting mode.

An overview of the general programme structure of the *LabVIEW* scripts, which are executed at the workstations that control the individual experimental set-ups, is shown schematically in Figure 4.

When detecting a new entry, the input data are retrieved from the corresponding user input form and parsed. Subsequently, a series of scripts are executed that perform a variety of subtasks involved with the execution of a particular experiment. These subtasks include for example:

- Switching on the lighting.
- Activating the microphone and video camera.
- Generating the required control signals and input waveforms based on the user input.
- Executing the experiment.
- Collecting the resulting experimental data.
- Formatting the results in text and HTML format.
- Generating the audio and video files.
- Deactivating the microphone and video camera.
- Removing the experiment from the queue on the Web server.

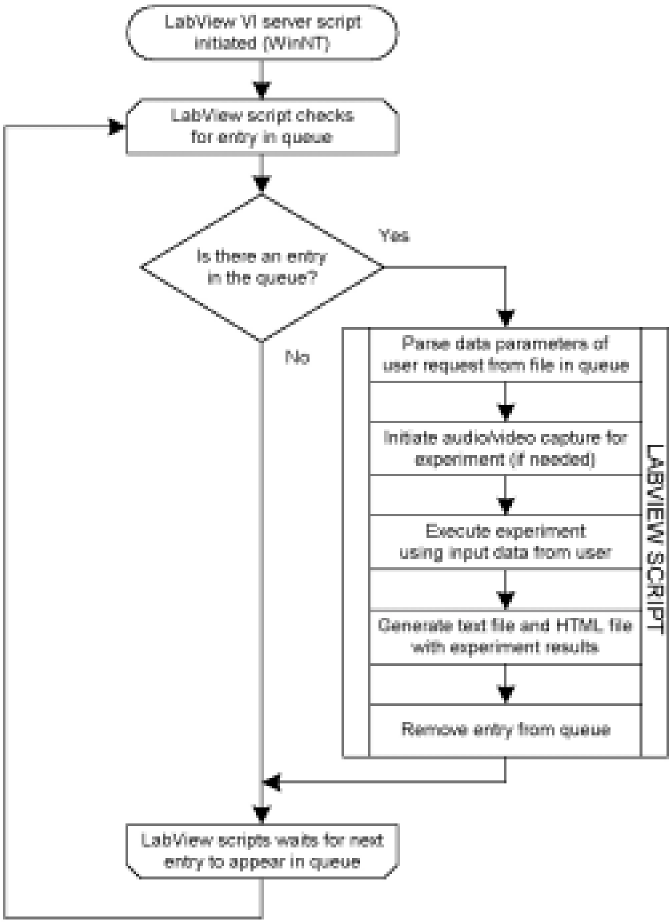

Figure 4: Flowchart of workstation actions.

Upon completion of these subtasks for a certain experiment, the *LabVIEW* scripts return to a holding pattern until the next experimental request is detected.

Each of the experiments also contains separate control hardware (see Figure 2). These customised controllers form a unit with the attached device. They manage standard operations such as data input/output, analogue-to-digital and digital-to-analogue signal conversion, function generation, power amplification and up/down counting.

The numerical data generated by the experiments can finally be imported into any software that the user selects for post-processing purposes. Replaying the video file requires the *RealPlayer* software [32]. The history of the experiments is kept in a searchable database residing on the Web server. The results of the individual experiments are stored in the database for 30 days before being automatically deleted.

SAMPLE SYSTEM IMPLEMENTATION

So far, four experimental set-ups have been developed and integrated into the remote laboratory architecture at SIT [33][34]. They include a mechanical vibration system, a duct acoustic system, a liquid-level control system and a set of electrical experiments based on operational amplifiers. All experiments were designed for small time constants and rapid execution of the experiments. This approach keeps the waiting queues very short and thus allows the inclusion of experimental demonstrations into lectures.

As an example, a brief description of implementation and experimental results for the one-degree-of-freedom mechanical vibration system is included here. A schematic of the set-up is depicted in Figure 5. It is actuated electro-magnetically (see Figure 6), and its modular design allowed straightforward extension to multiple degrees of freedom (see Figure 7).

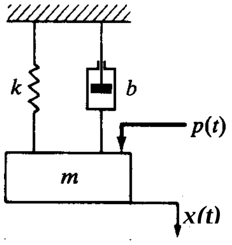

Figure 5: Schematic of one-degree-of-freedom mechanical vibration system.

