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Engineering eLaboratories: Integration of Remote Access and eCollaboration*

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A significant portion of the development efforts on remote access laboratories has focused on demonstrating their technical feasibility instead of investigating their implications for engineering pedagogy. Further, current implementations of remote access laboratories lack the social interactions that are fundamental to the engineering learning process. In response to these limitations a new paradigm for remote access laboratories, namely the eLaboratory, is introduced in this paper, which is a convergence of remote access technologies and collaboration-based eLearning. It implements web-portal technology to establish a seamless integration of content-delivery, collaboration tools, and direct access to hardware resources as well as software applications. The paper presents a generic and modular architecture for such a framework, and discusses its implementation. Students' evaluation of the learning outcomes of the eLaboratory paradigm, applied to Aerospace Engineering laboratory courses at the University of Toronto, is also analyzed.

Keywords: Distance learning; eCollaboration; eLaboratory; eLearning; engineering portal; remote access laboratory; web-based education.

INTRODUCTION

MANY ENGINEERING PROGRAMS have always considered laboratories as essential elements, particularly at the undergraduate level. The nature of instructional laboratories, however, has changed significantly over the last century [1]; the most significant impact coming from the widespread adoption of computers in education. The computer can be used to acquire data; to analyze, reduce and present results; to perform complex calculations and simulations. Consequently, student learning has become more efficient [2] and the practical experience gained through laboratory instruction has increased dramatically in scope.

The internet has also had a significant impact on education in both the classroom and the laboratory. Most engineering programs have begun to integrate web-based education, usually labelled as eLearning, into the traditional curricula both heuristically [3] and systematically [4]. At the same time efforts are underway to make instructional laboratories remotely accessible through telepresence [5], teleoperation [6] and telecontrol [7].

A number of motivations exist for providing students with remote access to laboratory resources. Increasing the accessibility and effective usage of expensive specialized equipment [8], adding a practical component to existing distance education programs [9], providing scheduling flexibility regardless of time and geographical location [10] and reducing the resource and time burdens imposed by the continuously rising engineering enrolment [11] have all been common incentives in the literature.

Nevertheless, the merit of remotely-accessible laboratories is beyond a merely new mode of experimentation. The newly-revised engineering curricula have begun to recognize the need for the diversity of scope, expertise and even resources in engineering education as a step towards globalization [12]. A multifaceted curriculum aims at training engineers who can work at multi-national corporations in teams composed of members with a wide range of expertise, technical experience and cultural background. Therefore, the formation of inter-disciplinary, inter-university engineering programs has changed course from wishful thinking to serious planning. Consequently, remotely-accessible laboratories have started to serve as platforms for inter-university collaborations aimed at establishing global distance education consortia [13].

This paper presents a new paradigm for remotely-accessible laboratories as complete web-environments that extend the scope of the traditional instructional laboratory and that compliment proximal experimentation through distributed collaborative learning.

LITERATURE REVIEW

Remote access laboratories have been extensively addressed in the literature from both the viewpoints of their technical feasibility and their implications for engineering pedagogy. Early works, such as [14–18], tended to focus on the technical merits and potential benefits of remote

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access technologies, whereas more recent works, such as [19], have started to focus on evaluating the effectiveness of the remote access modality in comparison with proximal or simulated experimentation. Several review papers, such as [20], have also emerged that evaluate and compare different remote access laboratory installations around the world.

Despite the increasing interest in remote access laboratories, the lack of a well-established scholarship in engineering education, particularly related to the role of instructional laboratories in engineering pedagogy, has resulted in research efforts being somewhat fragmented and *ad hoc*.

SOFTWARE

Several prevalent software technologies have emerged for providing remote access to laboratory hardware.

LabVIEW™ from National Instruments is a popular commercial software package for automated data acquisition and analysis. Using graphical dataflow programming LabVIEW enables easy and rapid development of control applications—called Virtual Instruments (VI)—that provide a software interface to a variety of measurement and control hardware, without the need to perform low-level coding. A complete survey of LabVIEW-enabled remote access technologies is provided in [21]. Examples of remote access laboratories that utilize LabVIEW for telecontrol include [22–26].

MATLAB® and Simulink® from The MathWorks are another popular set of commercial software packages for data acquisition, visualization, analysis and control. Using model-based design Simulink allows complex dynamic systems to be simulated, controlled, implemented and tested from a single interactive graphical interface, with full access to the high-level technical computing language and environment provided by MATLAB. Examples of remote access laboratories that utilize MATLAB include [27–30].

Another popular approach is to use custom-developed Java™ applets, based on the client-server architecture, to remotely control laboratory hardware. Ferrero *et al.* [31] implemented a remote electrical engineering laboratory with Java applets to control a remote data acquisition system used to measure and characterize a number of common electrical components.

ActiveX® Controls have also been used in remote access laboratories for either hosting the client-side control interface, or providing telepresence through live streaming audio and video of the experiment site. Chang *et al.* [32] developed a remotely-accessible photonics laboratory using custom ActiveX controls, written in Visual Basic®, to control a photonics test bed and to receive streaming video from a number of webcams.

Web services and server-side scripting have been used to develop client-side remote control interfaces that only require a web browser to run (i.e. the client is not required to install any applets or browser plug-ins). Capua *et al.* [33] designed a remote access laboratory using server-side scripted web pages, based on Active Server Pages (ASP), and ASP.NET web services to dynamically render a Hypertext Mark-up Language (HTML) experiment interface. Arpaia *et al.* [34] used Common Gateway Interface (CGI) scripts, written in Visual C++®, to control a remote measurement station for characterizing the active frequency response of various materials.

Finally, remote desktop software, based on the thin-client architecture, is another approach to providing remote access to laboratory resources. Sivakumar *et al.* [35] developed a remote internetworking laboratory using terminal servers to provide remote access to networking racks for configuring and testing hardware. Tang *et al.* [36] implemented a remote access laboratory for Intrusion Detection Systems (IDS) training using the Microsoft® Remote Desktop Web Connection client to provide browser-based access to remote network test stations.

