Virtual Engineering Laboratories: Design and Experiments

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ABSTRACT

This paper describes the creation and testing of computer-simulated laboratories for use in undergraduate engineering education. The design and implementation of a 'virtual laboratory' that closely mimics the capabilities of a physical laboratory is explained. Experiments that compare time and learning gains of students using physical and virtual laboratories are discussed. Experimental results indicate that students who use the virtual laboratory prior to a physical laboratory are able to complete the physical laboratory in a much shorter time, require less assistance, and also report that they are very satisfied with their laboratory experience.

I. INTRODUCTION

Introductory laboratories in engineering education are typically organized around groups of students learning to use instruments, taking measurements, organizing data, and plotting results. In electrical engineering, the first laboratory that students take is usually concerned with learning to use instrumentation such as oscilloscopes and voltmeters and with constructing simple circuits and making measurements. For decades, laboratories have been offered in electrical engineering that follow the paradigm of students spending an afternoon or an evening a week clustered around workbenches learning to use equipment guided by, more often than not, a teaching assistant. Students flounder, persist, and usually eventually complete the required assignments. The process requires too much time, students receive an uneven exposure due to team use of shared instruments, teaching assistants provide uneven instruction, and many universities cannot afford to maintain up-to-date laboratories equipped with the latest instrumentation. Our research has hypothesized that all these areas can be significantly improved by using computer-based laboratory modules as an integral part of the learning process. At the start of these experiments, we decided to investigate whether student use of virtual laboratories prior to taking physical laboratories would: 1) reduce time spent in the laboratory, 2) decrease students' requests for assistance (as an indication of improved skill, which could also reduce the need for teaching assistants), and 3) provide high student satisfaction with the laboratory experience.

This paper documents how a virtual laboratory was designed and implemented in an introductory electrical engineering laboratory, the experiments conducted to test the utility of the virtual laboratory as a pre-laboratory experience for the physical laboratory, and the results of these experiments.

II. BACKGROUND

The use of computers to facilitate education has been studied for over two decades. Early work in this field suffered from excessive amounts of time required to create learning modules (e.g., PLATO IV[1]). More recently, creation of authoring tools (e.g.,[2]) has very significantly reduced this time requirement. Authoring tools permit instructors to attend to the curriculum details and not programming. Most authoring tools however, only permit creation of combinations of screens of information and graphics for illustration, organized in a page-turning format* and coupled to questions about the material presented. This type of computer tutorial is not tremendously useful in engineering education in which interactive simulations are virtually a requirement for understanding how complex engineering systems work.

During the last decade, significant work has been conducted on intelligent tutoring systems (ITSs)[3]. ITSs add some 'intelligence' to computer-based training systems in the form of student modeling**, and improved knowledge communications by means of transparent domain knowledge and reactive learning environments[4]. This research has been part of the field of artificial intelligence and, as such, has not yet reached the maturity and simplicity needed to be widely used in engineering education. This immaturity poses difficulties for use of this technology in engineering education in which simple and direct solutions are needed for computer-based learning to become a reality. Due to decreases in computer costs coupled with increases

*Or card turning (e.g., hypercard-style systems).

**Student modeling is concerned with representing what the student knows, doesn't know, and which misconceptions are present. Student models are used to guide coaching, the presentation of lessons, testing level, help, etc.

in computer power, solutions appear now to be feasible due to the appearance of new software paradigms that will permit engineering instructors to easily create computer-based learning modules. For example, Visual Basic[5] permits construction of high fidelity tutorial systems that include interactive simulations that can be created rather quickly using graphical methods for building interfaces, and simple code generation using an event-driven paradigm.*

While there has been significant progress in building computer-based tutorial systems in many different areas (for example, see Wenger[3], progress has been less robust in engineering education. There are notable exceptions, however. For example, Oakley[6] has created a computer tool called 'CircuitTutor' for presenting exercises about electronic circuits in a hypertext format. Hollabaugh and Allen[7] have created a laboratory bench emulator also in a hypertext environment. Work at Vanderbilt has probed how to best use tutorial systems in engineering education. For example, investigations on multimedia and anchored instruction in engineering education[8], team learning using computer simulations[9], and tutorial building systems[8, 10] have taken place.