Figure 6: Remotely accessible mechanical vibration set-up with video monitoring.

Due to the unique design of the vibration device, high accuracy displacement measurements x(t) can be obtained that compare very favourably with theoretical predictions. Figures 8 and 9, respectively, show comparisons for the measured natural and frequency responses of the system with the corresponding theoretical results. The plotting of the experimental data was performed using *MATLAB* scripts [35].

ASSESSMENT AND FUTURE DIRECTIONS

The implementation of this expandable and scalable remote laboratory facility at SIT has sparked considerable excitement among the faculty, staff and students involved in the development, building and testing of the system. Multiple pilots were conducted in a sophomore-level course on dynamical systems and in a junior-level course on machine dynamics and mechanisms. In both courses, student feedback was solicited through personal discussions of the instructor with individual students as well as by questionnaires that were distributed to the entire class [36]. Students were asked to comment on various aspects of the general approach of remote experimentation and to provide their personal opinions on the specific implementation of the approach at SIT. The resulting student responses have been overwhelmingly positive and very encouraging for further extension of this approach to other courses. In particular, the vast majority of students said that they were very satisfied with the system implementation and they placed special value on the flexibility of executing the laboratory exercises on their own schedule.

Figure 7: Modular mechanical vibration set-up with multiple degrees of freedom.

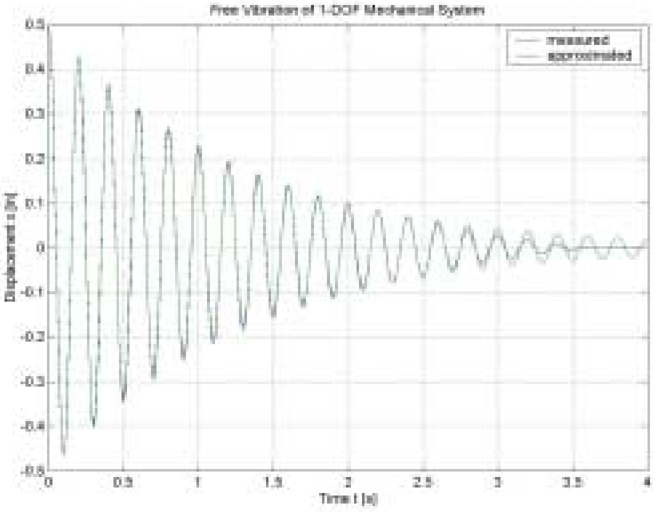

Figure 8: Natural response of mechanical vibration system.

In addition, the pilot study revealed that student performance in conducting the remote experiments was very similar to that encountered in previous years where the experiments were performed in the traditional on-site fashion [37]. This assessment is consistent with observations published elsewhere indicating that there is no discernable difference in performance between students performing experiments on campus or from a distance [38]. Based on the overall success of the pilot implementation, the development of additional remotely accessible experimental set-ups for other dynamical systems in electrical, civil and chemical engineering is presently underway and the propagation of the open laboratory approach to other educational laboratories at SIT is intended.

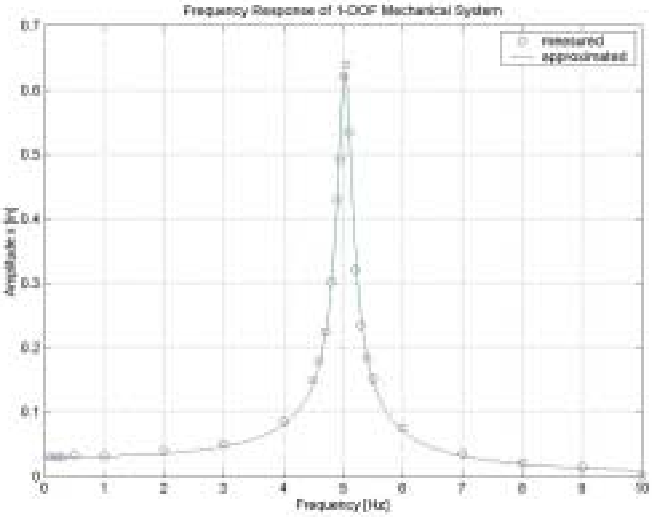

Figure 9: Frequency response of mechanical vibration system.

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