HARDWARE

The computing hardware used to host remote access laboratories varies significantly among different installations.

For singular experiments that require minimal control and only low-level measurements (e.g. a logic state or constant voltage) an embedded web server or microcontroller is usually sufficient. Humos *et al.* [37] used a microcontroller with embedded web server to remotely measure and characterize the response of a Bipolar Junction Transistor (BJT) using a simple ActiveX Control interface.

More complex experiments that require significantly more control and user interaction often use a target Personal Computer (PC) equipped with a number of data acquisition (DAQ) boards as the host. Wirgau *et al.* [38] developed a remote access laboratory for civil engineering using a real-time DAQ board installed on a host PC to control a shake table experiment using a LabVIEW interface.

Several remote access laboratory installations also include learning management support through multimedia content hosted on an additional web server or Course Management System (CMS). Wirz *et al.* [39] developed a distributed remote multi-robot laboratory with learning support provided by the Moodle [40] courseware package. A more comprehensive architecture was introduced by Rapuano *et al.* [41], using a network of servers and Target PCs to host a remotely-accessible measurement laboratory as part of an eLearning system.

PEDAGOGY

Most of the literature in the field only reports the technical merits of remote access laboratories, with most works being presented as feasibility studies to demonstrate that a particular experimental setup can be controlled remotely. The few papers that do attempt to evaluate the effectiveness of remote experimentation usually only report student feedback, with little or no systematic analysis of the results. In fact it wasn't until recently in [42] that the theoretical implications for learning of remote access laboratories were discussed. Clearly there is a deficiency between the technical and pedagogical development of remote access laboratories. However, despite this deficiency a few recent works have attempted a systematic approach to evaluating the effectiveness of remote access laboratories.

Corter *et al.* [43] compared the effectiveness of proximal vs. remote experimentation based on students' perceptions measured using student feedback, and learning outcomes measured using composite test scores. The results were correlated against students' Standard Aptitude Test (SAT) scores, Grade Point Average (GPA), and preferred cognitive learning styles measured using the VARK catalyst [44]. The study found that students with a visual cognitive preference tended to give a lower rating to the importance of being physically present in the lab, whereas students with an aural cognitive preference tended to feel more immersed in the remote experiment. Interestingly, these findings also correlated with a higher total VARK score (i.e. a strong preference for multiple cognitive modes). Overall, the study found that 90 per cent of students rated remote experimentation as equally effective as proximal experimentation.

Lindsay *et al.* [45] conducted an in-depth systematic study of the learning outcomes for different laboratory access modes as an extension to the work previously reported by Ogot *et al.* [46]. The study compared the effects of performing a piezoelectric accelerometer calibration experiment in three different modes; namely virtual, remote and proximal. Learning outcomes were evaluated based on student feedback and granular laboratory report scores. The report marking scheme was based on a systematic break-down of learning outcomes into criteria necessary to achieve each outcome. The criteria were then subdivided into specific behaviours required to demonstrate each criterion. The report scores represented an unbiased granular representation of student learning outcomes rather than an aggregate measure of overall performance. The study found that access mode did affect some learning outcomes, with different modes offering improved or degraded performance for different outcomes. The study also found that students' perceptions of the learning *objectives* were affected by access mode, whereas students' perceptions of their learning outcomes were unaffected. Interestingly the study found that 30 per cent of students preferred the mode that they had experienced, whereas 60 per cent of students preferred the proximal mode regardless of their access mode. Additional results from the study were also published in [47].

DISCUSSION

Almost all remote access implementations reported in the literature can be classified as the remote deployment of laboratory resources. However, the new paradigm for remote access laboratories that this work introduces is a significant extension to any previously reported works, and therefore requires a classification of its own. Since this new paradigm is part of the much larger eLearning for Engineering introduced by the authors in [48, 49], this new class of remote access laboratory is labelled as eLaboratory.

The defining feature that separates an eLaboratory from a collection of remotely-accessible laboratory resources is the inclusion of people as laboratory resources in addition to the physical hardware and software. An eLaboratory is an extension of the traditional instructional laboratory to a web-based domain that includes the social constructs and collaborative interactions that transcend any particular classroom, laboratory or course.

ELABORATORY ARCHITECTURE AND IMPLEMENTATION

The instructional laboratory environment is composed of two critical elements; namely a collection of physical resources and a community of users. The community aspect has been largely overlooked in the literature. The notion of a user community, however, is fundamental to engineering pedagogy and thus cannot be ignored; a vast portion of engineering knowledge is contextual and can only be learned through the senses and social interactions [50].

In order to extend social constructs to the remote laboratory environment the notion of eLearning must be expanded to include eCollaboration [51]. Consequently, a suitable framework for eLaboratories must include the convergence of eCollaboration with a traditional Learning Management System (LMS), plus the means of remotely accessing physical and conceptual laboratory resources. This framework can be realized through the concept of a corporate intranet portal. In general, a portal is a web system that provides an intuitive and personalized gateway to resources on a network. In the past, portals were synonymous with search engines that provided links to web sites on the internet. More recently, however, portals have expanded to include both the aggregation of resources and the platform for building collaborative user environments.

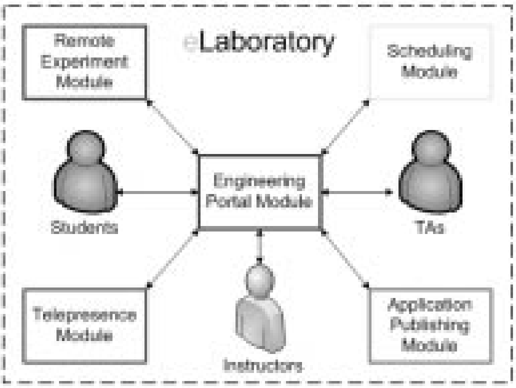


Fig. 1. eLaboratory functional architecture.