A working hypothesis for research on tutorial systems is that computer-based instruction can have a significant impact on the way instruction is delivered in the future. Both lectures and laboratories should retain a role in future educational scenarios; that is, computer-based instruction is not expected to replace the current paradigms, but simply to facilitate the way that we teach now. The concept of reducing time and cost while improving student satisfaction and learning is key to efforts to improve engineering education. Hence, we sought a way to retain and improve the old paradigms by introducing change to modify the measurable metrics of time, cost, student satisfaction, and learning.**

The concept of studying the effect of introducing computer-based laboratories as pre-laboratories for physical laboratories was chosen for several reasons. First, since physical laboratories provide essential learning experiences in engineering education, we decided to study how computer support could improve this experience. Second, we hoped to show that the time needed for learning how to use a physical laboratory could be reduced by utilizing a virtual laboratory as a pre-laboratory. Success in demonstrating this effect would permit us to argue that physical laboratory costs could be reduced (i.e., by decreasing the time requirements for teaching assistants and the demands on the physical laboratory). Third, we hoped to learn which knowledge and skills virtual laboratories could facilitate. Fourth, we hoped to determine if the use of virtual laboratories would improve student abilities to use a physical laboratory and what level of satisfaction students would attribute to using the virtual laboratories.

Engineering education in the future surely will be heavily facilitated by computers-in classroom instruction, laboratory instruction, and for learning outside structured academic formalisms. Decreases in the cost of computers coupled with increases in computer power and portability virtually guarantees that computer-facilitated learning will become a central issue in engineering education in the upcoming years. Most students will have their own computers, just as every student in the past had a slide rule or calculator. Hence, it is incumbent on engineering educators to understand how to use this technology for educational purposes.

*An event-driven paradigm couples events in a program, such as a button press or mouse movement, to a specific set of code.

**It is worth noting that these metrics are the key metrics for 'quality improvement' (11).

III. Virtual Laboratory Design

A virtual laboratory (VL) is a simulation of a physical laboratory, created for the purpose of providing instruction to students in the use of laboratory facilities. VLs are computer-simulated laboratories that look, operate, and produce results similar to real laboratories. The VL concept is derived from ideas in the research area known as virtual realities (VRs)[12]. In VRs, computer simulations attempt to duplicate experiences in the real world. By using computer methods to stimulate the visual, auditory and touch senses, one can experience simulations of environments that do not exist or are similar to situations that do exist in the real world. Physically immersive VRs are computer-generated by using high speed presentation of scenes fed to 3D rendering views (e.g., in a helmet), spatial sound, and in some cases tactile feedback[13]. Typically hand, head, and body position can also be sensed and presentations coordinated with this information. To achieve physical immersion, the computer power required and attendant interfacing difficulties are formidable. Furthermore, the equipment required may be distracting and disorienting to the user.

Because of the problems cited above and the cost, our VL focuses on mental immersiveness without building a complete VR. It is: 1) sufficiently realistic that the user can easily recognize the environment, 2) relevant to the task domain and 3) interesting enough to engage the user's attention and participation[(13)].

Even though there is significant research being conducted on VRs, there is little evidence, as yet, that educational VRs created in the same way would be really useful. Analogies to this line of inquiry, however, are potentially very useful to engineering education. We believe that the virtual laboratory offers the possibility of significantly improving the undergraduate laboratory experience. Several reasons for using VLs in engineering education can be cited: 1) VLs can provide students with experiences that often cannot be achieved in a real laboratory because of a lack of expensive equipment. 2) A VL can provide a precursor experience to a physical laboratory. Students can use VLs prior to working in a physical laboratory, thus gaining valuable experience and understanding in a self-paced format where complexity can be controlled (e.g., by providing components that are fully functional versus those that are degraded or failed, such as a broken connector). 3) The cost of operating physical laboratories can be decreased due to a decrease in the amount of physical laboratory time required. 4) VLs can provide on-line help and guidance during learning about laboratories. The student can obtain immediate help from a software coach at any time, day or night, instead of waiting for a teaching assistant to finish with another student during laboratory hours.

