International Journal of Business, Human and Social Sciences
ISSN: 2517-9411
Vol:11, No:1, 2017

The Importance of Student Feedback in Development of Virtual Engineering Laboratories

A. A. Altalbe, N. W Bergmann

***Abstract*—**There has been significant recent interest in on-line learning, as well as considerable work on developing technologies for virtual laboratories for engineering students. After reviewing the state-of-the-art of virtual laboratories, this paper steps back from the technology issues to look in more detail at the pedagogical issues surrounding virtual laboratories, and examines the role of gathering student feedback in the development of such laboratories. The main contribution of the paper is a set of student surveys before and after a prototype deployment of a simulation laboratory tool, and the resulting analysis which leads to some tentative guidelines for the design of virtual engineering laboratories.

***Keywords*—**Engineering education, electrical engineering, e-learning, virtual laboratories.

I. Introduction

UNTIL the last few decades, remote study had typically involved undertaking courses by correspondence, mostly by postal communications. Television allowed selected lectures to be delivered, while radio or telephone communications allowed real-time communications between some students and teachers.

In recent years, the Internet has revolutionized both remote study as well as campus-based study. For on-campus students, paper handouts and lecture notes transcribed from blackboards have been replaced with on-line repositories of lectures notes, and PowerPoint slides. Lectures are regularly recorded and are available for playback and review. Quizzes are conducted on-line. Essays and assignments are submitted on-line, and results returned on-line. Library resources are also available on-line.

The boundaries between on-campus and remote students have been blurred by Internet technologies, and the learning experience is becoming very similar. As the university student body is dominated by digital natives for whom the Internet is a regular part of their lives, the boundaries between physical and virtual meetings and activities become increasingly blurred. There is an increasing availability of on-line course offerings across many different disciplines, including the establishment of completely on-line degree offerings at many universities.

Interestingly, technologies which are essential for the delivery of remote courses, such as recorded lectures and on-line assignment submission, also end up being useful alternatives or additions to campus-based learning. There are, however, many activities in campus-based programs which are difficult to replicate in an on-line environment. In humanities courses, the small group tutorial is problematic. Either synchronous web-based voice discussions, or chat rooms, or asynchronous bulletin-board discussions achieve similar aims, but the learning dynamic is different. Clinical learning, especially those involving psycho-motor skill development would be difficult or impossible on-line.

The focus of this paper to investigate the on-line offering of engineering laboratories in the domain of electrical engineering, and particularly, to explore the importance of gathering student feedback at various stages of design and development, and lastly, provide guidelines inferred from this research that may be used by future developers of engineering virtual labs.

II. Background

A. Remote, Simulation, Virtual and Physical Labs

The terminology around on-line access to engineering laboratories is not consistent across the literature, and so the first step is to introduce the terminology used in this paper. In all cases, we are speaking here about 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 who are supervised and assisted by laboratory demonstrators.

A *Remote Laboratory* is where students still 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 [1]. 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 particular 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.

B. Previous Work

Academic education practices vary from one discipline to another. Engineering is unique in that it is both an objective hard science as well as one that often requires practice-based

A. A. Altalbe and N. W Bergmann are with the School of ITEE, University of Queensland, Brisbane, Australia (e-mail: a.altalbe@uq.edu.au, n.bergmann@uq.edu.au).

learning through the use of physical equipment [2]. Students are required to demonstrate their ability to correctly use equipment to perform experiments.

While simulators are used substantially as part of the learning experience in universities, Feisel and Rosa [2] found the focus in using these simulators is in circuit design, not as a replacement for laboratories.

Balamuralithara and Woods [3] reviewed virtual laboratories in 2009, but found that current systems had severe limitations. Simulations were very simplified, and user interfaces were rudimentary.

Ertugrul [4] in his analysis of virtual laboratories concludes that the traditional physical laboratory based approach has limitations that are keeping students from developing a complete understanding of the concepts and thereby correlating theory and practical, and virtual laboratories have significant potential advantages.