The eLaboratory architecture, a new paradigm for remotely-accessible instructional laboratories, is functionalized into four integrated modules; namely the Remote Experiment module, Engineering Portal module, Telepresence module, and Application Publishing module, as depicted in Fig. 1. The generic modular design makes the eLaboratory architecture applicable to all engineering disciplines, and allows new installations to be rapidly deployed and reconfigured.

Remote experiment module
The remote experiment module, illustrated in Fig. 2, is used to provide students with access to hardware resources and is the primary means of delivering experiential education.

Experiment hardware
The physical hardware for each experiment consists of either a pre-existing installation, similar to the wind tunnel in [52], or a custom developed test bed, similar to the robotic Hardware-In-the-Loop (HIL) simulators in [53], that has been modified for computer-aided data acquisition and control, using numerous electromechanical actuators and analogue and digital transducers. The actuators convert an electrical signal to a physical manipulation of matter, whereas the transducers are used to convert a physical phenomenon to an electrical signal.

Hardware interface layer
The hardware interface layer connects the transducers and actuators from the experiment setup to the logical control software. The heart of the hardware interface layer is a workstation, called the Target PC, which is equipped with one or more DAQ boards.

Software interface layer
The software interface layer connects the hardware layer to the user environment. It has three components; the Operating System (OS), Graphical User Interface (GUI) and Watchdog. Each Target PC runs Windows Server® 2003 R2 as the core OS and is configured as a Terminal Server. The GUI for each experiment is a multithreaded application written in Visual C++® that communicates with the DAQ boards using a C/C++ Application Programming Interface (API) provided by the DAQ board manufacturer. The Watchdog monitors the entire system to protect the physical hardware from incorrect user input or software failures.

Telecontrol layer
Remote access to the experiment GUI hosted on the Target PC is provided using the Remote Desktop Protocol (RDP). RDP is a low-bandwidth protocol for channeling a desktop session from a remote server to a local machine. An RDP session is transparent to software running on the Target PC allowing the interface for each experiment to be completely independent of the telecontrol layer.

Engineering portal module
The engineering portal module, illustrated in Fig. 3, is the central web-based gateway that enables students, instructors and Teaching Assistants (TAs) to access the eLaboratory and is analogous to the physical space of a traditional instructional laboratory. The core portal software

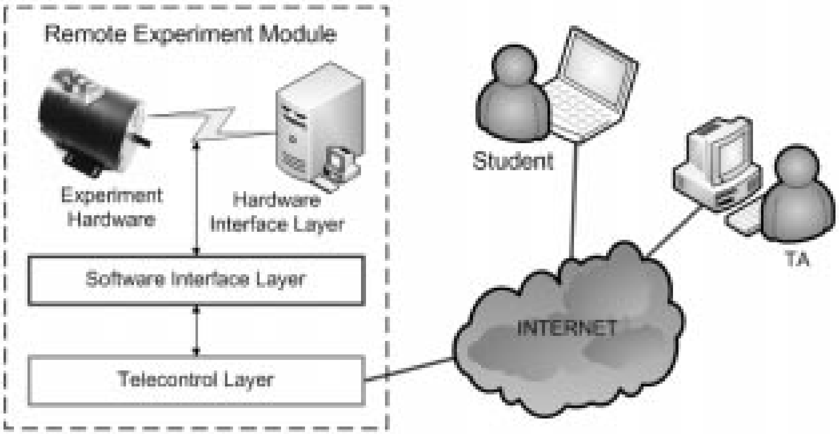


Fig. 2. Remote experiments architecture.

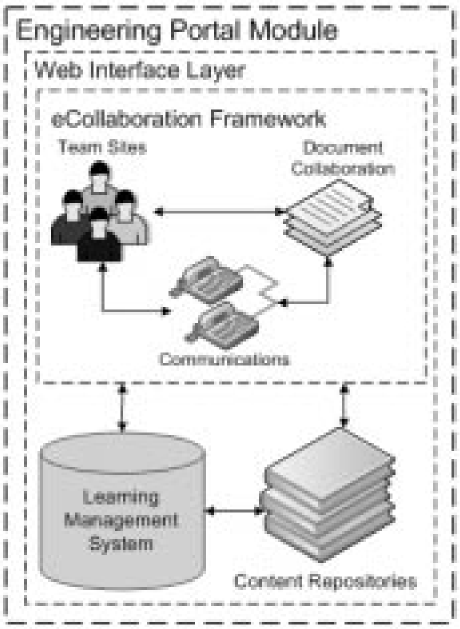


Fig. 3. Engineering portal architecture.

is a collection of ASP.NET web applications, web services and Collaborative Application Mark-up Language (CAML) templates that provide a media-rich interface to a sophisticated database.

Web interface layer

The web interface layer provides a convenient standardized interface for accessing all the eLaboratory resources through a web browser. It is built using template-driven wizards and reusable drag-and-drop web modules, called Web Parts. Using Web Parts enables novice users to build a web site without having to code even a single line of HTML. Web Parts can also be used as content wrappers to link multiple content sources together, forming an integrated and consistent user experience.

eCollaboration framework

The eCollaboration framework provides students with access to each other through a combination of communication and resource-sharing tools, and is fundamental to contextual-based engineering education.

Each student is given a personal site on the portal—analogous to a lab notebook—for storing and managing documents and laboratory work. Students can select portions of their personal site to publish to the portal, or post on the internet. Child sites can be created under each personal site, with dedicated workspaces for specific tasks or projects.

The portal contains a directory of all registered users that is searchable based on user profile entries, similar to a phone book. A group of students can use the directory to find each other and self-organize into a team for completing a group assignment. These groups can then create team sites in the portal on a self-serve basis using dynamic team-driven templates. Team sites are intended for group collaboration, and therefore contain a rich set of collaboration and project management tools. Each member of a team has a personal view of the site, allowing customization of the user interface and displayed content.