During 1992, we created an example VL and have been experimenting with understanding how to use the capabilities of VL in the education of sophomore engineering students[14]. The general finding, to date, is that VLs increase understanding of the operation of laboratories and reduce the amount of time that students require in physical laboratories to learn the same amount of material.

A. The Laboratory Environment.

Figure 1 displays the opening screen of the tutorial system created. The laboratory consists of eight experiments ranging from introducing the student to how to use the equipment to building a resonance circuit and active filters. The computer-based laboratory was created to duplicate an actual electronics laboratory that has been given for many years at Vanderbilt University as an initial practical experience with electrical circuits. The computer environment created consists of a high fidelity simulation of the physical environment embedded in a computer-structured copy of the original, physical laboratory curriculum.

After an introductory tour of the laboratory procedure, the student can elect to work the first laboratory or to go through a step-by-step tutorial. Tutorials are implemented for the components (i.e., resistor, capacitor, and inductor) and the instruments (breadboard, function generator, and oscilloscope). The component tutorials provide very basic information on how to select component values. In the case of resistors, after completing the tutorial, the student is asked to identify the specific value of a resistor from its color code. For the function generator and oscilloscope, the tutorial provides the name, location, and function of each control and indicator for both instruments. This method draws attention to key features of each instrument and shows how the features are used in the laboratory environment[15].

Problem statements are presented in dialog boxes to guide the student (see Figure 2). The student must complete each part of the problem and have it checked, before moving to the next topic. If a tutorial section is not completed correctly, an explanation is provided in the form of a concise informative message. Detailed help can be invoked by choosing either the Demo or Problem Assistance selection, described below.

After reading the problem statement, the student uses the

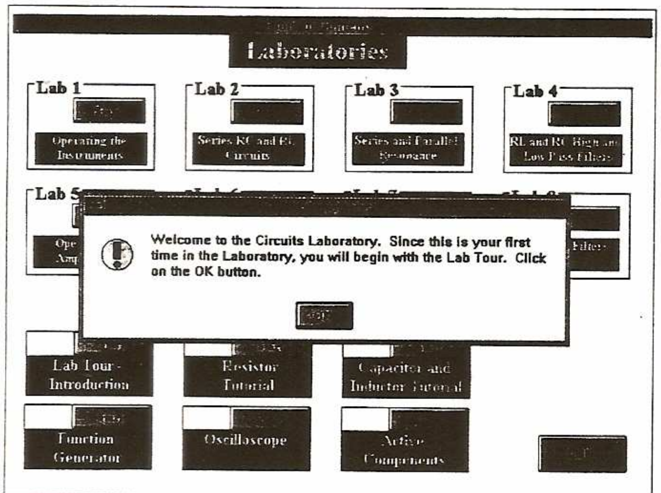

Figure 1. Opening screen of the laboratory tutorial, including Table of Contents.

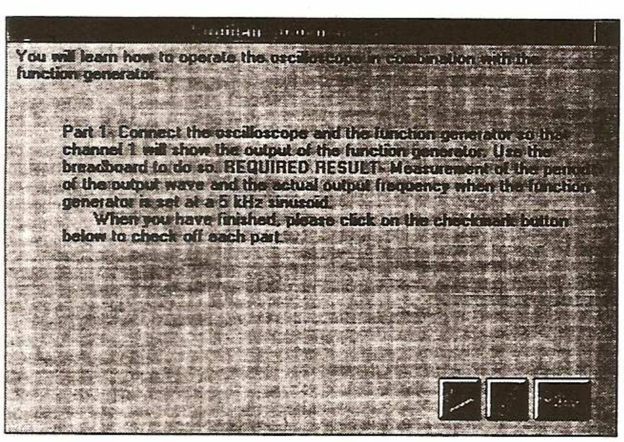

Figure 2. The problem statement.