Many universities are choosing to develop their own virtual laboratories; however, Grimaldi and Rapuano [5] found many of these tools experience disparity in design, and require extensive customized development and suffer from issues in integration with Learning Management Systems. In an effort to resolve these issues, there have been a number of initiatives over the past decade that aims to increase cooperation in the delivery of virtual laboratories.

LabShare [6] is a project that is headed by the University of Technology, Sydney, and is a joint initiative of members of the Australian Technology Network of Universities. This LabShare project aims to provide a network of laboratories which could be shared and accessed remotely by member universities and others. This will translate to allowing greater access to high-quality laboratory experimentation for both high school and university students around Australia and internationally. However, there are concerns regarding its ability to obtain grants and to expand to cover the virtual laboratory requirements of all universities [6].

WebLab-Deusto [7] is an open source project that offers the provision of an experiment-agnostic, expandable infrastructure of software, and can help to access a range of laboratories over the Internet by the students of Deusto University. It is however limited in that it caters to the needs of Deusto University curriculum and is not easily customizable for the specific requirements of other universities, although it is potentially feasible and inexpensive to do so [8].

I-Lab Shared Architecture [9] is an initiative of MIT that acts as a facilitator, allowing for new remote laboratories to be developed quickly and extensively deployed. It provides a medium for inter-university access to experiments and hardware instruments. However, it is a relatively complex package that requires substantial development time and expertise.

VISIR Laboratory is a remote laboratory system that is specific to the provision of online experiments relating to analogue electronics [10]. The experiments available include DC circuits, AC circuits, the use of function generators and oscilloscopes, and characterization of MOS transistors. The interface is quite similar to that investigated here, using a breadboard style interface, in this case connected to relatively expensive National Instruments switching systems to remote "connect" components together. There is a large body of literature describing the technology associated with the system, but very limited assessments of the system's effectiveness. One assessment showed positive impacts on student learning [11].

Another open source virtual laboratory framework is **OCELOT** "Open and Collaborative-Environment for the Leverage-of-Online-instrumentation" [12]. It is a web based middleware laboratory-framework that facilitates collaboration. It utilizes a combination of interactive multimedia and mixed reality. A key feature of this framework is the multiple delivery modes of "Graphic User Interface based on W3C widgets" to students.

LiLa [13] is a standard for Library of Laboratories. It is a project of the European "eContentPlus" initiative that facilitates the transfer of experiments and resources electronically between various educational institutions [13]. This is done through the use of an e-learning standard named SCORM. LiLa operates by packing the SCORM remote laboratories and launching the experiments with the help of JavaScript. It is not extensively used compared to other Virtual Laboratory systems.

As the above survey of existing systems show, there is substantial work in the development of virtual laboratories. However, investigation of the literature shows that the vast majority of the published work is about the technology of building such systems. In almost all cases, the goal is to replicate the physical laboratory environment more or less realistically. There is little, if any, investigation of the purpose of engineering laboratories, and very limited investigation of the effectiveness of laboratories.

So, rather than focusing on the technical issues associated with building and deploying virtual laboratories, this paper instead looks at the issues around the pedagogical design of virtual laboratories. It investigates the purposes of engineering laboratories, it involves students in the design requirements for a virtual laboratory experiment, it undertakes a short deployment of such a laboratory experiment and it evaluates student perceptions of such a laboratory as an adjunct to conventional laboratories.

III. Purposes of Virtual Laboratories

There are many reasons for the increased interest in virtual laboratories for engineering education. Firstly, it appears to be a general consensus that engineering laboratories are essential components of engineering education [2], and must be provided in undergraduate engineering undergraduate programs.

There are several different imperatives for providing at least part of this laboratory outside of the traditional physical laboratory [14]. Firstly, laboratories are a relatively expensive component of the cost of providing engineering education. The laboratory is almost always a separate teaching space, and in the case of very specialized experiments that space might be used for a small percentage of time. In the case of a more general purpose laboratory, there is time and staff needed to set up the correct equipment for the students.

The equipment itself is often expensive. In the case of rapidly changing disciplines, the equipment can quickly date and require replacement if the experiments are to be relevant for modern industrial practice. Especially in specialized areas such as integrated circuit manufacture and characterization, and microwave circuit and system design, the equipment can be very expensive and delicate.