Content repositories

Content within the portal is stored in a central content database and is aggregated using an Enterprise-grade content index. Each piece of content—whether it be a page, list, document, or user—is treated as an object with searchable metadata. Although external content is not stored in the central database, it is still listed in the content index, allowing external resources to be included in search results.

Learning management system

The LMS layer of the portal architecture includes all of the features found in a traditional educational Content Management System (CMS), with specialized tools for monitoring software and hardware. The LMS layer monitors each software module in the portal, as well as the physical laboratory hardware and server resources. The LMS layer also manages the registration and authentication of users against a central database that stores a user's profile.

Telepresence module

The telepresence module comprises a streaming video layer and a collaborative communications layer.

Streaming video from each of the experiment setups provide students with visual and auditory feedback that is necessary for achieving an immersive user environment. Video allows students to take remote readings from analog gauges, and also increases the transparency of the user interface, allowing students to directly experience what the experiment is actually doing. The same streaming video system is also used to display live video of the laboratory environment on the internet, which is important for extending the full laboratory experience to the web domain.

The communications layer comprises a Session Initiation Protocol (SIP)-based messaging network that connects students, instructors and TAs in real-time. Users access the communications network using either a web-based Instant Messaging (IM) client or a full SIP client that includes support for Voice-over-IP (VoIP), video chatting, and shared workspaces.

Application publishing module

The application publishing module is an extension of the telecontrol layer that allows students to access laboratory software and computing resources from a centralized application server (Terminal Server) using RDP. The instructor can define a list of pre-approved applications that students can run, along with a set of permissions for each application. Software usage is logged to a database so that the instructor can monitor resource utilization.

Report templates

Report templates are used to standardize the presentation of results. Each template consists of a Word® document with predefined fields for each section, and a series of embedded Excel® objects for displaying graphs and tables. Each Excel® object is preconfigured to import external data from the data files collected during each experiment. Students select which data files to load, and at the click of a button the data is automatically imported into preformatted figures.

A standardized report template is critical when report marks are used to evaluate the effectiveness of remote laboratories. Mitsui [54] suggests that a standardized report template with embedded graphs and charts is required to eliminate the presentation bias that is inherent to the marking of laboratory reports. Nevertheless, care should be taken to ensure that report templates do not limit students' freedom and flexibility in producing creative scientific writing.

Network topology

The eLaboratory network runs under a Microsoft Active Directory® domain with each server running Windows Server 2003 R2. The eLaboratory Portal is based on modular components of the Windows Server System and includes Microsoft Office SharePoint® Server 2007 (MOSS), Office Live Communications Server 2005 (LCS), Office Communicator Web Access (CWA), and SQL Server 2005. Hardware and software specifications for each server are summarized in Table 1.

Bandwidth requirements

Most of the early literature on remote access laboratories sighted bandwidth as a significant barrier to providing a fully immersive user experience through the use of live audio/video. However, the general assumption was that within several years high-bandwidth internet connections would become readily available and more importantly, that they would be affordable. Although clients may now be able to support the high-bandwidth required for live audio/video, the remote server may not be cable of providing multiple simultaneous broadcasts to all clients. Kikuchi *et al.* [55], for example, used a bandwidth of 15 Mbps to transmit a High Definition (HD) video stream of a motor control experiment, which would be prohibitive for multiple concurrent experiments hosted at the same site.

The full experiment interface for one experiment in the eLaboratory Portal consists of an RDP session (1–20 Kbps) for connecting to the remote Target PC, an audio stream (14.4 Kbps) for receiving sound from the microphones and up to two simultaneous video streams (56–256 Kbps) from the webcams. Based on tests with various experimental setups the nominal required bandwidth is approximately 128 Kbps with a maximum burst rate of 400 Kbps for the highest quality audio and video.

Latency considerations

A common assertion in the literature is that web technologies will enable universal access to laboratory resources 'at any time, from any place' [32]. Indeed, the authors used this same notion in establishing the motivation for remote access laboratories in the introduction of this work. However, very little research has been conducted to demonstrate that telecontrol is feasible on a global scale. In addition, time delays such as those reported in [56] are a common deficiency of remote access laboratories that greatly hinder the usability and transparency of the user interface.

The latency of the eLaboratory Portal was measured for several possible user scenarios using the Ping network utility. The Target PC for the supersonic wind tunnel experiment, described above, was pinged from 23 globally dispersed servers located across six continents. The bandwidth to each server was also measured as a metric for quantifying the quality of network infrastructure between the local Target PC and remote server. The results, which are summarized in

Table 1. Hardware and software specifications for the eLaboratory

Server	Processor	Memory	Network	Function
Target PCs	Pentium® IV (× 86) 2.0MHz	256 MB	100 Mbps	– remote desktop – user interface
Application	Dual Xeon® (× 64) 2.8 GHz	4 GB	1 Gbps	– remote desktop – software resources
Communications	Dual Xeon® (× 64) 2.8 GHz	2 GB	1 Gbps	– communications – IM web client
Portal	Dual Xeon® (× 64) 3.0 GHz	4 GB	1 Gbps	– engineering portal – backend database
Domain Controller	2 × Pentium® III (× 86) 1.1 GHz	2 GB	1 Gbps	– domain controller – firewall and VPN
Video	Pentium® D (× 86) 3.2 GHz	1 GB	1 Gbps	– video capture – streaming server

Table 2. Latency and bandwidth measurement from global servers

Location	Distance (km)	Latency (ms)	Download (Mb/s)	Upload (Mb/s)
Auckland	13800	222	0.6	0.9
Melbourne	16200	503	2.0	0.8
Jakarta	15750	480	0.5	0.9
Yokohama	10350	161	1.6	1.5
Quezon City	13150	439	1.6	0.9
Hong Kong	12500	594	0.1	0.1
Lahore	11200	398	1.2	1.2
Cape Town	13050	262	0.5	0.2
Tashkent	10050	285	1.7	0.4
Moscow	7450	213	0.3	3.0
Lublin	7050	143	1.9	3.4
Dusseldorf	6100	108	3.5	2.3
London	5700	111	4.4	1.7
Maceio	7350	234	2.2	0.2
Curacao	3600	97	2.5	4.9
Vancouver	3350	164	3.2	2.7
Los Angeles	3500	169	5.3	5.6
El Paso	2700	83	3.1	6.6
Dallas	1950	158	6.6	5.8
Twin Cities	1100	75	12.0	7.6
Chicago	700	153	3.7	8.5
Toronto	50	93	45.4	25.8

Table 2, indicate that most remote connections from outside of the host city have a latency that is greater than 100 ms.