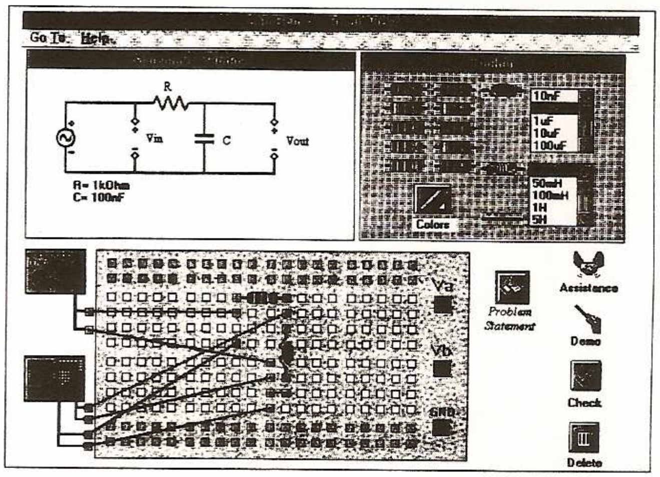

Figure 3. The Circuit View containing the simulated work bench.

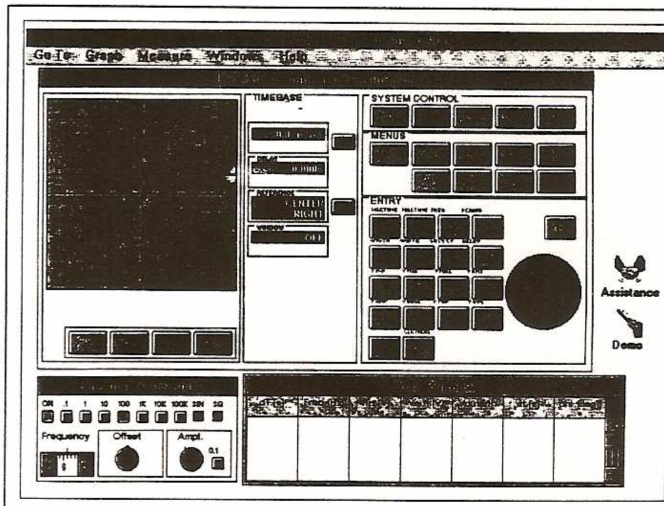

Figure 4. The Measurement View, containing simulated instruments for taking measurements.

workbench provided in the Circuit View to build the desired circuit (e.g., see Figure 3). Upon completion, the student moves to the Measurement View, which provides full function simulations of the instruments needed to take the measurements as shown in Figure 4. The environment also facilitates recording measurements and plotting of data (e.g., semi-log graphing of the transfer function of a low-pass filter). The views appear on different screens because typical monitors are not large enough to show both simultaneously.

B. The Help Facilities.

At any point, the student can request a guided demonstration of how to use the laboratory environment that shows the actions to be taken, their locations, and the result (see Figure 5). This facility essentially replays the moves of an expert using the system. The student can also request personal assistance, which provides an elaborate hypertext-organized, context-sensitive help. Help is formatted as a checklist that provides the student with a step-wise expert strategy to solve the problem. The student can acquire more detailed information on each step using hypertext (Figure 6).

We are also investigating software-initiated messages based on the constructive modeling approach[16]. A compilation of known mistakes made by students (e.g., measuring half a period of a wave form) is kept, triggering a software response when the corresponding events are generated. Research is continuing to improve the system by adding student modeling as well as Topic Assistance that explains the theory behind a given topic (e.g., what frequency is, and how it relates to the period of a wave). Affinity diagrams[17, 18] are used to analyze the categories of problems students have and the relative effects of virtual and physical laboratories in addressing the problems. This work will be reported in a subsequent paper.

C. Implementation.

Using Visual Basic[5], we implemented the computer-simulated laboratory in three layers. The top layer coordinates the selection of a specific laboratory experiment from the Table of Contents. This controlling layer is implemented as a stand-alone executable program that communicates with an Access[5] database that stores information about each user, including which parts of each laboratory experiment have been completed. We also created two lower levels for each laboratory. We compiled these labs into executable files. Each lab communicates with the Table of Contents via a dynamic data exchange (DDE) link.

