The Effectiveness of Virtual Laboratories for Electrical Engineering Students from Faculty and Student Perspectives

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CONTEXT This research is focused on understanding the role of virtual laboratories and physical laboratories, specifically in the context of the electrical engineering discipline. It is important to emphasize that the research is not aimed at replacing physical laboratories as they form an essential part of the education of electrical engineers, but focuses on how virtual laboratories are used to supplement learning in physical laboratories.

PURPOSE Specifically, this research aims to identify the important learning objectives and virtual laboratory design features, as well as how virtual laboratories supplement physical laboratories from both the student and faculty perspectives. Additionally, the important design guidelines for the implementation of virtual laboratories are explored.

APPROACH A mixed method approach was used in the research that included both qualitative and quantitative methods. A detailed literature review was performed, supplemented by multiple surveys of both students and faculty. A virtual laboratory was designed and implemented using the input of the students to better understand what users desire and require in their virtual laboratory and students provided helpful input to the development and refinement of the virtual laboratory. The results of the surveys, along with the findings in the literature and the findings from developing and implementing a working virtual laboratory were combined to address the research aims.

RESULTS In the literature, virtual laboratories have been found to be effective for students, particularly those with limitations, either physical or time-based, who may have difficulties with aspects of accessing physical laboratories and the associated scheduling. Instructors and technical staff may find virtual laboratories useful, but with additional challenges for set-up, maintenance and integration with coursework. Many studies argue the effectiveness of virtual laboratories but find disadvantages related to insufficient realism, ineffective groupwork capabilities, maintenance of the systems and a lack of appropriate skill set development for real-world situations. Advantages of physical laboratories included flexibility for students, more time for experimentation, fewer overcrowded classroom and lower costs than physical laboratories.

CONCLUSIONS From the surveys, it was determined that the concept of realism and teamwork in the virtual laboratory are most important to students. Realism supports students' abilities to meet learning objectives, such as experimentation, design, instrumentation and their ability to understand and replicate theoretical models, while teamwork skills improve their ability to be successful in the classroom and in their careers. For their virtual laboratory, they desire easy-to-use interfaces that are reliable and consistent, and help them to learn by providing feedback on errors and feedback from their tutors, as well as providing supplementary learning tools. Many students that were surveyed identified using the simulator to prepare for testing and the virtual laboratory gave them the opportunity to experiment at their own pace when time in the physical laboratory was more limited.

KEYWORDS Virtual laboratories, electrical engineering.

Introduction

Like many global industries, post-secondary education has seen a significant evolution over the past half century due to the influence of information technology. In particular, higher education at both undergraduate and postgraduate levels has seen considerable innovation in the means through which teaching is provided. While traditional delivery mechanisms such as lectures, laboratories involving real-world equipment and classroom examinations are still employed to a significant degree in higher education, they are being supplemented or replaced by technology-enhanced means such as online streaming of lectures, timed online examinations and virtual laboratories.

Such modern digital resources serve as tools for educators to enhance the quality of education whilst catering to the individual learning preferences of students. For instance, through traditional means of teaching, students may be limited geographically to the location of the classroom, whereas streaming of such lectures online frees them from such a restriction. This in turn, allows students to save time, manage their learning around a busy schedule with family, work and commuting. However, location is only one of the many limitations that digital education resources solve. Given the scalability of modern media, educators can provide teaching with reduced effort to large numbers of students. As a result, the fees for education can be lowered since delivery costs per student are reduced. The digital domain provides an enhanced delivery of education through visual, audio and information-gathering resources that are difficult to replicate otherwise in a purely non-digital domain.

On the other hand, there are some learning activities which are difficult to effectively replicate in an on-line environment. Engineering laboratories are one such activity, where on-campus delivery is still the dominant mechanism, and on-line delivery is in its preliminary stages. While various manifestations of education technology are highly capable from a functional point of view, the design itself must also address factors that are crucial to the learning process and crucial to skill development of electrical engineering students.

Background

The following definitions relate to educational laboratories where students build and investigate engineering structures to better understand their operation.