Delivering the experiment requires laboratory technicians to setup experiments, demonstrators to assist students during the session, and perhaps other staff to mark student reports or check student results.

Often the experiments are restricted to a fixed scheduled class time, and there is no opportunity for catching up or reviewing experimental results outside the scheduled class.

Experiments may have workplace health and safety issues. Experiments on large electric machines involve high voltages and currents, and high momentum spinning masses, all of which can cause injury to inexperienced operators.

Experimental equipment is unpredictably faulty, especially as the equipment ages. Students may spend some or all of the laboratory fault-finding equipment faults or misconfigurations. While fault-finding is a valuable skill, it is better learnt by introducing known faults to the whole class, not random faults on random experiments to random students. Virtual laboratories seek to overcome many of these difficulties.

Large dedicated spaces for equipment co-located with students are not needed. For remote laboratories, a few copies of the equipment can be compactly set up to be shared by many, and for simulation laboratories only computers to access the laboratory are needed. No pre-lab setup is required.

Simulation laboratories allow expensive equipment to be replaced by inexpensive computer simulations. Remote laboratories allow one set of equipment to be shared by tens or hundreds of students. In both cases, the equipment (or its simulation) can be replaced by more modern versions at lower expense that for a room with many copies of the equipment.

Minimal reliance on technical staff is needed to set up experiments, and checking of results can be semi-automated. One issue that is still unclear is the extent to which the input of a laboratory demonstrator to assist students can be replicated in an on-line remote environment.

An enormous benefit of virtual laboratories is that they can be accessed at any time, and from any web-connected devices. This is an essential element for distance education, but is also often seen as a significant benefit when virtual laboratories provide an out-of-hours adjunct to existing physical laboratories.

Safety issues are considerably reduced with virtual laboratories, although this introduces a new challenge. One of the aims of laboratory work is to teach students to work safely, and learning this remotely is challenging.

Previously, we have investigated the learning objectives of engineering laboratories as a whole, and how well virtual laboratories can fulfil these requirements [15]. Areas like safety, group work, and psycho-motors skills are all more challenging a virtual laboratory environment.

IV. Design of Virtual Laboratories

To date, most remote laboratories appear to have been designed using a design specification of replicating the physical laboratory environment. We have not found a good set of guidelines for virtual laboratory system design.

In order to investigate this issue and determine some preliminary guidelines, an experiment was undertaken as follows. Firstly, a pre-design survey of potential student users identifies some key design issues. Next, a prototype tool is developed and deployed for optional use by students as an adjunct to their physical laboratory work. Then, a post-survey asks students again for their opinions, and finally, some preliminary guidelines are suggested. In this process, at each of the two stages of student data-gathering, the results were contrasted with the designers' expectations.

The tool developed was a breadboard simulation for first year circuit theory courses measuring current and voltage relationships in DC circuits.

A. Initial Survey

An initial survey was conducted to formulate the design of the software tool. The detailed survey results were previously presented in [15].

In general, students enjoy teamwork. They prefer doing practical work or laboratory experiments in a group during scheduled classes as they think it results in a better understanding of the subject and lets them share knowledge and discuss the subject with other people. Students also prefer teamwork because it enables them to receive instant support and real-time feedback, as also noted by Fruchter [16]. Most students are eager to work in groups for a few reasons, but the highest ranked reason is because they think it gives them better understanding of the topic. This option scored highest (25.31%) in the survey. The second highest reason for working in groups is because they like to share knowledge and discuss the topic among the group. A chat function also was desired by the students in the proposed software suggesting a desire to discuss their experiments with each other. In addition, the survey examined the objectives of working in a laboratory. Out of the total respondents 69% strongly agree and 23% agree (92% agreement) that laboratories help them to learn how to use the equipment. While 40% of respondents agree and 28% strongly agree that laboratories are helping them to develop the ability to design experiments. Finally, 4% remain neutral on this issue, 1% disagrees and 2% strongly disagree to this issue.