Each laboratory contains a set of library forms (visual representation) and modules (program code) as well as a problem statement and a model of the specific laboratory experiment. The Problem Statement module is a general template that displays information about the problem for each laboratory exercise. It coordinates circuit and measurement view selection by keeping track of the specific sub-problem a student is working on. The laboratory module contains the model of the circuits to be built and their corresponding equations. The third layer consists of the simulated environment (the circuit view and the measurement view which are the same for all laboratory experiments). In addition, we provide stand-alone executable programs for the demonstration and help files created with Microsoft's Help Compiler 3.1 for problem assistance[5].

IV. Method

A. Subjects.

Subjects were student volunteers from a sophomore electrical engineering course on introduction to electrical circuits. Twenty students volunteered from a class of 50. The experiments described were conducted near the end of the Spring semester; hence students had already secured a rudimentary grounding in the theory of electrical circuits. No students had yet taken a laboratory course on this topic.

B. Apparatus.

The VLs were implemented in Visual Basic 2.0 for Windows. The laboratories will run on any PC that runs Windows and Visual Basic. However, the program is slow on 386/25 or less capable machines. Performance is quite satisfactory on any 486 system. The VL is easily extensible and inte-

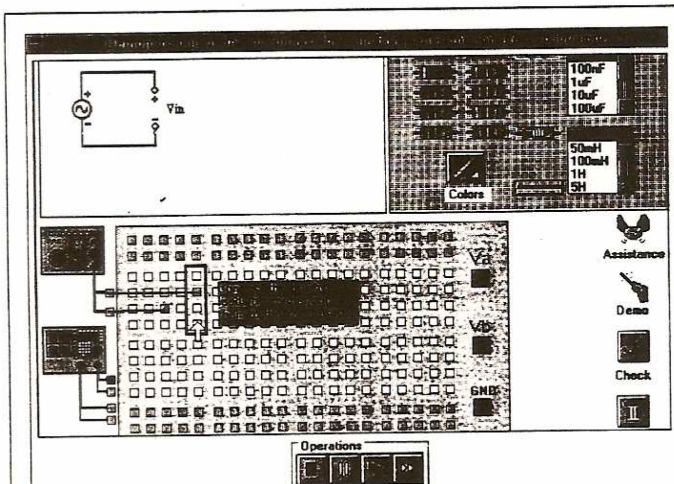

Figure 5. Demonstration of the laboratory.

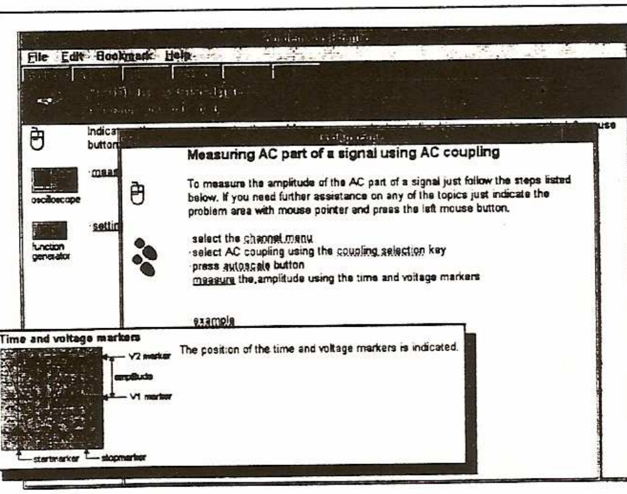

Figure 6. Problem assistance.

grates well with Windows. Assistance is implemented in Windows Help.

The physical laboratory (PL) consisted of one oscilloscope (HP 54501A Digitizing Oscilloscope), a signal generator (HP 3312A Function Generator), a breadboard for connecting components in the circuit, resistive, capacitive and inductive components, and connecting wires. The VL was constructed to mimic these same components. Any set of simulated components could be created to give students experience with different equipment models.

C. Procedure.

Students were randomly assigned to two groups of ten students each. One group took the virtual laboratory first and the physical laboratory next (VL-PL); the other took the laboratories in reverse order (PL-VL).

Two graduate students, who served as trackers, monitored the students and collected data, tracking each student during the sequence of both of the labs. The trackers were carefully cross-trained to insure comparability between the results. For each of the described groups, the trackers recorded the time in minutes to complete a laboratory, the number of requests for assistance made to the tracker, and the type of problems each student encountered. When a question was asked, the topic was recorded as a problem. However, students often overcame problems that the tracker had noted, without asking a question.