A *Physical Laboratory* is a traditional laboratory where students are physically co-located with the apparatus under investigation. Often (but not always) students perform their experiments in groups that are supervised and assisted by laboratory demonstrators. A physical laboratory refers to the traditional laboratories which are built upon real estate and have physical equipment (Budhu, 2002).

In a *Remote Laboratory,* students also perform their experiments on physical equipment, where control and data acquisition to the equipment is mediated by sensors and actuators which in turn are accessed by a web interface (Tawfik, et al., 2013). Students may still conduct the experiments together in groups supervised by a demonstrator, or they could access the equipment at times and places of their choosing.

A *Simulation Laboratory* is where students perform experiments using a computer simulation of a system. The simulator may implement a realistic model of a system (such as a simulated circuit breadboard into which simulated wires, components and meters are connected) or on a more abstract model (such as a circuit schematic).

A *Virtual Laboratory* is an umbrella term for both remote and simulation laboratories, i.e., any laboratory where access to the experiment is entirely on-line. A virtual laboratory is a laboratory experience without the physical laboratory (Keller & Keller, 2005). Virtual laboratories are programmed systems that can simulate the features and activities of the real experiments that are done inside a real laboratory (Harry & Edward, 2005); (Altalbe, Bergmann and Schulz, 2015).

In a virtual laboratory, experiments are conducted and controlled partially or totally by using computers, simulation and animations, and more recently with the use of mobile devices (Frank & Kapila, 2017). Various models of virtual laboratories differ in their level of replication of reality (Budhu, 2002). The "MIT iLab" system is an open-source software framework which supports online (usually remote) laboratory experiments (Hardison, DeLong, Bailey, & Harward, 2008). It was first developed for batch-mode remote experiments and has been recently extended to support interactive experiments with the addition of a highly configurable service of the laboratory resource scheduling, a huge and strong data storing system, and capability to support high bandwidth communication systems between the laboratory server and the client.

The International Federation of Automatic Control (IFAC) has been studying virtual and remote laboratories for over a decade, including a control education remote laboratory (Esquembre, 2015). The remote options at the RobUALab include robots, servers for the network and teleoperation, camera, and software for modelling, access control and the robot interface (Jara, Candelas, Puente, & Torres, 2011). Some of the earliest work with remote laboratories and robotics was developed at the University of Western Australia along with remote robotics developed in the Mercury Project (industrial robot arm with a camera) and the Telegarden Project (Jara, Candelas, Puente, & Torres, 2011).

Individual differences amongst students and relative openness of the laboratories are important factors to be considered while designing experiments. Quality of interface and level of social interaction are important aspects to be considered to meet the student needs (Jara, Candelas, Puente, & Torres, 2011). It is important that while designing such laboratories the perceptions of the relevant students should be considered. This is because the perception of realism can be manipulated to improve the effectiveness (Nickerson, Corter, Esche, & Chassapis, 2007).

The design of online group work and the teaching method should be conducive to improving its effectiveness (Koh & Hill, 2009). Features of the online environment, personal attributes of the learners, and the teaching strategies employed by the instructors impact the learning process (Koh & Hill, 2009). Frustration with working in online groups can lead to situations where members drop out of the interactions (Warkentin, Sayeed, & Hightower, 1997). Other important barriers hindering participation of students in online group work include lack of availability of time and students' preference for reading compared to discussing matters online (Fung, 2004).

The process of conducting an experiment on the system should be explained in simple terms and be easy to understand (Stefanovic, 2013). The software needs to have a good interface, should have multi-platform portability, and should offer modularity by allowing development of the program in parts. Further, it should be compatible with the available hardware and should align with the existing code (Stefanovic, 2013). Debugging and help options are important. Features, such as extendable program libraries, increase the flexibility of the system. Multimedia features are particularly important (Tiwari & Singh, 2011). However, ease of use of the interface is more important in the context of learning and cognition compared to smoothness of navigation (Budhu, 2002). Help features can provide real-time guidance and support (Keller & Keller, 2005).