Although performance of thin-clients such as the RDP client used in the eLaboratory are difficult to quantify [57], based on the authors' personal experience the user interface for RDP begins to exhibit degradations with latencies above 100 ms. Obviously the cut-off for acceptable real-time control will vary among different hardware setups. Marín *et al.* [58], for example, report a total latency of 3000–4000 ms for the remote operation of a robotic arm.

HARDWARE EXAMPLE

Supersonic wind tunnel

The supersonic wind tunnel, depicted in Fig. 4, demonstrates some basic concepts of supersonic flows using a nominal Mach 1.6 wind tunnel. The contoured tunnel floor is slotted and sealed to permit the insertion of either a traversing Pitot impact tube or knife-edge probe. The Pitot impact tube is used to measure the stagnation pressure throughout the supersonic flow, while the knife-edge probe is used to visualize oblique shockwaves using a Schlieren camera system.

The pressure from the Pitot impact tube is measured using a Honeywell absolute pressure transducer that converts pressure values to a voltage that can be read by the Analog-to-Digital (A/D) converter on the DAQ board. The position of the probe in the tunnel test section is changed using a probe manipulation platform that has two degrees of freedom. The manipulator consists of linear stepper motors, controlled using digital Input/Output (I/O) from the DAQ board, to position the probe with an x-resolution of 0.006096 mm and y-resolution of 0.00075 mm.

Experiment workflow

From the experiment interface page the student logs onto the Target PC through an embedded RDP client control. Live video from the experiment is displayed alongside the interface using a pair of streaming video controls also embedded in the page. During the initialization of the user interface, depicted in Fig. 5, the software maps the student's personal document library to a network drive using the Web-based Distributed Authoring and Versioning (WebDAV) protocol.

If students encounter difficulties during the experiment they start an IM web client from the experiment page and contact the TA or instructor for help. The TA then logs onto the experiment to take control of the user interface to show the student what to do. When the TA is done helping the student the TA disconnects from the student's session, which allows the student to continue the experiment unaided.

Report workflow

During the course of the experiment any data files, images or videos that the student collects are saved to the student's personal document library. After completing the experiment the student accesses software on the application server to analyze his/her data and write a report. The student saves the completed report to the online repository as a Portable Document Format (PDF). After the submission deadline the TA for the experiment downloads the submitted report for grading, and comments the document using embedded tags in the PDF file. The student then downloads the commented PDF file to receive

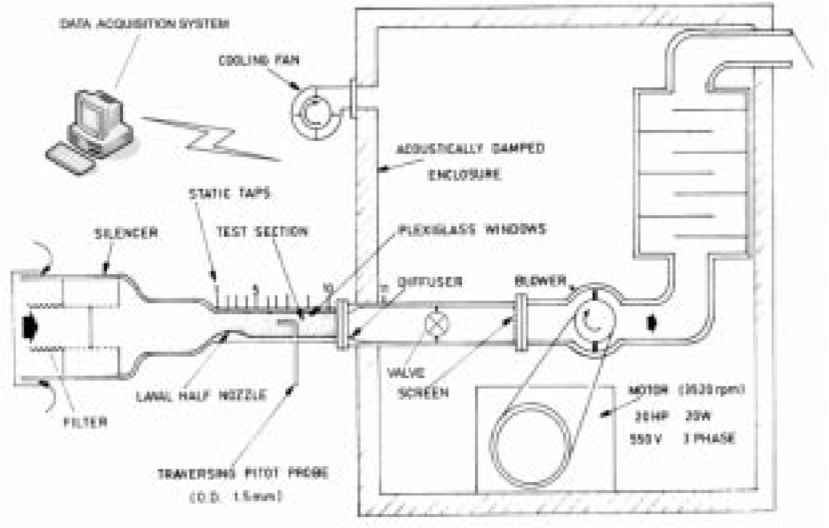
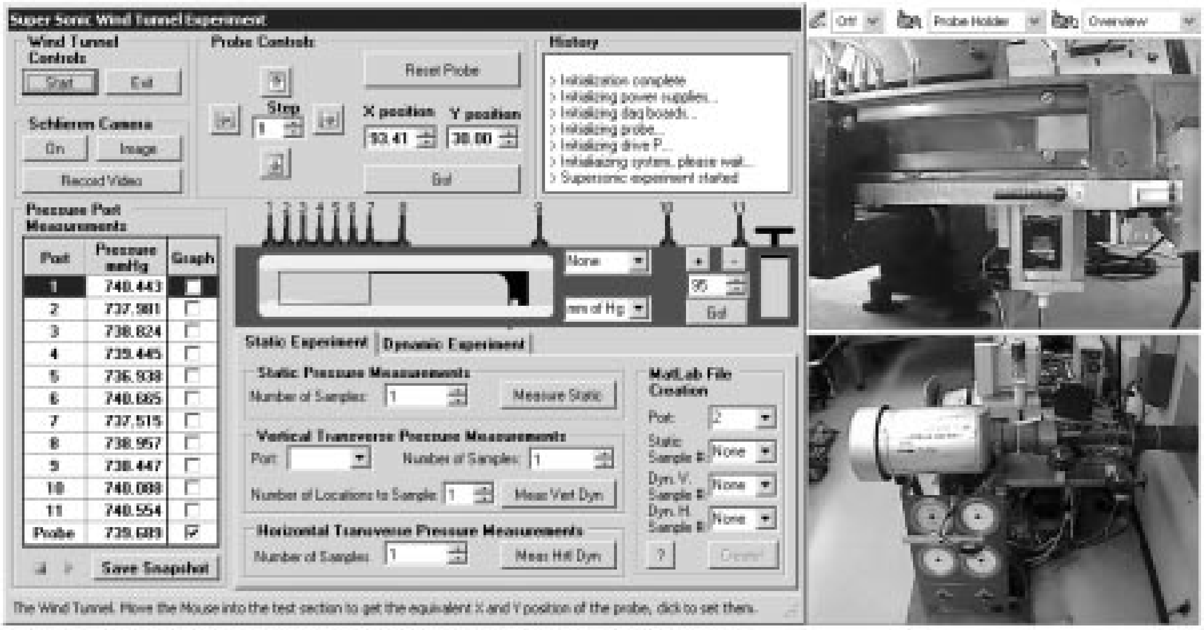