Lastly, we asked students about desired software characteristics for virtual laboratories. The responses are the functionality and reliability of the software, and how much it resembles real equipment. Also, students look for an intuitive user interface with high speed, responsiveness, stability and accuracy. They are also looking for live support and immediate feedback from their tutors. This initial survey assisted the developer to design the virtual laboratory according to the initial data provided by students. Before and while developing the tool, we considered all the preferences of students and all their requirements about the simplicity, closeness to reality, high speed and reliability of the software.

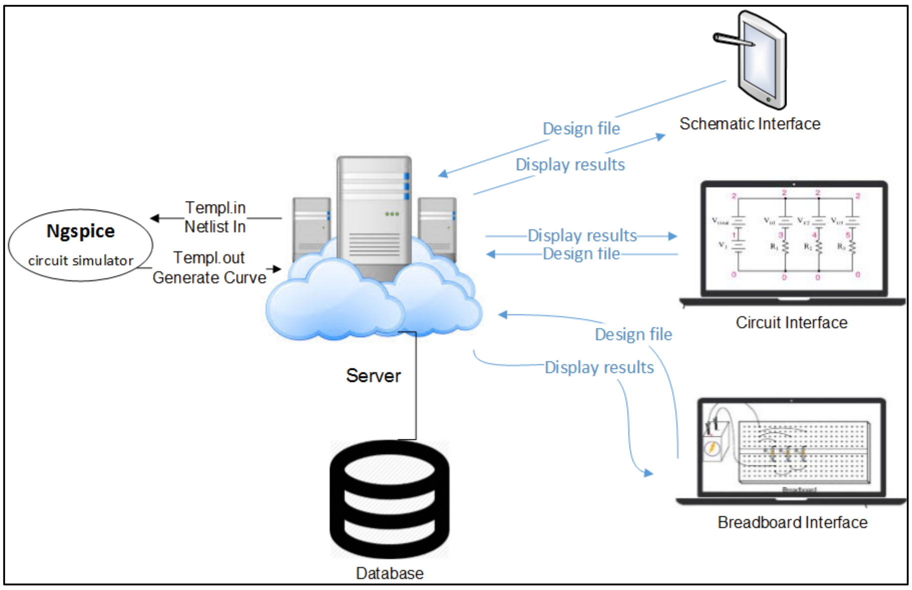

Fig. 1 Lifecycle of the simulation software

After developing the first version prototype of the tool, researchers informally asked students at the University of Queensland in Australia and King Abdulaziz University in Saudi Arabia (second semester 2015) to try the tool and give feedback. The responses from both cohorts encouraged deployment of the tools as a learning aid (voluntary use) in the first year Electrical Engineering class at the University of Queensland (500 students).

Points of agreement between student's perception and the designers expectations:

1. The designers expected a high importance to be attached to the role of laboratories in getting real-time feedback, developing critical thinking and looking at concepts from a different perspective.
2. The designers were not surprised by the fact that a relatively low importance was attached to the role of laboratories in supporting creative thinking in contrast to other advantages.
3. The researchers expected group work to play a significant role in the students' perceptions of laboratories

Points of disagreement between student's perception and the designers expectations:

1. The designers expected students to most value the advantage of a better understanding of the subject in considering the role of labs. However, not only was this not the most important advantage as per students perspective, it was not weighted nearly as high as expected by the designers (they expected over 50% in total weight).
2. The most significant take-away from this contrast was that the two options corresponding to working in scheduled laboratories far outperformed options corresponding to working on one's own time. Thus, more students actually preferred doing the laboratories as scheduled classes rather in their own time at home.
3. It was also surprising that group work was found to be the single most deciding factor. Students most valued the aspect of being able to share knowledge in their assessment of labs. However, it was not a unanimous choice, only that it was a preference of the highest weighted group.

B. Tool Design

Based on the initial survey the virtual laboratory prototype was designed to be a breadboard simulator for electronic circuits (DC based) and allowed students to connect components like resistors, diodes, LEDs, a power supply and a multi-meter on the given platform in a manner very similar to a real breadboard. It allows them to simulate the results in the form of currents and voltages based on real mathematical data and formulas based on the Spice circuit simulator. The app makes heavy use of modern web browser features like JavaScript, DOM manipulation, SVG graphics and AJAX.