Ideally, a virtual laboratory must include a real-life scenario from which the student can collect data in a realistic environment (Stefanovic, 2013). This is because, in effect, working with a simulation is like exploring an algorithm which tries to imitate the real world. The discoveries made in the process of experimentation may be those related to the algorithm. One approach makes the system appear to control like a real lab (Keller & Keller, 2005). The laboratory responds with a video of the experiment. Students can remotely control the system, watch the video and gather data at various points in the video. The software collects and presents the data gathered or generated by the students. This is different from the simulation where the data is already fed into the algorithm (Keller & Keller, 2005). Animation techniques, videos, and 3D models help make the system more attractive for the students (Babateen, 2011).

In (Balamuralthara, 2013), student feedback was obtained on attitudes towards computer-based laboratories and experimentation. When students were asked to rate important aspects of laboratories, the authors found teamwork to be the highest rated item by the students. Students indicated that teamwork was essential to successfully conducting an experiment. Besides rating teamwork highly, students also felt that having assistance from a supervisor or technician was important.

The Simulator

The virtual laboratory prototype was designed to be a breadboard simulator for electronic circuits (DC based) and allowed students to connect components like resistor, diode, LED, IC, inductor and power supply on the given platform in a manner much like a real breadboard. It allowed them to simulate the results in the form of current and voltages based on real mathematical data and formulas based on Ngspice. The app makes heavy use of modern web browser features like JavaScript, DOM manipulation, SVG graphics and AJAX. The tool is different from a standard simulator as it can be coded to work with real equipment so students can have the experience of being in a real laboratory. When there is a good camera with proper zoom, students can see the same results on their simulator as they see on the camera attached to physical equipment, making the tool a remote laboratory and a simulation laboratory.

The virtual electronic circuit simulation laboratory system is a process that enables users to assemble and simulate electronic circuit via the library of SPICE3f5. Electronic circuit components were designed to be dragged and dropped into place in the schematic drawing. The term UQEEVL refers to UQ Electrical Engineering Virtual laboratory which allows students, tutors and professors to interact remotely and conduct virtual versions of their experiments (electronic circuits) at any time and obtain required results. Additionally, they also help carry out experiments that cannot be performed in physical laboratories due to limitations in equipment. Once users log in, they can then create a new project and drag components into the schematic drawing.

The tool is designed such that users can create their own experiments, retrieve saved reports from the database, and share and edit experiments. The system also provides a chat option to ease communication with tutors, classmates and groups. Spice3 was installed on the university server and a trusted domain at EAIT was registered for the tool at UQ (https://virtual-laboratories.eait.uq.edu.au). Ngspice release 23 was installed and is based on three open source software packages: Xspice, Cider1b1 and Spice3f5. There was a need for three separate programs and these are explained below:

1. A custom Java-based circuit editor that operates using an Internet browser, and generates circuit diagrams and netlists that can be stored on a database as <any name>.cir, able to display simulation results.
2. A web-server application that enables students to store user's circuits and simulation results on a database, that can also communicate with the simulation package. An example of this is currently operating on the University of Queensland's webserver.
3. A simulation package that can create circuit netlists and produces circuit waveforms, voltages, etc. Users never access this package, only the webserver does. This also runs on a server.

After successful completion of the whole circuit, the system's intelligent logic layer will determine the mode of the circuit. The power source management, diode and resistors are stored with their corresponding values, properties. The collected data can thereafter be sent to the application server and via this server the whole data are processed using the SPICE3f5 library. The total circuit is solved and the simulation result is then sent to the user's browser window.