Fig. 4. Supersonic wind tunnel schematic.



X position 93.41 Y position 30.00

> Initialization complete
> Initializing power supplies...
> Initializing daq boards...
> Initializing probe...
> Initializing drive P...
> Initializing system, please wait...
> Supersonic experiment started

Pressure Port Measurements

Port	Pressure mmHg	Graph
1	740.443	☐
2	737.981	☐
3	738.824	☐
4	739.445	☐
5	736.938	☐
6	740.665	☐
7	737.515	☐
8	738.957	☐
9	738.447	☐
10	740.088	☐
11	740.554	☐
Probe	739.689	☑

None
mm of Hg
95

Static Pressure Measurements
Number of Samples: 1

Vertical Transverse Pressure Measurements
Port:
Number of Samples: 1
Number of Locations to Sample: 1

Horizontal Transverse Pressure Measurements
Number of Samples: 1

Port: 2
Static Sample #: None
Dyn. V. Sample #: None
Dyn. H. Sample #: None

The Wind Tunnel. Move the Mouse into the test section to get the equivalent X and Y position of the probe, click to set them.

Fig. 5. User interface for the supersonic wind tunnel experiment.

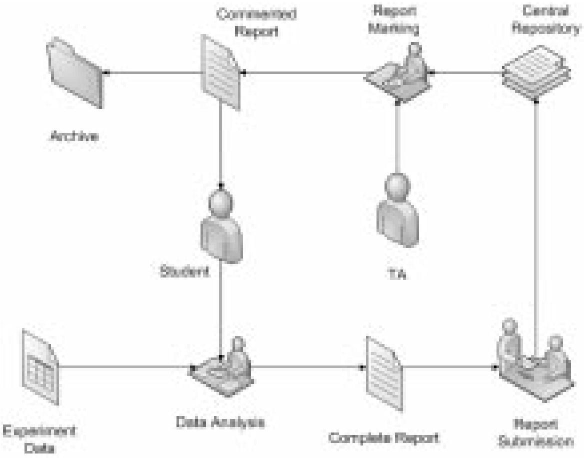


Fig. 6. Laboratory report workflow.

feedback. Finally, the instructor for the course can archive the submitted and commented reports for future reference or automatic plagiarism detection. The complete report workflow is depicted in Fig. 6.

EVALUATION

The eLaboratory Portal architecture was developed and evaluated for two stand-alone laboratory courses (AER303 and AER304) for third-year undergraduate Aerospace students in the Engineering Science program at the University of Toronto. The first two years of Engineering Science provide a rigorous background in engineering fundamentals, with students specializing into a particular option in the third and fourth years. Hence, all students had an identical background in terms of their undergraduate engineering education. A total of 26 students was considered for the quantitative analysis of this study.

Courses

The learning objectives for AER303 are to teach students proper data analysis techniques and to introduce them to formal scientific writing (i.e. the course was integrated with an engineering communications course). The procedure and expectations for each experiment are explicitly defined at the start of the course to ensure students are not overwhelmed by their first experience with computer-aided data acquisition. Comprehensive experiment manuals are provided that explain the background theory and have step-by-step instructions on how to complete each experiment and analyze the resulting data.

The learning objectives for AER304 are to teach students the fundamentals of experimentation and experiment design. Students are assumed to be fully familiar with the remote access modality and well versed in data analysis and scientific writing. The experiment manuals still provide background theory, but instead of providing step-by-step instructions only explain the hardware setup and user interface.

Student feedback surveys

Students were advised to complete a seven-question survey to determine their perceptions of the effectiveness of the eLaboratory. The questions were based on a similar survey used by Lindsay *et al.* [45]. The following seven questions were asked:

1) What effect do you think remote access had upon this course?
2) If given a choice between proximal (in person in the laboratory) or remote which access mode would you have chosen and why?
3) Did you feel that the data you collected was accurate?
4) What do you think the learning objectives of this course were?
5) What was the most important thing you learned from the laboratory class?
6) Did you find this course intellectually stimulating? Why or why not?
7) Did you enjoy this course? Why or why not?

In addition to completing the survey, students were asked to complete the VARK learning style catalyst. The VARK catalyst measures students' cognitive learning style preferences in four categories: namely visual, aural, read-write, and kinesthetic. Although the VARK catalysts has not been statistically verified in terms of its accuracy, it has been proven useful in several studies related to the preferred learning styles of engineering students [59–61].