The virtual electronic circuit simulation laboratory system is a process that enables users to assemble and simulate electronic circuit using SPICE3f5. Electronic circuit components were designed to be dragged and dropped into place in the schematic drawing.

The system uses three separate components.

1. A custom Java-based circuit editor that operates using an Internet browser, and generates circuit diagrams and netlists that can be stored in a database as *<any name>.cir*. After simulation, the interface displays the voltages and currents on a simulated multi-meter.

2. A web-server application running on a central server that communicates with the circuit editor running off the client machine. It converts the circuit into the correct format for Spice, transmits the results to the simulator, receives the simulation output back and sends the relevant data to the circuit editor.
3. A simulation package that is able to input circuit netlists and produces circuit waveforms, voltages, etc. In this case, Ngspice is used, which is based on three open source software packages: Xspice, Cider1b1 and Spice3f5. Users never access this package directly, only the web server does, and users do not need to know anything about the circuit netlist format used. Ngspice also runs on a networked server. Fig. 1 above illustrates how the system works.

The simulated circuit components are resistors (customized to any value), LED, Diode (using Spice models of the typical components used in our lab). These are sufficient for initial DC circuit experiments in the first year EE course. Fig. 2 below shows part of the interface of the tool. It shows a circuit consisting of resistors, diodes, LEDs, a power supply and a multi-meter. This view shows the post-simulation results when the voltage results from the simulation are indicated on the multi-meter.

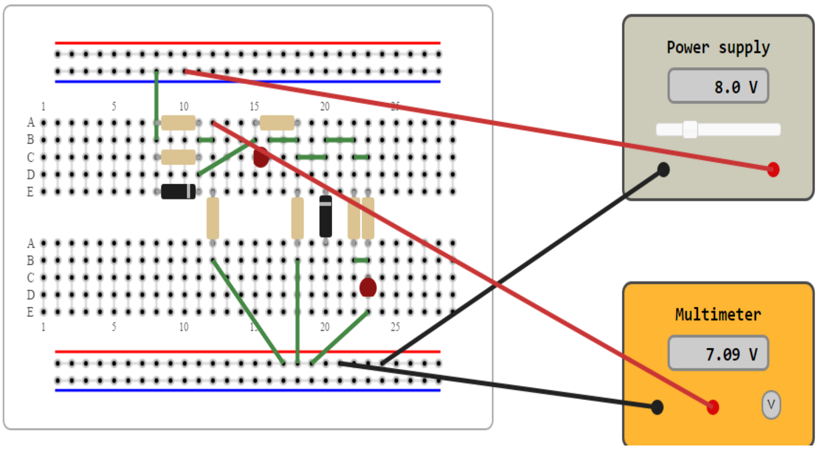

Fig. 2 View of the Simulation Tool Output

C. Post Survey

Upon the completion of the development of the virtual laboratory prototype, students were surveyed to provide feedback regarding the prototype's speed, complexity, handling, reliability and control. The virtual laboratory platform was used by a total of 120-140 students for the purpose of understanding the fundamentals of circuit implementation. The participants of the survey were asked to rate the virtual laboratory under different metrics. The data obtained as a result is displayed in the form of a bar chart in Fig. 3.

Selected students also volunteered to be interviewed. The interview process conducted as part of the survey comprised of a total of 12 questions that were asked to participants in the study. The questions are listed as follows along with an example response provided by one of the students at University of Queensland. His answers are typical of the interviewees.

1. How do you rate the overall performance of the simulation lab?

"Amazing! Because I don't need to take any physical risk in order to test and run the electronic circuit. So if I were to give it a rating out of 10, I will give 9."

2. Do you prefer face-face or simulation software to do experiments?

"Yes, I prefer both; however, simulation software could help in more ways. We can carry out experiments in simulation which may not be done physically so fast. Sometimes due to a lack of time in laboratories we can't carry out experiments on them, but with this simulation tool I can work anytime and anywhere, and with any kind of components which are available (For example, I can do some experiment before my scheduled class or even at 4.00 a.m.)."