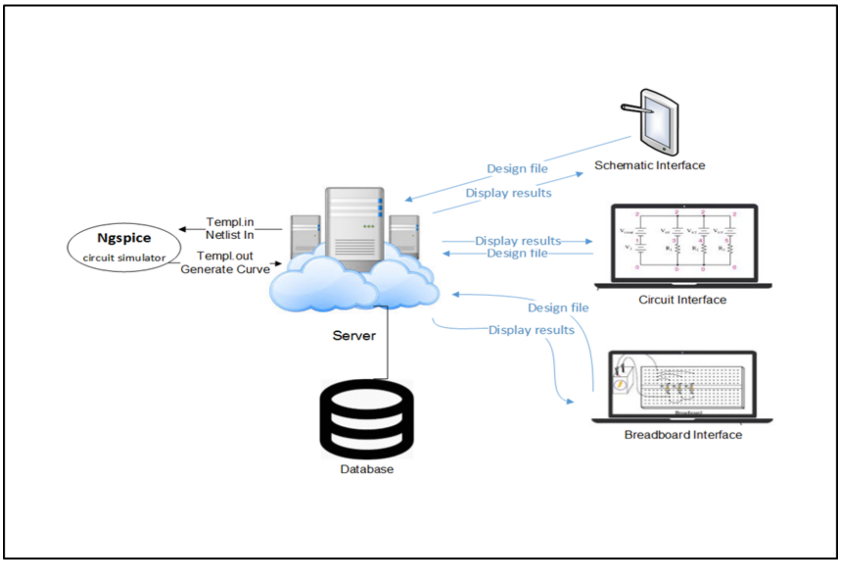

Figure 1: Lifecycle of the Simulation Software

Methods

In this research, a mixed method approach was used that consists of both qualitative and quantitative methods (Creswell, 2013). Firstly, a detailed critical analysis of the available literature was performed using a scoping study approach where a systematic review of existing literature related to virtual and physical laboratories is undertaken. Secondly, an experimental approach was employed by developing an example virtual laboratory to better understand the challenges related to the laboratory implementation. Thirdly, survey data and interviews were analyzed including the quantitative data and qualitative data.

Results

In the literature, faculty and student evaluations of virtual laboratories were mixed. Some students felt that computer experiences were not capable of replacing the physical laboratory experience and argued that computer screens are not capable of replacing many laboratory instruments. Collaboration in online environments was found to be frustrating for some students, but others felt their teamwork skills improved. Studies found that students find physical laboratories easier and more satisfying than virtual laboratories and that virtual laboratories are integral to traditional laboratories, but not a replacement.

Several studies in the literature advocated that the learning outcomes obtained in virtual laboratories are comparable to the outcomes obtained in the physical laboratory and for disabled students, and students in remote or rural areas, access to laboratories is now a reality. Educational leaders found it increasingly important to provide online learning, while for faculty, generating the exercises was found to be more burdensome. Again, the literature was somewhat mixed in that monitoring of students was found to be more difficult in one study, but others found that virtual laboratories improved the monitoring of students.

In the survey results, realism was the most important consideration of the respondents as shown in Figure 4, and indicates that a virtual laboratory should provide an experience that gives students the same capabilities that they have in the virtual laboratory. The students expressed desires for realism so that their education received in the virtual laboratory is comparable to the education they receive in the physical laboratory and that the skills developed are transferrable to a real-world setting. The ability of a virtual laboratory to supplement physical laboratories appears to be highly dependent on the concept of realism.

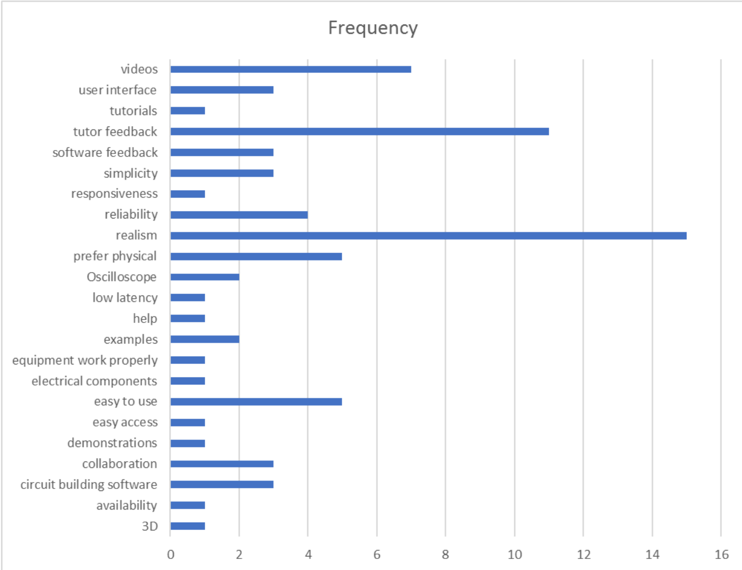

Figure 2: Analysis of Open Ended Survey Responses

Around 7% of the respondents indicated that they were more interested in using a physical laboratory as opposed to any virtual laboratory. While overall, most respondents were excited about using the simulator, it is important to note that there is a contingent of the student population that prefers the experience in the physical laboratory. Some of the student responses were quite adamant about their desire to work in a physical laboratory, including the following:

- *"I would not want to use virtual laboratories. I am paying to learn how to use equipment in the real world. It is of no use to me if I am using a virtualization of a physical device, if I have not understanding of how it works in the real world."*

One student commented, although not an advocate, that virtual laboratories are highly relevant in the cases of hazardous circumstances or where the real-world application of the skills require use of a virtual or remote operation of equipment.