RESULTS

Students' preferred access modality for proximal versus remote access is shown in Fig. 7 below. In both courses the majority of students either preferred remote access or showed no preference. The percentage of those who preferred proximal access remains almost the same in both courses. However, the reasons for this preference as indicated by the students are different. In AER303, there were concerns with the transparency of the user interface, with the most prevalent comment being that students did not understand what the apparatus was doing when a particular button on the user interface was clicked. Partially this was due to the lack of basic background knowledge in computer-aided data acquisition and partially due to the overly rigid template imposed on the user interface. Concerns with the transparency of the experiment interface tended to correlate (confidence level higher than 95 per cent) with the perception that the data collected were somehow incorrect or inaccurate. These results support the notion introduced by Benmohamed *et al.* [62], which establishes that a remote experiment interface must be designed for specific pedagogical activities to provide learning support, but that a balance must be struck to maintain transparency.

In AER304, on the other hand, students related their preference for proximal access to the numerous hardware problems with the setups, so that they perceived these problems as being intrinsic to

Fig. 7. Preferred access modality for AER303 and AER304.

Table 3. Cross-correlation of student survey responses

	Q2	Q3	Q4	Q5	Q6	Q7
Q2	1 (1)	0.34 (0.91)	0.17 (0.58)	–0.22 (0.73)	–0.12 (0.45)	0.17 (0.59)
Q3	0.34 (0.91)	1 (1)	0.15 (0.53)	0.26 (0.8)	0.15 (0.54)	0.40 (0.96)
Q4	0.17 (0.58)	0.15 (0.53)	1 (1)	0.19 (0.65)	0.05 (0.2)	0.04 (0.14)
Q5	–0.22 (0.73)	0.26 (0.8)	0.19 (0.65)	1 (1)	–0.10 (0.38)	–0.01 (0.05)
Q6	–0.12 (0.45)	0.15 (0.54)	0.05 (0.2)	–0.10 (0.38)	1 (1)	0.49 (0.99)
Q7	0.17 (0.59)	0.40 (0.96)	0.04 (0.14)	–0.01 (0.05)	0.49 (0.99)	1 (1)

the remote modality. However, most of the problems were associated with limitations in the available equipment and could not have been overcome in the proximal mode. Students that experienced hardware failures during the course of an experiment tended to blame the remote aspect of the experiment. Clearly, this would result in a preferential bias against the remote modality since students generally felt that hardware failures could be corrected in person.

Nevertheless, a common concern with the remote access was the lack of physical interaction with the equipment, with one student commenting "Proximal, I want to smell the oil". Interestingly, the only two students who performed the experiments both remotely and proximally (using a workstation in the laboratory) showed no preference for either modality. This may indicate that the preference for proximal interaction is a result of students' preconceived notion of what constitutes a "laboratory". In addition, the extensive use of computer-aided data acquisition may have resulted in a greater abstraction from the physical hardware than if students had been asked to collect data using remote perception (e.g. reading an analogue instrument gauge).

Another interesting observation is the significant increase in the number of students that showed no preference for either mode from AER303 to AER304. Based on students' qualitative feedback responses it appears that more students in AER304 recognized the advantages in the flexibility of remotely-accessing laboratory resources. This is confirmed by the system usage data, which indicated a more varied usage pattern for AER304 than AER303 (i.e. students accessed each experiment at various times throughout the day). However, it should be noted that this increase is at the expense of preference for remote access not proximal. Again, faulty hardware can be the cause for such a shift, or one can argue that in AER304 the novelty of remote access had faded and consequently both modes of access were perceived equally.

The survey responses were converted from nominal categorical data to numerically encoded data (i.e. each categorical response to a particular question was encoded as a different positive integer), so that the results could be tabulated and cross-correlated using the MATLAB® (R2007a) Statistics Toolbox.

Table 3 shows the cross-correlations between the students' feedback responses with the confidence levels indicated in the bracket. Several correlations are observed. The strongest correlation is between questions 6 and 7. Students that found the course intellectually stimulating also tended to enjoy the course more than those that did not. Clearly, interest in a course can lead to improved enjoyment, which may lead to improved educational outcomes. Interestingly, there was also a correlation between questions 3 and 7. Students, who thought the data they collected were accurate, also tended to enjoy the course more than those who did not. In addition, the rather significant correlation between questions 2 and 3 indicates that the perception of data accuracy is related to the preferred access modality. Students who felt their data were accurate also tended to prefer remote experimentation or show no preference at all. However, most students who felt their data were inaccurate also indicated that they felt the inaccuracies were due to faulty equipment. Therefore, it is likely that the lack of interest in remote access modality in those students was due to the hardware failures.

For the questions related to students' perceived learning objectives and outcomes (questions 4 and 5 respectively), despite the variety of responses to the open-ended questions clear trends emerged that could be categorized into several groups, similar to those suggested by Lindsay *et al.* [45].

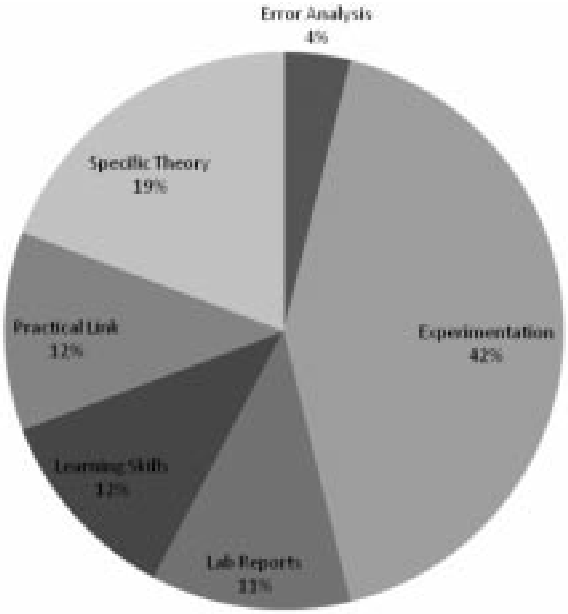


Fig. 8. Students' perceived learning objectives.