In the physical laboratory, the tracker also acted as a teaching assistant (TA). This resulted in each student having a personal TA. When the student needed help, the TA was immediately available to assist - a situation that would not occur in an actual laboratory in which a TA would be shared between 10 to 20 students. When students requested help in the virtual laboratory, the trackers redirected them to the built-in assistance facilities.

V. Results

A. Quantitative Results.

Table 1 summarizes the results of the data collected from students who participated in the experiments. The important comparisons are between the time required, and the number of requests for assistance when students took the virtual lab before the physical laboratory versus taking the physical lab first. As shown in Table 1, students taking the physical lab first required 73% longer mean time, with $t(18) = 4.14$, $p < .01$. They also had a mean of 152%* more questions asked of the teaching assistants, with $t(18) = 4.99$, $p < .001$.

The mean of the total time to complete the combined virtual laboratory followed by the physical laboratory was longer than the mean of the total time to complete the physical laboratory alone in this study. We also note that there is no significant difference in total time to complete both labs, depending on whether a student begins in the VL or the PL. These values, however, were acquired with a TA sitting by the student's side in our experimental sessions. In a physical laboratory setting with multiple students at multiple workbenches, asking multiple questions-the typical laboratory setting in engineering education today-there is no doubt that the physical laboratory time would be similar to what we typically experience from year to year. This time is approximately 180 minutes. To expend 180 minutes in a laboratory that requires 80 minutes on the average with an individual TA-and could take about 45 minutes when students are well prepared by a virtual laboratory-indicates that students are spending unnecessary time reading and receiving instructions, setting up equipment, floundering, getting and receiving help, sharing equipment, and waiting.

In contrast, the virtual laboratory prepares students individually and permits them to complete the laboratory in a much shorter time period. Taking the virtual laboratory prior to taking the physical laboratory permits the time spent in a physical lab to be reduced by almost half. Further, questions asked of the TA are dramatically reduced-a benefit for student, faculty and administration alike.

B. Student Satisfaction.

The responses made by the students to the question on the exit questionnaire, "what is your overall impression of the virtual laboratory?" showed a consensus on the helpfulness of the software, comments included: "I was very impressed and thought it was very easy to use and very helpful"; "Very good concept and I think it will help students"; "It was confusing but helpful," and "This is a wonderful way to help a lower level EE student who has never had hands-on contact with actual equipment." Another aspect that was noted by the students was the immediate feedback provided in the virtual laboratory. When asked what was the best part of the virtual laboratory comments from both groups included statements like, "It did not let you go on until you completed a section correctly"; "you know immediately if you are correct or not," and "the constant reminder of screw-ups." Furthermore, students tended to feel more at ease working with the physical equipment after exploring its functionality in a virtual environment: "The program made me feel more comfortable working with the actual instruments"; and "I could figure out what was going on myself by using the computer, instead of having to go and bother someone to explain it to me." Also, the students found the overwhelming number of controls and indicators to be less

	Virtual Lab Taken First		Physical Lab Taken First	
	Time (Minutes)	Assistance (# Times)	Time (Minutes)	Assistance (# Times)
Physical Lab				
M	46.30	5.90	80.10	14.90
SD	13.91	4.23	21.72	3.84
Virtual Lab				
M	100.30	8.10	80.70	7.10
SD	19.24	4.79	13.22	2.77
Overall				
M	146.60	14.00	160.80	22.00
SD	23.27	7.70	28.20	5.14

N=10 for both virtual lab taken first and physical lab taken first.

Table 1. Mean time required to complete a laboratory exercise and mean number of requests for assistance made during the laboratory.

*Percent increase in time = (80.1/46.3)-1. Percent increases in number of questions = (14.9/5.90)-1.

intimidating in the coached virtual environment. Finally, students felt they had a better understanding of the material. When asked what they learned from the virtual laboratory, answers included: "I think I learned more about oscilloscopes and function generators today than I have learned my entire time at college"; "It reminded me of what I'm actually measuring when I measure peak to peak voltage. . .the reminders made it hard for you not to understand why you made your circuit connection"; and "I could better understand what was actually happening."