From the comparison survey of virtual laboratories to the Breadboard simulator, it was found that students were using the Breadboard in timeframes associated with exams and rated using the Breadboard prior to an exam as the highest-ranking working style. Efficient use of time was the highest- ranking advantage. Some students found a very effective use of the tool by confirming physical laboratory work using the simulator prior to testing. The online setting provided the additional time to work and rework exercises however the results from the surveys fail to indicate that virtual laboratories can completely replace physical laboratories.

In the literature user interface, realism, individualization, storage capacity, social interaction, simplicity, multimedia features, help features and qualified technical staff were identified as important design considerations in virtual laboratories. Features identified in the surveys were the user interface, realism, real-time tutors, chat, online help, system response to errors, speed and reliability, message consistency, visual clarity, knowledge sharing capabilities, and individualized and group scheduling.

While social interaction is mentioned in the literature, real-time (or almost real-time) feedback and chat features are specific items mentioned by the students that do not appear in the literature. The use of error correction feedback was extremely important to the students as a design feature.

Discussion

The most important learning objectives for students were ***teamwork*** and ***learning from failures,*** skills that help students become more successful in the classroom and in their careers. Both the literature review and the survey results were consistent in finding that virtual laboratories need to provide ***realism*** for students to meet their learning objectives. Beyond what is currently in the literature, it was also found that students prefer to have online tools for communicating with their tutors and they would prefer that ***the interaction be in real-time***. Both real-time interaction with tutors and real-time corrections to mistakes were important to students.

A new finding in this research was that the ***students preferred to use the virtual laboratory to prepare for examinations***, which is consistent with concerns regarding time management. Students may not have sufficient time in the physical laboratory to master the concepts being presented, or may have difficulties scheduling laboratory-based classes due to institutional resource constraints. Another important finding, suggested by the students, was ***the need for virtual laboratories to prepare them for real-world situations where virtual or remote skills are necessary***. As technology has improved, engineers have more opportunities to respond to hazardous, or otherwise dangerous settings by using virtual and remote tools.

From this research, it would be difficult to argue that virtual laboratories can completely replace physical laboratories, but the students were found to be effective at using the virtual laboratory to improve their learning and supplement their learnings to perform better on their tests. They also point out the need to learn how to develop skills using remote and virtual environments that are currently necessary in real-world environments (for example, hazardous situations).

From the literature and the survey responses and interviews, this suggest the development of design guidelines, which are still under development. In summary, these guidelines suggest that a successful virtual laboratory deployment should (i) enable sharing of knowledge and real-time feedback, (ii) enable options for individualized learning and group scheduling, (iii) provide an intuitive user interface that is simple and easy to use, (iv) provide visual clarity in the user interface, (v) provide speed and reliability, (vi) provide functionality for experimentation, (vii) provide consistent messages and message positioning, (viii) provide system responses to errors, (ix) provide realism, (x) provide real-time access to tutors, (xi) provide online help and (xii) provide an environment that supports the physical laboratory.

Limitations and Future Work

The surveys and interviews are specific to the participants and users of the laboratory in this research, so the findings must be understood as such. There are a wide variety of online learning systems that are tailored to different academic programs, where opinions of their usefulness may be much different. While there were no findings presented in this research that deviated severely from previous findings in the literature, it is possible that students and faculty that chose not to respond may have had much different responses than the students and faculty that did respond.

The measurement of realism in the virtual laboratory and how it is measured would be a useful area of research. Perception-based measurements may be useful, supplemented by quantitative techniques for calculating the deviation of a virtual environment from a physical environment. As commercialization of the tools increases, a standardized measure of realism could be developed.

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