3. Is it easy to use the user interface? What suggestions would you offer?

"I think the simulation can be improved but the 'Drag and Drop' method is best for me. I can simply pick a resister or any other components; it's like a real experiment that we do in my college lab. A suggestion from my side is that the quality of the images can be improved and make it more real with all dimensions. If we can see the circuit in 3D it would be more observable."

4. Did you find it easy to perform the experiment?

"Yes. As I mentioned, the 'Drag and Drop' method is the best and suitable method I have ever seen and experienced. We can set up the voltage easily rather than taking any kind of physical risk."

5. Did the information provided in the User Guide allow you to easily set up and run the experiment?

"Yes. It's clear cut and to the point. Once I had an issue about how to setup voltage and I got the solution easily."

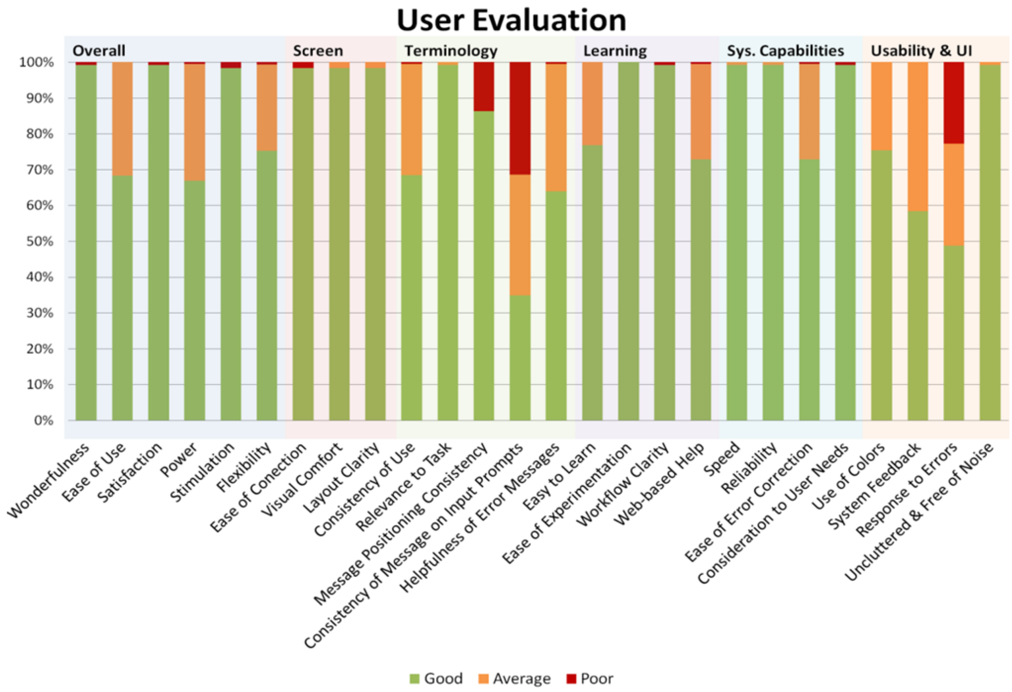

Fig. 3 Summary of Post Survey Metrics

6. While you were using the simulation lab, did you feel like you were operating real equipment?

"Yes. The reason is that real kind of output! It shows exactly the same output as if we are doing experiment in real life."

7. Did the simulation laboratory help you understand the practical aspects of ENGG1300 (Introduction to Electrical Systems at the University of Queensland)?

"Yes."

8. Did the flexibility of the simulation laboratory allow you to fit the laboratory work into your schedule?

"Yes. I can use simulation in all ways that is given in laboratory work. I used simulation many times for many purposes. For experiments, laboratory work and other practice work. It helps a lot and save time as well."

9. Based on your experience using the simulation lab, do you prefer to use the simulation laboratory in the future?

"Yes. It saves time and money for me. I will use it in the future too because they keep updating components and other stuff related to electronic components. I wish that I could use all the components covered in my syllabus."