C. Qualitative Observations.

When investigating areas of improvement between the labs, the trackers frequently observed that students who took the physical lab first made a wider variety of mistakes in the virtual lab than students who took the virtual lab first. It may be that students developed a certain amount of sloppiness that was not tolerated in the strict virtual environment. For example, not returning to zero offset, though requested, does not result in an explicit erroneous measurement when in the physical lab. The virtual environment however, ensures that the instruments are set up correctly.

The trackers also observed that theoretical topics that caused difficulties in the virtual lab decreased for students who had taken the physical laboratory first, while there was no corresponding effect in the physical lab after taking the virtual laboratory. This difference might be explained by the fact that when a student ran into a problem in the physical lab, the TA embedded the answer into the underlying theory, while the virtual laboratory software did not (because it was assumed students would already have mastered the theory). These results are indicators that help evaluate which factors in each laboratory can decrease student problems in subsequent versions of the virtual lab.

D. Field Study.

In addition to the experiment described above, during Fall semester of 1993, the VL was used by all 49 students enrolled in the first class in Electrical Engineering. Students used the VL in an open computer laboratory for undergraduate students using a networked version of the VL software. Data about the time used to complete each part of the laboratory and the number of times a student failed to move to a subsequent section were automatically logged in a central database. After the laboratory, students were asked to fill out a questionnaire. Excluding two students who had taken the VL previously, results show a mean time required to complete the VL of 108 minutes with a standard deviation of 52 minutes. These values are similar to the mean time of 100 minutes found in the more controlled experiments described above. However, there is a much larger standard deviation. Four possible causes for this difference can be identified: 1) in the original experiment, the sample population of 20 volunteers out of a class of 50 could have resulted in a more uniform sample, 2) when individually working in the computer laboratory, students may have chosen to experiment more than when being observed continuously by the trackers, 3) students did not necessarily work the laboratory in one session, consequently adding restart times when re-entering the VL and 4) from time to time, the network would be slow, causing waiting time for some of the students.

For this particular course, the model of the oscilloscope used in the physical laboratory differed from the one in the VL. Nevertheless, the comments on the questionnaire were very much like the ones found in the experiment: "Time was saved because you can check your answer immediately without having to wait for the TA to answer question"; "By the time I got to the [physical] lab I knew what I was doing . . ."; and "The setup of the lab was helpful." Overall, students felt that the VL had helped them develop their knowledge and skill.

VI. Discussion

The results of the evaluations of data taken in these experiments support the initial hypotheses proposed. First, the time students take to complete physical laboratories is significantly reduced by first taking a virtual laboratory. Although the mean total time to take both laboratories is not significantly affected by the order in which the laboratories are taken, virtual laboratories can be taken on a student's own time, thus freeing the physical laboratory to accommodate more students or reduce the need for staffing of laboratories with teaching assistants. Second, requests for assistance using instrumentation in the physical laboratory were reduced by having the virtual laboratory completed first. The reduction in requests for assistance indicates a better comprehension and skill of using the instrumentation. Third, student satisfaction with the overall experience was high.

The field study showed similar results. An important observation is that students felt that the VL was helpful even when using a different oscilloscope model. However, we feel that the best results will be obtained when the VL is equipped with the same instruments used in the physical laboratory. This need can be satisfied by establishing a library of a variety of types of instruments.

There are many interesting anecdotal incidents that occurred during the course of these experiments. For example, some students who took the virtual laboratory said that this was the 'first real engineering experience' that they had experienced. This type of statement is interesting since this laboratory was a virtual experience-they only thought it seemed real. This anecdote, however does point out that simulated laboratories probably can enhance many physical laboratories, if the fidelity of the simulation is sufficiently high. If simulated laboratories can substitute for physical laboratories, then we can attempt to mimic situations that cannot be easily obtained in a physical laboratory in a university. For example, a physical simulation of a control room at a complex nuclear engineering plant would be nearly impossible to have in an academic setting, but would be feasible to create in a virtual laboratory environment. Virtual laboratories may also make access to "hands-on" experience more widely available in rural settings and with groups that are under-represented in the engineering profession.