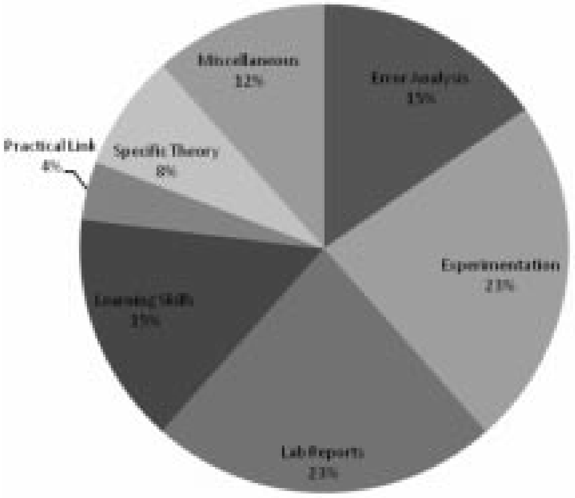


Fig. 9. Students' perceived learning outcomes.

Figures 8 and 9 depict the distribution of these categories in students' learning objectives (question 4) and learning outcomes (question 5), respectively. There is significant dissonance between students' perceived learning objectives and their perceived learning outcomes. Similar observations were made in [39] with the most significant finding being that the dissonance was independent of access modality. Notable is that the majority of students identified learning objectives and outcomes that were consistent with those initially defined for the AER303 and AER304 courses; namely error analysis, experimentation, and lab reporting. This result suggests that the remote modality is effective in so far as meeting the aforementioned course goals. Further study is required with a larger population to determine if there are significant differences between students' perceptions of learning objectives and outcomes based on their preferred access modality.

There were no statistically significant correlations between the student survey responses and the VARK scores except for the course enjoyment (question 7) and preference for *read-write* cognitive learning style. This means that those students who prefer read-write communications in their learning tended to enjoy the laboratory courses more. Corter *et al.* [43] reported a mild correlation between VARK scores and students' ratings of different aspects of the remote laboratory experience. Further study, however, is required with the inclusion of granular laboratory report scores in the analysis to confirm this finding.

Several typical positive responses to the remote access modality include:

- simplified access/communication
- easier on time and travel
- it makes the lab more straightforward
- it's very easy to perform the experiment while sitting at home
- made data collection simple and straightforward, but a bit tedious

Several typical negative responses to the remote access modality include:

- not the best idea, lack physical interaction
- a sense of lack of motivation to do it at home
- took out 'hands-on' experience, made it difficult to visualize . . .
- involving new technology inevitably may let more things go wrong
- I would choose to do it in the lab because I could feel more involved to do things myself, than clicking the buttons

Feedback from the TAs indicated a fundamental problem with remote communications. The TAs felt that despite the usefulness of the remote control interface that synchronous text messaging did not provide adequate problem solving support. This result supports the findings of Böhne *et al.* [63], which indicated that video chatting was the only remote communications mode that was nearly as effective as proximal interaction. A later study conducted by Böhne *et al.* [64] also found that desktop sharing (i.e. remote control) could be effective as a collaborative problem solving tool, if combined with synchronous video chatting. One limitation, however, is that not all students have access to a webcam, which makes video chatting limited in its application. Despite the support for video chatting in the eLaboratory architecture, no student used this communications mode.

Finally, most students commented about the positive impact of integrating new technologies into laboratory teaching. The comments focused mainly on the benefits of computer-aided data acquisition and the use of software tools (e.g. automatically importing data into the report templates), although several responses also recognized the scheduling advantages to having laboratory resources remotely-accessible. Interestingly one student commented that the remote access modality gave a "new perspective of a laboratory". Based on this comment further research is required to determine if access modalities can be used to alter students' perceptions of Engineering.

CONCLUSIONS

Despite the gradual emergence of remote access laboratories in engineering curricula, little has been addressed in the literature about their pedagogical implications, nor can one find a unified and consistent framework for their implementation. This paper presented a generic and modular architecture for remotely-accessible elaboratories, which is based on a convergence of remote access technologies and collaboration-based eLearning, and also discussed the implementation of such a framework and students' evaluation of its learning outcomes.

The eLaboratory architecture consists of four independent but integrated modules that are instrumental for the engineering eLearning, namely Remote Experiment module, Engineering Portal module, Telepresence module, and Application Publishing module. The generic modular design makes the eLaboratory architecture applicable to major engineering disciplines, and allows new installations to be rapidly deployed and reconfigured.

An evaluation of the eLaboratory architecture produced several significant findings. Students are generally receptive to new technologies introduced into the learning process. However, there is a natural tendency for students to prefer what they are used to (i.e. proximal experimentation), but their acceptance of new access modes increases over time. Abstracting students from the physical hardware shifts the focus from the experimental setup to the user interface and remote technologies. Hence, in the case of hardware failure students tend to associate the failure with the remote aspect of the experiment, rather than with the physical hardware. In addition, there is a general perception that proximal experimentation would allow these failures to be easily corrected.

The major areas of concern that were highlighted in the evaluation were an overall lack of transparency in the user interface and insufficient communications between the students and TAs. Both of these concerns are related to the telepresence aspect of the user experience. Future works will attempt to address these concerns by increasing the transparency of the user interface and reducing the transactional distance [65] between the students and TAs.

Based on the evaluation of the eLaboratory paradigm several new research tasks have been identified. The most significant unanswered question is the contribution of the computer control interface to learning outcomes, regardless of access modality. Previous pedagogical studies in the field have compared the learning outcomes of students performing an experiment in person to those of students performing the experiment through a remote computer-mediated interface. Recently Lindsay *et al.* [42] drew parallels between the Clark-Kozma debate [66–69]—which focuses on the effect media has on education—and the use of technology-mediated interfaces in remote laboratories, which further highlights the need for an investigation of the role of the computer interface in remote laboratories. Future works will attempt to address this issue with a comparison of remote vs. proximal experimentation using the *same* computer interface.

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