10. Any other comments??

"Keep improving operations and speed of it. There are so many other effects in circuits that you can improve like the aging effect for transistors. And also add many components as well."

11. What was the most important thing you learned from the breadboard online simulator?

"Complex circuit calculation. Once I was stuck to understand the Kirchhoff's voltage law in complex circuits and then I used simulation to understand. It made me understand so easily that I never forget the concept in future."

12. What did you think the learning objectives of the laboratory class were?

"To understand how circuit theorems work! It helps us to remember concepts for the long term. I defiantly recommended this tool to my other friends also, and the reason is its simplicity and reliability. For every experiment I would like to first implement my circuit on a simulator and then in actual world. It helps us to save money and time. It adds safety and minimises hazards."

Points of disagreement between student's feedback and the designer's expectations: It can be seen from Fig. 3 that although designers successfully implemented most of the technical requirements expected by the students, the following points showed a discord between the designer's expectations of what the students needed in the virtual laboratory and the evaluation of the prototype by the students. The students felt that the following aspects of the virtual laboratory required improvement:

- Message positioning consistency,
- Consistency of messages on input prompts, and
- Response to errors.

It can be seen that where the designer did not successfully address the needs of the prototype from the students point of view that all factors are related to messages and errors. From the point of view of the designer, the prototype was ready to launch. However, his perspective in this respect is clearly different from the students' perspective. More importantly, this discord has occurred despite receiving information from the students prior to the design of the prototype as to what technical features are important to address. Thus, not only is it important to gather perspective from students prior to design and development but also at various stages along the way.

V. Guidelines for Virtual Laboratories

Our investigations into remote laboratories are still a work-in-progress, and complete development of a set of guidelines is continues to be under refinement. However, we can present our tentative list of guidelines for virtual experimental design, acknowledging that their derivation so far is based on our anecdotal understandings of student responses.

Guideline 1. Decide how it is expected that the virtual laboratory will be used – as the primary laboratory experience or as an adjunct to physical laboratories. An adjunct should largely replicate the look and feel of the lab, and can rely on knowledge from those laboratories (e.g., what a power supply and a multi-meter do).

Guideline 2. Decide upon the relevant laboratory learning objectives that the tool is meant to cover, e.g. if it aims to teach fault finding, have a mechanism to introduce faults, if it aims to replicate real-world imperfections from theory include those in the model, and if it aims to promote group work have a chat facility.

Guideline 3. Provide lots of ways for students to learn how to use the tools – on screen help, example videos, intelligent design assistant (e.g. which identifies common errors like shorts, open circuits, unconnected terminals), occasional unsolicited hints or messages. Familiarity with modern computer games interfaces can provide many ideas.

Guideline 4. Decide how to provide help either on the tool, or on the fundamental theory that the virtual laboratory is illustrating. This might be bulletin boards or chat rooms. It might involve videos of "correct" solutions from the experiments.

Guideline 5. Think about how students can learn cooperatively with their peers using the tool. Chat boxes, audio links, screen sharing for collaborative circuits, sharing circuits, accessing circuits.

Guideline 6. If the experiment consists of data collection and analysis (e.g., plotting the response of a filter at different frequencies), think about how the tool might assist in collection, analysis and visualization of this data.

Guideline 7. Ensure that the user interface is intuitive and easy to use and easy to learn. Digital natives are used to good quality, reliable and responsive tools.

Guideline 8. Most importantly, involve the eventual users of the system (usually students) throughout the design process to suggest useful features and to identify areas for improvement.

VI. Conclusions

This paper presents an overview of the research work carried out in the field of virtual laboratories, the technical development overview of a new Virtual laboratory for Electrical Engineering students and the data gathered from students during this process. The research findings presented in this paper can be summarized as follows: Student perceptions can be useful to consider in the design and development process of virtual laboratories as the designer's perspective and understanding of requirements may differ from that of the students. Secondly, based on the researchers experience with the development and assessment of the virtual laboratories, it may be useful for future designers and developers to consider the tentative list of guidelines presented in the previous section.

Acknowledgment

The authors thank the students and lecturers of class ENGG1300 who assisted with the data collection for this study.

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