The outcomes of this research indicate that a virtual laboratory given as a pre-laboratory to a physical laboratory can significantly decrease the amount of time and the number of requests made for help from a teaching assistant. This result, in itself, is very significant in that one can argue that it would be important to implement VLs as precursors to PLs in order to save money and improve student understanding of laboratories.

Through the experiments described here, we have initial evidence to support our hypothesis that a computer-based virtual laboratory can improve student understanding while decreasing time and providing high student satisfaction with the learning experience. Given the high probability that all engineering students will have a computer in the near future, it now seems possible that we have a clear basis on which to recommend the utility of virtual laboratories as adjuncts to physical laboratories.

VII. Acknowledgments

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VIII. References

1. (CERL (Computer-Based Education Research Laboratory), "Demonstration of the PLATO IV Computer-Based Education System," Final Report, University of Illinois, Urbana-Champaign, Illinois, 1977.

2. Macromedia, Inc., Authorware Professional for Windows, 600 Townsend St., San Francisco, CA, 94103.

3. Wenger, E., *Artificial Intelligence and Tutoring Systems*, Morgan Kaufmann Publishers, Los Altos, CA, 1987.

4. J.S. Brown, R.R. Burton, and J. de Kleer, Pedagogical, *Natural Language, and Knowledge Engineering Techniques in SOPHIE I, II, and III* in Intelligent Tutoring Systems, edited by D. Sleeman and J.S. Brown, Academic Press, London, UK, 1982.

5. Microsoft Corporation, One Microsoft Way, Redmond, WA, 98052-6399.

6. Burks Oakley II. "Computer Aided Instruction: Implementation of Interactive Tutorials for Introductory Circuits Analysis." *Proceedings: New Approaches to Undergraduate Engineering Education III*, July 1991, pp. 189-202.

7. C. Hollabaugh and P.E. Allen, "PC-Based Interactive Computational Server for Educational Purposes." *Proceedings: Frontiers in Education*. July 1992, pp 38-42.

8. Bourne, J.R., Brodersen, A.J., Cantwell, J., Debelak, K., Kinzer, C., Koussis, A., Haden, G., van der Molen, H., and Droes, S., "Intelligent Hypertutoring: Investigation of Intelligent Tutoring Systems for Use in Undergraduate Engineering Education," *Proceedings of New Approaches to Undergraduate Engineering Education III*, pp. 301-312, July 28-August 2, 1991.

9. Bourne, J.R., and Brodersen, A.J., "The Virtual Engineering Reality: An Introductory Freshman Engineering Course," *Proceedings of the Undergraduate Engineering Education IV Conference*, Santa Barbara, California, July 26-31, 1992.

10. Campbell, J.O., and Andrus, G.R., "Cutting Development Time for Computer-Based Instruction," *Proceedings of the Ninth Annual Conference on Interactive Instruction Delivery*, Warrenton, VA, SALT, pp. 52-53, 1991.

11. Bourne, J.R., "Quality Tools: A Study of Japanese and Other Tools and Methods for the Improvement of Quality," Internal Report, Department of Electrical Engineering, Vanderbilt University, Nashville, 1992.

12. Rheingold, H., *Virtual Reality*, Summit Books, New York, 1991.

13. Encyclopedia of Virtual Environments, "Immersion," Internet ftp-site umd5.umd.edu in pub/eve, 1993.

14. Bourne, J.R., and Brodersen, A.J., "Anchored Instruction in Engineering Education," *Proceedings of New Approaches to Undergraduate Engineering V Conference*, July 25-30, 1993, in press.

15. Burow, Craig, "Computer-Aided Instruction in the Electronics Laboratory of the Future," Master's Thesis, Electrical Engineering Department, Vanderbilt University, December, 1992.

16. Barr, A., and E. Feigenbaum, The *Handbook of Artificial Intelligence*, Volume 2, William Kaufmann, Inc., 1982.

17. Tetsuichi Asaka and Kazuo Ozeki (Eds.), *Handbook of Quality Tools, The Japanese Approach*, Productivity Press, Cambridge, MA, 1990.

18. S. Mizuno, *Management for Quality Improvement: The 7 New QC Tools*, Productivity Press, Cambridge, MA, 1979.